Gearbox Reliability Collaborative Gearbox 3 Planet Bearing Calibration

Jonathan Keller
National Renewable Energy Laboratory

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March 2017

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List of Acronyms

CRB	cylindrical roller bearing
GRC	Gearbox Reliability Collaborative
kW	kilowatt
mV/V	millivolts per volt
NREL	National Renewable Energy Laboratory
TRB	tapered roller bearing

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1 Introduction

In 2007, the U.S. Department of Energy established the National Renewable Energy Laboratory (NREL) Gearbox Reliability Collaborative (GRC). Its goals are to understand the root causes of premature gearbox failures and to improve gearbox reliability. The GRC uses a combined gearbox testing, modeling, and analysis approach focused on a 750-kilowatt (kW) drivetrain with a nonproprietary, purpose-designed gearbox. Two identical gearboxes, GB1 and GB2, were manufactured and tested to investigate the loads on the cylindrical roller bearings (CRBs) used to support the planets in the gearbox [1]. A major finding was the detrimental effect of rotor nontorque loads (NTLs) on load sharing, predicted fatigue life in high-torque conditions, and the risk of bearing skidding in low-torque conditions [2]. Prior to this testing, the strain gages installed on the planetary bearings were calibrated in a load frame [3]. A similar calibration and bearing loads investigation was also conducted on the tapered roller bearings (TRBs) supporting the high-speed shaft in GB2 [4].

Based on the initial tests of GB1 and GB2, the nonproprietary gearbox design was updated to improve its planetary load-sharing characteristics and predicted fatigue life. This new gearbox is referred to as gearbox 3 (GB3). The most important aspect of the redesign was to replace the CRBs with preloaded TRBs in the planetary section, while the majority of the gearing and housing remained the same [5–8]. Similar to previous work, the strain gages installed on the new planet TRBs were calibrated in a load frame [9]. The new and reused components were assembled and GB3 was recently delivered to the National Wind Technology Center (NWTC). Dynamometer testing is being conducted to measure the actual planet TRB loads [10].

This report describes the calibration tests and provides the factors necessary to convert the measured units from dynamometer testing to bearing loads, suitable for comparison to engineering models.

2 Test Bearings

2.1 Bearing Description

The GRC gearboxes discussed in this report are composed of one low-speed planetary stage with three planet gears and two parallel shaft stages. A gearbox internal cut-away and planet TRB schematic are shown in Figure 1. The planet-gear bore was specially designed to serve as the planet bearing outer race. Each planet contains identical but separate upwind and downwind planet bearings. The bore of each planet bearing was also specially designed to include grooves for instrumentation and wire routing, a stop for overload protection, and an anti-rotation keyway [9, 11]. Both the planet gears and planet bearings, shown in Figure 2, were designed, manufactured, and instrumented by The Timken Company (Timken). Important characteristics of the planet bearings are listed in Table 1.

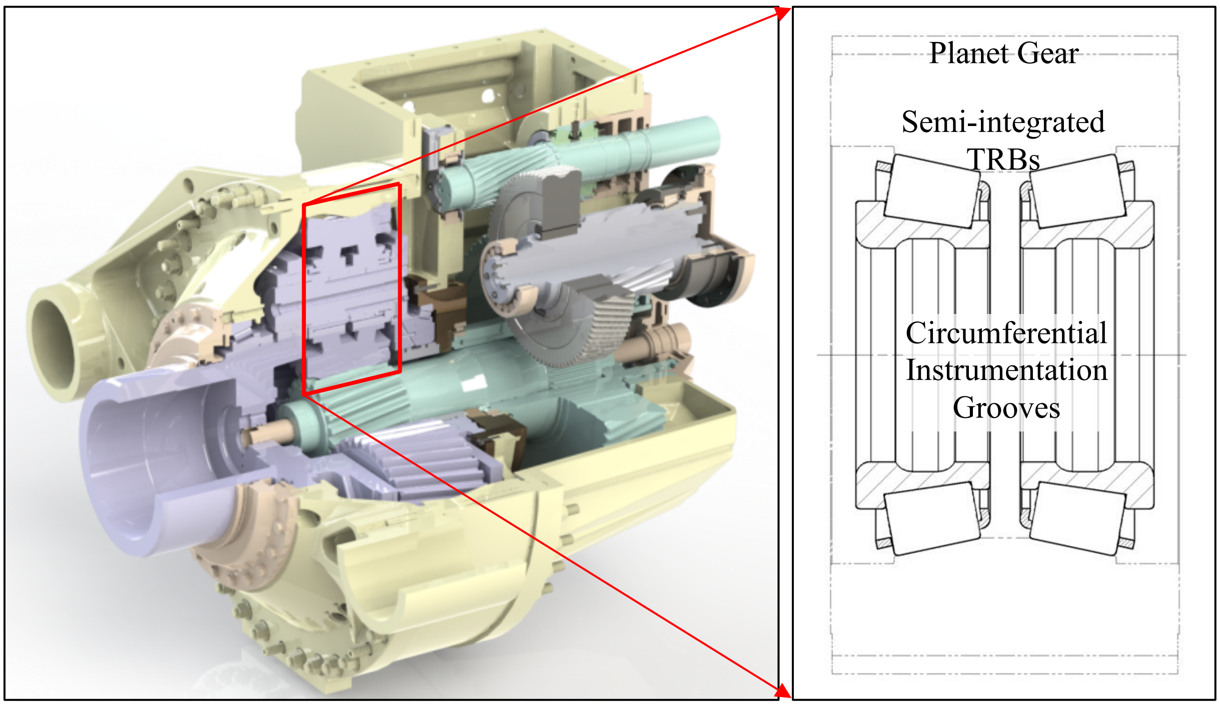

Figure 1. Gearbox 3 planet bearings. *Illustrations by Romax Technology (left) and Timken (right)*

Figure 2. Planet bearings and gears. *Photos by Jonathan Keller, NREL (left) 36523, (middle) 36524, and (right) 36521*

Table 1. Planet Bearing Characteristics

	Symbol	Value
Bearing Designation		NP527934
Planet Center Diameter	d	308 mm
Number of Rollers	Z	16
Poisson's Ratio	ν	0.3
Mounted Contact Angle	α	10°

2.2 Bearing Instrumentation

To assess the planet bearing load distribution and planet-load sharing effectively, one planet bearing pair has more instrumentation than the other two. The planet B bearing set of GB3 has strain measurements at 10 circumferential locations per row to measure the load-zone distribution in detail. The other two planet bearing sets (A and C) have measurements at only four circumferential locations per row [9]. For the complete gearbox, this results in 36 strain measurements. The measurement locations for all three planets are summarized in Table 2 and shown in Figure 3 through Figure 5. The strain gages are Micro-Measurements type EA-06-062TT-350, general purpose, 90° tee rosettes with a gage factor (G_F) of 2.13 [12, 13]. The gages are mounted in pairs. The primary gage was aligned with the maximum expected principal strain within the bearing race, whereas the other gage acts as the Poisson gage. Each bearing also contains several thermocouples [10].

Table 2. Planet Bearing Sensor Locations

Planet	Bearing	GB3 Locations (clockwise from top dead center)
A	Upwind (PL-A)	1 axial location at 70°, 160°, 250°, and 340°
	Downwind (PL-B)	1 axial location at 20°, 115°, 200°, and 285°
B	Upwind (PL-A)	1 axial location at 10°, 32°, 70°, 160°, 250°, 288°, 310°, 327.5°, 340°, and 352.5°
	Downwind (PL-B)	1 axial location at 7.5°, 20°, 32.5°, 50°, 77°, 115°, 200°, 285°, 323°, and 350°
C	Upwind (PL-A)	1 axial location at 70°, 160°, 250°, and 340°
	Downwind (PL-B)	1 axial location at 20°, 115°, 200°, and 285°

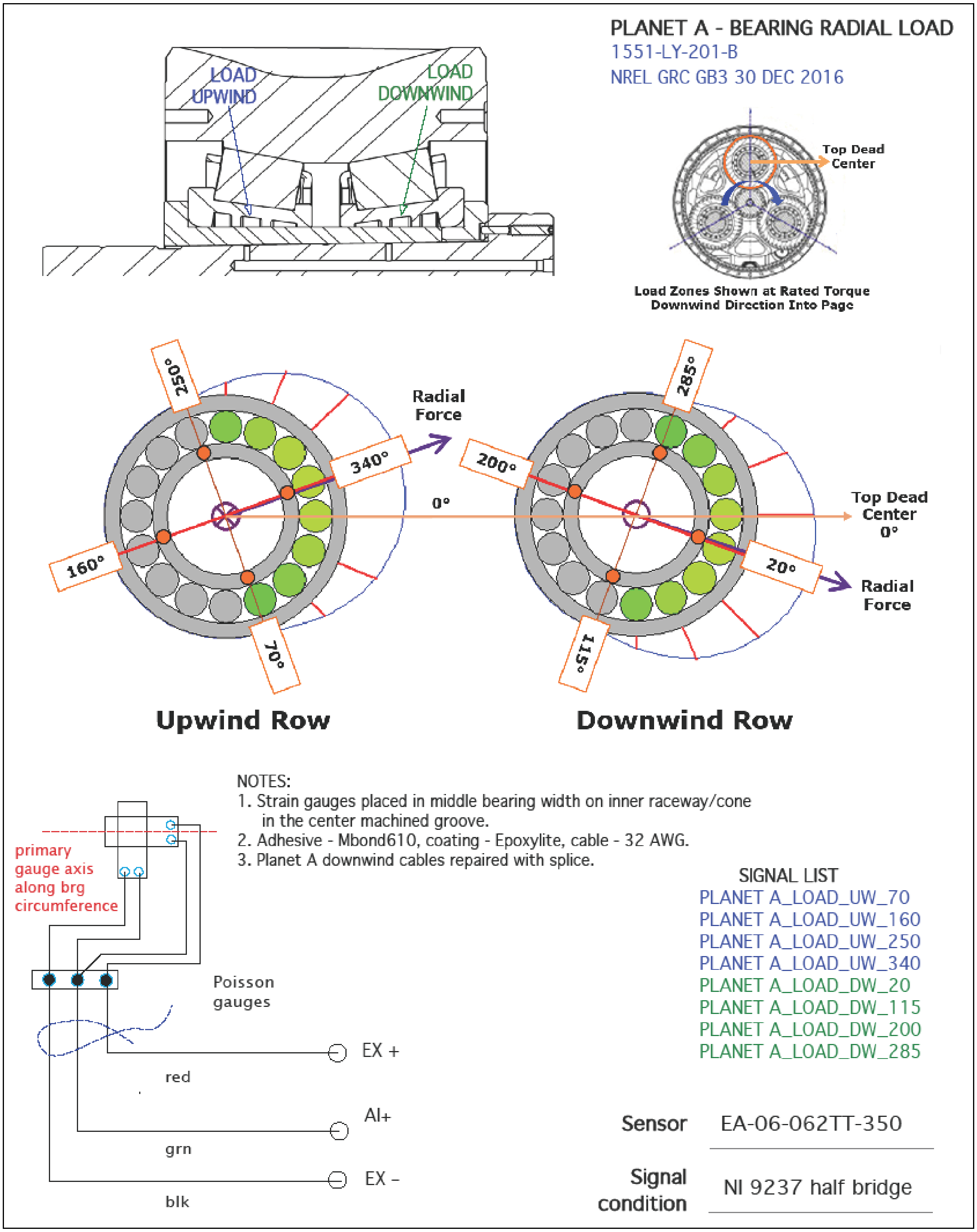

Figure 3. Planet bearing A instrumentation. *Illustration by Romax Technology*

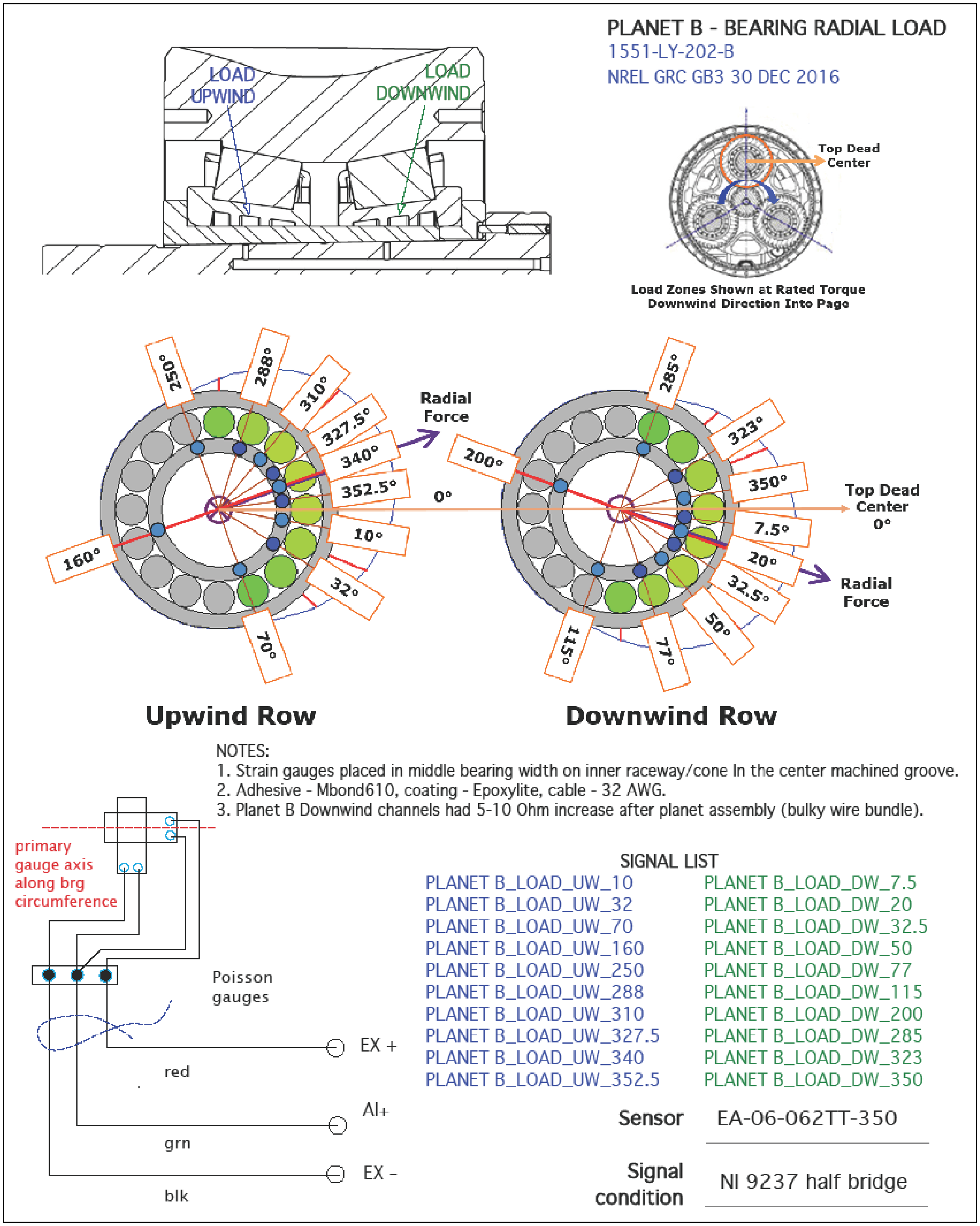

Figure 4. Planet bearing B instrumentation. *Illustration by Romax Technology*

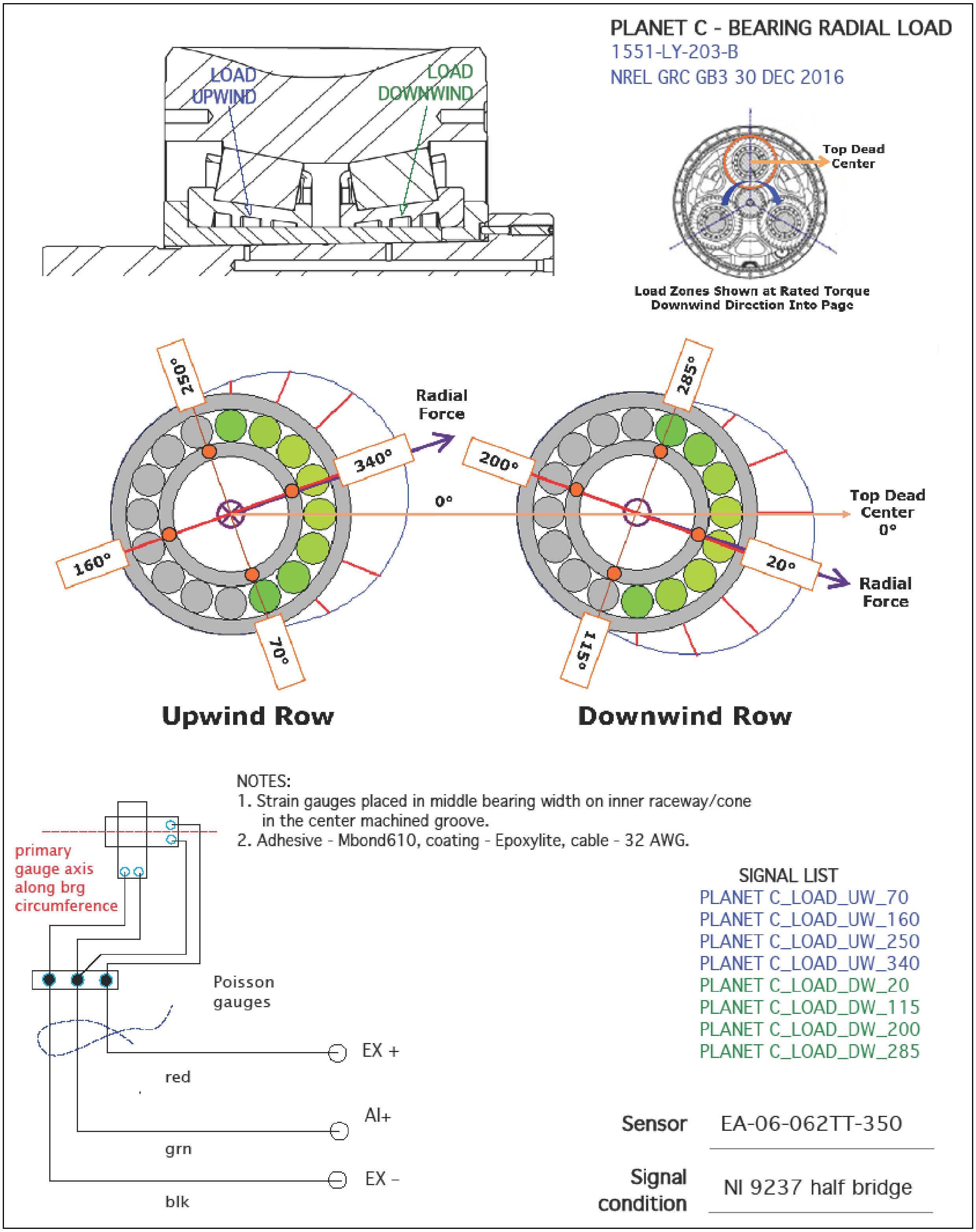

Figure 5. Planet bearing C instrumentation. *Illustration by Romax Technology*

3 Test Environment

The bearings were calibrated in a load frame at Timken [9], shown in Figure 6. The bearings were not installed with any preload. A press was used to apply a purely axial load (F_a), measured with a calibrated load cell, resulting in roller loads up to 200% of those expected at rated torque. At each load level, the bearing assemblies were rotated by hand and the resulting strain was measured. Similar to previous testing, the quantity of interest is the difference (maximum–minimum, or peak to peak) in strain as the rollers pass over the strain gage pairs, rather than the mean strain [4, 9]. This difference in strain caused by the roller passage relates the measured strain signal to the bearing load.

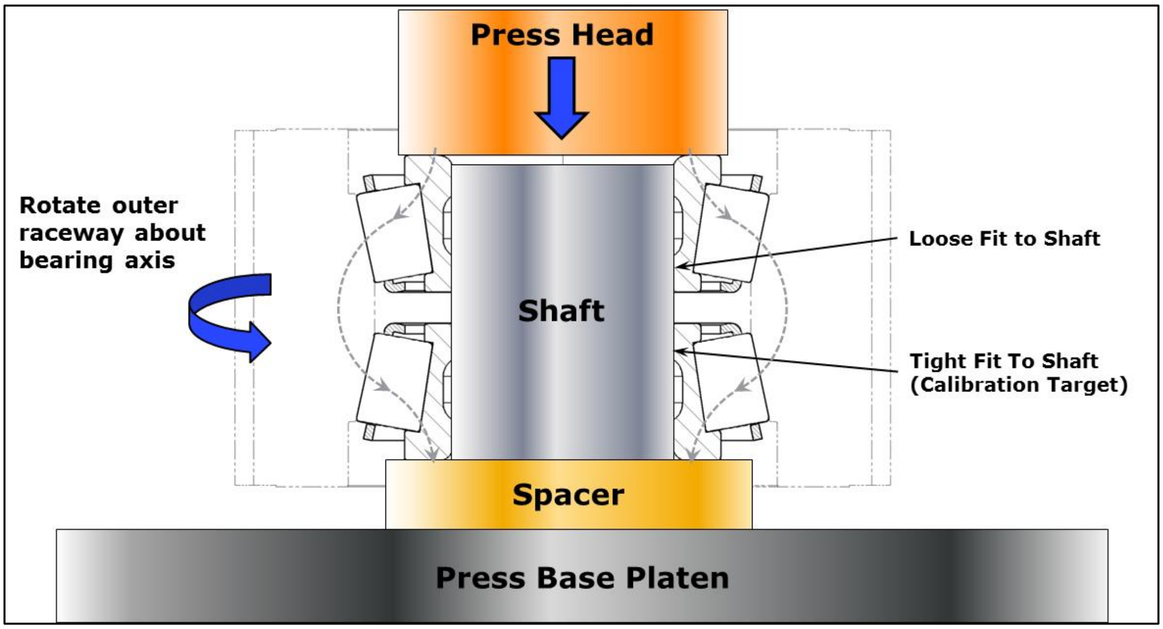

Figure 6. Planet bearing strain calibration setup. *Illustration by Timken*

4 Data Analysis

Gage calibration is determined from the measured data by regression analysis of each gage response to the applied load. The roller load (Q) normal to the raceway was calculated assuming the applied load was distributed equally among the rolling elements [14].

$$Q = \frac{F_a}{Z \sin \alpha} \tag{1}$$

The strain is converted from units of millivolts per volt (mV/V) to millistrain (mε) [15].

$$m\varepsilon = \frac{4}{G_F \left(1 + \upsilon\right)} \frac{mV}{V} \tag{2}$$

Examples of the regression analysis are shown in Figure 7 through Figure 9 for planets A, B, and C, respectively. In each case, the strain gages at the center of the expected load zone for each bearing are shown. Results for the remaining gages on each planet are similar.

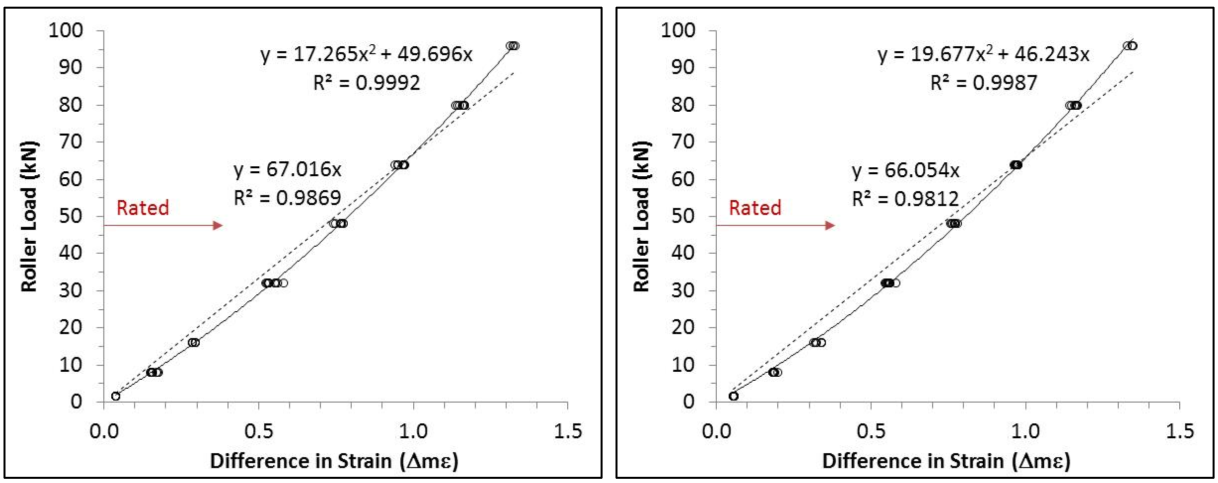

Figure 7. Regression analysis for Planet A upwind 340° (left) and downwind 20° (right) strain gages

For the GRC gearboxes, which have three planets and two bearing rows per planet, the maximum expected roller load (Q_{max}) at rated torque (T) is approximately [14]:

$$F_r = \frac{1}{2}\frac{T}{3d}$$
$$Q_{\max} = \frac{4.08 F_r}{Z \cos \alpha} \tag{3}$$

It should be noted that Eq. (3) ignores the effect of the overturning moment on the bearing loads because of the helical gearing and mounted preload. For normal operations in the dynamometer, the torque required to produce 750 kW of electrical power is typically 340 kilonewton-meters, resulting in a maximum roller load of 47.6 kilonewtons (kN), as indicated in each figure.

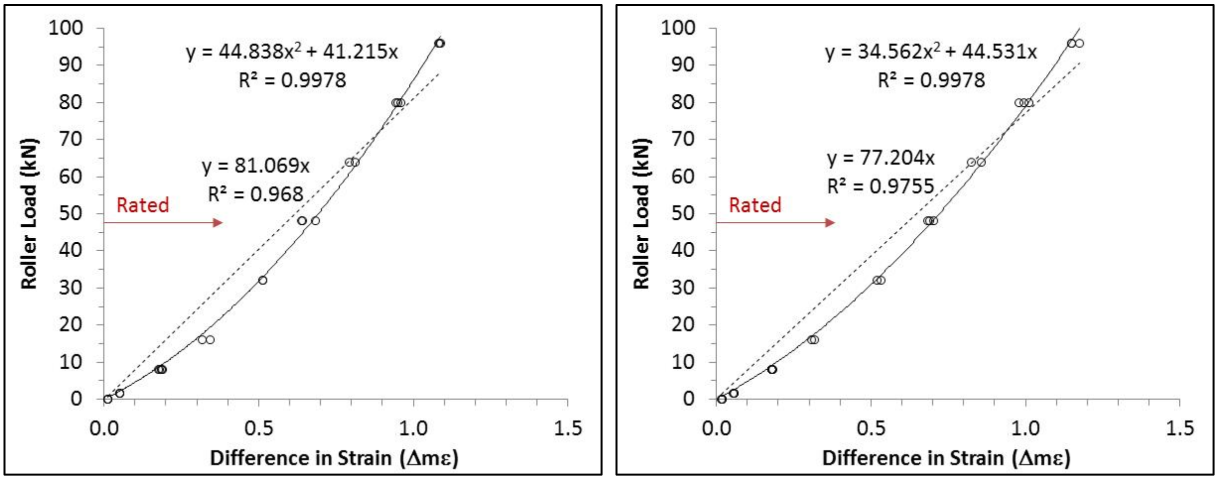

Figure 8. Regression analysis for Planet B upwind 340° (left) and downwind 20° (right) strain gages

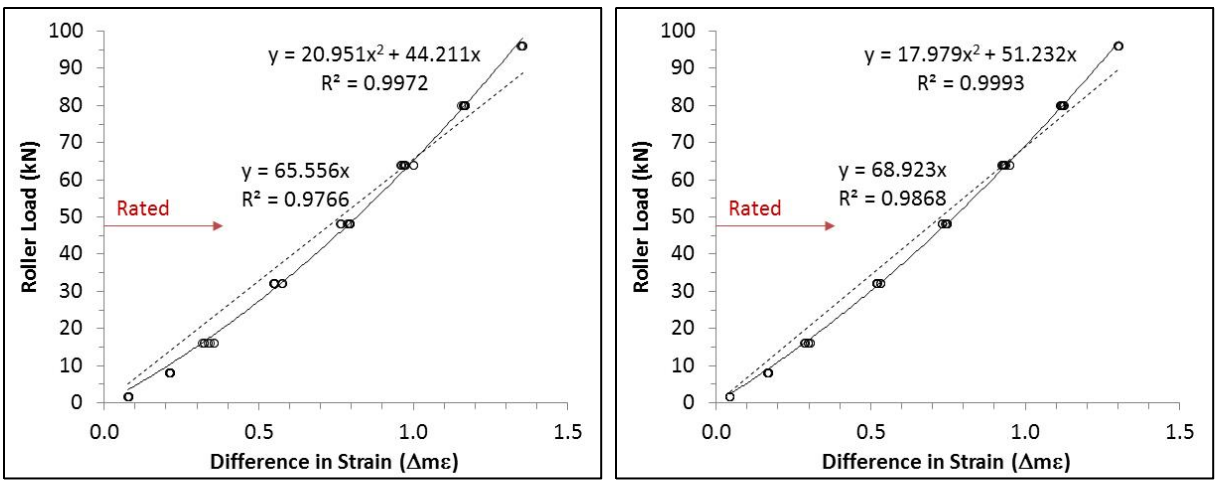

Figure 9. Regression analysis for Planet C upwind 340° (left) and downwind 20° (right) strain gages

Although the responses are fairly linear with coefficients of determination (R^2) of over 0.98, a second order approximation yields an even better fit. The difference between the two fits is most evident at approximately 50% of rated load. The calibration coefficients for both fits are also shown in the figures. Note that the fits were calculated assuming zero measured strain at zero load. The measured behavior is very similar for the bearings installed in planets A and C; however, for the bearings installed in planet B the same applied load resulted in approximately 20% less strain. In operation, the measured roller load for each strain gage measurement can be calculated from

$$Q = m_2 \Delta m\varepsilon^2 + m_1 \Delta m\varepsilon \tag{4}$$

where the strain gage measurement is converted from mV/V to mε per Eq. (2). The calibration coefficients (m_2 and m_1) for all 36 strain gage measurements are listed in Table 3. The calibration coefficients for all gage measurements on planets A and C combined are also shown. This combined data set is shown in Figure 10.

Table 3. Planet Bearing Calibration Coefficients

Planet	Bearing	Circumferential Location	m_2 kN/(Δmε)^2	m_1 kN/Δmε
A	Upwind (PL-A)	70°	16.713	48.949
		160°	17.718	45.749
		250°	19.620	48.406
		340°	17.265	49.696
	Downwind (PL-B)	20°	19.677	46.243
		115°	20.987	47.710
		200°	18.965	53.086
		285°	20.239	45.078
B	Upwind (PL-A)	10°	34.396	46.456
		32°	31.828	51.679
		70°	29.820	59.543
		160°	35.862	44.961
		250°	32.104	55.253
		288°	34.004	53.745
		310°	44.779	47.100
		327.5°	43.970	45.736
		340°	44.838	41.215
		352.5°	45.915	44.105
	Downwind (PL-B)	7.5°	35.108	45.009
		20°	34.562	44.531
		32.5°	35.668	47.145
		50°	32.267	52.359
		77°	35.854	49.138
		115°	37.392	49.492
		200°	38.541	39.988
		285°	34.673	43.792
		323°	37.185	42.092
		350°	34.854	46.819
C	Upwind (PL-A)	70°	17.245	48.062
		160°	17.968	48.375
		250°	17.890	53.978
		340°	20.951	44.211
	Downwind (PL-B)	20°	17.979	51.232
		115°	20.648	51.337
		200°	21.108	47.512
		285°	17.296	53.484
A and C	Both	All	17.826	49.846

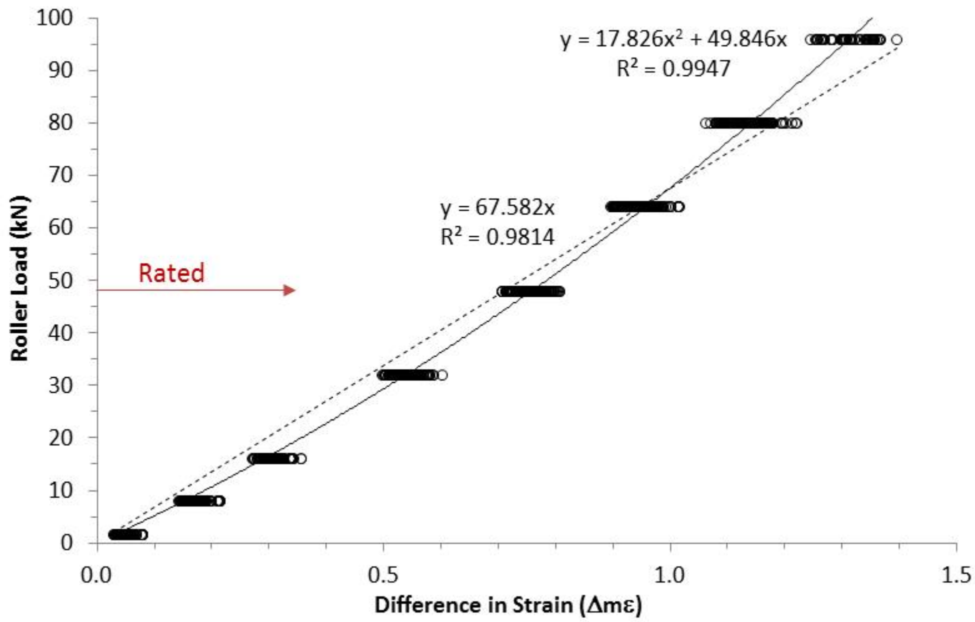

Figure 10. Regression analysis for all Planet A and C strain gages

5 Summary

An instrumentation package was designed, installed, and calibrated for the tapered roller bearing pairs supporting the GRC GB3 planets. The instrumentation consisted of 36 strain gage pairs installed in circumferential grooves machined in the inner ring of each bearing. The gages were wired in a Poisson half-bridge configuration and measured the strain response when a roller passed underneath the gage pairs.

The strain gages underwent calibration testing in June 2014 in a load frame located at Timken. The load frame applied axial loads resulting in roller loads up to 200% of those expected at rated torque. At each load condition, the bearings were rotated and the resulting strain response was recorded. The strain gage response during the bearing rotation was then postprocessed to extract the strain range. A regression analysis was used to correlate each of the 36 measured half-bridge outputs with the roller load, resulting in calibration factors suitable for analysis of data gathered during planned dynamometer testing of the gearbox and comparison to engineering models. Validation of the engineering models with test data will demonstrate the improvements in load sharing and the theoretical increase in planetary section fatigue life.

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