Investigation of Bearing Axial Cracking: Benchtop and Full-Scale Test Results

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NREL/TP-5000-67523
Revised January 2019

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Errata

This report, originally published in August 2017, was revised in January 2019. The equations for velocities originally shown in Figure 7 were removed, as they no longer correspond to the same set of equations in NREL/TP-5000-70639. The discrepancy was caused by a change in the frame of reference for the roller speed measurement. The figure itself was also updated to match a similar figure in NREL/TP-5000-70639. Additionally, the figure caption was updated to indicate that the roller speed shown in the figure was from a previous experiment, not the work described in this report.

Acknowledgments

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Table of Contents

Errata iii
Acknowledgments iv
Table of Contents v
List of Figures v
List of Tables v
1 Abstract 1
2 Introduction 2
3 Tribological and Material Testing 3
3.1 Benchtop Testing 3
4 Full-Scale Gearbox Testing 6
4.1 750-Kilowatt Gearbox 6
4.2 1.5-Megawatt Gearbox 7
5 Summary 9
References 10

List of Figures

Figure 1. Micro Pitting Rig tribological benchtop test rig overall view (a) and view of the test housing showing the three-ring-on-roller configuration (b) [5] 3
Figure 2. Benchtop test sample roller post-test; top view of roller race with spall (a) and circumferential cross section etched showing WECs (b) [5] 4
Figure 3. Plot of the results from the benchtop tests showing the threshold of WEC formation with respect to cumulative frictional heat energy [5] 5
Figure 4. Braking event speed and torque event (left) and resulting bearing roller contact stress and sliding indicator (right) 6
Figure 5. Grid-loss event speed and torque event (left) and resulting bearing roller contact stress and sliding indicator (right) 7
Figure 6. Normal power production speed and torque event (left) and resulting bearing roller contact stress and sliding indicator (right) 7
Figure 7. Bearing roller sliding velocities (left) and measurements (right). *Illustration (right) by SKF* [17] 8
Figure 8. High-speed-shaft instrumentation package 8

List of Tables

Table 1. Benchtop Test Conditions and Results with Calculated Cumulative Frictional Energy 4

1 Abstract

The most common failure mode in wind turbine gearboxes is axial cracking in intermediate and high-speed-stage bearings, also commonly called white-etching cracks (WECs). Although these types of cracks have been reported for over a decade, the conditions leading to WECs, the process by which this failure culminates, and the reasons for their apparent prevalence in wind turbine gearboxes are all highly debated. This paper summarizes the state of a multipronged research effort to examine the causes of WECs in wind turbine gearbox bearings. Recent efforts have recreated WECs on a benchtop test rig in highly loaded sliding conditions, wherein it was found that the formation of a dark etching microstructure precedes the formation of a crack, and a crack precedes the formation of white-etching microstructure. A cumulative frictional sliding energy criterion has been postulated to predict the presence of WECs. Bearing loads have also been measured and predicted in steady state and transient drivetrain operations in dynamometer testing. In addition, both loads and sliding at full scale will be measured in planned uptower drivetrain testing. If the cumulative frictional sliding energy is the dominant mechanism that causes WECs, understanding the amount of frictional sliding energy that wind turbine bearings are subjected to in typical operations is the next step in the investigation. If highly loaded sliding conditions are found uptower, similar to the examined benchtop levels, appropriate mitigation solutions can be examined, ranging from new bearing coatings and improved lubricants to changes in gearbox designs and turbine operations.

2 Introduction

Failures in gearbox bearings have been the primary source of reliability issues for wind turbine drivetrains, leading to costly downtime and unplanned maintenance. The most common failure mode is attributed to so-called axial cracks or white-etching cracks (WECs), which primarily affect the intermediate and high-speed-stage bearings. According to the Gearbox Reliability Database maintained by the National Renewable Energy Laboratory, bearing failures account for over 60% of all failures, and axial cracking represents over 70% of all bearing failures. “Axial crack” refers to the orientation of the crack as it appears on the raceway of the bearing inner ring. These cracks tend to propagate to spalls or lead to a complete splitting of the ring. Upon cross-sectional and metallographic analysis of the cracked bearing, the microstructure of the steel surrounding the crack is observed to have experienced alterations. The altered steel microstructure is evident by how the material responds to chemical etching in which the alteration appears white compared to the unaltered material, lending to the name “white-etching cracks.” These failures in wind turbine bearings occur well before the design life as predicted by the standard L10 life defined by the International Organization for Standardization and American Bearing Manufacturers Association. Furthermore, the morphology of the crack and alteration of the microstructure is not consistent with typical features observed in classical rolling contact fatigue, namely: butterflies and white-etching bands. This inconsistency indicates that the WEC failures are either the result of drivers beyond the load used in calculating L10 rolling contact fatigue bearing life, or the load in wind turbine bearings are not well understood and exceed predicted levels.

Considerable research efforts have focused on understanding the possible root causes of WECs, which have included: high strain rates [1−3], hydrogen embrittlement [4,5], bearing skidding and sliding [6–8], inclusions [2,3,5,9,10], bearing assembly, corrosion fatigue cracking [11], and electrical current [12,13]. To date, there is little consensus on the root causes of WECs in wind turbine bearings. It is the aim of the current study to evaluate the causes of WECs in wind turbine bearings with a multipronged approach that includes: a system-level analysis to measure the real operating conditions in a wind turbine gearbox and the contact conditions that exist in field-representative operations, and a tribological and materials analysis to understand how bearing steel responds at a microstructural level to a range of contact conditions. The current work will focus on the influence of skidding/sliding between the bearing rolling element and the raceway.

3 Tribological and Material Testing

To provide a platform to readily evaluate the range of possible root causes of WECs cited in the introduction, a tribological benchtop rig is utilized that is capable of replicating the contact conditions that are experienced between a rolling element and raceway in a wind turbine gearbox bearing. The benchtop rig is capable of inducing a range of highly controllable contact conditions, including load, slide-to-roll ratio (SRR), speed, and temperature. The rig is also configurable to test nonstandard conditions like electrical currents across the contact. The advantage of conducting tests on a benchtop rig is that it not only accelerates the ability to evaluate a range of conditions on WEC formation, but also enables detailed study of the evolution of the failure initiation and propagation through post-test microstructural analysis of the test samples.

3.1 Benchtop Testing

The tribological test rig used in this study is a PCS Instruments Micro Pitting Rig, shown in Figure 1, which provides a three-ring-on-roller splash-lubricated line contact and allows for testing at customizable user-specified conditions: SRRs ranging from pure rolling to pure sliding, at loads ranging from 0.5 gigapascal (GPa) to 3 GPa, and at lubricant temperatures in excess of 100°C.

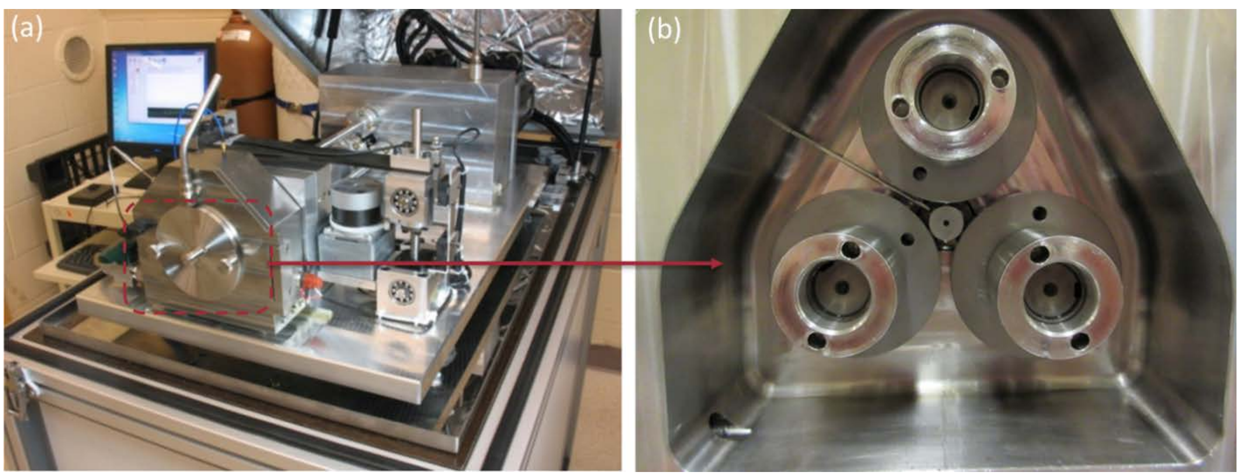


Figure 1. Micro Pitting Rig tribological benchtop test rig overall view (a) and view of the test housing showing the three-ring-on-roller configuration (b) [5]

The lubricant used in this study is a fully formulated gear oil mix consisting of Group I+IV semisynthetic base stock, viscosity-grade 68. This specific gear oil formulation has been shown in several studies to readily form WECs. It is used in this current study to demonstrate which range of contact conditions would lead to WEC formation. The test samples are made of American Iron and Steel Institute 52100 through hardened, tempered, martensitic steel for both the rollers and rings with a Rockwell C hardness of 60 and 63, respectively. Experiments were conducted with a range of loads, speeds, and SRR conditions, as shown in Table 1.

Table 1. Benchtop Test Conditions and Results with Calculated Cumulative Frictional Energy

Test	Normal Load (N)	Contact Stress (GPa)	Rolling Speed (m/s)	SRR (%)	Contact Cycles ($x10^6$)	WECs?	E (megajoule)
1	500	1.9	1	-30	38.2	Yes	8.04
2	500	1.9	1	+30	18.2	No	3.32
3	500	1.9	1	-5	100	No	3.52
4	500	1.9	1	+5	34.5	No	1.03
5	40	0.5	3.4	-30	100	No	2.89
6	135	1.0	3.4	-30	100	Yes	7.93
7	300	1.5	3.4	-30	100	Yes	13.14
8	500	1.9	3.4	-30	42	Yes	9.70
9	500	1.9	1	-30	20	No	4.63
10	500	1.9	1	-30	30	Yes	6.26

Tests were concluded when a spall failure occurred, as indicated by the measured vibration between the roller and top ring. If no failure occurred, the test was stopped at 100 million cycles. To determine if WECs were formed, the roller sample was sectioned after the test and exposed to a Nital etchant, as shown in Figure 2.

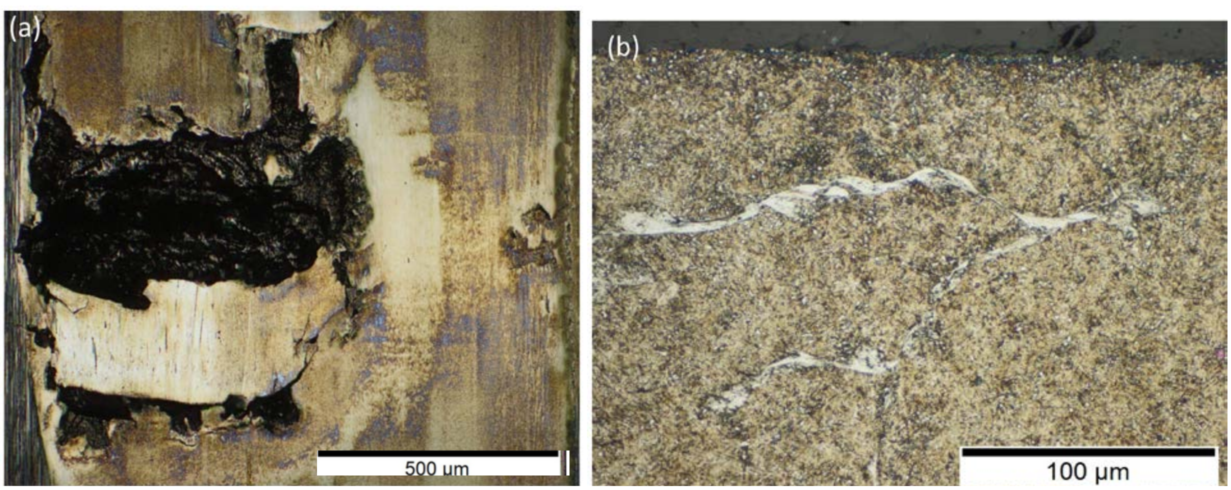


Figure 2. Benchtop test sample roller post-test; top view of roller race with spall (a) and circumferential cross section etched showing WECs (b) [5]

The first four tests, 1–4, show the dependence of WEC formation under a range of SRR conditions between +/-5% and +/-30%. Of these four tests, only the test performed at -30% SRR resulted in WEC formation. The next four tests, 5–8, show the WEC dependence under a range of load conditions between 0.5 and 1.9 GPa. Only the test at 0.5 GPa did not result in a WEC within the 100-million-contact-cycle duration. The final two tests, 9–10, showed the effect of test duration between 20 and 30 million cycles. Both tests were stopped deliberately at the respective contact cycles. The test at 20 million cycles did not result in WECs, whereas the test that stopped at 30 million cycles did. To correlate these tests using one parameter, a value was calculated to represent the cumulative frictional heat energy, E, generated during each test, as demonstrated in Eq. 1, where ΔV is the sliding speed (the difference between the velocity of the ring and the velocity of the roller at the contact), μ is the average measured friction coefficient, N is the normal load, and t is the total testing time:

$$E = \frac{3}{2} \Delta V \mu N t \tag{1}$$

Considering this energy parameter, the results of the 10 tests are plotted with respect to the occurrence and number of WECs observed in the roller sample post-test as shown in Figure 3. This plot shows a threshold of WEC formation with respect to the cumulative frictional heat energy parameter. The magnitude of this energy parameter is likely to only be specific to the current benchtop test configuration, materials, lubricant, and conditions; therefore, it is not necessarily directly translatable to the full-scale application. However, the premise is that frictional heat resulting from high-load and sliding contact is likely one possible driver for WEC formation in wind turbine gearbox bearings. It is not evident from these results what physical connection friction energy has on WEC formation, as it could be a response of the material to the heat input or a response of the lubricant resulting in hydrogen liberation, leading to material embrittlement. These physical responses will be the focus of future research. However, the likelihood of high-load and sliding contact conditions is considered at the full scale in the following sections of this report.

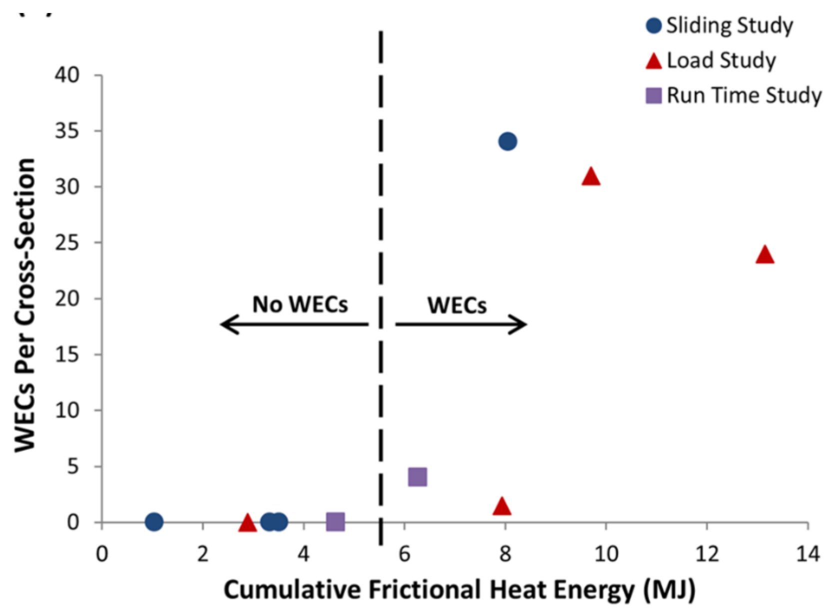


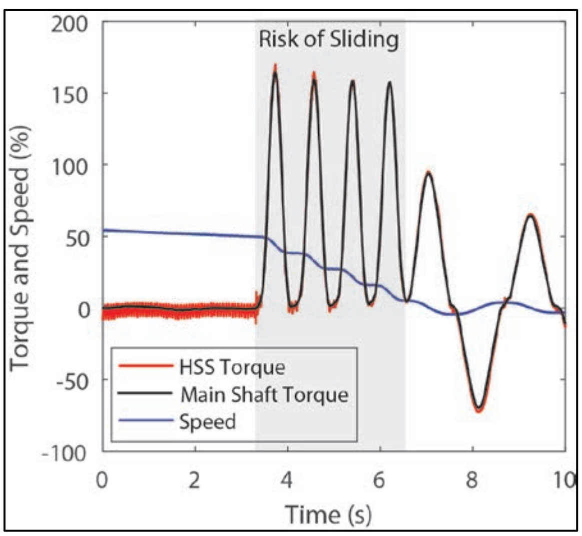
Figure 3. Plot of the results from the benchtop tests showing the threshold of WEC formation with respect to cumulative frictional heat energy [5]

4 Full-Scale Gearbox Testing

Currently, there is only speculation, rather than strong evidence, that high-load and sliding contact conditions in excess of the proposed criteria occur during typical wind turbine operations. In recognition of this, full-scale gearbox testing is required to determine the causal factors that result in bearing roller sliding and high loads. That is, which plant and turbine operations, configurations, and situations result in the bearing roller sliding, load, and tribological conditions sufficiently often enough to exceed the cumulative frictional heat energy? A secondary goal is to examine the presence of additional tribological factors in operation, such as temperatures, stray currents, and moisture also suspected of relating to WECs. These full-scale test results might also inform additional cases for the current benchtop tests; for example, if the loads, sliding, or other tribological factors measured were well in excess of or well below those already tested.

4.1 750-Kilowatt Gearbox

Field-representative dynamometer tests of the Gearbox Reliability Collaborative 750-kilowatt drivetrain were conducted [14] and high-speed-shaft and bearing loads were examined. Bearing roller speed was not measured. Steady-state operations were examined first [15], whereas more recently, bearing contact stresses and roller sliding were examined during normal power production, braking, and grid-loss events [16]. As shown in Figure 4 through Figure 6, roller sliding was evident within the bearing outer race loads, although without dedicated roller speed instrumentation its magnitude was unknown.



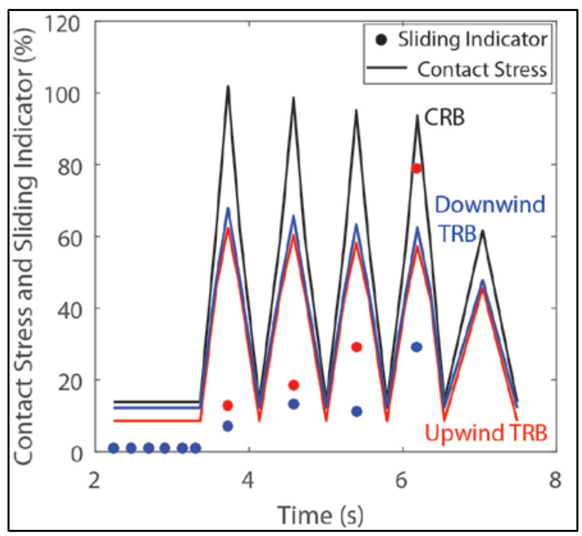


Figure 4. Braking event speed and torque event (left) and resulting bearing roller contact stress and sliding indicator (right)

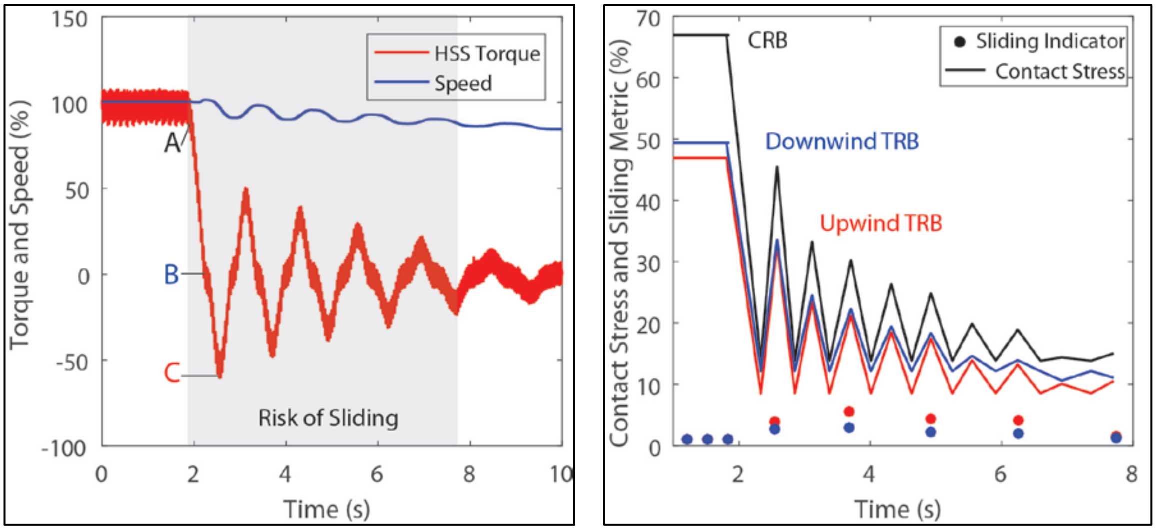


Figure 5. Grid-loss event speed and torque event (left) and resulting bearing roller contact stress and sliding indicator (right)

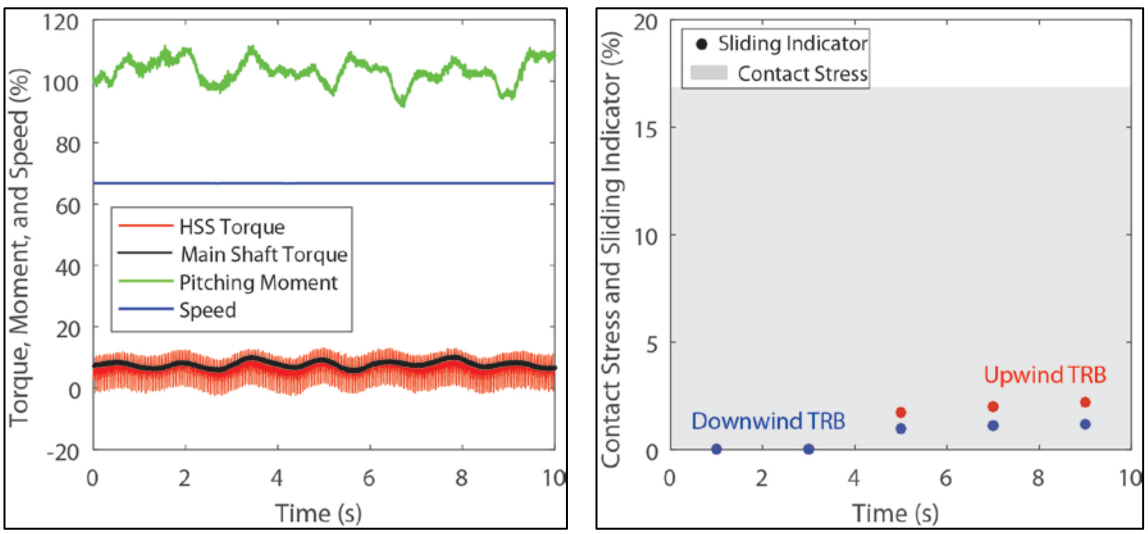


Figure 6. Normal power production speed and torque event (left) and resulting bearing roller contact stress and sliding indicator (right)

4.2 1.5-Megawatt Gearbox

Because of the importance of sliding to the formation of WECs, both loads and sliding will be measured in upcoming tests. Sliding must be measured, because it cannot be predicted with sufficient accuracy—especially in the highly dynamic wind turbine gearbox application. As shown in Figure 7, bearing roller sliding can be determined by the rotational speed of the shaft (ω_s), bearing cages (ω_c), and bearing rolling elements (ω_r). Of all of these speeds, by far the most difficult to measure is the rolling element speed. Patented instrumentation from SKF will measure it by sensing the change in voltage in a nearby inductive coil as a magnetized roller rotates in operation [17].

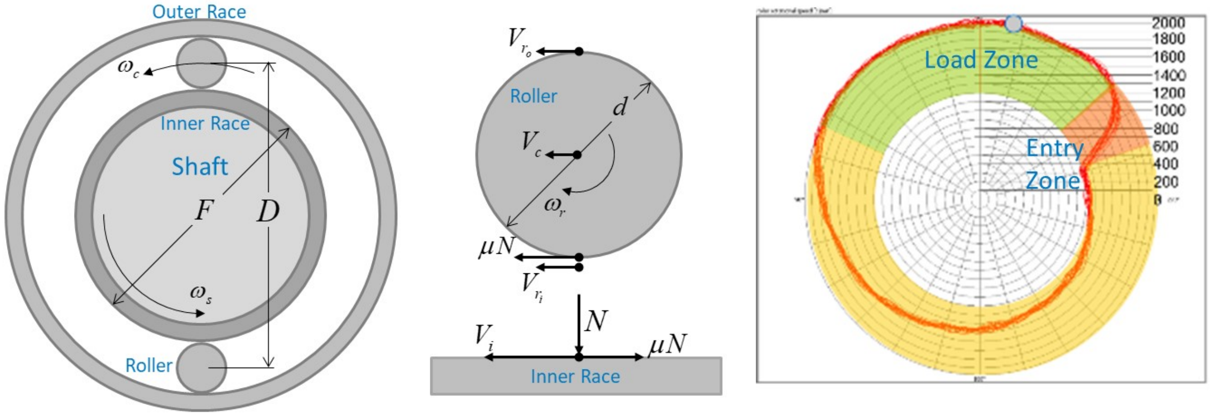


Figure 7. Bearing roller sliding velocities (left) and previous measurements (right). ***Illustration (right) by SKF*** **[17]**

A commercial gearbox will be instrumented and installed in the GE 1.5 SLE turbine at the National Wind Technology Center in late 2017 [18]. As shown in Figure 8, the high-speed-shaft cylindrical roll bearing speeds will be measured along with torque, bending moments, and other tribological factors such as temperatures, humidity, stray current, and water-in-oil content, and correlated to the turbine and grid conditions over a range of controlled operations.

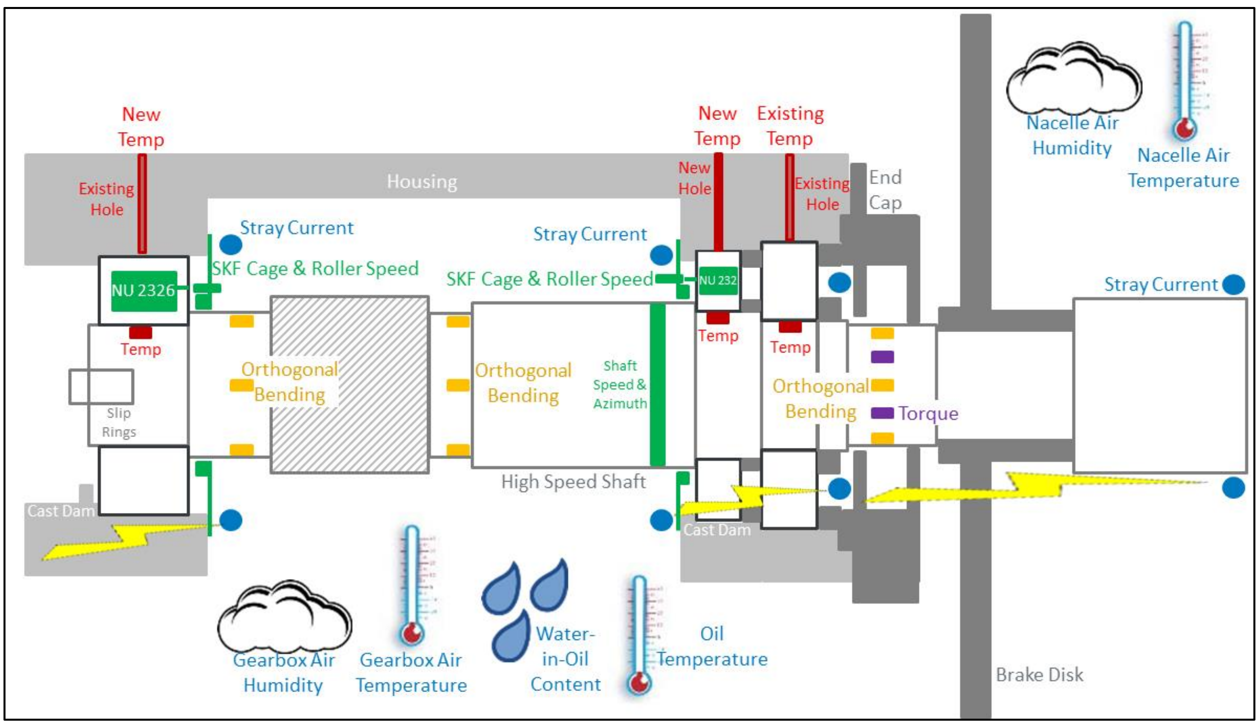


Figure 8. High-speed-shaft instrumentation package

5 Summary

Axial cracking or WEC bearing failures continue to have a significant impact on the reliable operation of wind turbine gearboxes, and the root cause of WECs are still a subject of scientific debate. This study demonstrates a multipronged research approach by the U.S. Department of Energy to investigate axial crack failures from a system level to a material/tribological level. The current work shows a benchtop test methodology that successfully replicates WEC formation under controlled contact conditions, from which an energy-based criteria related to frictional heat is identified for WEC formation. This driver for WEC formation depends on the occurrence of sliding/skidding between the bearing rolling element and race. Evidence of this roller sliding is demonstrated at the system level through analysis of a gearbox dynamometer test with field-representative conditions. With a WEC formation methodology and operational understanding firmly established, the most cost-effective mitigation methods ranging from the part level (e.g., materials, coatings, lubricants, and microgeometry) to the system level (e.g., gearbox or bearing modifications, controller and converter software, mechanical torque-limiting devices) can be developed, tested, and verified. Future research activities will focus on assessing additional WEC drivers and identifying the physical processes at a material level. Additionally, in-field testing on a 1.5-megawatt turbine of high-speed-shaft bearings will be used to validate the actual conditions that could lead to axial crack bearing failures.

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