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Robustness Test for Wind Turbine Gearbox Bearings

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Abstract. This paper introduces an innovative approach for the creation of the robustness test against specific failures of the planetary and HSS bearings (e.g. classical fatigue, smearing, micro-pitting, and lip fractures) in the wind turbine gearboxes. The introduced Bearing Robustness Test (BRT) considers the system-dependent characteristics (e.g. drive train design, interaction between components, assembly process, lubricant aging) and real dynamic load conditions, frequencies and sequence. The creation of the BRT is based on field and simulation data. The core element is the simulative approach for the determination of the relation between external wind and grid loads on the one side and local loads of the bearing on the other side. BRT aims the mapping of the most critical, but real, field load situations in the bearing test rig. By means of the BRT it is possible to evaluate the robustness of bearing against specific field conditions in the early stage of the product cycle and consequently to enhance the quality and to reduce the failure rate of the bearing.

1. Motivation and Objectives

The cost-efficiency of the wind turbines is reduced by the frequent failures of the main gearboxes. The main gearbox is responsible for nearly 60 % of the downtime of the wind turbine, see **Figure 1**. This fact is caused by a fluctuating and dynamic wind and grid loads, dynamic interaction between drive train components as well as the demand for high power density of the gearbox components [1]. Therefore, the rolling contact bearings are the most critical component of the main gearbox. They contribute to over 67 % of main gearbox failures according to the current research, see **Figure 1**. The planetary and high-speed shaft (HSS) bearings failures cause high reparation, replacement and service costs [3].
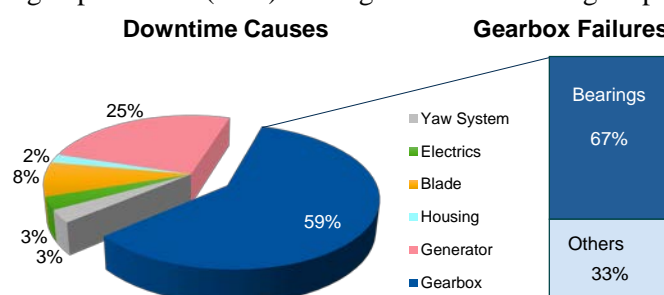

Figure 1. Causes for wind turbine downtime.

Bearing testing methods within the product development process could contribute to more reliable and robust gearbox bearings and thereby increase the availability of the wind turbines. Nowadays, the existing testing methods cannot completely simulate the real elastic surroundings and reproduce the complex load situation on the bearing as well as the complex interaction between the gearbox components. Consequently, it is difficult to reproduce specific wind turbine bearing failures in a realistic way [4]. To solve this challenge, a diversified consortium of a complete product value chain (bearing, gearbox and wind turbine manufacturer)[1] under the lead management of Chair for Wind Power Drives (CWD) got together to develop a new bearing test rig designs (a planetary

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[1] Schaeffler, SKF, Timken, NTN, Siemens Winergy, ZF Wind Power, Eickhoff, Vestas, Nordex, Senvion

and a HSS test rig) as well as testing procedures for the planetary and high HSS bearings in original size (outer diameter up to 400 mm) [5]. The objective of this paper is to introduce an approach for the creation of a bearing robustness test (BRT).

1.1. *High speed shaft (HSS) test rig and planetary test rig*

The main parts of the HSS test rig are the drive motor, the main shaft, on which the test bearings are located as well as the hydraulic unit with load cylinders. It is possible to apply 2 MN radial force (up to 3000 MPa contact pressure) with a frequency of 70 Hz and displacement of $\pm$ 0.4 mm as well as an axial force of 0.5 MN with a frequency of 70 Hz and displacement of $\pm$ 1 mm. Four HSS test bearings can be examined during one test under a rotational speed up to 3000 min^{-1} and angular acceleration up to 200 rad/s^2.

The planetary back-to-back test rig consists of a drive and load motor as well as a test gearbox. The test gearbox comprises three gears as a chair. The middle gear is a planet gear, which is suspended by a test planetary bearings and can be easily substituted. This design allows to test bearings under different bearings mounting conditions (e.g. integrated bearing design). It is possible to test the bearings under bearing forces up to 1.1 kN (up to 3000 MPa contact pressure) and rotational speed up to 60 min^{-1}.

The test on the both test rigs are executed under measurement of bearing and gear load distribution, shaft displacements, slippage of cage and rolling bodies, lubricant characteristics, temperature of inner and outer ring as well as deployment of acoustic emission and vibration measurement for failure detection.

2. Structure of the Bearing Robustness Test (BRT)

The first six years of the operating time are the most critical for the bearing failures according to the current research [6]. For these critical six years, BRT shows a robustness of the original size planetary and HSS bearings against failures, such as **classical fatigue** and **specific bearing failures** such as smearing, micro-pitting, failures due to slippage or lip fractures. White Etching Cracks are excluded, but are considered in another specific bearing test, which is developed in the frame of the previously mentioned research project.

The basis of the BRT is the six years load spectrum for the **classical fatigue**, which has been condensed to a maximum 2 months of testing time by the omission, truncation, increase of a load and rotational speed. The test time acceleration ratio is approximately 35. BRT comprises the critical operation modes, which trigger the **specific bearing failures**. The critical operating modes consist of realistic (not synthetic) transient and idling conditions, which lead to critical internal bearing loads (e.g. high dynamic loads) and subsequently to critical bearing behavior (e.g. low lubricant film height, high energy input). These operating modes are integrated in the fatigue load spectrum with the realistic sequence, amount and characteristics according to the field experience and simulations, see **Figure 2**
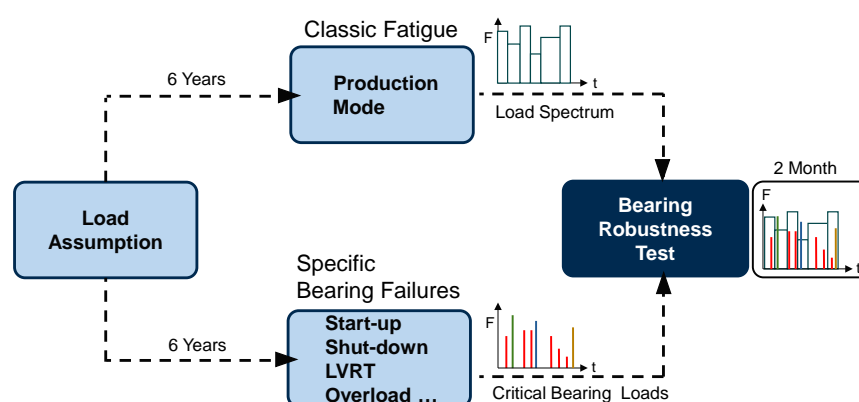

Figure 2. Structure of the Bearing Robustness Test (BRT)

The critical operation modes are selected after the comparison between the failure criteria of the specific bearing failures (e.g. maximal contact pressure, minimal lubricant film height) and prevailing contact conditions caused during the operation. If some failure criterion is triggered by a specific operational mode, then this operational mode is implemented into the BRT.

The selected division of the loads into the relevant loads for the classical fatigue and for the specific bearing failures is a common approach which is also used in [21] and [26]. Detailed description of this approach is compiled in the **Section 4.**

The BRT is not a synthetic load step test (e.g. FE8 wear test [9], FZG Load-Carrying Capacity [10], false brinelling test [11]) and considers system-dependent characteristics (e.g. deformation, assembly process, lubrication aging) of the bearing environment. Furthermore, BRT is not a standard test for a specific bearing type or size, but it is valid for a specific wind site and drive train characteristics (gearbox type and suspension, main frame elasticity, main shaft suspension, controller strategy). As robustness test, BRT comprises most critical operation conditions for a test bearing.

3. Transfer Path from Wind and Grid Loads to Bearing Failure

The key factor for the determination of the bearing robustness is the understanding of the transfer path of the external wind and grid loads to the bearing failure. By knowing this transfer path, it is possible to describe the behaviour of the bearing and to define critical operation modes as well as to derive the test cycles of the BRT. **Figure 3** shows exemplarily the transfer path of the external loads to bearing failure for general geared wind turbine drive train. This transfer pass is a basis for the creation of the BRT and is described more in detail in the subsequent Section 4.
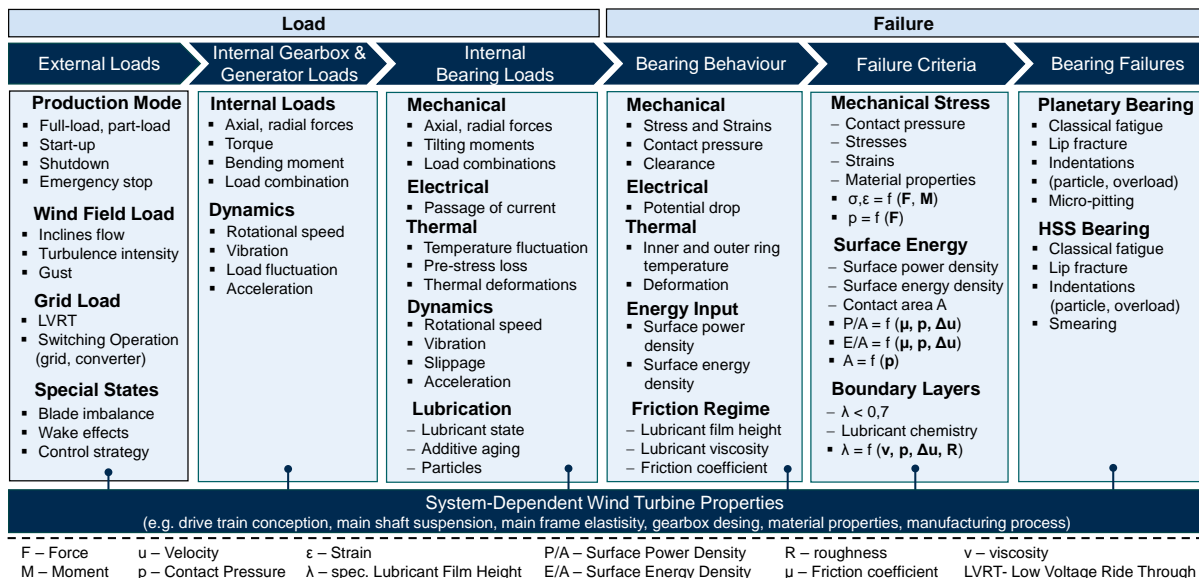

Figure 3. Transfer path from Wind and Grid Loads to Bearing Failure

Operation modes (e.g. production under full-load) and specific wind conditions (e.g. gust) as well as influence of the grid characteristics or critical grid states (e.g. Low Voltage Ride Through (LVRT)) lead to axial and radial forces, bending moments and torque on the wind turbine hub and also to electro-magnetic loads on the generator. On one side, these hub loads are transferred over the main shaft to the main bearing and main frame and define the internal loads and dynamics on the gearbox. On the other side, the grid conditions, controller strategy and electro-magnetic loads cause the internal loads on the generator shaft. Additionally, the internal load of the gearbox and the generator result in internal loads on the planetary and HSS bearing, depending on the gearbox design and bearing characteristics. These loads can be divided into

- mechanical (axial and radial forces, moments),
- electrical (passage of current),
- thermal (temperature fluctuation of the bearing, shaft and housing)
- dynamical loads (vibrations, acceleration, slippage).

Finally, these internal bearing loads define bearing behaviour and conditions such as roller body contact pressure and area, deformation, slippage, temperature distribution and lubricant characteristics (additive aging, particle concentration) and lubricant film height. These bearing conditions can trigger failure

criteria and lead to damage accumulation or propagation. Finally, bearing failures can occur under frequent repeating of these bearing conditions. By knowing of the failure criteria, it is possible to select the critical operation modes and implement them into the BRT.

4. Creation of the Bearing Robustness Test (BRT)

Based on the understanding of the transfer path of the external loads to bearing failure it is possible to define the steps for the creation of the BRT as follows:

- determination of external loads (Section 4.1.),
- determination of internal loads (gearbox and generator, then bearing)(Section 4.2.)
- determination of bearing behaviour (Section 4.3.) and
- evaluation of failure criteria (Section 4.4.) as well as
- derivation of test cycles for BRT (Section 4.5.).

Subsequent sections describe step by step the approach for the creation of the BRT.

4.1. Determination of External Loads

The determination of the external loads is based on the load assumptions. The load assumptions, such as wind field properties, frequency and sequences of the critical operation modes, should be made in the best case according to the field measurement data or available site characteristics. Field measurement data in high resolution is available for a short period time (e.g. 2 month). In this case the available field data should be upscaled (e.g. by simulation) up to the desired duration under consideration of weather-related fluctuations of the wind field. Furthermore, IEC 61400-4 requirements [15] and DIBt standard [16] or experience gathered on the system nacelle test benches (e.g. [7]) as well as simulation data can be used to define the load assumptions.

Within the BRT development, CWD has executed an industry survey to compile the industry experience (wind turbine, gearbox, bearing manufacturer) regarding the proper load assumptions and dwelling time of the wind turbine in specific operation modes. Furthermore, the conducted industry survey compiles information about the drive train characteristics (lubrication, elasticities, manufacturing), relation between the external load and the bearing failures (failure criteria, influence factors, failure hypothesis) as well as bearing testing methods (testing time acceleration, testing methods, test rig design, dynamic loads). The gathered information is used for the development of BRT. **Figure 4** shows the survey results regarding the dwelling time and frequency of specific operation modes.
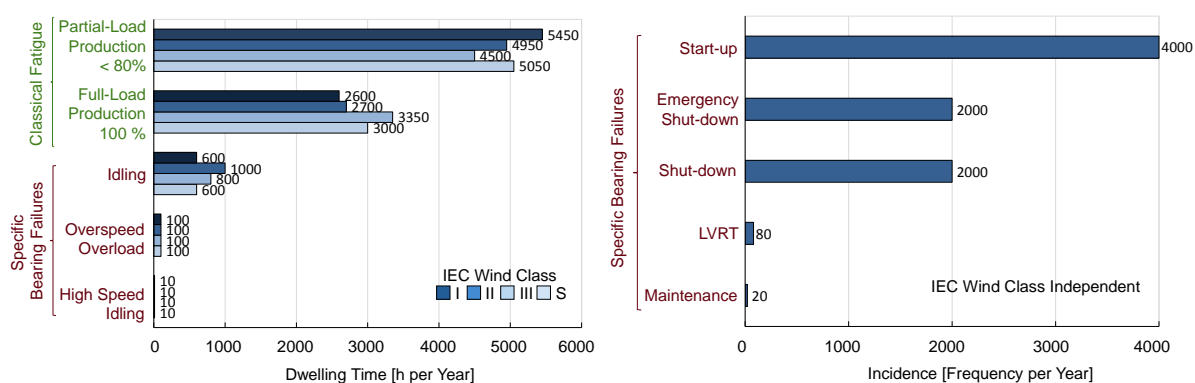

Figure 4. Dwelling time and frequency of specific operation modes

As mentioned before BRT comprises two main parts: load spectrum for the classic fatigue as well as load cycles for the specific bearing failures. The load estimation is executed in the same manner by defining relevant operating modes for these two BRT parts separately, see **Figure 4**. The stationary production mode is considered during the development of the classic fatigue load spectrum. On the other side, transient operation modes, e.g. start-up, shut-down, gust, LVRT, are used for the load cycle derivation for the specific bearing failures.

4.2. Determination of Internal Loads

For the creation of the BRT it is essential to determine the **internal bearing loads** (forces, bending moments, load dynamics) and the **behaviour of the bearing** (local contact conditions) under specific

system-dependent conditions, which have been summarised in the previous sections. Subsequently, the internal loads have to be transferred one-to-one on the test bearing by the deployment of the bearing test rigs. The internal loads of the planetary and HSS bearing are calculated separately for **production mode** (classic fatigue) and **transient operation modes** (specific bearing failures).

The bearing loads (rotational speed, radial and axial forces) due to **production mode** are calculated in two steps. First, the internal loads on the rotor hub and gearbox are determined under the defined load assumptions with Multi Body Simulation (MBS) model according to [23] (wind field calculation e.g. by NREL TurbSim). This MBS model contains flexible blades, main shaft and frame as well as tower. The gearbox and generator are simplified as a point mass and moment of inertia. Second, the gearbox input loads and analytical gearbox model are used for the calculation of the internal bearing loads of planetary and HSS bearing. Finally, the results are summarised and classified into the critical 6 years loads spectrum, which is used for the determination of bearing behaviour under the operation mode (full-load and partial-load).

The internal loads due to **transient operation modes** are calculated directly with a sophisticated MBS model under specification of a wind field and under detailed consideration of the controller strategy and electro-mechanical coupling (electrical co-simulation of generator and converter) as well as gearbox components [22]. Subsequently it is verified if the designed bearing test rigs are capable to reproduce these internal loads on the tested bearing. Afterwards, the internal loads and transient operation mode characteristics (load frequency, torque/rotational speed gradients, accelerations) of the transient operation modes under different mean wind speeds and turbulence intensities are summarised.

4.3. Determination of Bearing Behaviour

By knowing the internal loads of the planetary and HSS bearing as well as the characteristic of the transient operation modes it is possible to calculate the bearing behaviour. On one side, the bearing behaviour is used to calculate the classic fatigue life time of the bearings and subsequently to accelerate the testing time for it. On the other side, knowledge of the bearing behaviour allows to select the critical operation modes and afterwards the critical loads for specific bearing failures.

In case of the classic fatigue, the bearing behaviour is described by the contact pressure, rotational speed and lubricant temperature at steady state which are caused by the internal bearing loads under operation mode [24]. In case of the specific bearing failures, the bearing behaviour is described by the several parameters (e.g. contact pressure, lubricant film height, slippage, accelerations, deformation of the surrounding), which are evident under the transient operation modes [25]. The bearing behaviour is calculated by means of detailed MBS and Finite Element Method (FEM) simulation of the single bearing and additional elastohydrodynamic (EHD) or thermoelastohydrodynamic (TEHD) simulation of a contact. The selected simulative approach for the determination of the bearing behaviour has been exemplarily executed for the 2.75 MW research nacelle of the Research Association for Power Transmission Engineering (FVA) [8] and is compiled in **Figure 5**.
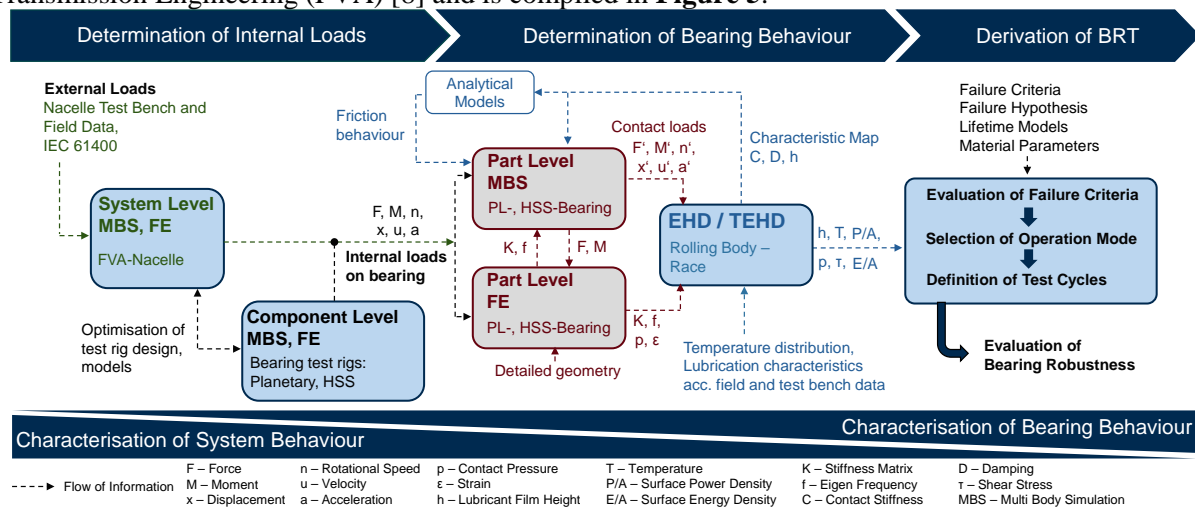

Figure 5. Simulative approach for the determination of bearing local loads as well as bearing behaviour and derivation of BRT

Additionally, **Figure 6** shows exemplarily the steps for the determination of the bearing behaviour for the FVA-nacelle HSS bearing under the emergency shut-down due to grid failure. The internal bearing forces and load gradients are determined by the MBS model. Afterwards, the bearing forces are transferred to the FEM. Finally, the behaviour of the bearing (global and local force distribution and contact pressure) is determined.
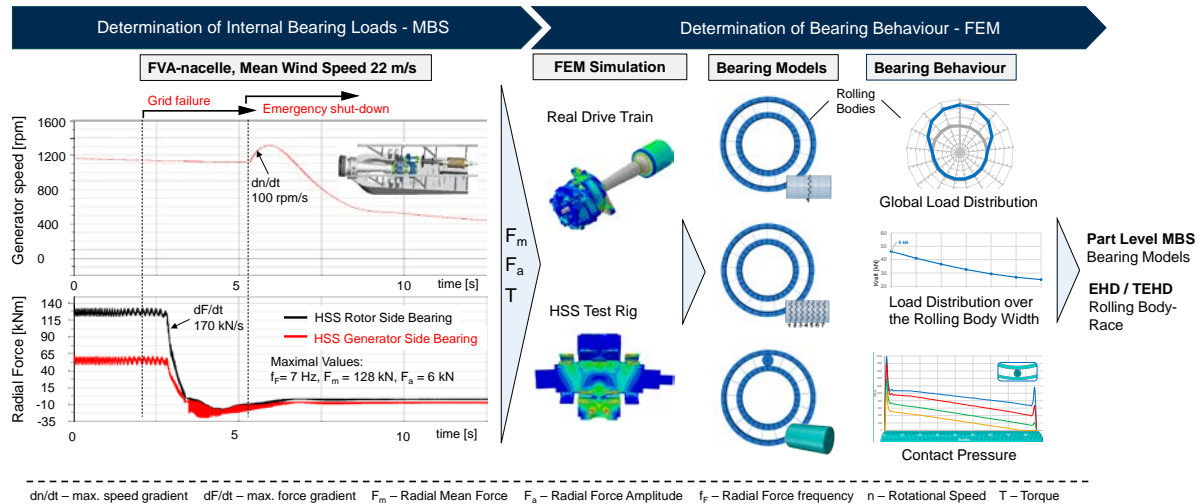

dn/dt – max. speed gradient   dF/dt – max. force gradient F_m – Radial Mean Force F_a – Radial Force Amplitude f_F – Radial Force frequency   n – Rotational Speed   T – Torque

Figure 6. Determination of bearing behaviour by MBS and FEM

The developed MBS and FEM are validated by measurements on the 4 MW nacelle test bench [17].

4.4. Evaluation of Failure Criteria
The evaluation of the failure criteria is executed separately for the classic fatigue and specific bearing failures. In the case of classic fatigue, the result of the evaluation is a test time accelerated load spectrum based on 6 years of operational mode. The evaluation results in case of specific bearing failures are selected and characterised critical operation modes. This characterisation comprises load gradients (force, bending moments and rotational speed), load frequencies, load values and sequences.

4.4.1. Evaluation of the Failure Criteria for Classic Fatigue. Failure criteria evaluation for the **classic fatigue** is executed by calculation of the fatigue life time for 6-year load spectrum according to DIN ISO 281 [12]. The load-time curve of the load estimation has to be classified to the first critical 6 years. The classification of fatigue bearing loads is executed by time-at-level count method [19] and pictured as load revolution distribution (LRD) [18]. Time-at-level count is a two-parametric classification method, which considers the rotational speed and corresponding torque. By knowing the duration of rotational speed, it is possible to calculate the number of load cycles. At the beginning the classification is done for the gearbox input shaft and subsequently for the planetary and HSS bearing. **Figure 7** shows the classified and upscaled 6 years load spectrum of the gearbox input shaft for the production mode and idling, which is based on the 2-month field data. The field data has been sampled with 25 Hz and comprises measurement data (almost 2000 single files – 10 min) for idling, normal and transient operation.

The 6-years load spectrum for classical fatigue is divided into six similar one-year load spectrums to consider wind field fluctuations over the year. Each of these one-year spectra considers the weather-related fluctuation of the mean wind speed and turbulence intensity, which can be estimated according to the known site characteristics or can be extracted from the field or simulation data. Consequently, e.g. the BRT for European latitudes comprises higher mean loads during the winter months. This means that the sequence and frequency of relevant loads for the classical fatigue are considered in the BRT.
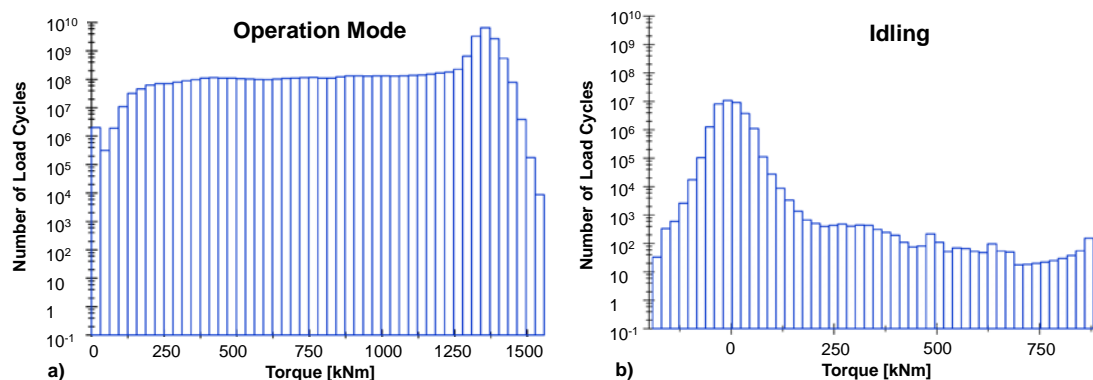
Figure 7. Upscaled 6 years load spectrum of the gearbox input shaft according the 2-month field data of a 2 MW IEC 3a wind turbine: a) production mode, b) idling

The classified 6-year load spectrum has to be condensed to a maximum 2-month load spectrum (fatigue load spectrum) to get acceptable test time during the robustness evaluation. The test time acceleration is done according the state of the art by the omission, truncation, increase of a bearing force and rotational speed [20], [21]. The 2-month load spectrum has the same damage accumulation as the 6-years load spectrum and reproduces the critical fatigue conditions on the test rig in a short time. Furthermore, the weather-related influences (day and night as well as seasons) are considered in the fatigue load spectrum by appropriate arrangement of the each load class. Afterwards, the consistence of the bearing behaviour (same lubrication film height, no plastic deformation) under the fatigue load spectrum has to be ensured. If the bearing behaviour has changed, the fatigue load spectrum is adapted in the loop-back iteration. **Figure 8** shows the entire process of the fatigue load spectrum definition.
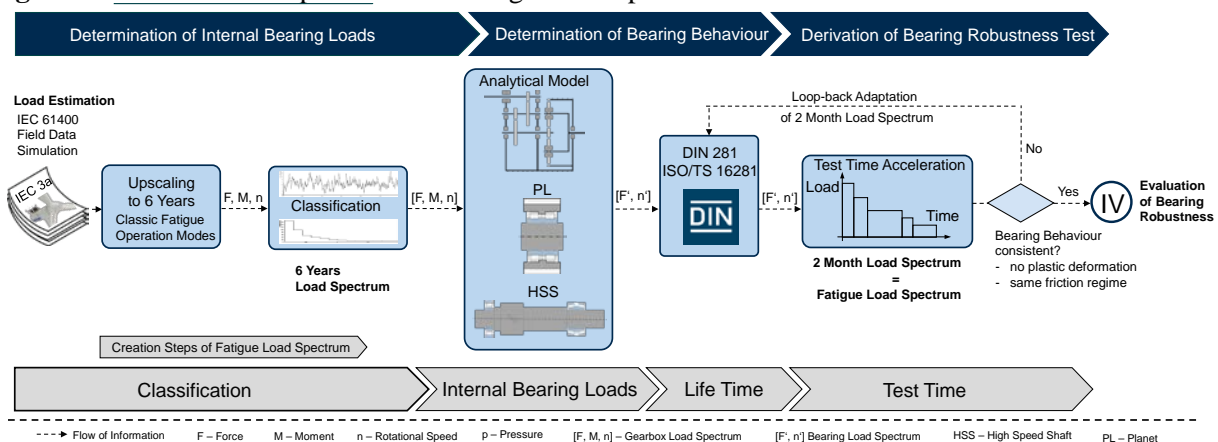

Figure 8. Definition of the 2 month fatigue load spectrum

4.4.2. Selection of Critical Operation Modes. The failure criteria of the classical fatigue, such as contact pressure and over-rolling frequency of the bearing, accumulates over the operational time and can lead to fatigue damage if the maximal damage accumulation is achieved. This mechanism can be described by generally accepted and validated life time models, e.g. Miner's rule [12]. In case of the specific bearing failures (micro-pitting, smearing, lip fractures) there is no general accepted life time prediction models. Several hypotheses and research efforts exist for description of this failures (e.g. micro-pitting [13], smearing [14]). These hypotheses are used in the BRT for the selection of the critical operation modes, which trigger the specific bearing failures. This approach allows to determine the critical operation conditions for micro-pitting, smearing and lip fracture and subsequently to reproduce them on the bearing test rig. Figure 9 compiles the failure criteria for the specific bearing failures, for which the bearing robustness can be investigated during the BRT. The failure criteria are extracted from the state of the art by using literature research (e.g. [13], [14]) and industry surveys. In case of the lip fracture the prevailing stress and strain values of the critical lip area (fillet or undercut) are the failure criteria which

can lead to structural fatigue. Failure criteria for smearing is the energy input caused by slippage and contact pressure. Bearings react vulnerably to the micro-pitting by mixed friction conditions ($\lambda < 0.7$) [13]. The critical state conditions of the bearings, under consideration of the system-dependent influences and different operation modes, can be determined by FEM, MBS and Computational Fluid Dynamics (CFD) simulations. Consequently, any contribution to the failure cause as well as any deviation from the normal state can be described by simulation and used to derive test cycles.

Figure 9. Failure Criteria of the specific bearing failures
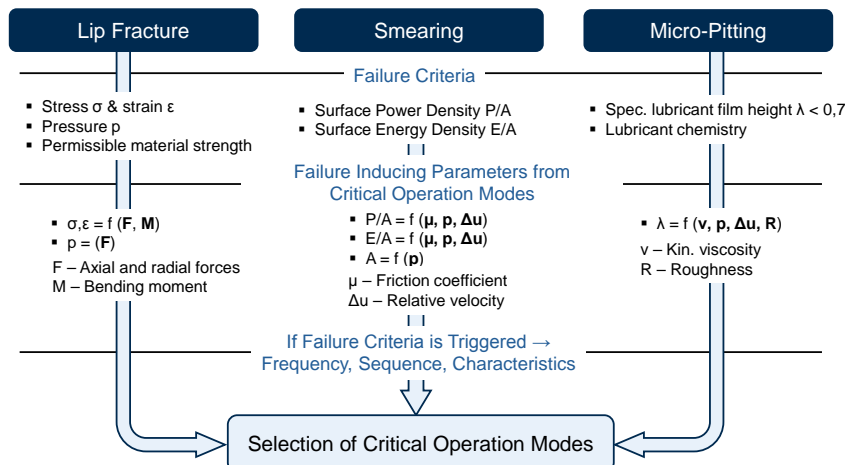
The critical state conditions of the bearings, under consideration of the system-dependent influences and different operation modes, can be determined by FEM, MBS and CFD simulations. Any contribution to the failure cause as well as any deviation from the normal state can be described by simulation and used to derive test cycles. This approach is pragmatic and does not aim to precisely predict the emergence of the specific failure or to describe its mechanism. Nevertheless, it can be used to estimate the bearing robustness by frequently exposing the bearing with critical operation conditions.

As mentioned in previous sections, the specific bearing failure, such as smearing, micro-pitting, failures due to slippage or lip fractures (White Etching Cracks are excluded), are considered by the inducing of critical operation conditions to the fatigue load spectrum. The selection of the critical operation modes is executed by comparison of the failure criteria with the prevailing bearing behaviour. If a failure criterion is triggered under specific operation mode, then this operation mode is classified as critical. The selection of the critical operation modes is done under evaluation of transient conditions such as start-up, shut-down,(LVRT, High Voltage Ride Through (HVRT), electrical short of generator, gust, cross wind, pitch error and rotor imbalance. To narrow down the transient operation mode, CWD has executed industry surveys which have revealed a critical quantity of operation modes, see **Figure 10.**

Operation Mode	Bearing Failures						
	Classic Fatigue	Lip Fracture	Indentations	Micro-Pitting	Smearing	Ring Creep	Abstentions No.
Full-Load Production	xxxxxx	xxxx	xx	xxx		xxxxxx	2
Partial-Load Production	xx	x	xx	xx	x	xxx	2
High-Speed Idling				x	xxxxxxxx		1
Standstill			xxxxxxx	x			1
Idling			x	xx	xxxx		3
Start-up					xxxx		4
Shut-down					xx		6
Emergency Shut-down		x	x		xxxxx	x	2
LVRT					xxx		5
Pitch Error			x	x	xx	xx	4
Yaw Error	x				x	x	6

In total 8 participants (bearing, gearbox and wind turbine manufacturer) have attended on the industry survey　　　X = one choice

Figure 10. Results of the industry survey according critical operation modes

As expected, **Figure 10** shows that besides the classic fatigue, production mode has an influence on the specific bearing failures. This is considered in BRT by the fatigue load spectrum.

The emergence of the specific bearing failures (smearing, micro-pitting, failures due to slippage or lip fractures) are not accelerated under deployment of the life time model, as it is done in the case of the classical fatigue. The test time acceleration has been achieved under frequented induction (according to the field frequency) of the critical operation modes which can lead to the specific bearing failures. If the emergency stop occurs twenty times per year (e.g. every second week) in the field, the test cycles of the BRT will include the emergency stop every second day. Consequently, it is important that the critical operation modes are induced under normalized conditions and not directly behind each other to ensure realistic load situation.

4.5. Derivation of BRT Test Cycles

By knowing the fatigue load spectrum and characteristics (e.g. sequence, frequency of evidence, dynamics) of the critical operation modes it is possible to define the test cycles of BRT. Therefore, the load classes of the fatigue load spectrum are finally checked for the feasibility and arranged according to the estimated, weather-related (winter-summer, day-night) wind field fluctuations. The plausibility is checked by comparison of the bearing behaviour under 6 years load spectrum with a 2-month load spectrum. The 2-month load spectrum should not lead to a plastic deformation and different friction regime due to test time acceleration (higher loads and rotational speed). Afterwards, the critical operation modes, which triggers the specific bearing failures, are induced to the arranged fatigue load spectrum, see **Figure 11**.
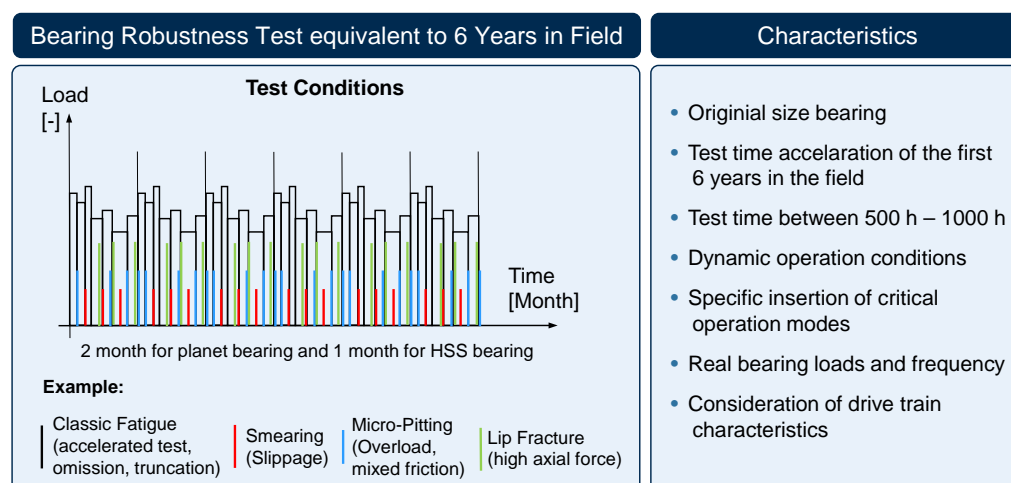

Figure 11. Bearing Robustness Test for Wind Turbine Gearbox Bearings

Within the research project, the BRT is executed for 48 HSS and 14 planetary bearings, wherein cylindrical and tapered roller bearings are investigated. After the BRT, the test bearings are examined by destructive and non-destructive methods to describe the bearing state after the test. Finally, the bearing state allows to make statement regarding the robustness against specific field load conditions.

The evaluation and specification of the bearing robustness is done in two steps: execution of BRT and evaluation of test results. The test cycles of the BRT are executed on the mentioned test rigs for original size bearings. The classic fatigue and specific bearing failures are tested simultaneously. First critical 6 years of field operation are tested on the test rig within maximum 1000 hours.

5. Summary

The paper introduces an approach for the creation of the test cycles to prove the robustness of the original size wind turbine gearbox bearings (e.g. planetary and HSS bearings). The consideration of the dynamic loads, system characteristics and realistic load estimation are essential to reproduce the real load conditions and to develop the test cycles. By means of the BRT it is possible to evaluate the robustness of bearings against specific field conditions in early product cycle and consequently to enhance the quality and to reduce the failure rate of the bearing. Finally, the development method can be adapted on

different bearing types, drive train concepts and sites by execution of the describe steps for the creation of the BRT.

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