Stress analysis and modal analysis of the largest bearing test rig in the world - Astraios

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Abstract: The use of renewable energy sources is being expanded strongly all over the world. Wind power plays an important role in this field. In recent years, the output of wind turbines has increased continuously. In such plants, the important mechanical components include bearings which, with increasing output, are becoming increasingly larger.

Therefore the Schaeffler Group took the decision to build the largest bearing test rig in the world. This makes it possible to strongly drive forward the development of large size bearings for wind turbine manufacturers. With a maximum bearing outside diameter of approx. 3.5 m, the highly versatile test rig can also be used to test all other large size bearings.

The principal objective was to ensure reliable design of the large size bearing test rig. The main challenge here concerned the simulation method for representing the complex mechanical construction of the machine with sufficient precision in an FE model. For this reason, and since only a short time was available for calculation, a simulation team was formed. Each team member was then assigned individual domains of the test rig. A further reason for the division into domains was the very large number of individual components. Since these had to be modeled precisely, the calculation models included numerous degrees of freedom. Due to the large number of load cases to be calculated, the limits of the available computing capacity were reached.

In simulation, the versatile options available in Abaqus for more efficient model creation were applied. For example, the rolling elements were modeled by means of user elements based on the specialist know-how of the Schaeffler Group. As a result, the precise stiffness behaviour of the bearings could be represented. In addition to volume elements, beam and shell elements were also used and suitably connected to each other. The Python interface was used within the framework of efficient modelling and for strength assessment. Through all these measures, the quality of results for the domain models was increased and the authoritativeness of the complete model was continuously improved. The work was made significantly simpler by the intelligent use of the integrative options in Abaqus CAE.

As a result of the simulation concept successfully carried out by the team, it was possible to achieve a reliable mechanical design of the individual components and the complete machine. At present, the test rig passes the first tests of wind turbine bearings successfully.

Keywords: Assembly Deformation, Bolt Loading, Connectors, Design Optimization, Dynamics, Elasticity, Fatigue, Postprocessing, Scripting, Shell Structures

1. Introduction

The large size bearing test rig was especially designed to test large size bearings (see figure 1) for wind turbines. Therefore it is called Astraios, who is a figure in Greek mythology. Astraios is one of the Titans and the father of the four Wind Gods.

This test rig is the most modern, largest and highest performing large size bearing test rig in the world. It can be used to test bearings with outside diameters of up to 3.5 meters. Realistic test conditions can be achieved due to a very comprehensive program for the control system that is available for the test rig. This is the reason why application-related functional tests can be carried out for the main application sector wind power. Due to its universal concept, Astraios can also be used for all other kinds of large size bearings.

During the design and construction time of two years, there was a very small time frame for the mechanical simulation. The combination of this short time schedule, the high complexity and the large number of parts of the test rig represented a major challenge for the FE experts of the Schaeffler Group.
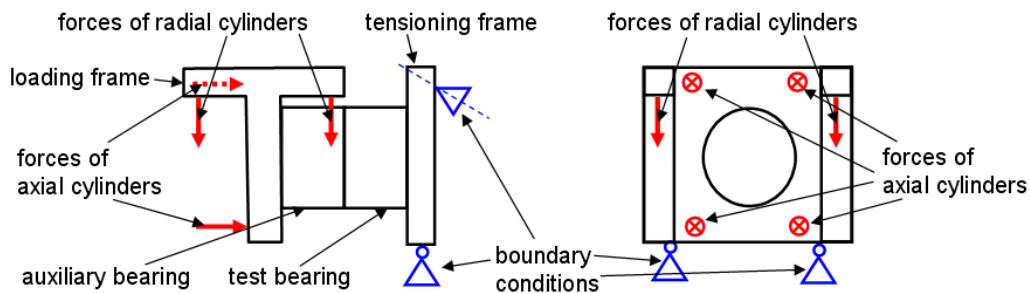
An overview of the large size bearing test rig and its calculation is presented here.

Figure 1: Large size bearing

2. Function and Benefits

The function of the large size bearing test rig (see Figure 2 and Figure 4) can be explained using the example of a wind turbine (see Figure 3).

Figure 2: Principal drawing of the large size bearing test rig

2.1 Function

In large wind turbines, the rotor and the hub weigh well over 100 tonnes. This weight acts on the bearing and generates a static radial load F_{rad} and a static pitching moment M_p (see Figure 3). The weight of rotor and hub is generated by radial cylinders of the test rig (see Figure 2 and Figure 4). Four 1000 kN radial cylinders generate the static radial load and the static pitching moment.

Wind is not a constant factor. It acts with varying intensity at different points on the wind turbine. The rotor blades of large wind turbines can sweep a surface area equivalent to two football fields. The wind generates both a static and dynamic axial load F_{ax}. These wind loads are generated by axial cylinders which are controlled using sinusoidal loads. Four 1500 kN axial cylinders generate the axial load.

When the wind acts on the rotor blades, this generates two types of moments (pitching M_p and yawing moment M_y), whose magnitude depends on the position of the rotor blades. With the rotation of the rotor, these two moments vary continuously, which means that they can be regarded as dynamic moments superposing the static pitching moment.

Both dynamic moments are also generated by the four 1500 kN axial cylinders which are controlled using sinusoidal loads. The yawing moment increases as the wind acts laterally on the turbine as a function of the rotor blade position. The pitching moment at the top or bottom of the turbine is increased by the action of the wind if the rotor blades are in a different position.

Wind turbines are constantly subjected to changing wind conditions - from calm weather to storms. The eight cylinders work together to simulate all the forces and moments that actually occur in a wind turbine.

2.2 Benefits

The first test rig of these dimensions worldwide is able to test large size bearings for multi-megawatt wind turbines. This makes it possible to design wind turbines with increased reliability and cost-effectiveness. The most important features of the new test rig are:

- Realistic forces and moments for wind turbines can be reproduced.

- It can be used for rotor bearings and slewing rings.

- All rotor bearing support concepts can be tested.

- The results of these tests are reliable since they are carried out under parameters that are representative of realistic conditions.

This contributes to a better understanding of the system, its influencing factors, and the relationships between them. On the basis of this new knowledge, the following improvements can be realized:

- Products can be optimized more easily.

- The friction of the bearing can be reduced.

- The design safety can be increased.

- Better instructions and recommendations for operating and maintaining the turbine can be given.

- Recommendations for an optimum adjacent construction can be given.
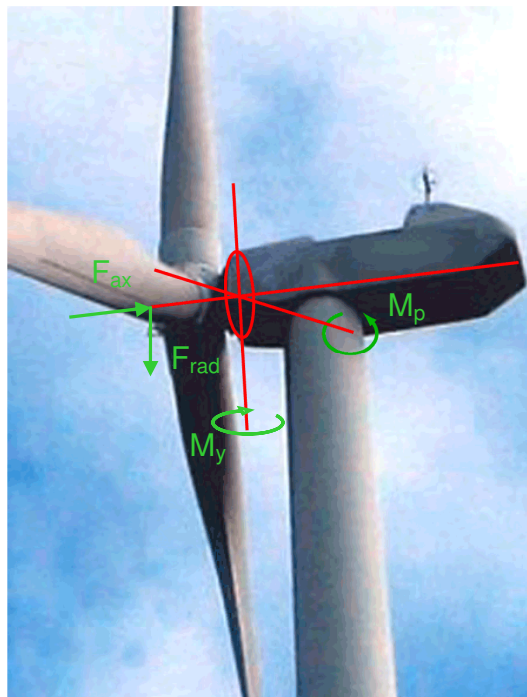
**Figure 3: Loads acting on the main bearing of a wind turbine**

3. Technical Details

3.1 Drive and auxiliary units

The drive and auxiliary units have a power capacity of 1 MW. It is possible to provide a variable lubrication with oil and grease for each bearing.

3.2 Measuring equipment

More than 300 sensors record data which is evaluated for various analyses. This data can be used, for example, for analysis of the kinematics, the temperature and friction behaviour of rolling bearings. In addition, the measurement data can assist in evaluating stresses and deformations, distribution of lubricant and the wear behaviour of bearings.
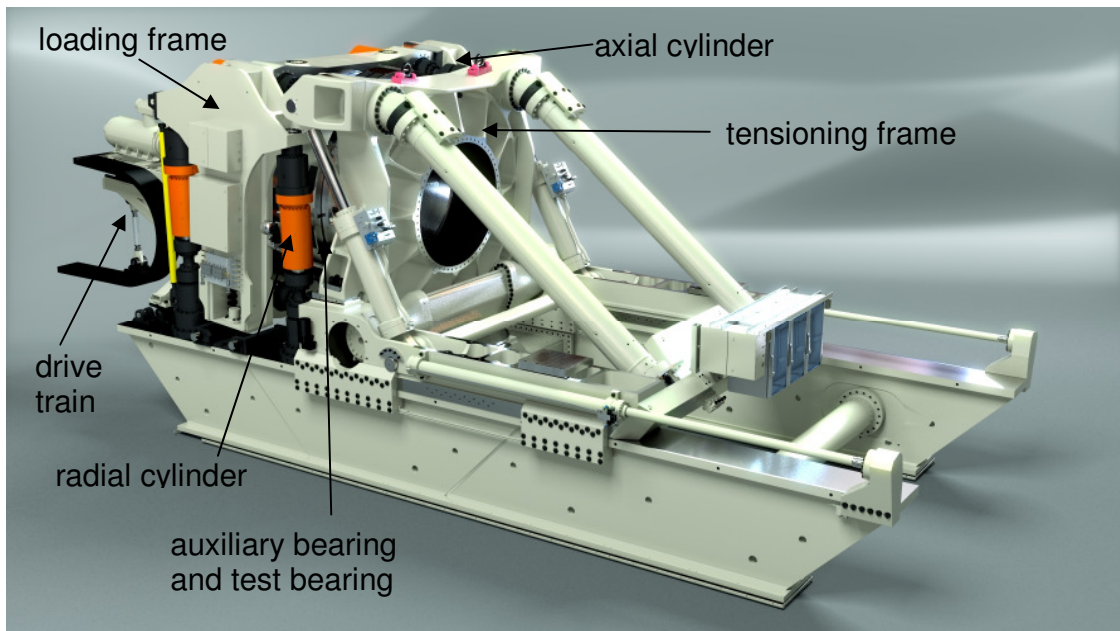
Figure 4: Large size bearing test rig

3.3 Test rig

The test rig is 16 m long, 6 m wide and 5.7 m high. It weighs approx 350 t and is tilted by 5°, as is the case with real wind turbines. The tilt angle can also be varied. The mounting of two bearings requires 500 screws, with a cumulative mass of approx. 3 t.

It can be divided into the following units which can be seen in Figure 4 from left to right.

3.3.1 Drive train

The drive train simulates various wind speeds which are typically between 4 and 20 rpm. For special tests faster rotation speeds are possible.

3.3.2 Loading frame with radial and axial cylinders

The loading frame generates the forces and moments that occur in practice in a wind turbine and is connected with the auxiliary bearing.

3.3.3 Auxiliary bearing

The auxiliary bearing simulates the motion of the rotor and transmits loads to the test bearing.

3.3.4 Test bearing

The test bearing is subjected to the precisely specified time-dependent forces and moments.

3.3.5 Tensioning frame

The tensioning frame represents the connection side of the wind turbine's nacelle and is connected with the test bearing.

4. Calculation

4.1 Challenges to calculation

The biggest challenge to calculation was the short time frame in which the calculation and the design optimization had to be carried out. Due to a very strict time schedule, the strength assessment and modal analysis had to be completed within two months. It was also necessary to ensure that highly cost intensive parts, such as the loading and tensioning frame, could be classified as reliable.

During this time, a complex FE model of the entire large size bearing test rig had to be created. Since no experience of similar calculation projects was available, it was not possible to determine the level of detail required in the model in order to obtain reliable results. It was not sufficient to model the preload of the more than 500 screws required for mounting of the two bearings. There were numerous other screws and details such as slide bearings, contact behaviour characteristics, etc. that might influence the safety of important components.

Since so many individual components had to be modeled in great detail, this resulted in a very large model.

In addition, it was necessary to take account of a very wide range of load cases that might occur during operation of the test rig. This would include not only those occurring during "normal" wind turbine operation, but also those resulting from any combination of all possible axial and radial cylinder loads. In particular, the loads occurring due to misuse of the test rig had to be considered.

In relation to these two issues of large model size and the large number of load cases, there was a query as to whether hardware capacity available within the Schaeffler Group was powerful enough to handle this calculation problem. At this stage, no consideration had yet been given to whether such a major task could easily be handled in terms of convergence.

4.2 Solution strategy

Due to the time pressure, a team of calculation specialists within the Schaeffler Group was formed who all had good experience of Abaqus Standard and Abaqus CAE. The whole large size bearing test rig was then subdivided into functional groups that could be handled more easily. Each

member of the team was then allocated one of these functional groups and created an appropriate FE model. Loads, transitional and boundary conditions (e.g. stiffness, mass, damping, etc.) were applied at those points where the models were connected to other parts of the test rig. It was important to select appropriate interfaces between the individual FE models.

Where possible, parts of the models were replaced by transitional conditions that could be determined by analytical or simulation based calculation methods. By means of this approach, the models could be reduced in size and convergent models could be created quickly. The level of detail in the models could then be increased in order to obtain reliable information for stress analysis of the models.

In order to validate the individual models and allow valid modal analysis, it was necessary to create a complete FE model of the whole test rig (see Figure 5). This required the creation of a uniform nomenclature for the sets, surfaces, etc. of the individual models so that they could be combined easily in Abaqus CAE. In addition to the creation of a complete FE model, an analytical model of the whole test rig was created in order to obtain an early evaluation of its modal behaviour.

Further details regarding the solution strategy and the individual models will be given in the presentation at the 2012 SCC.
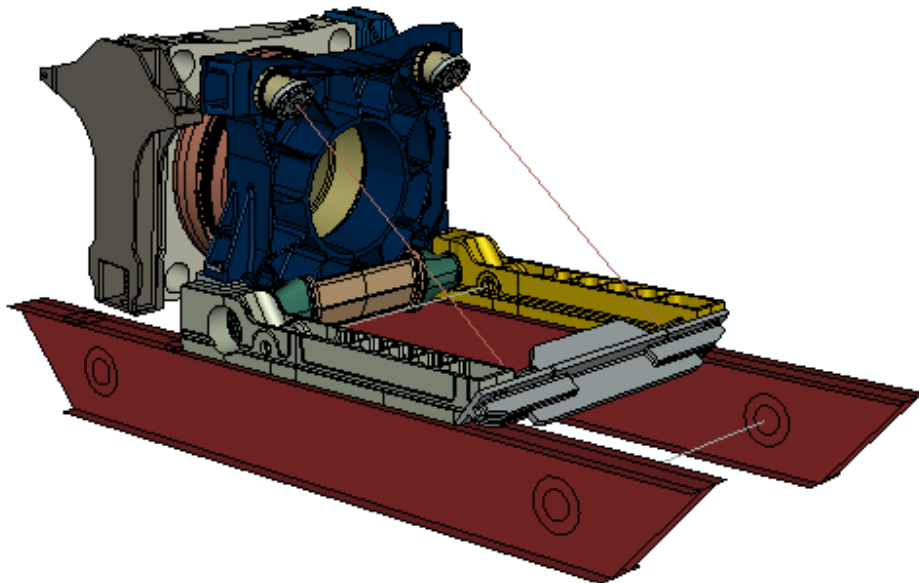

**Figure 5: Complete FE model of the large size bearing test rig**

4.3   Results

After stress analysis (see, for example, Figure 6), it was possible to carry out the necessary strength verifications according to the FKM directive and the standard VDI 2230 (for screw connections). In order to achieve positive results, certain design modifications were necessary:

- Screw connections were optimized, e.g.: grade, preloads, nominal diameter, grip length, etc.
- Components were added to increase the reliability of certain areas.
- Radii were optimized to reduce stresses.
- Additional reinforcing ribs were inserted in order to achieve the required stiffness.
- Surface quality requirements were upgraded to fulfil fatigue standards.
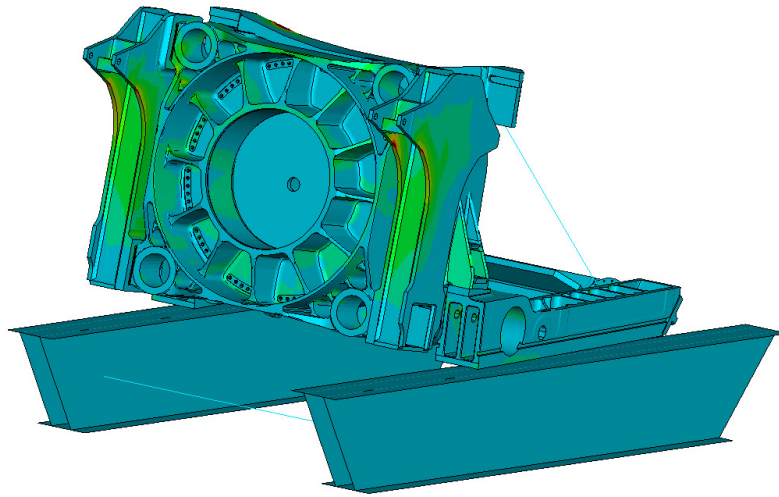
Figure 6: Maximum principal stress with load-free bearing
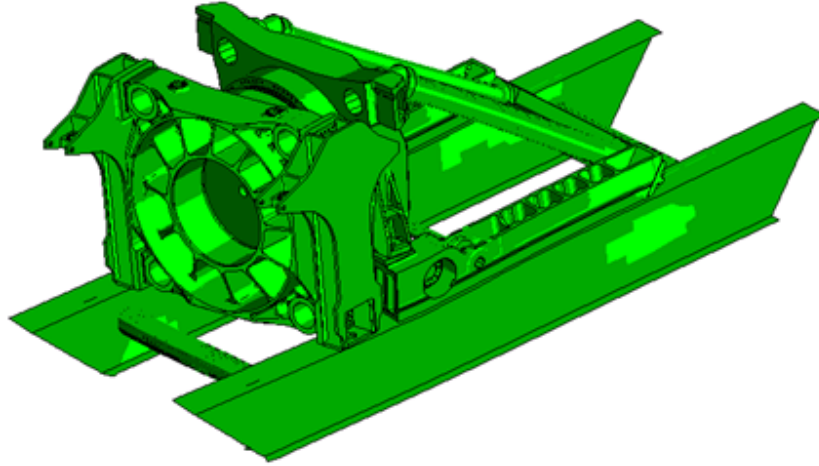
Figure 7: First eigenmode

The most important result of the modal analysis was that the first eigenfrequency (see first eigenmode in Figure 7) was well in excess of the highest possible excitation frequency.

4.4 Benefits of Abaqus CAE

There were certain features of Abaqus CAE that allowed a convenient approach to solving the calculation concerning the large size bearing test rig.

- The geometry based modeling in Abaqus CAE was very useful in quickly creating mesh variants of both the whole model and the numerous individual models.

- Due to the available scripting technology, not only the modeling but also the evaluation of results was easier and less time-consuming.

- Due to the assembly / part / instance functionality, it was very easy to exchange parts between team members or to replace instances or parts with others in those cases where the design or FE properties had changed.

- Since there were numerous screws with preload, the screw modeling function available in Abaqus CAE was extremely useful.

- The available options for abstraction (e.g.: mass, stiffness, connectors, etc.) were also very beneficial. The size of the models could be reduced by replacing large 3D structures with shell or beam structures, or by linking whole model parts by means of appropriate transitional conditions.

5. Summary and Conclusion

The calculation strategy applied made it possible to design the large size bearing test rig to the necessary standards within a limited time frame. Based on the comparison of test and calculation results, further improvements will be made to the calculation models. Before very expensive

testing of large size bearings is carried out, the most critical operating conditions can be identified by means of simulations using the test rig model. As a result, the time and operating costs of the test rig can be reduced.

Following an investment of approx. € 7 million, the Schaeffler large size bearing test rig represents a significant investment in the further development of renewable energy.