Pitch bearing lifetime prediction considering the effect of pitch control strategy

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Abstract. Ambitious worldwide renewable energy targets are pushing for wind energy to become a mainstream power source. Pitch bearings are some of the most vulnerable components of wind turbines. Inside bearings, damage in the inner raceways is significant due to the rolling contact fatigue (RCF) caused by balls. It is well known that methodologies for RCF recommended by international standards are not suitable for fatigue cases where fatigue mechanism encompass multiaxiality, as well as the loading being non-proportional, leading to unnecessary design over-costs. The objective of this work is to develop a new accurate methodology to predict the lifetime of the raceway for a pitch bearing under RCF failure mode and analyse the effect of the pitch control strategy. This methodology will help both, the manufacturer of the bearing and the manufacturer of the turbine, to design a concept focused on the overall performance of the machine.

1. Introduction

Nowadays climate change and global warming are very worrying issues for humanity. To tackle these problems, there is a rapid growth in utilizing the wind power as an electricity generation [1]. Pitch bearings are some of the most vulnerable components of wind turbines. Theses bearings are supporting high axial and radial loads while transmitting movement between adjacent elements. The Rolling Contact Fatigue (RCF) is a failure mode (Figure 1), which occurs mainly at near-end-of-expected lifetime stages, that produces the initiation of a crack under the contact surface after an alternating process of stresses and deformations that may lead to failure. Since the critical location is not known firstly, the failure time prediction becomes complex [2-4]. Most part of the literature and the standards are focused on the study of shear stresses or strains as the main cause of this failure mode, although the effect of the normal stresses and strains should not be ignored [5-6]. In the case of bearings, the international standard currently uses probabilistic methods for life prediction under RCF, such as ISO281 [7]. All hypotheses of this method are based on the rolling element rotating with a constant speed; if the rolling element oscillates; new hypotheses should be included [8]. The real stress state under the raceway is multiaxial, and as real components are subject to magnitude and direction varying load histories.

Figure 1. Example of the RCF damage in a pitch bearing [9].

In this work, a novel methodology is developed to predict the lifetime of the raceway for a pitch bearing under rolling contact fatigue failure mode. The methodology will consider the loads on the blade root obtained from simulation softwares (e.g. Bladed, Fast), the movement of the pitch angle control strategy, the multiaxial stress-state at different depths of the raceway and the flexibility of the surrounded structures. Considering the new methodology, the importance of the pitch control strategy in the rolling contact fatigue is analysed.

2. Individual pitch control vs Collective pitch control

With increase of wind turbine size the mechanical loading of its structure increases rapidly resulting in extreme values of structural loads and pronounced fatigue. Collective pitch control (CPC) defines the movement of blades simultaneously, however, Individual Pitch Control (IPC) defines the movement of each blade individually. The most important objectives of using the IPC control is to significantly reduce the axisymmetric loads observed in the rotor caused by: wind gradients, the effect of the blades´ shadow, turbulence and other factors such as misalignment effects. In general, applying this control strategy, the observed loads in the wind turbine components are reduced. But for the pitch bearing, the continuous oscillating movement that is applied increases significantly the number of cycles for RCF failure mode, reducing considerably the lifetime [10-12]. In the Figure 2 can be seen the CPC strategy against the IPC strategy.
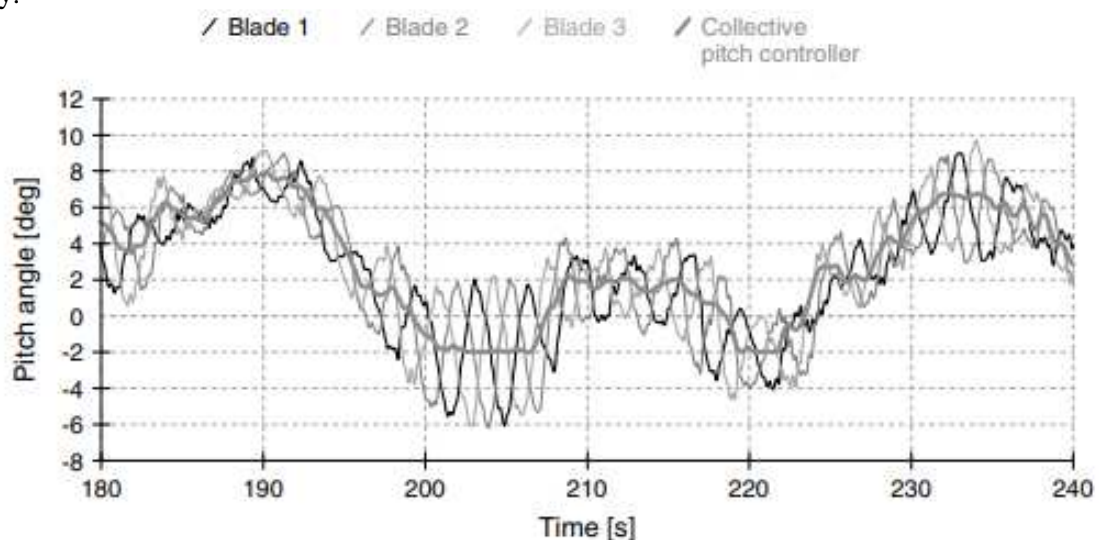

Figure 2. Comparison between CPC and IPC [11].

3. Methology

This section introduces the methodology developed in this work that describes in detail the fatigue life prediction and the total damage calculation procedure [13]. Furthermore, the different obstacles overcome are explained in terms of the basis of the problem and all the measures that have been taken to fix it. Figure 3 outlines the general procedure followed, from gathering loads to obtaining a damage value.
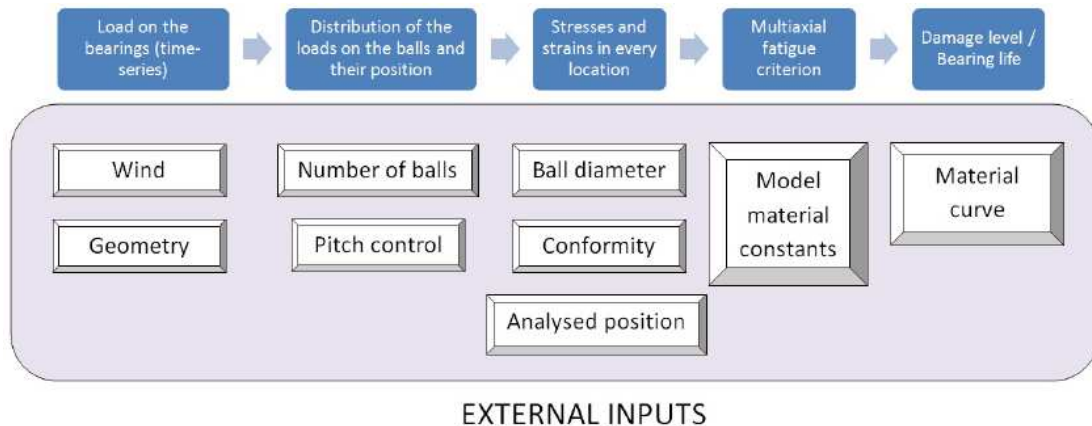

Figure 3. General procedure to obtain the damage value of the pitch bearing.

The methodology is divided in three main steps: the first is concerned with loads, the second describes the process to convert those loads into stresses and strains and the last reveals how to assess bearing damage from the former. These three steps are also divided into 10 sub-steps or blocks, shown at Figure 4 and detailed described below.
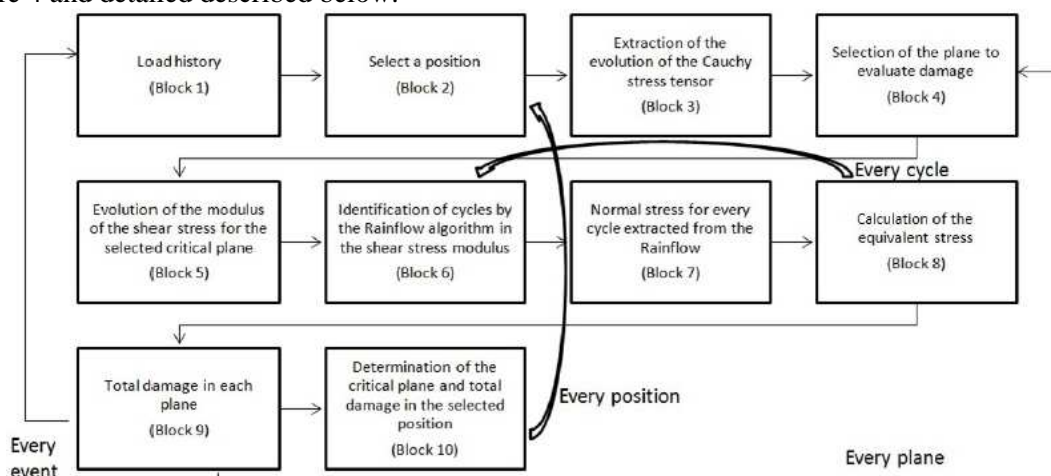

Figure 4. Detailed description of the methodology for multiaxial damage evaluation.

3.1. Load distribution along the time

Before proceeding with the fatigue analysis of the component itself, data information concerning the magnitude and direction of the different forces acting over time is collected. The input data included moments (M_x and M_y), radial forces (F_x and F_y), axial forces (F_z), time step and pitch global position. This kind of data is obtained using software like Bladed (R) (Figure 5), which is a program that provides a sophisticated numerical model of wind turbines and their operational environment.
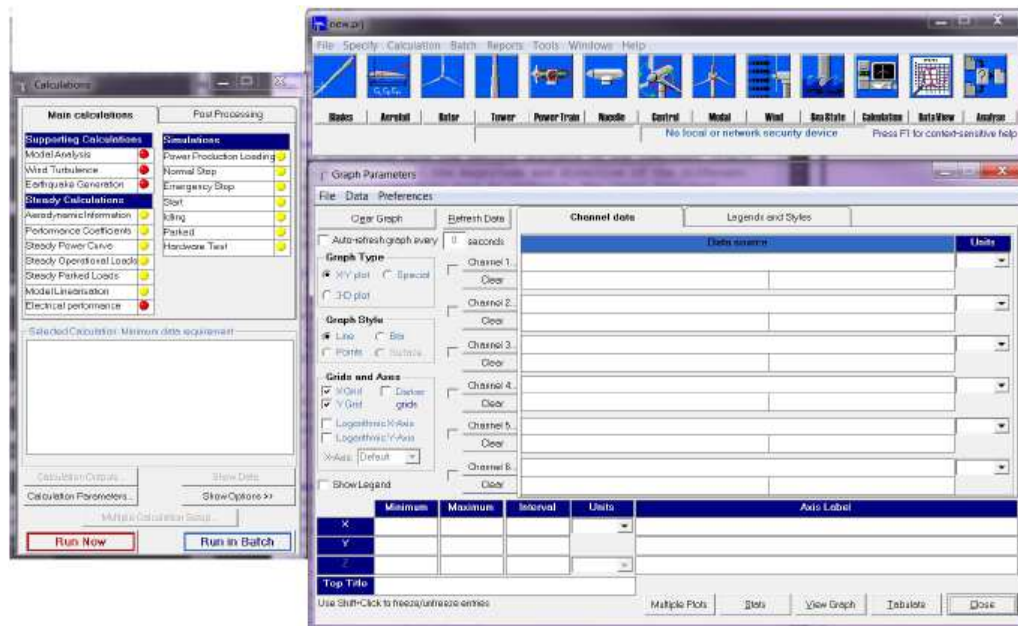
Figure 5. Bladed® program interface.

In order to simplify the calculation of the stresses in the following steps, a linearization of three main forces is performed with the purpose of converting them into a unidirectional varying vector as a function of time. Since the worst load case scenario implies, in principle, loads acting in the three principal directions, the main procedure to achieve this step goal must include superposition of those loads.

The final result of this step is a Q load matrix (Figure 6), which contains data on the loading distribution on every ball, this being a function of the rolling element of the bearing and time. Such data is obtained from complex FE model considering the bearing geometry and stiffness of the surrounding components [13]. These data are essential to calculate the stress or strain values at the subsurface of the bearing.
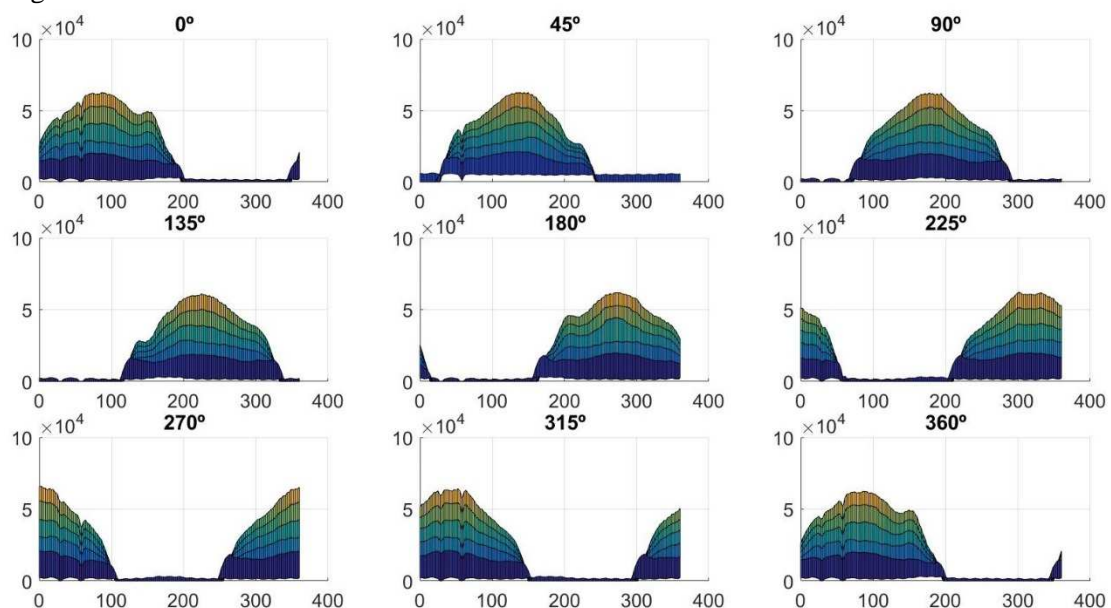

Figure 6. Example of the Q ball load for the first row and the first diagonal for each external load applied in the corresponding angle (x axis: ball position in degrees and y axis: Load [kN]).

3.2. Stresses and strains at the subsurface

An elastic simulation based on the software program ANSYS, provides the values of six components of the stress tensor. The model has to be modified to represent the required ball diameter, conformity and raceway radius. The finite element model requires the following four input parameters: the loads, the depth within the layer, the relative distance between the location of the applied load and any measured position considered and the arc angle of the raceway.

3.3. Critical plane approach

The damage assessment required the multiaxial stress and strain system to be converted into a uniaxial system by considering an equivalent stress, strain, or particular parameter, specifically selected for the fatigue model itself, though before reaching this point, some simplifications were necessary. On the one hand, the normal stresses and strains were combined to create a unique normal stress and strain vector of reference. On the other hand, the shear stresses and strains could be projected on the selected plane and simplified as two shear stresses and strains orthogonal to each other. The Papadopoulos' model [14] is used to define the normal and shear stresses for each plane rotation position (Figure 7).
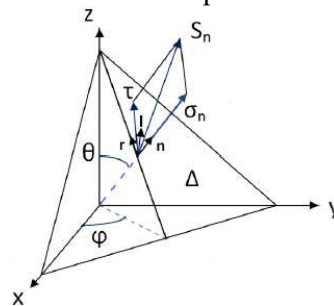

Figure 7. Stress vectors in a rotated Δ plane

Once the calculation is completed, different matrices are obtained as a function of time and each rotation plane, namely normal stresses and strains and shear stresses and strains.

3.4. Cycle definition

The first obstacle to apply the methodology proposed arose from the cycle counting method. Figure 8 a) illustrates how the peaks and valleys of the normal and shear vector do not coincide due to the non-proportional condition of the stress. The same problem arises with the strains due to the proportionality implied by the Young modulus in the elastic field.

The complex randomness of the direction and scale of the loads, however, added complexity in the derivation of stresses and strains according to the multiaxial fatigue models because it resulted in different numbers of cycles for the normal and shear stress and strain due to the unilateral analysis of both vectors (Figure 8 b)).

The resulting vectors of the shear stress and strain (τ, γ) are used to define the initiation and duration of the cycles [13], since the shear stress and strains are the main factors influencing crack initiation in RCF-type loading [14].
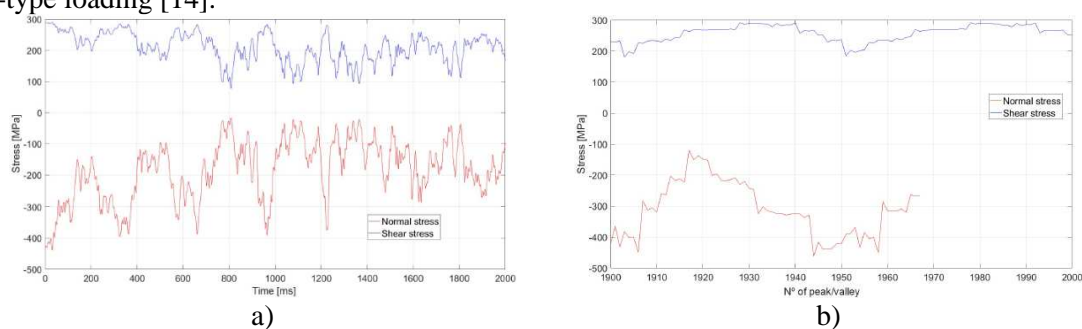

a)   b)

Figure 8. a) Normal and shear stress vectors and b) time history of normal and shear stress vectors suppressing intermediate values

3.5. Fatigue models

A number of different multiaxial fatigue models are proposed as a reference parameter to evaluate the damage induced on a certain location and at a certain orientation, as a result of the particular loading acting on the component. Following a brief description of each fatigue model [15]:

3.5.1. ISO

The ISO standard defines the procedure to calculate the basic dynamic load rating for different sizes of the bearings. The standard defines the fatigue life of a bearing using a Wöhler curve and it includes a life factor to adjust the life to the desired probability of survive.

3.5.2. NREL

The design guideline 03 of NREL has modified the ISO standard for bearings with oscillating movement, which corrects the dynamic load rating $C_{a,osc}$ depending on the oscillating angle and the number of rolling elements for each row.

3.5.3. Maximum orthogonal shear stress

Lundberg and Palmgren found that when pure rolling happens on the surface of a component, the critical parameter is the maximum orthogonal shear stress.

3.5.4. McDiarmid

This criterion is included as a critical plane criteria, which are called this way since they consider the plane with the orientation that has the maximum output parameter value, in this case, identified mainly with the variation of the shear stress within a load cycle.

3.5.5. Findley

In Findley's criterion the equivalent shear stress amplitude is calculated considering the maximum value of the normal stress on the plane where the maximum equivalent shear stress is produced.

3.5.6. Fatemi-Socie

This criterion takes into account the shear strain's range instead of the stresses. Besides, it introduces as a parameter the maximum normal stress perpendicular to the plane where the maximum shear strain propagation happens.

3.5.7. Smith-Watson-Topper

The SWT parameter is defined as the maximum value of the product of the strain amplitude and the maximum normal stress between all possible orientations.

3.5.8. Brown-Miller

After observing the fast microcrack propagation, Brown and Miller proposed considering normal and shear strains in the maximum shear stress. Two strain parameters are required to describe the fatigue process since both normal and shear strains reduce the component's life.

4. Case study

The case study of 5MW-NREL wind turbine is selected for the application of the methodology developed in this work. This case study is a reference turbine defined by the National Renewable Energy Laboratory (NREL) of the Department of Energy of the United States (DOE) for the development of conceptual studies to evaluate the wind technology. For this analysis, a simplified 11 operational wind events (each one related to its concurrence value for the entire lifetime of 20 years) are selected for defining the RCF damage on the bearing. Two control types are defined: CPC and IPC.

As stated above, the IPC strategy increases the number of cycles for RCF, this difference can be seen in the Figure 9. The number of revolutions for the same tilting moment increases considerably for the IPC strategy.
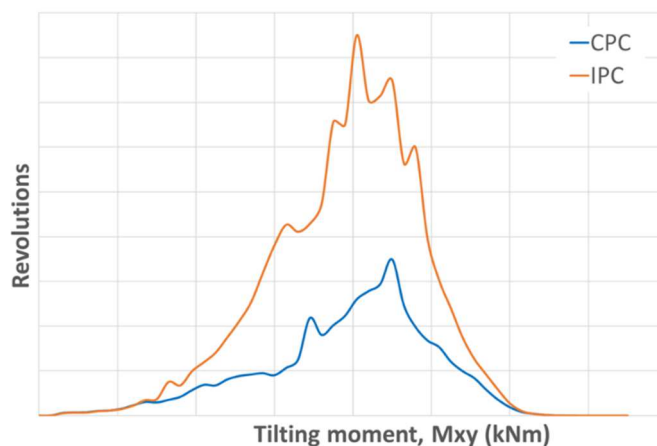
Figure 9. Revolutions against tilting moment for CPC and IPC strategies.

Figure 10, highlights the most critical values for each model, which allows us to make a direct analysis by comparing them. In this comparison, it is important to recall that the orthogonal shear model, which is the model used by ISO Standard, is the less conservative one, thus contradicting the idea of ISO as being a conservative standard. This contradiction could be assigned to the consideration of a safety factor that creates the highest damage value. Among the different models, the McDiarmid model is the most conservative. Note that because the McDiarmid and Findley models are similar though based on different parameters, the ratio between them remains constant. NREL is the most conservative methodology and there exist a wide scatter between the damage values.

Considering the results for the CPC and IPC strategy, as expected, with the IPC strategy the RCF lifetime reduces drastically. The RCF damage applying the IPC strategy is more or less 10 times the damage obtained without this control strategy.
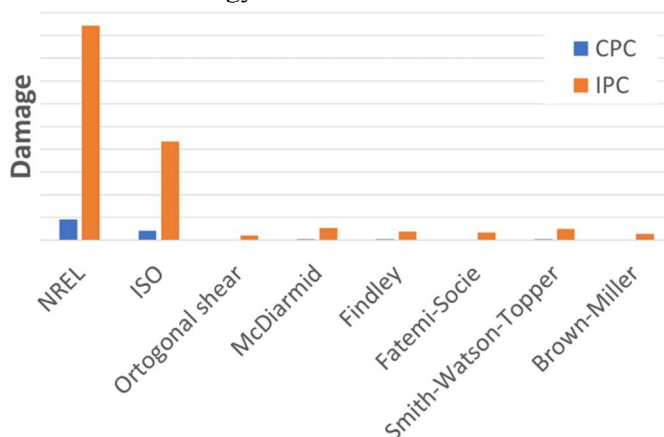

Figure 10. Maximum damage value for each fatigue model considering the pitch strategy.

5. Conclusions

The current standards for calculating the RCF failure mode do not take into account the actual conditions of the bearings during their service life. This methodology reduces the calculation uncertainties that contribute to the use of equivalent loads, the effect of the flexibility of the structures and the simplifications that are made to include the effect of the oscillatory pitch angle control. The new rolling fatigue calculation methodology allows the bearing manufacturer to iterate with the wind turbine manufacturer in:

- The optimization of the bearing to minimize the obtained damage.
- The optimization of the adjacent structures (hub, bolted connections, flexibility changes…), defining the zones to increase the rigidity.

- Defining maintenance strategies: defining the most likely starting points for failure.
- Determining control strategies for a global optimum operation of the wind turbine, detecting the worst wind event, in other words the wind event which generate the higher damage.

Regarding to the comparison between the IPC and CPC strategies, as expected the IPC strategy reduces drastically RCF lifetime. Although this control strategy can improve the lifetime of other wind turbine components, for the special case of RCF of the pitch bearing opposite situation is happened.

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