Gearbox Reliability Collaborative Bearing Calibration

J. van Dam

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5000-47852
October 2011

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NATIONAL RENEWABLE ENERGY LABORATORY

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Introduction

NREL has initiated the Gearbox Reliability Collaborative (GRC) to investigate the root cause of low wind turbine gearbox reliability.

The GRC follows a multi-pronged approach based on a collaborative of manufacturers, owners, researchers and consultants. The project combines analysis, field testing, dynamometer testing, condition monitoring, and the development and population of a gearbox failure database.

At the core of the project are two 750kW gearboxes that have been redesigned and rebuilt so that they are representative of the multi-megawatt gearbox topology currently used in the industry. These gearboxes are heavily instrumented and are tested in the field and on the dynamometer.

One of the measurements the collaborative is targeting is the load distribution on the planet bearings. For this purpose, the planet bearings were instrumented with strain gages. The strain gages measure the roller load as the roller moves over an arch ground into the inner race of the planet bearings. The objective of the calibration was to measure the correlation between the load applied to the bearing and the strain gage response. This report documents the set-up, the calibration procedures, the issues, and the results.

The calibrations took place between 16 July and 9 December 2008 in the 100 kip load frame at the National Wind Technology Center.

Bearings

Two sets of planets bearings were used, one set for each of the two GRC gearboxes. Each set consists of six bearings for three planets (two bearings per planet). The bearings were numbered 1 through 12. The planets are labeled A, B and C. Each bearing has three grooves in the inner race. One of the grooves is in top dead center (TDC) on all bearings. The other two grooves are different for each planet. Note that each groove arc has a 2mm flat spot as indicated at the top right of Figures 1 through 3.

Figure 1 through Figure 3 show the groove locations for three bearings. (Note that these drawings are included only to provide a visual representation of groove locations. High resolution drawings are available upon request.) Since the groove pattern is not symmetric on planets B and C, an additional designation was added to the bearing label. BL is the downwind bearing on planet B. BR is the rotor side or upwind bearing for planet B. The configuration is similar for planet C.

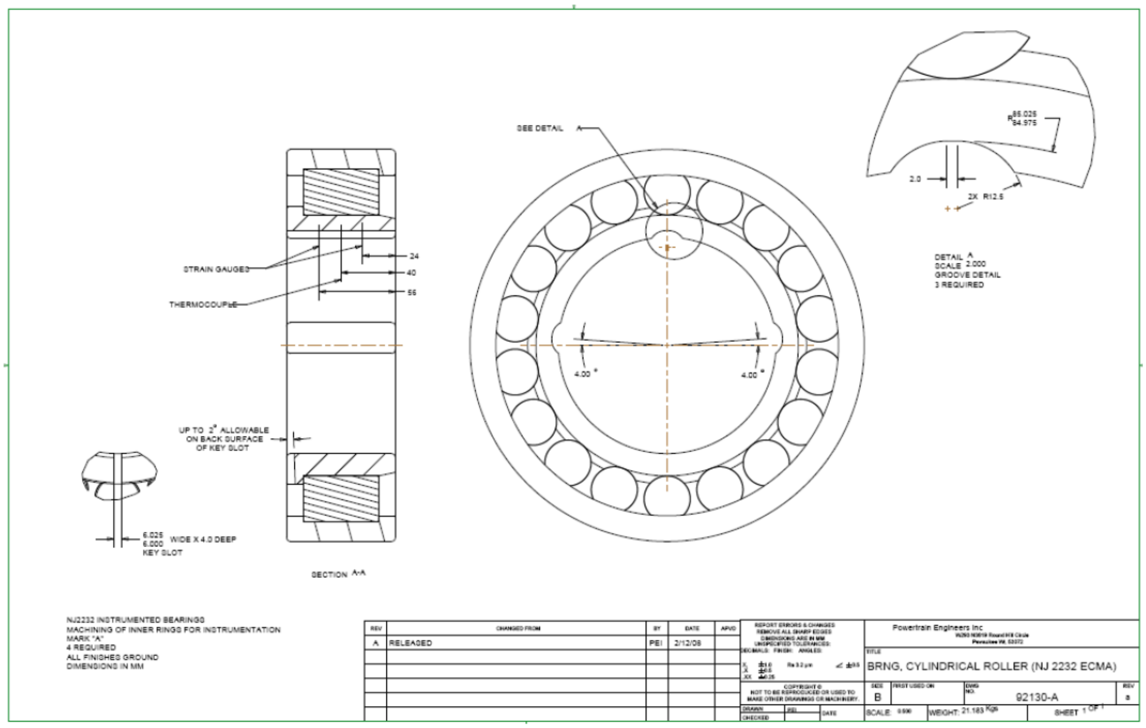


Figure 1. Groove locations on planet A

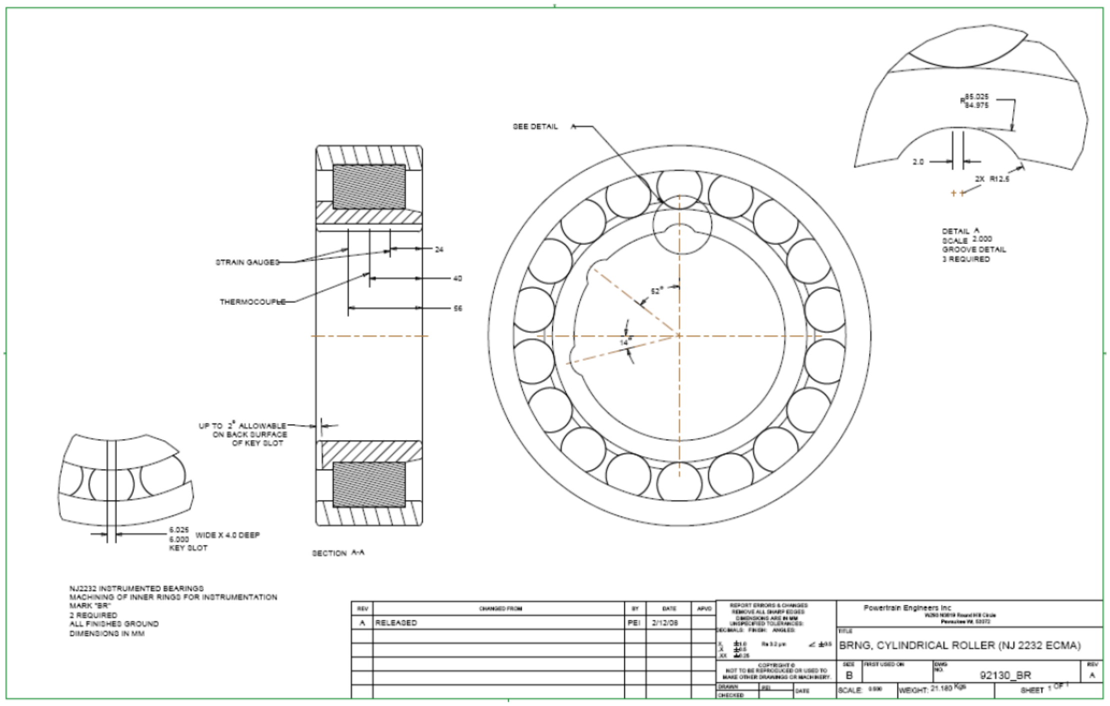


Figure 2. Groove locations bearing BR

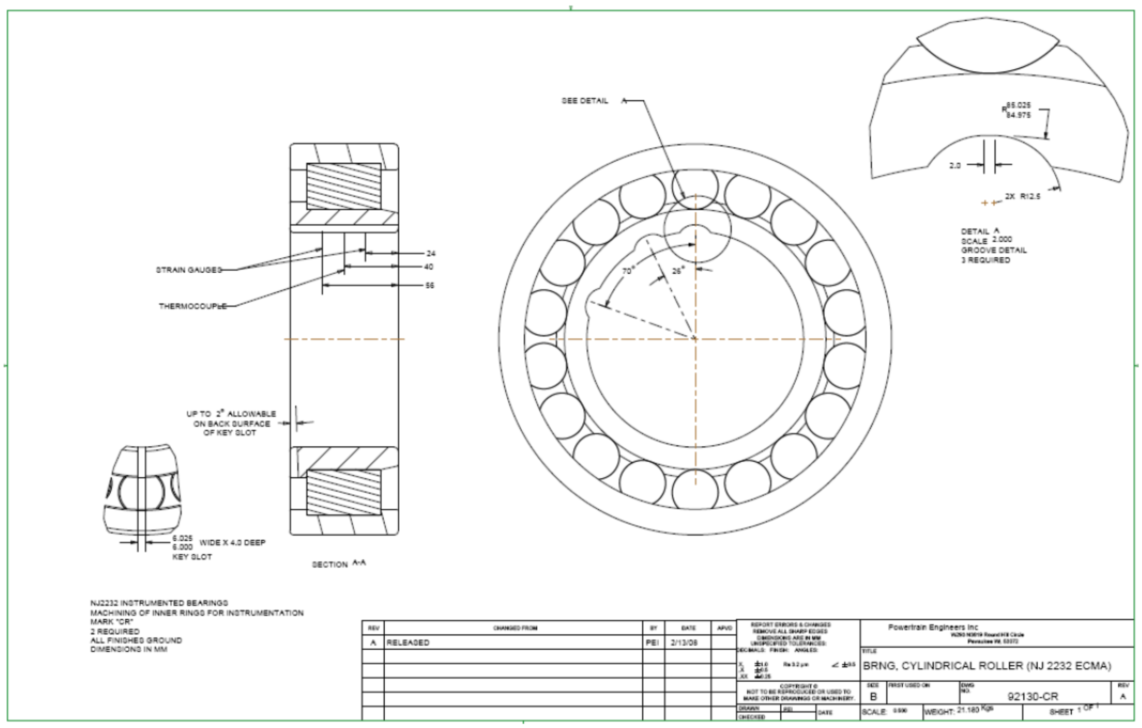


Figure 3. Groove locations bearing CR

Each groove contains two strain gages. The one closest to the rim of the inner race is designated A, while the other one is B. The gages are Poisson gages, type CEA-06-062UT-350 shown in Figure 5. Figure 4 shows a gage in a groove. The gage factor for all the gages is 2.095.

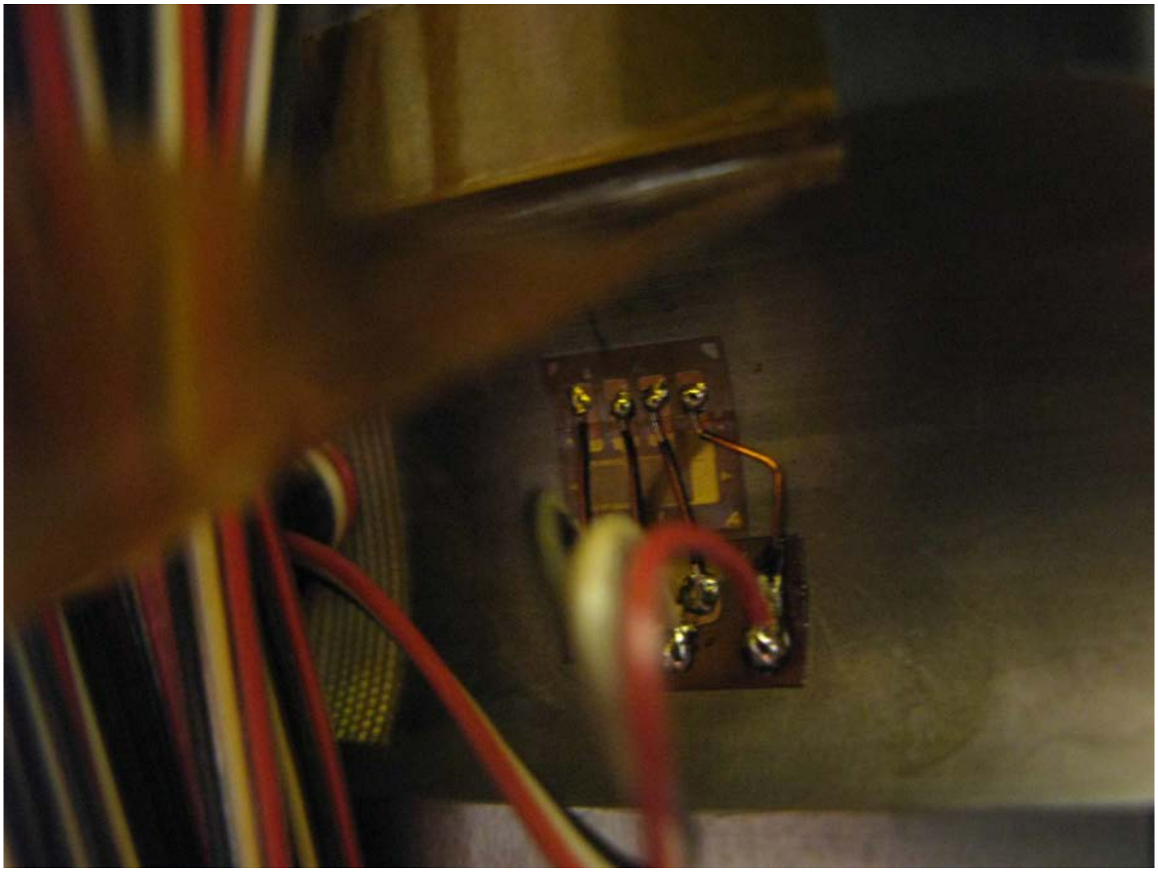


Figure 4. Close up of one of the strain gages on the bearings. The edge of the bearing is on the right. PIX #19679.

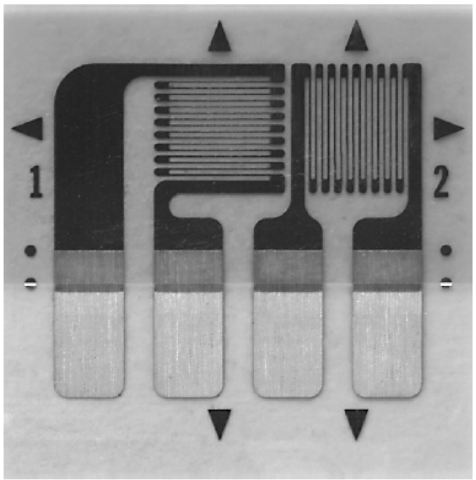
VISHAY

062UT

Vishay Micro-Measurements

General Purpose Strain Gages - Tee Rosette

GAGE PATTERN DATA



actual size

GAGE DESIGNATION See Note 1	RESISTANCE (OHMS)	OPTIONS AVAILABLE See Note 2
CEA-XX-062UT-120	120 ± 0.4%	**P2**
CEA-XX-062UT-350	350 ± 0.4%	**P2**

DESCRIPTION

Small general-purpose two-element 90° tee rosette. Exposed solder tab area 0.07 x 0.04 in [1.8 x 1.0 mm].

GAGE DIMENSIONS Legend: ES = Each Section; S = Section (S1 = Sec 1); CP = Complete Pattern; M = Matrix — inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
0.062 ES	0.205 CP	0.080 ES	0.225 CP	0.31	0.31
1.57 ES	5.21 CP	2.03 ES	5.72 CP	7.9	7.9

GAGE SERIES DATA See Gage Series data sheet for complete specifications.

Series	Description	Strain Range	Temperature Range
CEA	Universal general-purpose strain gages.	±3%	–100° to +350°F [–75° to +175°C]

Note 1: Insert desired S-T-C number in spaces marked XX.

Note 2: Products with designations and options shown in bold are not RoHS compliant.

Document Number: 11125
Revision: 05-Nov-08
micro-measurements@vishay.com
www.vishaymg.com
65

Figure 5. Spec sheet for strain gages used on the planet bearings

Calibration fixture

A calibration fixture, shown in Figure 6, was designed by Powertrain Engineers (Figure 7). The idea behind the test stand is that it allows for independent rotation of the inner race and outer race of the bearings. This allows the grooves to be put in any orientation while rolling the roller elements over them when they are under load.

The bearings were installed on a shaft that was equivalent to the actual planet pins to show the effect of shaft bending, if present.

The bearings were inserted into the tapered sleeve (item 7 in Figure 7). Between the bearings, a spacer was keyed to the shaft (Figure 8). The bearings were keyed to the spacer through a slot in the inner race.

The tapered rollers (item 9 in Figure 7) can be pulled onto the sleeve by tightening the M20's (item 19 in Figure 7) and by applying hydraulic pressure to the ports. This process contracts the tapered sleeve to reduce the radial clearance in the bearings to match the installed clearance in the gearbox.

Assembly of the bearings into the calibration assembly took place inside a "clean room". The clean room was constructed using plastic over a wooden frame. Air was blown into the clean room by an external air handler equipped with a HEPA filter.

Pictures and drawings of the calibration fixture are shown in Figure 6 and Figure 9.

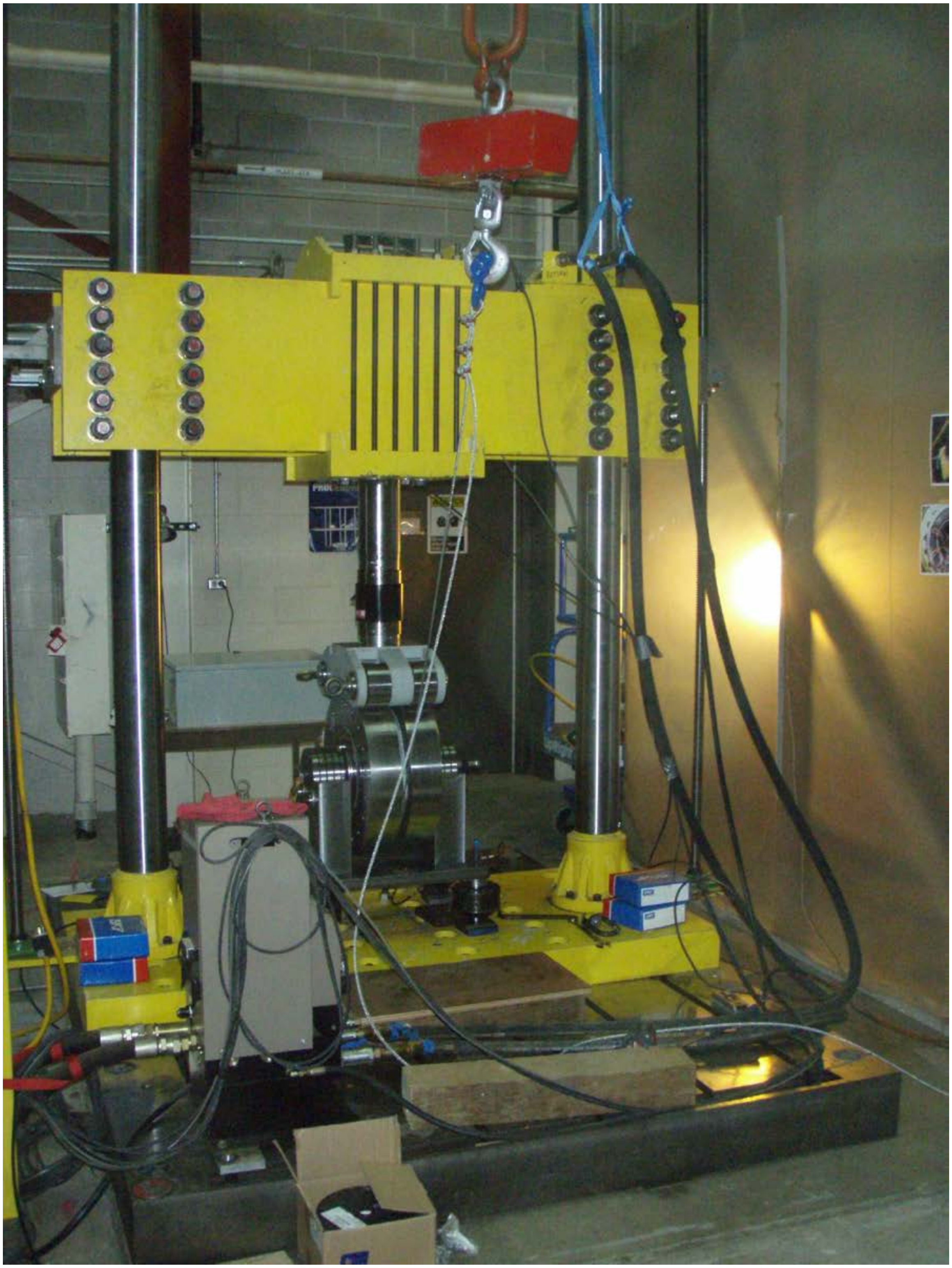


Figure 6. Calibration stand in the 100 kip load frame in the 251 highbay. PIX #19676.

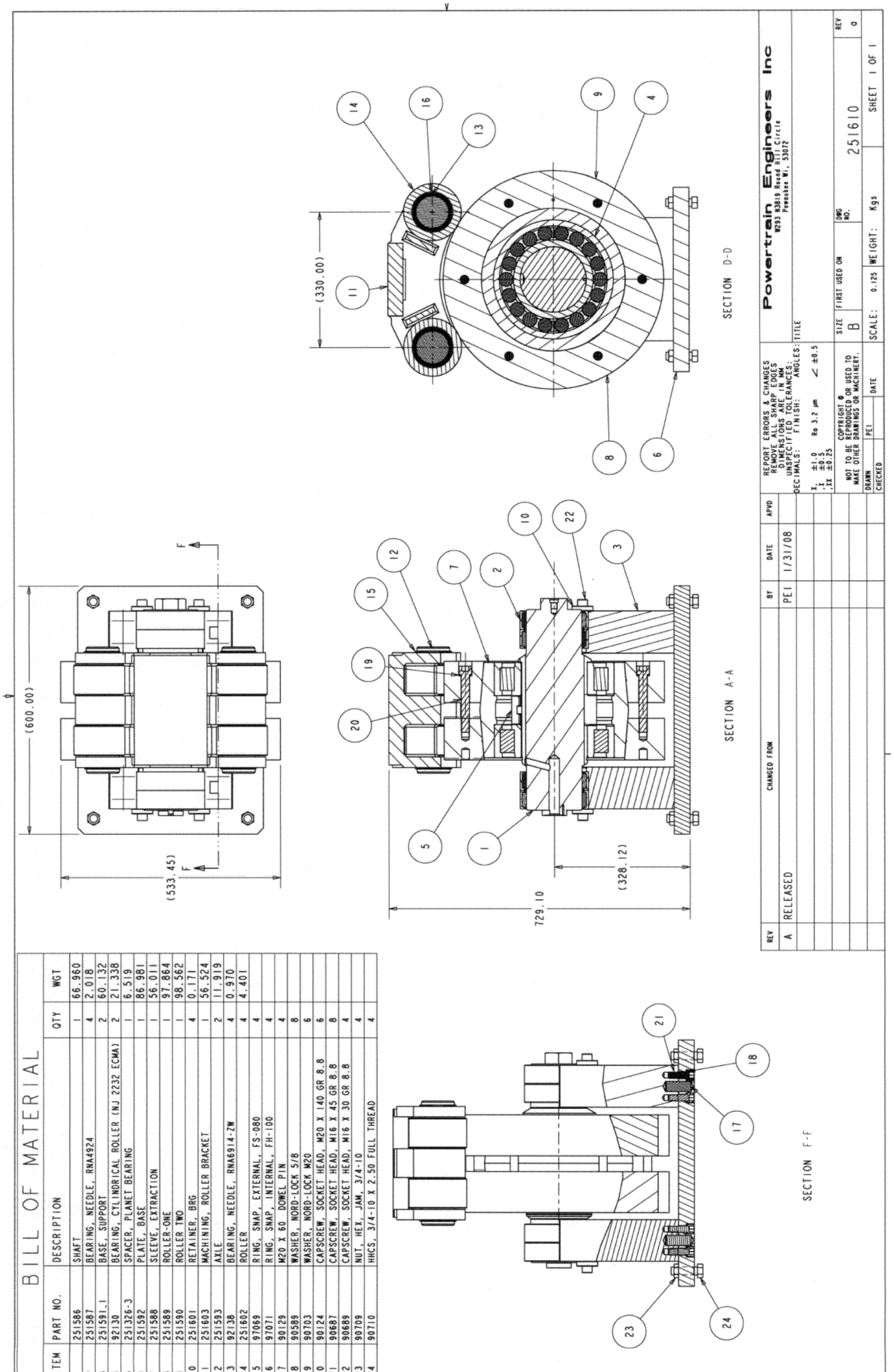


Figure 7. Drawing of calibration fixture

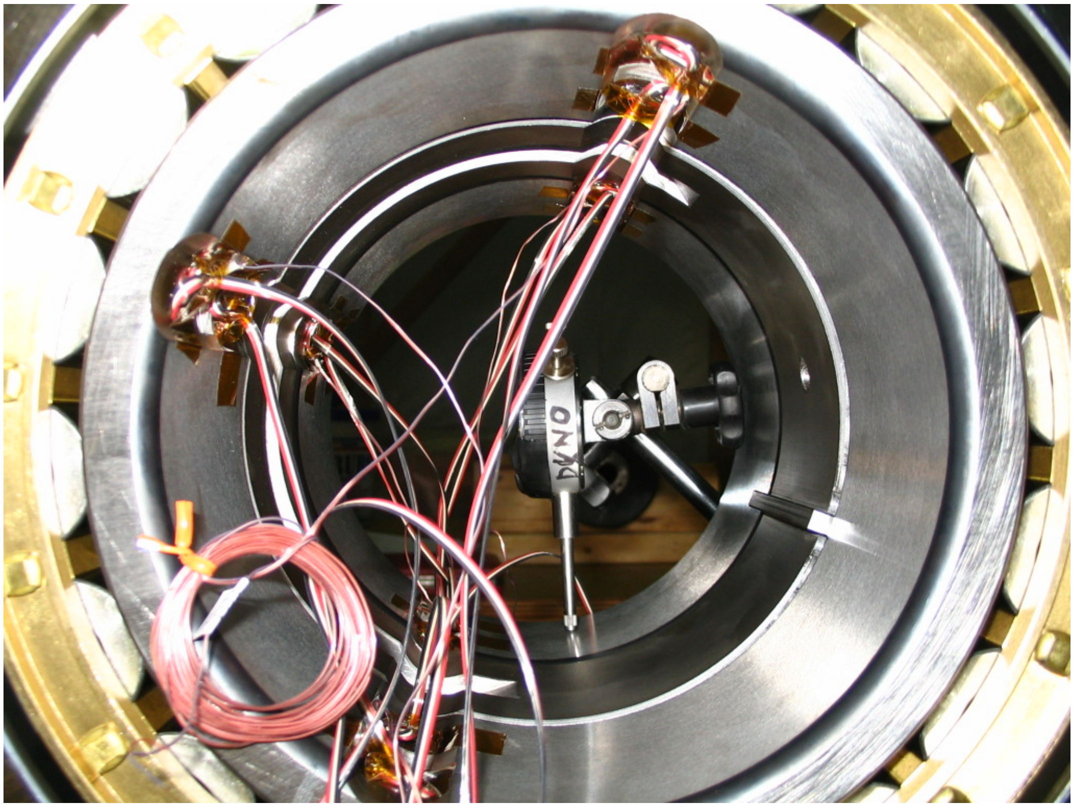


Figure 8. Two A bearings assembled in the tapered sleeve with spacer in between. PIX #19680.

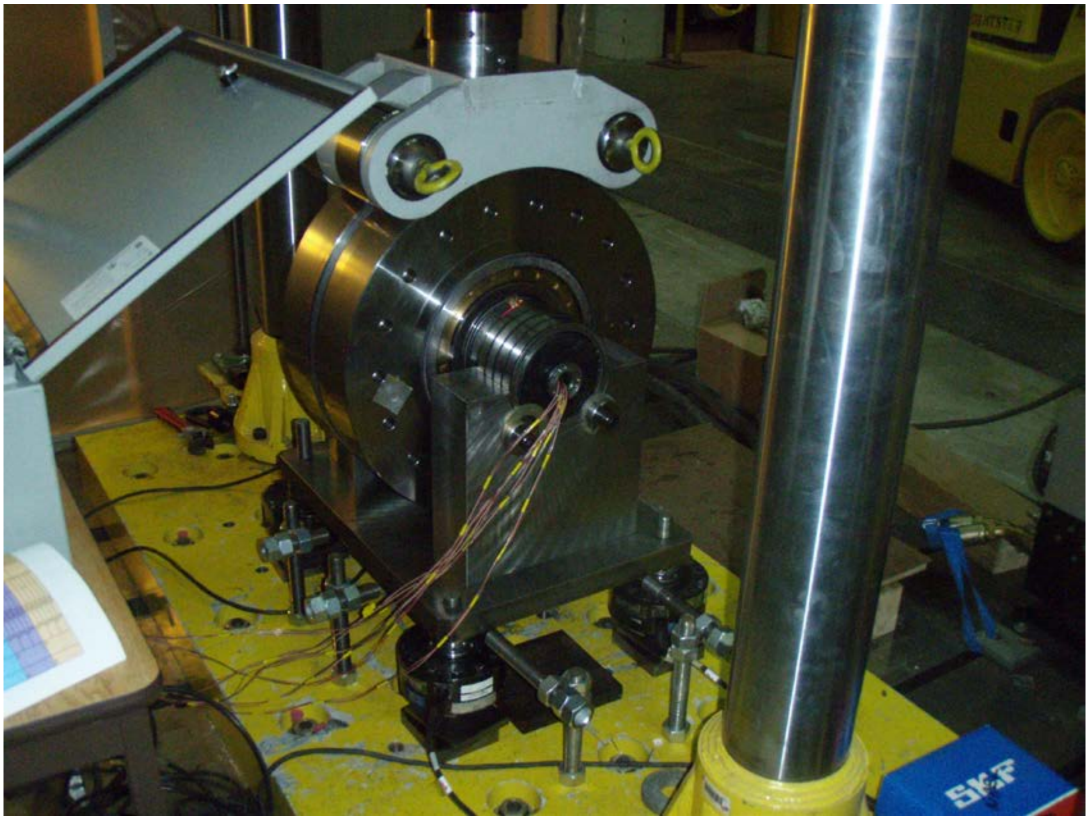


Figure 9. Calibration fixture in the load frame. PIX #19678.

Data acquisition system

The data acquisition system used for the calibration is the Low Speed Shaft Data Acquisition System (LLS DAS). This DAS also was used for the GRC field test. It consists of one enclosure containing two cDAQ backplanes. The USB output of the chassis was converted to fiber optic and sent to the control room. In the control room, the signal was converted back to USB and plugged into the DAS computer.

Four 25 kip load cells were used on the bottom of the calibration fixture. The load cells were configured in the National Instruments' mode, "Full Bridge I," with an excitation voltage of 2.5V. Load buttons were inserted into the bottom of the load cells. The load frame had a 100 kip load cell for control of the applied load. Load cell details are provided in Table 1

Table 1. Load cell details

Channel	Make model	Serial number	Slope
LC1	MTS 661.20E-03	13570	20451800
LC2	MTS 661.20E-03	78893	20226400
LC3	MTS 661.20E-03	78892	20082000
LC4	MTS 661.20E-03	109696	20013400
Load frame control load cell	MTS 661.23E-01	390276	NA

The strain gages in the bearing grooves were configured as Half Bridge Type I with a k-factor of 2. Table 2 shows how the gages were connected to the DAS. The naming convention for the channel names assigned to the strain gages was:

Bearing name_number_groove number_gage location in groove.

Thus, BL2_1A is the gage closest to the rim in groove 1 of bearing number 2, which is the downwind bearing on planet B. Table 3 and Table 4 provide the correlation between the channel names used in the bearing calibration and the channel names used in the dynamometer and field testing. Set 1 was used in gearbox 1, which went to the field test. Set 2 was used in gearbox 2, which was used for the dynamometer testing.

Table 2. Strain gage wire colors

Gage wire color	cDAQ wire color	Signal
Red	Purple	Excitation -
White	Grey	Signal +
Black	Blue	Excitation +

Table 3. Correlation between bearing calibration names and GRC DAS names; Set 1.

Type	Bearing	Groove	from TDC CW=+	Position	DAQ	Module	Channel	Bearing calibration name	GRC DAS name
A	1	1	-86 deg	A	Master	1	0	A1_1A	AD_274_25
				B	Master		1	A1_1B	AD_274_75
		2	0 deg	A	Master		2	A1_2A	AD_00_25
				B	Master		3	A1_2B	AD_00_75
		3	86 deg	A	Master	2	0	A1_3A	AD_86_25
				B	Master		1	A1_3B	AD_86_75
A	4	1	86 deg	A	Master		2	A4_1A	AU_86_25
				B	Master		3	A4_1B	AU_86_75
		2	0 deg	A	Master	3	0	A4_2A	AU_00_25
				B	Master		1	A4_2B	AU_00_75
		3	-86 deg	A	Master		2	A4_3A	AU_274_25
				B	Master		3	A4_3B	AU_274_75
BL	6	1	0 deg	A	Master	4	0	BL6_1A	BU_756_25
				B	Master		1	BL6_1B	BU_756_75
		2	52 deg	A	Master		2	BL6_2A	BU_308_25
				B	Master		3	BL6_2B	BU_308_75
		3	104 deg	A	Master	6	0	BL6_3A	BU_00_25
				B	Master		1	BL6_3B	BU_00_75
BR	9	1	-104 deg	A	Master		2	BR9_1A	BD_00_25
				B	Master		3	BR9_1B	BD_00_75
		2	-52 deg	A	Master	7	0	BR9_2A	BD_308_25
				B	Master		1	BR9_2B	BD_308_75
		3	0 deg	A	Master		2	BR9_3A	BD_756_25
				B	Master		3	BR9_3B	BD_756_75
CL	3	1	-70 deg	A	Master	8	0	CL3_1A	CU_290_25
				B	Master		1	CL3_1B	CU_290_75
		2	-26 deg	A	Master		2	CL3_2A	CU_334_25
				B	Master		3	CL3_2B	CU_334_75
		3	0 deg	A	Slave	1	0	CL3_3A	CU_00_25
				B	Slave		1	CL3_3B	CU_00_75
CR	8	1	0 deg	A	Slave		2	CR8_1A	CD_00_25
				B	Slave		3	CR8_1B	CD_00_75
		2	26 deg	A	Slave	2	0	CR8_2A	CD_334_25
				B	Slave		1	CR8_2B	CD_334_75
		3	70 deg	A	Slave		2	CR8_3A	CD_290_25
				B	Slave		3	CR8_3B	CD_290_75

Table 4. Correlation between bearing calibration names and GRC DAS names; Set 2

Type	Bearing	Groove	from TDC CW=+	Position	DAQ	Module	Channel	Bearing calibration name	GRC DAS name
A	7	1	-86 deg	A	Master	1	0	A7_1A	AD_274_25
				B	Master		1	A7_1B	AD_274_75
		2	0 deg	A	Master		2	A7_2A	AD_00_25
				B	Master		3	A7_2B	AD_00_75
		3	86 deg	A	Master	2	0	A7_3A	AD_86_25
				B	Master		1	A7_3B	AD_86_75
A	12	1	86 deg	A	Master		2	A12_1A	AU_86_25
				B	Master		3	A12_1B	AU_86_75
		2	0 deg	A	Master	3	0	A12_2A	AU_00_25
				B	Master		1	A12_2B	AU_00_75
		3	-86 deg	A	Master		2	A12_3A	AU_274_25
				B	Master		3	A12_3B	AU_274_75
BL	2	1	-104 deg	A	Master	4	0	BL2_1A	BU_756_25
				B	Master		1	BL2_1B	BU_756_75
		2	-52 deg	A	Master		2	BL2_2A	BU_308_25
				B	Master		3	BL2_2B	BU_308_75
		3	0 deg	A	Master	6	0	BL2_3A	BU_00_25
				B	Master		1	BL2_3B	BU_00_75
BR	5	1	0 deg	A	Master		2	BR5_1A	BD_00_25
				B	Master		3	BR5_1B	BD_00_75
		2	52 deg	A	Master	7	0	BR5_2A	BD_308_25
				B	Master		1	BR5_2B	BD_308_75
		3	104 deg	A	Master		2	BR5_3A	BD_756_25
				B	Master		3	BR5_3B	BD_756_75
CL	11	1	-70 deg	A	Master	8	0	CL11_1A	CU_290_25
				B	Master		1	CL11_1B	CU_290_75
		2	-26 deg	A	Master		2	CL11_2A	CU_334_25
				B	Master		3	CL11_2B	CU_334_75
		3	0 deg	A	Slave	1	0	CL11_3A	CU_00_25
				B	Slave		1	CL11_3B	CU_00_75
CR	10	1	0 deg	A	Slave		2	CR10_1A	CD_00_25
				B	Slave		3	CR10_1B	CD_00_75
		2	26 deg	A	Slave	2	0	CR10_2A	CD_334_25
				B	Slave		1	CR10_2B	CD_334_75
		3	70 deg	A	Slave		2	CR10_3A	CD_290_25
				B	Slave		3	CR10_3B	CD_290_75

Calibration procedures

Assembly

The bearings were inserted into the tapered rollers. The M20's were torqued (typical values 325-350 ft-lb) until the bearings' diametrical clearance was less than 0.0005, but still positive. The step between the tapered rollers and the inner sleeve was measured around the perimeter throughout this tightening process ensuring the straight fit of the roller into the sleeve. A maximum of 0.005" was allowed between maximum and minimum measurements. If needed, hydraulic pressure could be applied to the hydraulic port on the rollers with a maximum pressure of 2000psi.

Load cells zero

The load cells were all zeroed while hanging from the base plate. An Enerpac was used to jack up the base plate.

Load cell leveling

To ensure all load cells had about the same contact with the load frame base plate, the load cells could be turned on their thread to be extended or retracted. This was an iterative process. First, two load cells on the diagonal (for example load cells 1 and 3) would be extended. They were adjusted until they read about the same under load. Then, the load cells on the other diagonal were extended slowly until the readings of all four load cells were equal (within 3%).

Static calibration

For the static calibration, one of the grooves was put on top dead centre (TDC). The spanner wrench was used to move the outer races until the strain gages on one of the bearings reached a maximum. It was assumed that this meant a rolling element was on the centre of the groove. A new data file was started and the load was increased from 10,000 lbs to 80,000 lbs, and then decreased to 10,000 lbs in 10,000 lb steps. This was repeated at least three times. Figure 10 shows an example of the bearing response during this type of calibration where gages, CR8_1A and CR8_1B were at TDC. Plots of the responses of the other four gages are shown here for reference purposes only. Rolling elements were not positioned over these grooves and, in some cases, this loading configuration produced negative (compressive) strain.

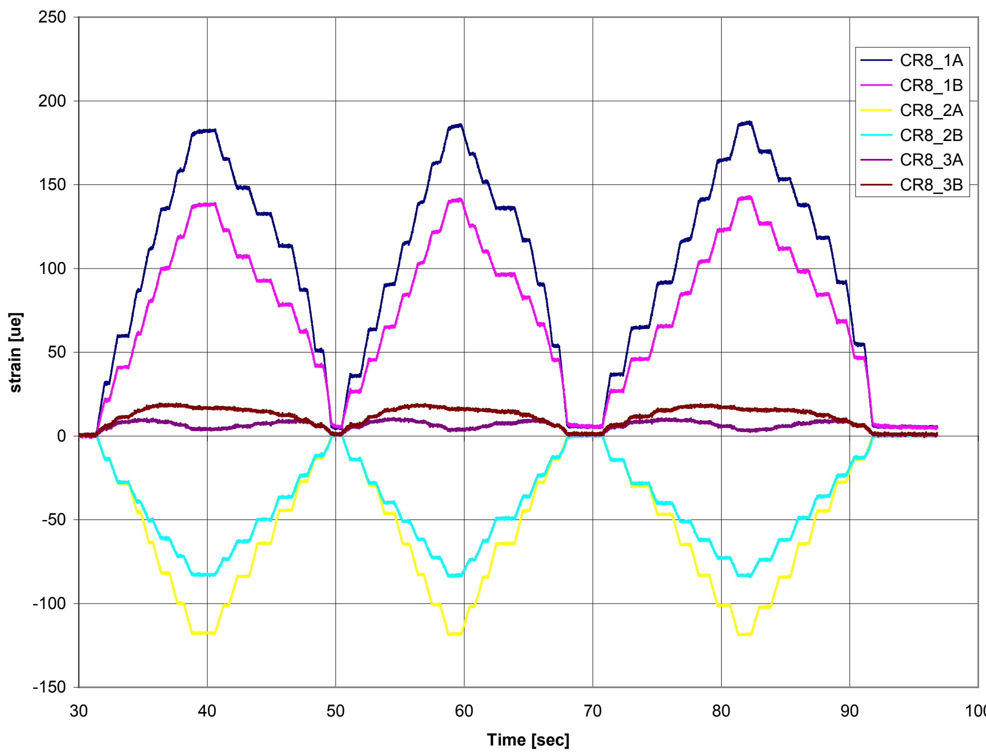


Figure 10. Example of time series of strain during static calibration.
Data file: 2008_12_09 10_30_18 100Hz

Crane (Dynamic) calibration

Dynamic effects were investigated using an overhead crane. For the crane calibration, a groove was put in the TDC position and a wire rope was wound around the rollers (Figure 11). The crane was used to unwind the wire rope and thus rotate the outer races of the bearings. The outer races of the bearings were allowed three full rotations, thus assuring each roller went past the groove at least once. This test was done for five load levels: 20, 35, 50, 65 and 80 kip (total load on the fixture).

Figure 11. Crane calibration method set up. PIX #19677.

Strain gage zero

To obtain a zero on the strain gage, the groove was rotated to dead bottom. The load frame was shut off, leading to an applied load of about 50lbs. Since there was positive clearance in the bearing, it was assumed that the rolling element on the bottom would not be touching the inner race. A short data file was collected.

Analysis

Static calibration

For the static calibration, the strain was plotted against load. An example is given in Figure 12. There is hysteresis present; the strain for the increasing load was consistently lower than for the decreasing load. As in Figure 10, CR8_1A and CR8_1B are the only gages at TDC. Then, the data was filtered for increasing load only. A linear regression was applied to the data. The entire load range was used for the fit (Figure 13).

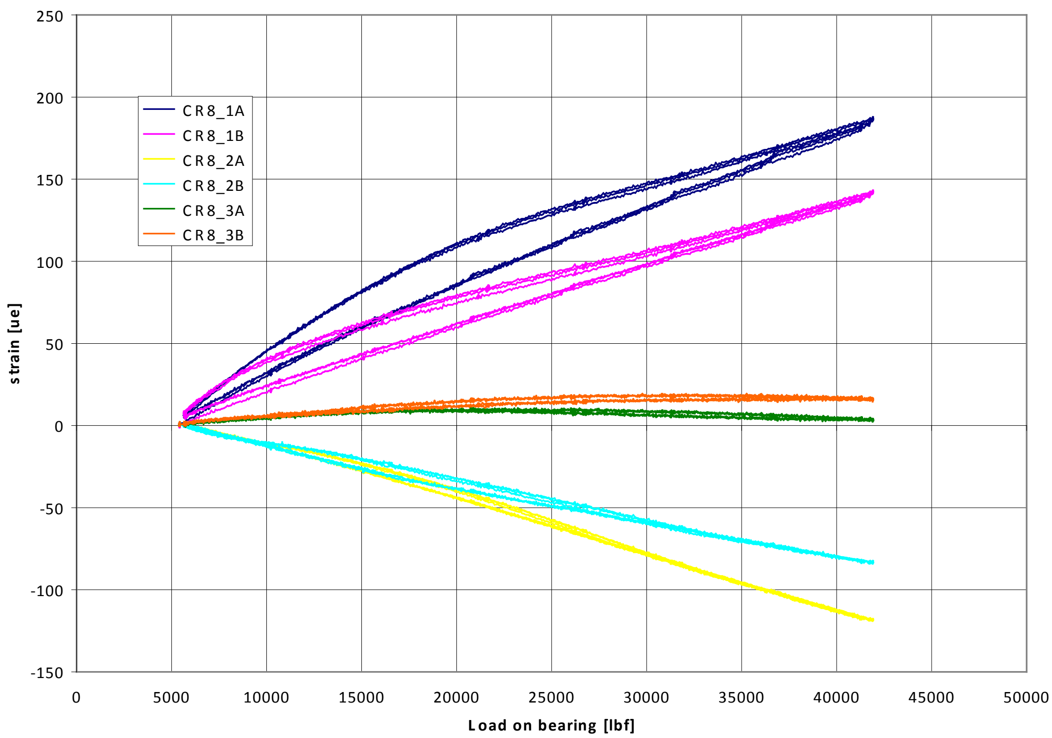


Figure 12. Example of static calibration. Data file: 2008_12_09 10_30_18 100Hz

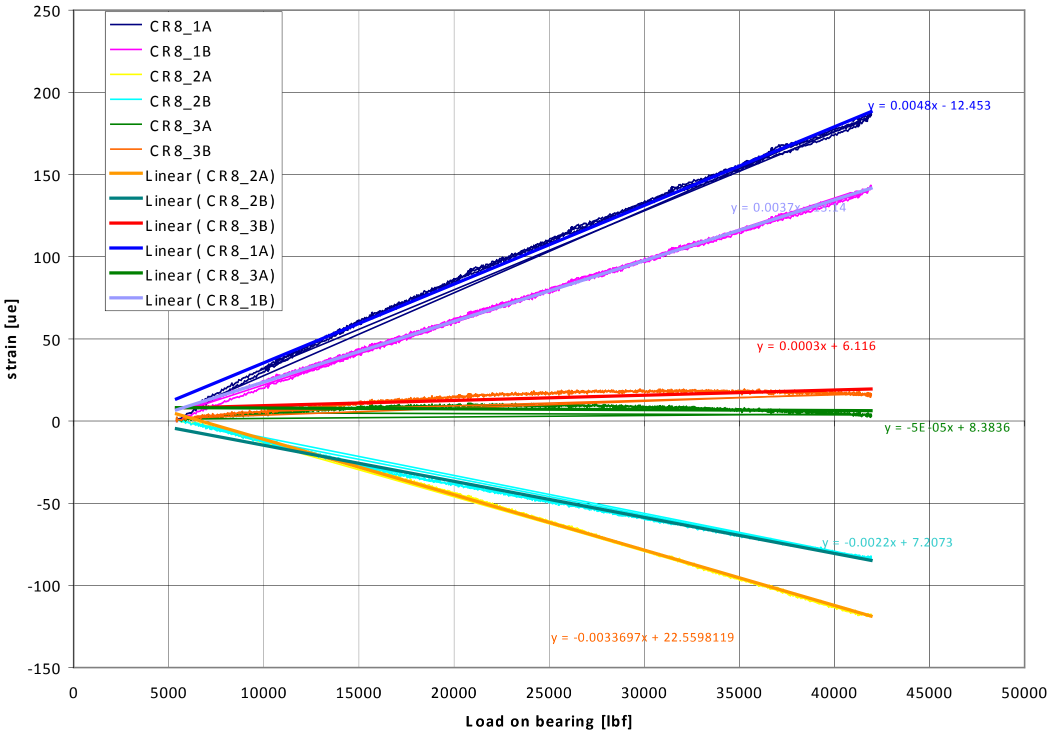


Figure 13. Example of fitted slope in static calibration with CR8_1A and CR8_1B at TDC.
Data file: 2008_12_09 10_30_18 100Hz

Crane (dynamic) calibration

Time series were plotted and the peaks and valleys were identified (Figure 14). The strain value of each peak and valley is plotted against the load for that peak or valley. Data for the different load steps is then combined into one plot (Figure 15). A linear regression was fit through the peaks and the valleys separately.

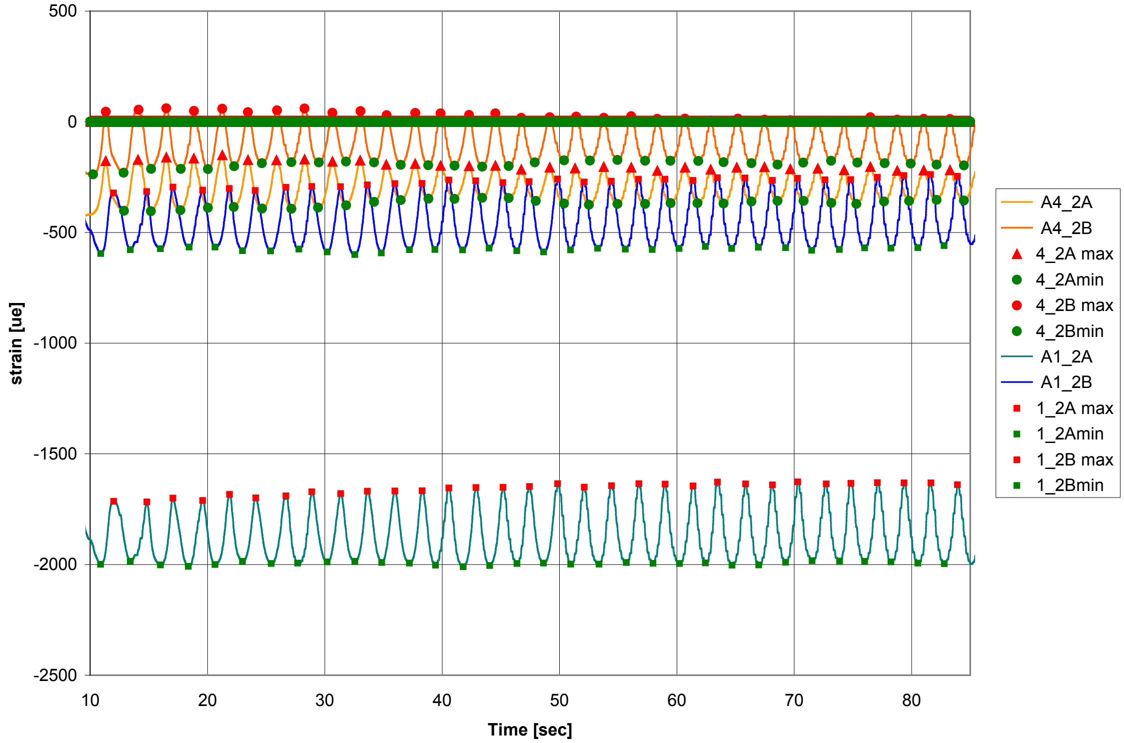


Figure 14. Example of a time series of crane calibration with identified peaks and valleys

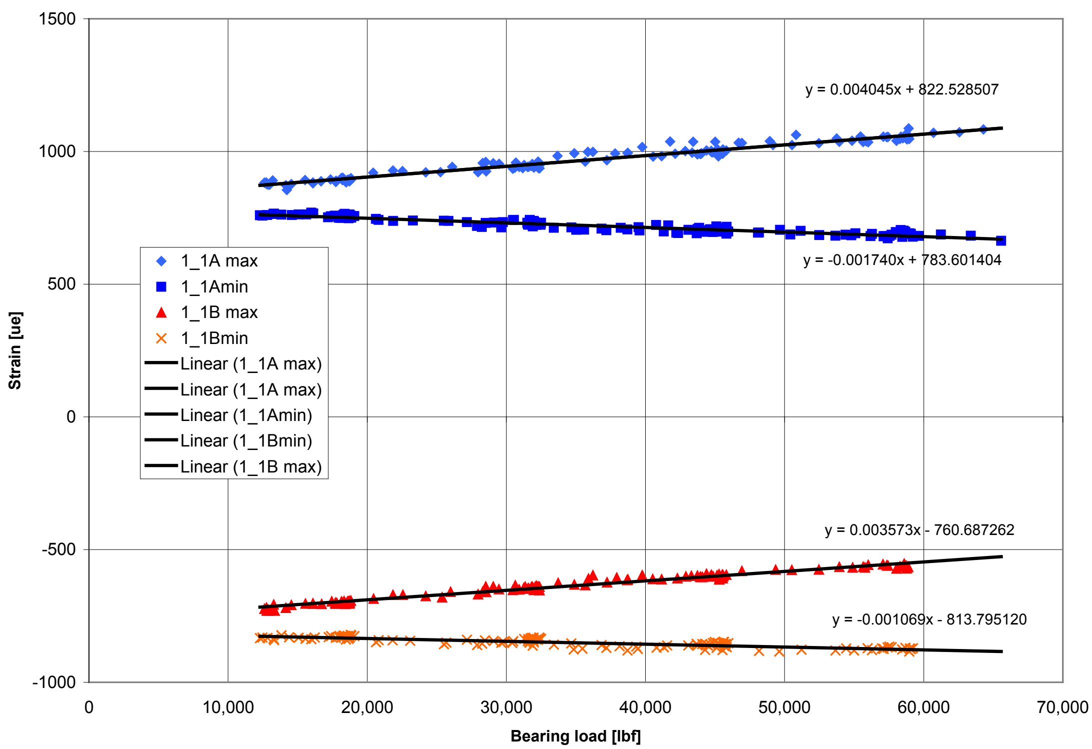


Figure 15. Crane calibration results for Bearing 1 groove 1 (A1_1A and A1_1B)

Results

Table 5 and Table 6 provide the key for the filename and calibration. The data file name format is “yyyy_mm_dd hh_mm_ss”.

Table 5. Static calibration files

Bearing	Groove	Data file
1	1	2008_11_06 10_14_54
	2	2008_11_06 09_22_29
	3	2008_11_06 10_33_48
2	1	2008_11_06 15_44_11
	2	2008_11_06 14_58_42
	3	2008_11_06 14_51_18
3	1	2008_12_08 15_37_56
	2	2008_12_08 14_50_11
	3	2008_12_08 14_44_11
4	1	2008_11_06 10_31_27
	2	2008_11_06 09_24_48
	3	2008_11_06 10_23_36
5	1	2008_11_06 14_53_32
	2	2008_11_06 15_00_48
	3	2008_11_06 15_46_16
6	1	2008_10_09 14_58_57
	2	2008_10_09 13_40_01
	3	2008_10_07 15_27_01
7	1	2008_10_06 10_12_05
	2	2008_10_06 10_36_37
	3	2008_10_06 10_44_27
8	1	2008_12_09 10_30_18
	2	2008_12_08 14_52_15
	3	2008_12_08 15_40_04
9	1	2008_10_07 15_30_26
	2	2008_10_09 13_40_01
	3	2008_10_09 15_03_08
10	1	2008_11_05 12_51_12
	2	2008_11_05 13_00_03
	3	2008_11_05 13_51_09
11	1	No good data
	2	2008_11_05 13_02_31
	3	2008_11_05 12_54_36
12	1	2008_10_06 10_49_05
	2	2008_10_06 10_22_48
	3	2008_10_06 10_08_05

Table 6. Crane calibration files

	Load level [lbf]				
Grooves:	20	35	50	65	80
3_3 & 8_1	2008_12_08 14_18_44	2008_12_08 14_23_46	2008_12_08 14_27_36	2008_12_08 14_30_59	2008_12_08 14_34_12
3_2 & 8_2	2008_12_08 14_55_48	2008_12_08 15_00_03	2008_12_08 15_03_27	2008_12_08 15_06_53	2008_12_08 15_10_08
3_1 & 8_3	2008_12_08 15_16_17	2008_12_08 15_19_29	2008_12_08 15_22_56	2008_12_08 15_26_32	2008_12_08 15_32_55
1_2 & 4_2	2008_11_06 09_32_20	2008_11_06 09_37_03	2008_11_06 09_44_08	2008_11_06 09_48_58	2008_11_06 09_52_18
1_1 & 4_3	2008_11_06 09_51_15	2008_11_06 10_00_24	2008_11_06 10_03_37	2008_11_06 10_07_02	2008_11_06 10_10_53
1_3 & 4_1	2008_11_06 10_40_26	2008_11_06 10_51_13	2008_11_06 10_54_32	2008_11_06 10_58_41	2008_11_06 11_02_10
2_3 & 5_1	2008_11_06 14_07_08	2008_11_06 14_11_53	2008_11_06 14_16_31	2008_11_06 14_23_49	2008_11_06 14_46_53
2_2 & 5_2	2008_11_06 15_06_12	2008_11_06 15_10_13	2008_11_06 15_13_55	2008_11_06 15_17_43	2008_11_06 15_20_58
2_1 & 5_3	2008_11_06 15_25_51	2008_11_06 15_29_28	2008_11_06 15_32_42	2008_11_06 15_36_17	2008_11_06 15_39_56
11_1 & 10_1	2008_11_05 12_32_19	2008_11_05 12_35_51	2008_11_05 12_39_05	2008_11_05 12_42_40	2008_11_05 12_46_30
11_2 & 10_2	2008_11_05 13_06_17	2008_11_05 13_09_40	2008_11_05 13_14_26	2008_11_05 13_19_40	2008_11_05 13_23_49
11_1 & 10_3	2008_11_05 13_28_07	2008_11_05 13_31_56	2008_11_05 13_35_39	2008_11_05 13_38_51	2008_11_05 13_43_11
6_3 & 9_1	2008_10_07 15_36_40	2008_10_07 15_40_08	2008_10_07 15_44_01	2008_10_07 15_47_47	2008_10_07 15_51_13
6_2 & 9_2	2008_10_09 13_45_54	2008_10_09 13_49_56	2008_10_09 13_53_37	2008_10_09 13_57_07	2008_10_09 14_00_39
6_1 & 9_3	2008_10_09 14_22_42	2008_10_09 14_25_51	2008_10_09 14_29_12	2008_10_09 14_33_42	2008_10_09 14_37_24
7_2 & 12_2	2008_10_06 14_29_53	2008_10_06 14_34_03	2008_10_06 14_37_42	2008_10_06 14_41_12	2008_10_06 14_44_37
7_3 & 12_1	2008_10_06 15_04_50	2008_10_06 15_08_08	2008_10_06 15_11_46	2008_10_06 15_15_36	2008_10_06 15_18_47
7_1 & 12_3	2008_10_06 15_37_38	2008_10_06 15_41_21	2008_10_06 15_55_55	2008_10_06 15_59_18	2008_10_06 16_02_31

The results of the static calibration are found in Figure 16. The results of the crane calibration are found in Figure 17.

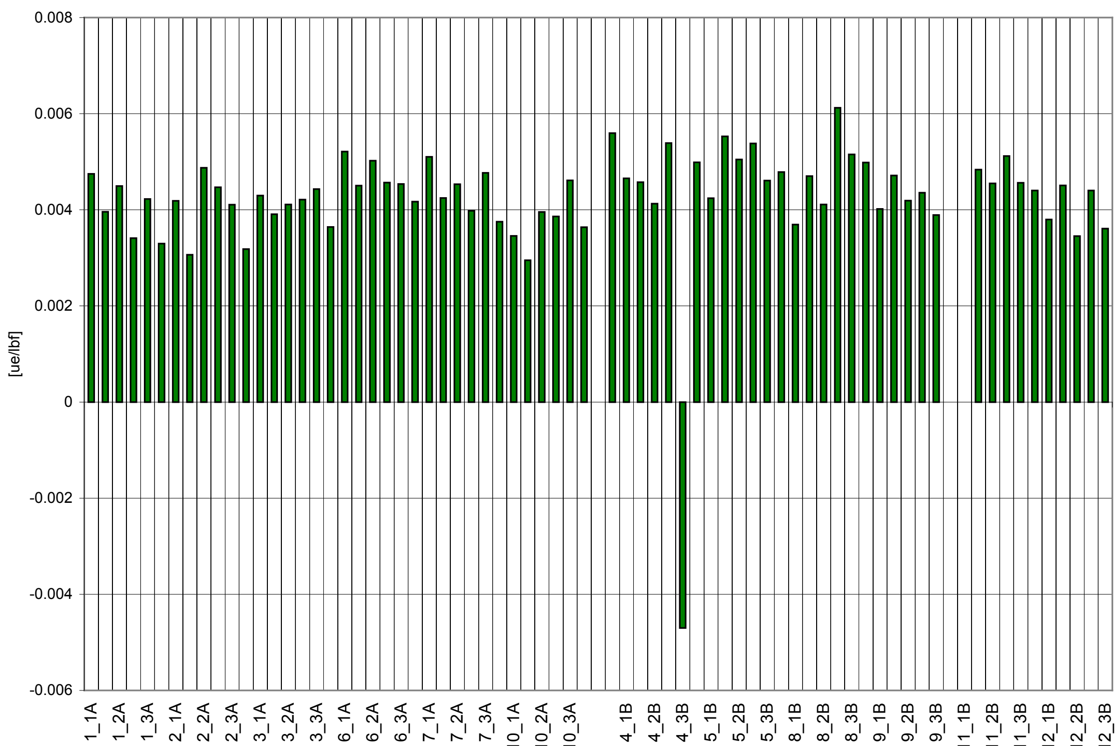


Figure 16. Results of the static calibration. Note that not all gages are labeled in this figure. Gage 4_3B appears to be miswired.

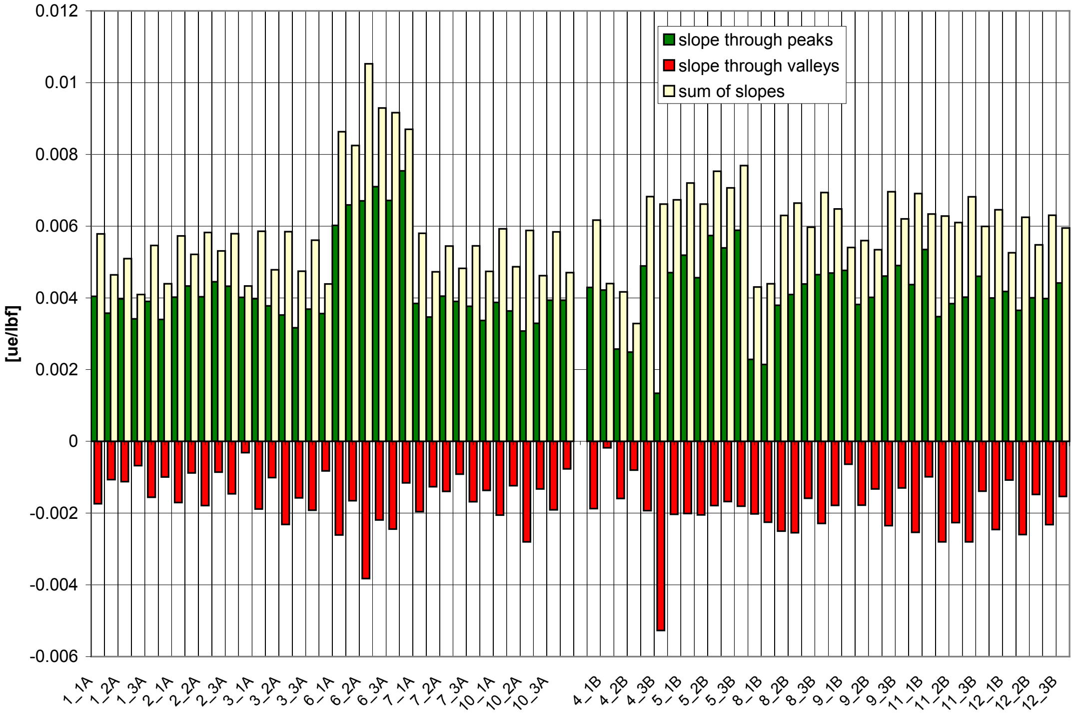


Figure 17. Results of crane calibrations

One of the strain gages (4_3B) was wired or hooked up backward to the DAS. It is recommended that the negative slope be implemented because the comparison with the other gages during the first rotations of the gearbox will quickly show, if this should be reversed.

There is excessive scatter in the resulting, calculated slopes. The slopes calculated using the two methods do not seem to show much correlation (Figure 18 and Figure 19). Therefore, we recommend using the population average for all gages except 4_3B, where the minus of the average slope should be applied initially.

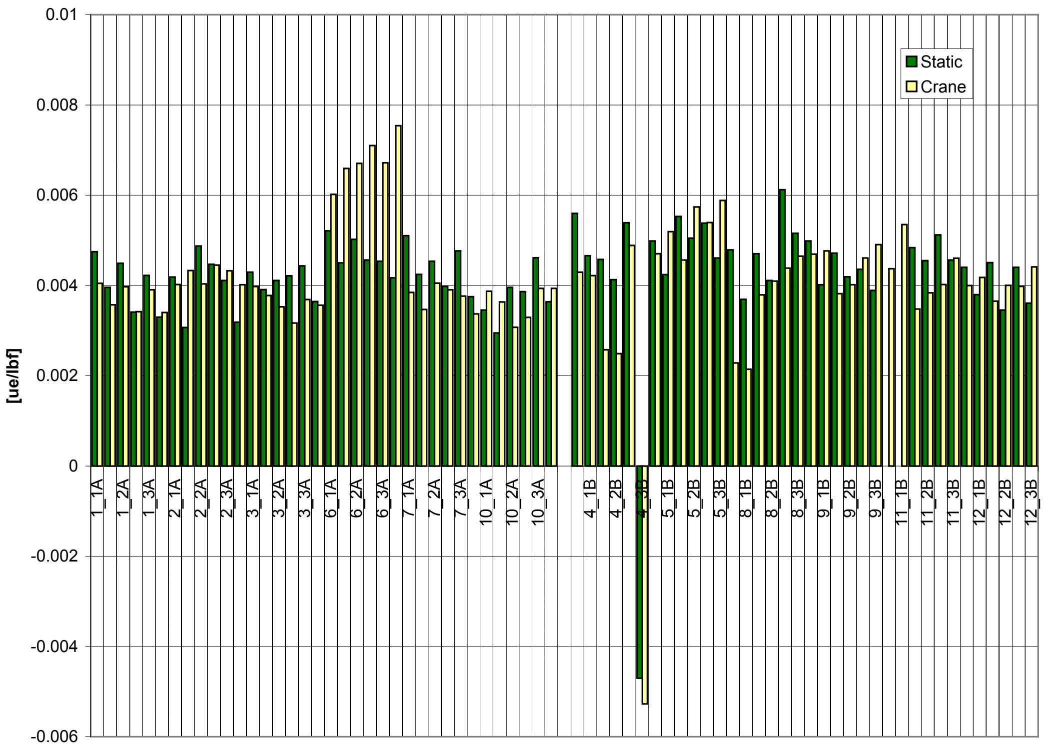


Figure 18. Comparison of slope of static calibration and positive slope of crane calibration

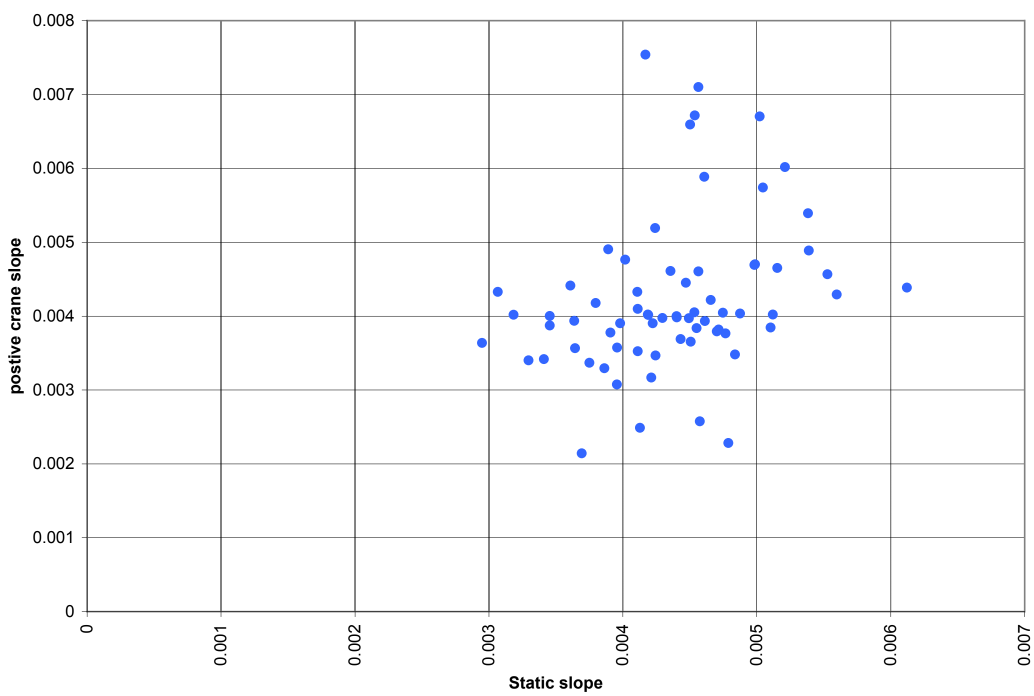


Figure 19. Positive slope of crane calibration versus the slope from the static calibration

Table 7 shows the average slopes found from the two methods and the standard deviation of the mean.

Table 7. Calibration results

Methods	Mean		StDev
	[uε/lbf]	[lbf/uε]	[uε/lbf]
Crane (peaks)	0.004267	234.36	0.001036
Crane (valleys)	-0.00169	-591.72	0.000661
Crane (range)	0.005961	167.76	0.001316
Static	0.004241	235.79	0.001244

In Table 8 and Figure 20, the slopes are separated for the A and B locations. The static calibration results indicate that perhaps separate mean values should be applied for these two groups. However, the crane calibration results do not support this conclusion (Figure 20).

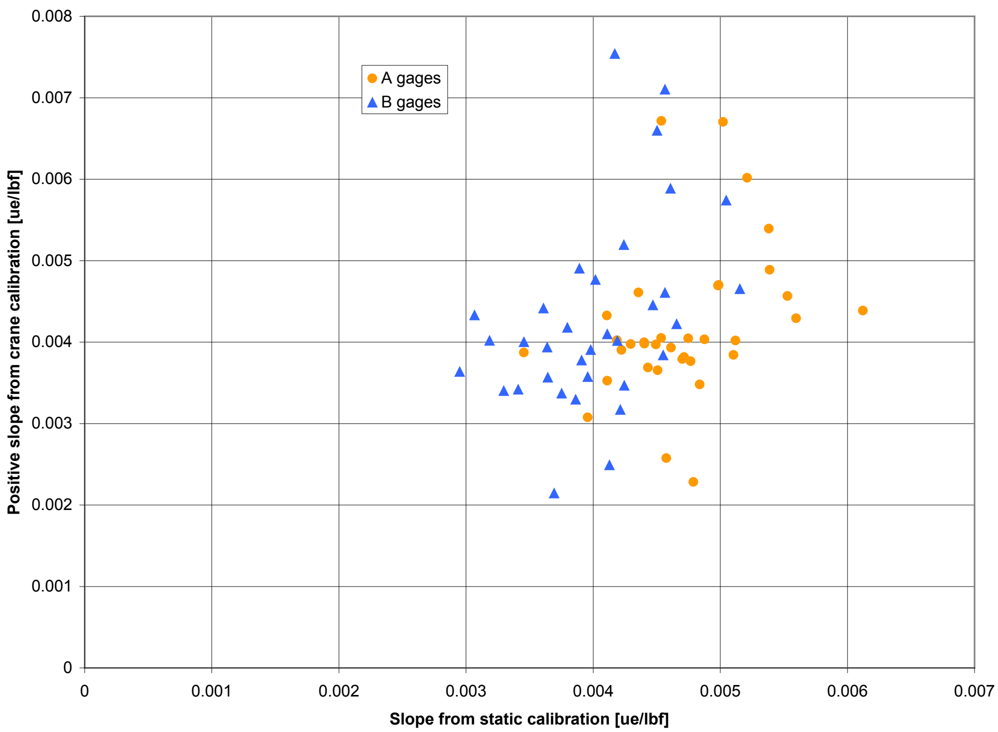


Figure 20. Found slopes separated for A and B locations

Table 8. Calibration results separated for A and B location gages

Methods	Mean [uε/lbf]	
	A	B
Crane (peaks)	0.004193	0.004341
Crane (valleys)	-0.002079	-0.001308
Crane (range)	0.006273	0.005649
Static	0.004716	0.003766

After the calibrations were completed, the GRC data acquisition system was changed from the cDAQ platform that was used during the calibrations to an EtherCAT based system. The EtherCAT system no longer uses the strain gage bridge configuration to calculate microstrain, but instead puts out V/V. Table 9 gives the average slopes that would need to be used for the EtherCAT-based data acquisition system.

Table 9. Calibration results for EtherCAT

Method	slope	Slope
	[lbf/V/V]	[N/V/V]
Crane (peaks)	360.45	1603.26
Crane (valleys)	-910.07	-4047.97
Crane (range)	258.01	1147.65
Static	362.65	1613.05

Issues with calibration

The following issues were found with the calibration set up, which likely resulted in the scatter seen in the calibration results:

- Four point contact on bottom: There were four load cells on the bottom, an over constraint for a plane. It was decided to put the load cells on a sandwich of hardened plates, with grease in between, to add some compliance.
- Four point contact on the top: The yoke had four rollers that contacted the dummy planet gear. This was over-constraint for a plane. It was decided to loosen the yoke a half turn to give it compliance.
- Movement of the yoke rollers on their shaft: The rollers moved side-to-side on their shafts. Also, the bearings were not located in the center of those rollers. The rollers were not all mounted in the same orientation during the original assembly (some had the bearing offset to the outside and some had it offset to the inside).
- Main shaft not hardened: The main shaft was supported on needle bearings. The main shaft acts as the inner race for those bearings. At high loads (80-90kip), the needles dug into the main shaft causing the whole setup to hang up (difficult to impossible to rotate).
- Yoke shafts not hardened: The yoke rollers have needle bearings inside. The yoke shaft acts as the inner race for the needles. At high loads (80-90kip), the needles dug into the shaft making it impossible to rotate the outer race of the planet bearings.
- Bearings were not axially constrained on main shaft. Due to the four load cells, it was nearly impossible for the load cells to attain an even reading while keeping the stand level. Small deviations in level caused the bearings to "walk off" the shaft during the crane calibrations and this caused a shift in the load from one side to the other.

Comparison with FEA model

Romax prepared a Finite Element Analysis (FEA) of the bearing grooves. The results are described in a separate report: "Max Qiao, Analysis of Static Calibration Test for Planet Bearing for NREL by Romax Technology Limited, 12/01/2009."

The strain sensitivity reported in that report was 0.006325uε/lbs. This number differs from the number NREL found (0.004267 uε/lbs) for several reasons:

- Wrong groove geometry provided: The groove geometry provided by Romax did not include the flat spot in the center of the groove. Anecdotal information from some testing done on different groove geometries predicts a reduction of 20-25% in strain if the flat spot is present.
- Gage factor: For the purpose of the calibration, NREL did not address the actual gage factor because the calibration was from the load to microstrain and back. For comparison with the FEA, NREL would apply the actual gage factor, which is 2.10 instead of 2.0. Thus, the strain levels measured by NREL would need to be increased by 5%.
- Strain averaging: The values reported by Romax were the strains at the actual strain gage centers. The strain gradient in the groove is quite large. By interpolating the strain, and averaging it over the actual location of the active part of the strain gage, it was found that a 5% lower strain would be measured by the gages.

Accounting for the above deviations, the Romax slope is 0.004819 uε/lbs. The NREL slope was 0.004480uε/lbs. These values are about 7% apart.

Acknowledgements / Team

The following people contributed to the physical bearing calibration: Ed Overly, Troy Boro, Bill Gage, Braden Kappius, Hal Link, Mike Jenks, Scott Hughes, Jerry Hur, and Jim Adams.

Annex A Transformation from load cell readings to bearing loads

Background:

Shown in Figures A.1 through A.4, the bearing calibration jig is supported by four load cells located on the corners of the stand. These load cells are numbered 1 through 4 in a clockwise direction. Load cells 1 and 2 were on the west, load cells 3 and 4 were on the east. Load cells 1 and 4 were on the North.

Assumptions:

The loads on the bearing act through the center of the banana rollers. This is indicated in Figure A.1

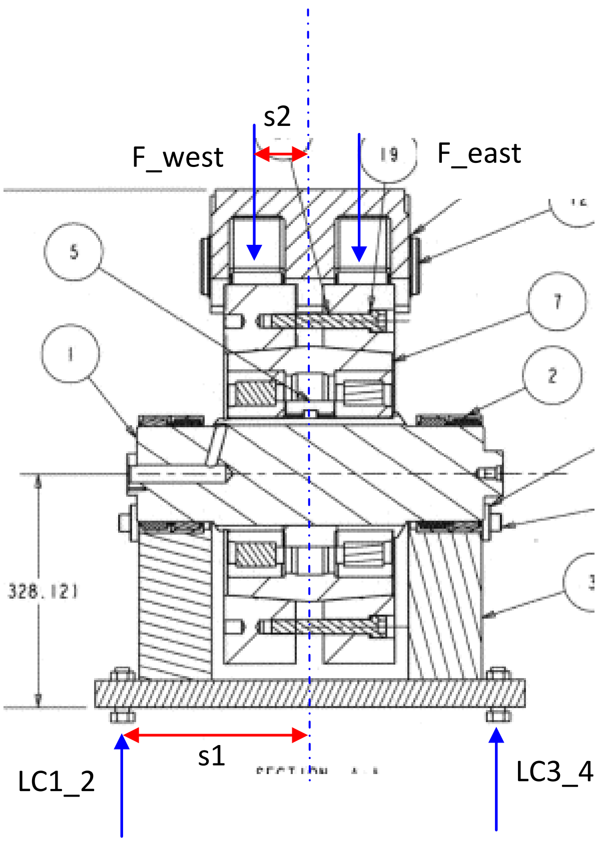


Figure A.1. Drawing showing basic load path

Two basic calculations:

- Moment around west bearing: LC1_2*(s1-s2)+F_east*(2*s2)-LC3_4*(s1+s2) = 0
- Sum of vertical forces: LC1_2 + LC3_4 = F_west +F_east

The load cells are located in the holes indicated near the corners of the base plate. To be able to install the load cells, the dimension of the hole was changed from the drawing below (figure A.2).

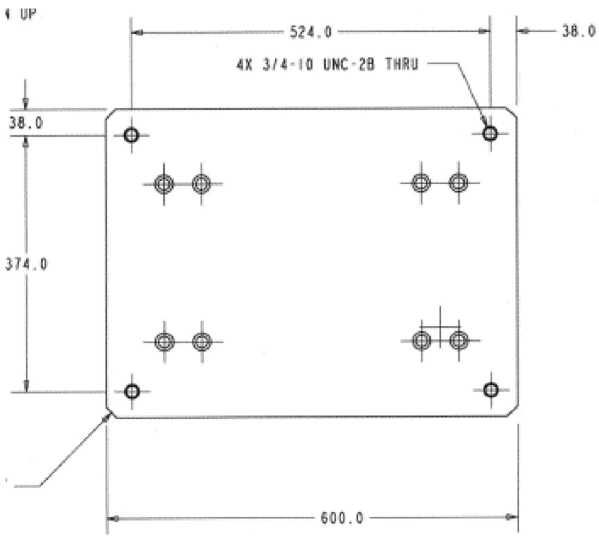


Figure A.2. Base plate showing distance between loadcells

s1 = 524/2 = 262

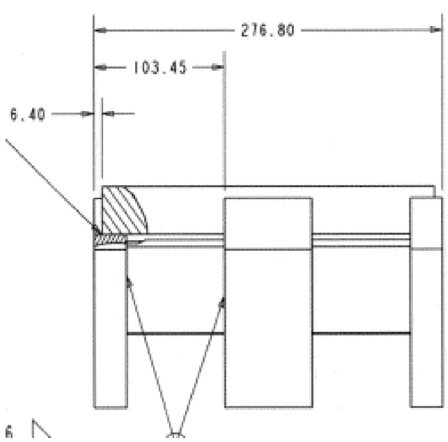


Figure A.3. Dimension of yoke

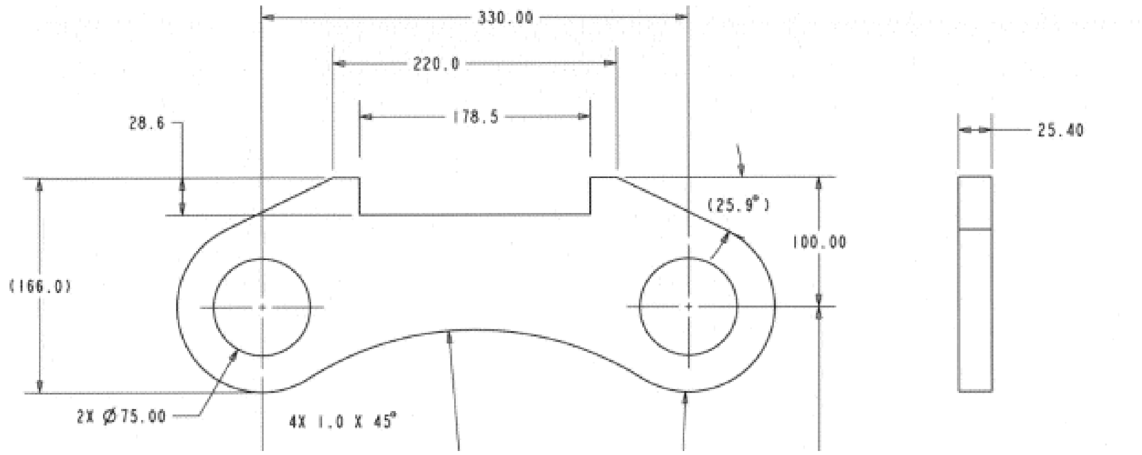
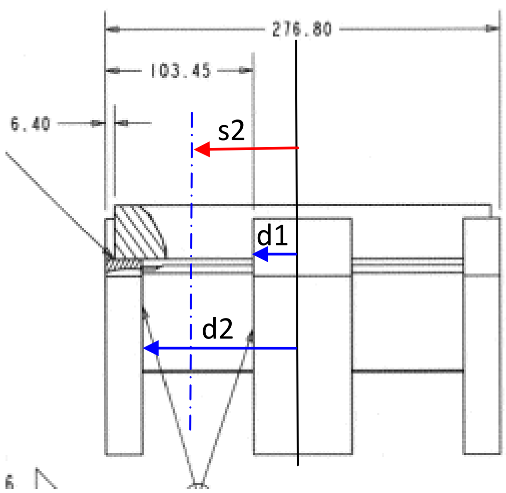


Figure A.4. Drawing indicated thickness of yoke end plate.



The bearing load acts at $(d1+d2)/2$ from the center of the jig

$d1 = 276.80/2 - 103.45 = 34.95$

$d2 = 276.80/2 - 25.4 = 113$

$s2 = 73.975$

Thus:

$$LC1\_2*(s1-s2)+F\_east*(2*s2)-LC3\_4*(s1+s2) = 0$$

$$F\_east=[LC3\_4*(s1+s2)-LC1\_2*(s1-s2)]/(2*s2)=[LC3\_4*335.975-LC1\_2*188.025]/147.95$$

$$F\_west = LC1\_2 + LC3\_4 - F\_east$$