Determination of Wind Turbine Main Bearing Load Distribution

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Abstract. The presented paper introduces simulative method for the determination of load and pressure distribution in the main roller bearings in multi-MW wind turbines. This method has been developed using the example of a generic 6 MW research wind turbine (WT). The investigated drive train comprises of a main gearbox and is mounted with a four point suspension. The fixed rotor bearing is a spherical roller bearing and the floating rotor bearing is a cylindrical roller bearing. The load and pressure distribution is determined by finite element (FE) simulation under consideration of real hub loads and elastic surroundings. The hub loads have been calculated using Multibody Simulation. Three different rotor bearing models are introduced, which consider FE contact conditions, macro-geometry, stiffness and rolling element profile. The developed method is transferable to different rolling bearing types and can be used to improve bearing load and pressure distribution in multi-MW WTs under consideration of elastic surroundings (main shaft, frame and bearing housing).

1. Introduction

1.1. Motivation

The nominal power of installed onshore and offshore wind turbines is growing continuously [1]. Nowadays, 10 MW offshore wind turbines (WTs) equipped with rotors reaching up to 164 m in diameter are already commercially available. The main bearings of this multi MW WTs are exposed to high dynamic axial and radial forces as well as bending moments. These high dynamic loads can lead to main shaft and bearing housing displacements to be in the mm range [2]. Consideration of elastic structure and deformations during the product development process is becoming ever more important in order to cope with increasing main bearing dimensions.

Additionally, the aforementioned loads and displacements can cause unequal bearing load and pressure distribution and also change the kinematic conditions of the main bearing. Such local contact conditions when subject to simultaneously slow rotational speeds, mixed friction and slippage can induce main bearing failures, such as micro-pitting, classical wear or cage fractures [3]. Consequently, the main bearings do not usually reach the calculated lifetime of 20 years and have to be replaced on average after seven years of field operation [4], [5]. These main bearing failures lead to high repair and replacement costs as well as long downtime of the affected wind turbine [6] while reducing the competitiveness of wind energy compared to conventional energy sources. Therefore, there is a need for a reduction of the main bearing failures.

Besides the testing methods, modern simulation tools contribute to a better understanding of the main bearing behaviour and reduction of the prevailing failures. This simulation tools are used to design and optimize the main bearings. One of the most important parameters for the optimization of main bearings is the knowledge of the main bearing load distribution.
1.2. Objective

The objective of this paper is to quantify the influence of the elastic surroundings (bearing housing, main shaft, main frame) on the main bearing load distribution on the example of a generic 6 MW research WT (4 point suspension). Furthermore, this paper introduces a method for determination of the bearing load distribution by the Finite Element Method (FEM). By knowing the bearing load distribution it is possible to identify edge loading or unequal pressure distribution. Subsequently, this unfavourable load conditions can be changed by adjusting of the rolling element profile or stiffness of the elastic surroundings.

2. Approach

The selected approach to achieve the objectives can be divided into two main steps: determination of the hub loads and determination of the main bearing load distribution, see Figure 1. The presented paper focuses on the second step.

The determination of the prevailing hub loads have been executed under consideration of the IEC wind class IIb: averaged medium wind speed of 8.5 m/s and lower turbulence up to 14%. The prevailing loads on the hub of the 6 MW research WT have been calculated by means of Multibody Simulation (MBS) model under start-up operation [7]. This MBS model considers all relevant structural components of the wind turbine as flexible bodies (e.g. blades, hub, main frame and shaft and gearbox housing) leading to a realistic calculation of the hub loads. The maximal hub loads for the specific time step (thrust up to 1.4 MN, radial force up to 1.1 MN and bending moments up to 900 kNm) during the start-up operation have been selected for the determination of the main bearing load distribution, see Figure 2. The prevailing torque under this conditions is 4407 kNm. Subsequently, the hub loads and torque are transferred to the FEM model for the determination of the global load distribution, the load distribution over the rolling element width and the contact pressure considering variations of

- elastic surroundings, clearance,
- rolling element profile, and hub loads.

The FEM model considers the detailed three-dimensional geometry of the elastic surroundings and of the main bearing. The FEM model includes the contact between housing and inner parts of the main bearing as well as the bolt connection to the main frame and is capable of simulating this nonlinear connections.

**Figure 1:** Approach for the determination of the main bearing load distribution

The core element of the FEM simulation is the modelling of the main shaft suspension. The main shaft suspension comprises of a fixed bearing (spherical bearing) and floating bearing (cylindrical bearing). The presented paper discusses the simulation results of the cylindrical bearing. Three bearing models with different numbers of parameters were used for the modelling, see Figure 1. All models consider the elasticity of the bearing rings as well as contacts between ring and housing as well as ring and shaft.
Furthermore, the stiffness of each rolling element is modelled. The first model considers rolling elements as a single stiffness and is used to describe global bearing load distribution so that each rolling element force can be calculated. The second model considers each rolling element with multiple stiffness’s and is used for the calculation of force distribution over the rolling element width. This model is useful for the determination of tilting effects caused by deformations. The third model comprises of the 3D geometry of the rolling element, which has maximum load. This model is used for the calculation of the pressure distribution and optimisation of the roller profile.

3. Results

The next subsection comprises of the generated results. The behaviour of the bearing is described by calculation of the global load distribution, force distribution over the roller element width as well as the pressure distribution in the rolling contact. The sensitivity of these results to variations of elastic surroundings, hub loads and clearance of the main bearing has been analysed.

3.1. Influence of elastic surroundings on bearing loads

Figure 2 shows the results regarding the influence of the elastic surroundings (main shaft, bearing housing and main frame) on the global main bearing load distribution. It can be seen that with the consideration of the elastic surroundings more rolling elements are loaded. The main bearing load distribution becomes more irregular under simultaneously decreasing of the rolling element forces. The elastic surroundings determine the amount of the rolling elements under load, the highest force on the rolling element and general load distribution.

Figure 2: Influence of elastic surroundings on global load distribution of main bearing (maximum rolling element force is in the black rectangle)

Figure 3 shows the influence of elastic surroundings on the local load distribution over the rolling element width. The rolling element (without profiling) is simulated by seven equal springs which are responsible for the description of the elastic behaviour. The local load distribution is unequal and has almost linear gradient due to tilting and deformation of the main shaft.
Figure 3: Influence of elastic surroundings on local load distribution over the rolling element width (maximum force over the rolling element width is in the black rectangle)

The upwind side of the rolling element is loaded higher than the downwind side. The difference in maximal rolling element force over the width between the model 1 (rigid surroundings) and the model 4 (elastic surroundings) is 115 %.

Model 4 has lower rolling element forces than model 1 due to the unloading of the rolling elements by deformation of the main shaft and frame as well as housing.

Figure 4 shows the influence of elastic surroundings on the pressure distribution over the rolling element width. In this case the rolling element has a logarithmic profile according to Lundberg [8]. The three-dimensional rolling element is meshed finely at the contact area to resolve the contact pressure values and the contact area properly. The logarithmic profile avoids the pressure peak at the end of the rolling elements. The difference in the contact pressure over the rolling element width between the model 1 (rigid surroundings) and the model 4 (elastic surroundings) is 28 %. Model 1 has higher pressures. The contact distribution over the width is more equal due to profiling in comparison to the rolling element force distribution, see Figure 3.

Figure 4: Influence of elastic surroundings on pressure load distribution of rolling element (maximum contact pressure is in the black rectangle)

The results of model 1 (rigid surroundings) have been validated by the bearing manufacturer software BEARINX. In case of the global load distribution there is a deviation of 2 % in comparison to the FEM. In case of the pressure load distribution there is a deviation of 8 % in comparison to the FEM. These
deviations can be attributed to the unknown material properties and unknown detailed geometry of the real bearing.

3.2. Influence of hub load directions

Figure 5 shows the results regarding the influence of direction of the hub loads on main bearing load distribution. Direction of the hub loads has an impact on the shape of the bearing load distribution and value of the maximal rolling element force. This can be attributed to the fact that bearing housing has fluctuating stiffness over circumference. If the hub loads are acting in the direction of area with high stiffness, fewer rolling elements are preloaded. In this case the rolling element forces are higher. Maximal rolling element forces can fluctuate up to 50% under variation of hub load direction. This fact underlines the importance of the consideration of the elastic surroundings during the stress assessment of the main bearing.

3.3. Influence of hub load increase

The main bearings are exposed to highly dynamic and fluctuating loads, which effect the behaviour of the main bearing. Figure 6 shows the influence of load increase on global load distribution of the main bearing. The hub loads, see Figure 6, have been calculated for start-up operation under consideration of IEC IIb wind field with a mean wind speed between 4 m/s and 5 m/s and a turbulence intensity of 0.2.

Figure 5: Influence of load direction on load distribution of bearings loads (maximum rolling element forces are shown with the corresponding color)

Figure 6: Influence of load increase on global load distribution of main bearing
It can be seen that the load increase has an effect on load distribution shape, maximal rolling element force as well as number of loaded rolling elements. Under high hub loads the influence of housing high stiffness in the area of the main frame connection can be seen clearly, see Figure 6 right hand graph. In this case the rolling force is higher and reaches 225 kN. With an increase of the hub loads more rolling elements are loaded. The maximal rolling element force has a progressive gradient if the hub loads are increased.

3.4. Influence of bearing clearance

The main bearings have an operational clearance, which depends on the manufacturing tolerances, mounting condition, temperature distribution of the bearing and on the hub loads. The effect of different clearances on the global load distribution have been carried out with the same load conditions as in the previous chapter. Figure 7 compiles the results and shows the influence of clearance on the main bearing load distribution.

![Figure 7: Influence of clearance on global load distribution of main (maximum rolling element force is in the black rectangle)](image)

The clearance has been varied under the same load conditions between zero and 0.86 mm. It can be seen that clearance especially effects the amount of preloaded rolling elements. With less clearance, more rolling elements are in contact and the rolling element forces are smaller. The difference in maximal rolling element force can be up to 8% between zero clearance (205 kN) and 0.86 mm clearance (224 kN).

4. Conclusion

The elastic surroundings have a high impact on the global and the local bearing load distribution as well as on the pressure distribution over the rolling element width and should be always considered in development and fatigue life determination of multi-MW main bearings. In the case of the 6 MW research wind turbine with four point suspension of the main shaft, the elastic surroundings lead to a lower loading of the main bearing, but more unequal load distribution. The difference in prevailing maximal rolling element force between rigid and elastic surrounding can be up to 51%.

The project generated further insights as there are:

- High stiffness fluctuation of the main bearing housing can lead to high loads on the main bearing.
- The contact between bearing housing and bearing outer ring as well as shaft and inner ring should be modelled. Neglecting this contact can lead to an error of up to 14%.
- The hub load direction has a high impact on the bearing load distribution. Resultant hub load, acting in the direction of the connection point of the main bearing housing and the main frame, leads to high loads on the main bearing.
Gradual increase of the hub load leads to a non-linear, progressive increase of the maximal rolling element force.

Gradual increase of the bearing clearance leads to higher loads on the main bearing.

Validation of the simulation method has been done by measurement of main housing strains of the FVA-nacelle [9], [10]. In this case the deviation between simulation and measurement results is between 3% and 20%.

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