Appendix G: Spoke Strains

Introductory Comments

Basic Approach

- Combine Individual Strain Measurement into Strain Associated with:
  - Tension in Spoke (F1, F2, R1 and R2)
  - In-Plane Bending of Spokes (F1 and F2)
  - Out-of-Plane Bending in Spokes (R1 and R2)
- Compare Test Results with Finite Element Analysis
- Laboratory Testing to Support Analysis

Three Components

- Tension in Spoke(F1, F2, R1 and R2)
  - $\varepsilon_T = (\varepsilon_{F1} + \varepsilon_{F2} + \varepsilon_{R1} + \varepsilon_{R2})/4$
- In-Plane Bending Of Spoke, BIP (F1 and F2)
  - $\varepsilon_{BIP} = (\varepsilon_{F1} - \varepsilon_{F2})/2$
  - BIP = bending in plane
- Out-of-Plane Bending in Spoke, BOP (R1 and R2)
  - $\varepsilon_{BOP} = (\varepsilon_{R1} - \varepsilon_{R2})/2$
  - BOP = bending out-of-plane
- These 3 Strains Explain the Most Strain Seen at the 4 Strain Gage Locations

Names

- Bending Out-of-Plane (BOP)
  - Bending of the Spoke out of the Plane of the Disc
- Bending in-Plane (BIP)
  - Bending of the Spoke in the Plane of the Disc

General Observations

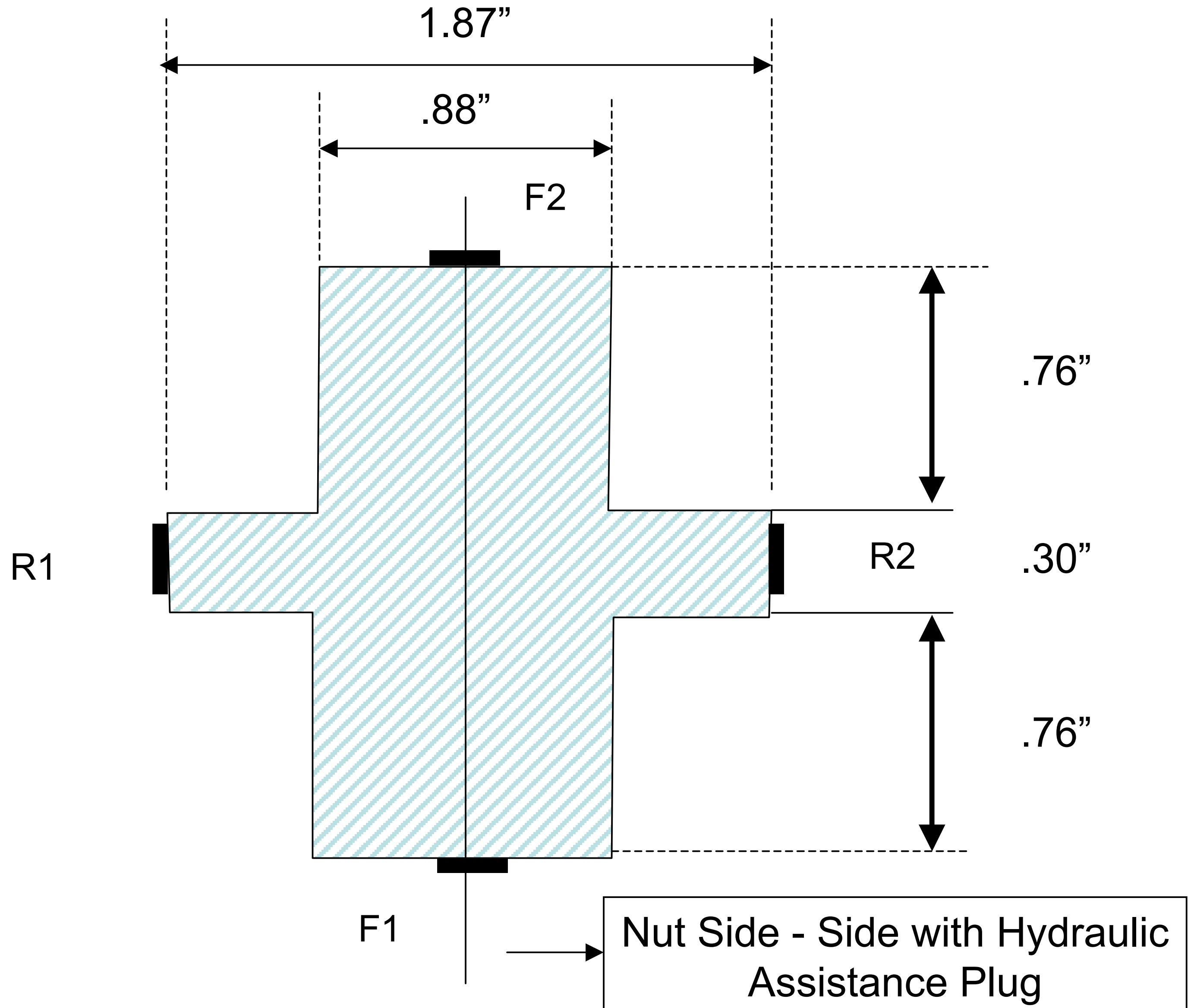
- Large Tensile Strain
  - The Tensile Strains Appear To Be Generated As The Friction Rings Heat-up Expanding The Circumference Of Friction Ring, Causing Tension In The Spokes Which Resist The Expansion
  - The Thermal Time Constant Once The Friction Discs Are Heated During Braking Is 7 Minutes Or More – 20 Minutes To Cool Down

General Observations

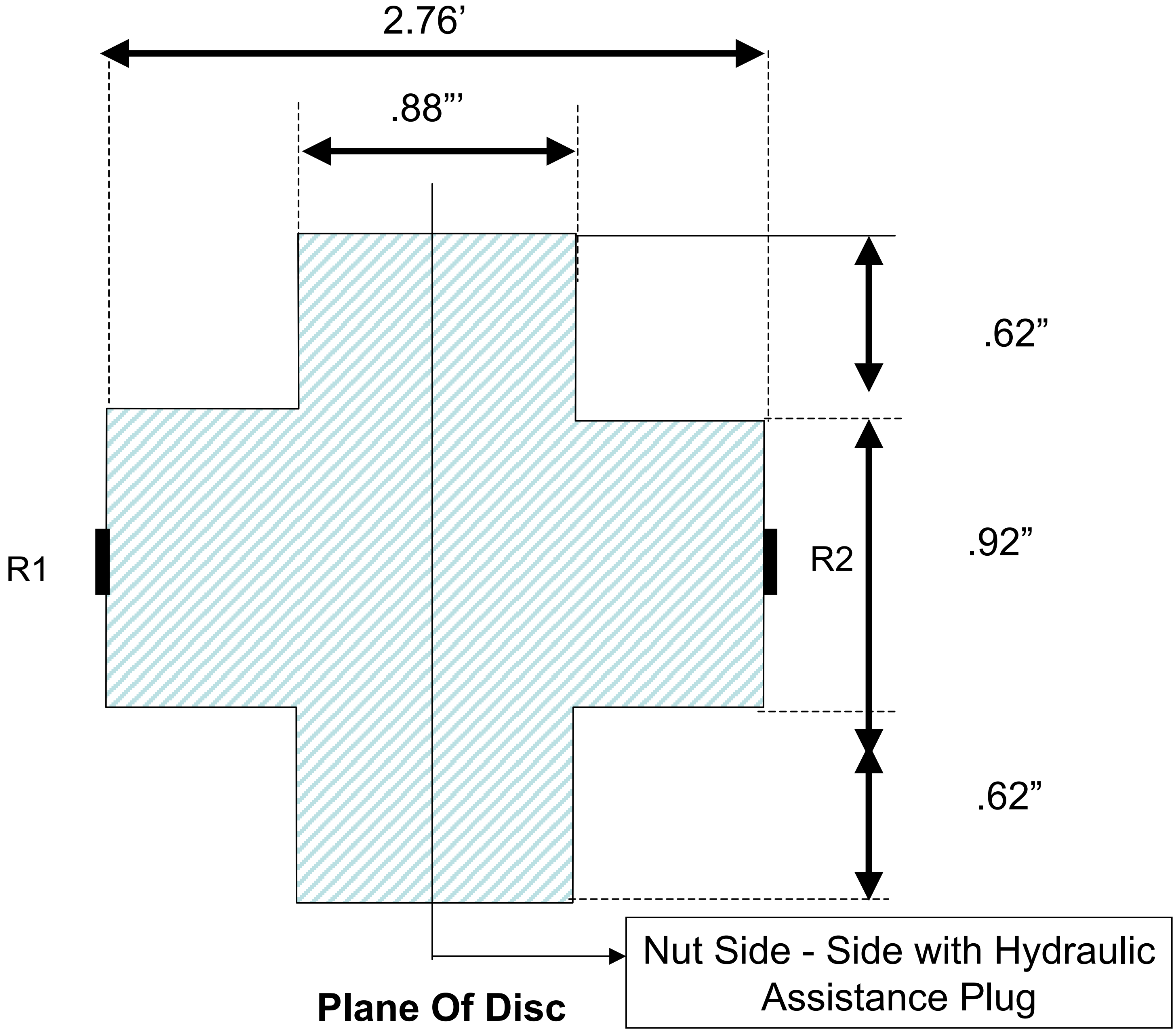
- BOP occurs during braking
  - Many times long sustained periods
  - Sustained oscillations only with axle in lead position
- BOP occurs during non-braking conditions
  - Usually short duration
  - Appears to be associated with vertical acceleration
- Frequency
  - ~187 Hz during braking
  - ~230 Hz non-braking conditions
- BIP strain
  - Small compared to BOP strain
  - Rarely greater than 100 μE
- Measurements modulated by wheel rotation rate

Strain Gage Locations

- WABTEC/SAB-WABCO Disc
  - On Spoke at Location Where Spokes Cracked
  - 4 Locations
    - 2 on out-of-plane side of spoke
    - 2 on in-plane side of spoke
- Knorr Disc
  - Location Provided by Knorr
  - 4 Locations
    - 2 on out-of-plane side of spoke
    - 2 on in-plane side of spoke



Plane Of Disc
WABTEC/SAB-WABCO Disc



Knorr Disc

G-10

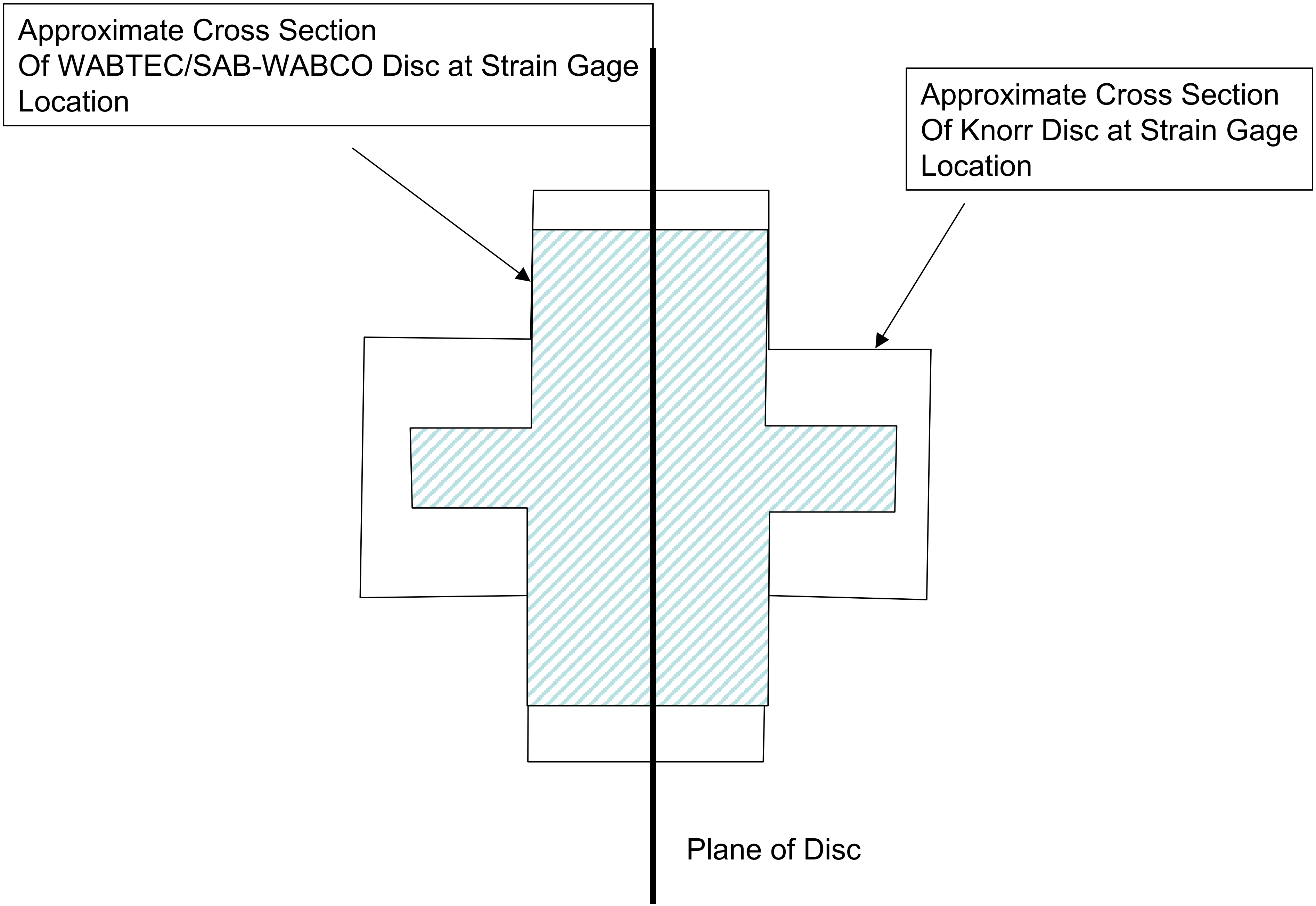
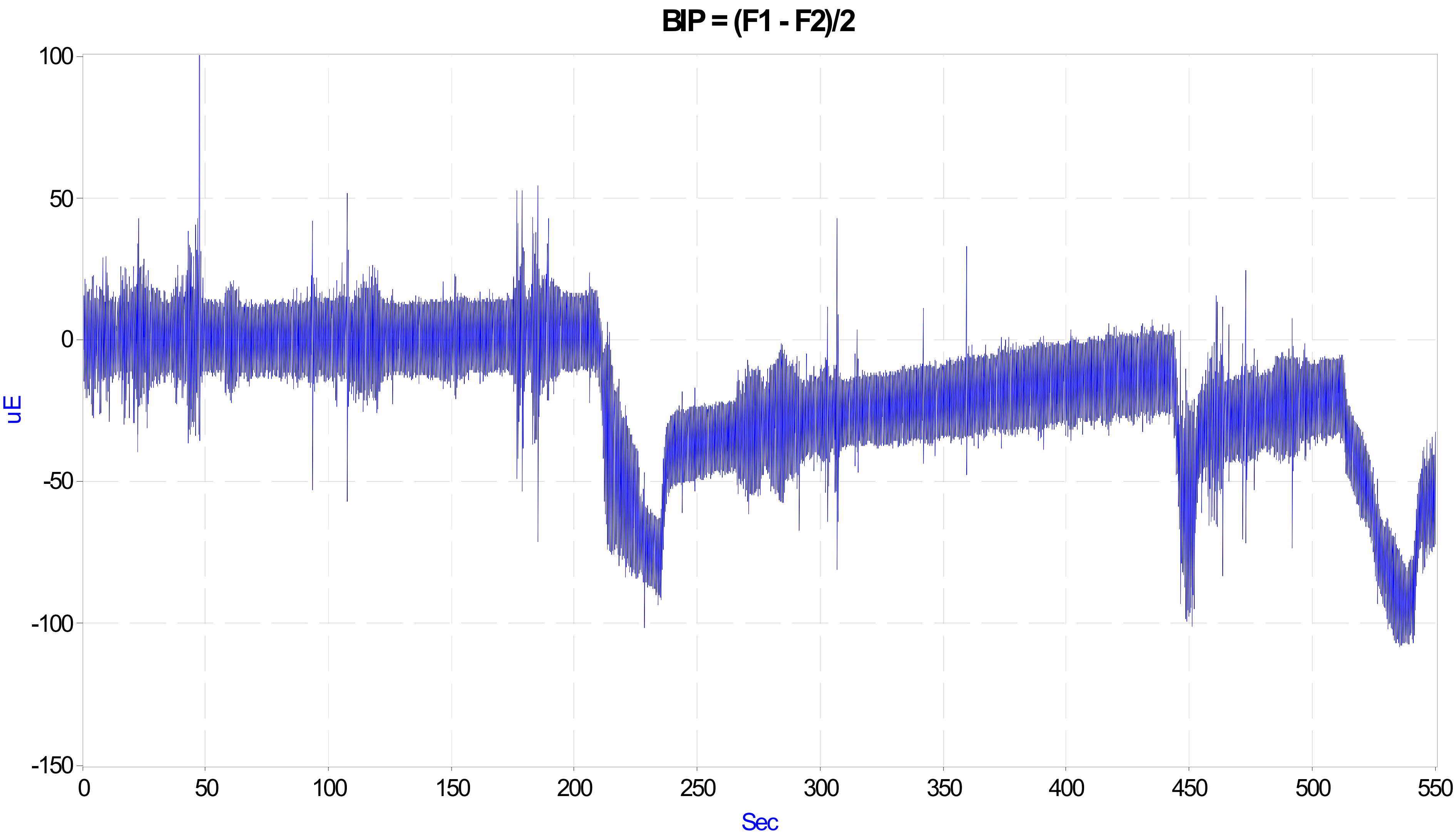

Approximate Cross Section
Of WABTEC/SAB-WABCO Disc at Strain Gage
Location
Approximate Cross Section
Of Knorr Disc at Strain Gage
Location
Plane of Disc

Table G.1. Spoke Cross Section Values

	WABTEC/SAB-WABCO	Knorr
Area	1.9 in^2	3.6 in^2
Moment of Inertia (bending in-plane)	0.44 in^4	0.85 in^4
Moment of Inertia (bending out-of-plane)	0.25 in^4	1.69 in^4

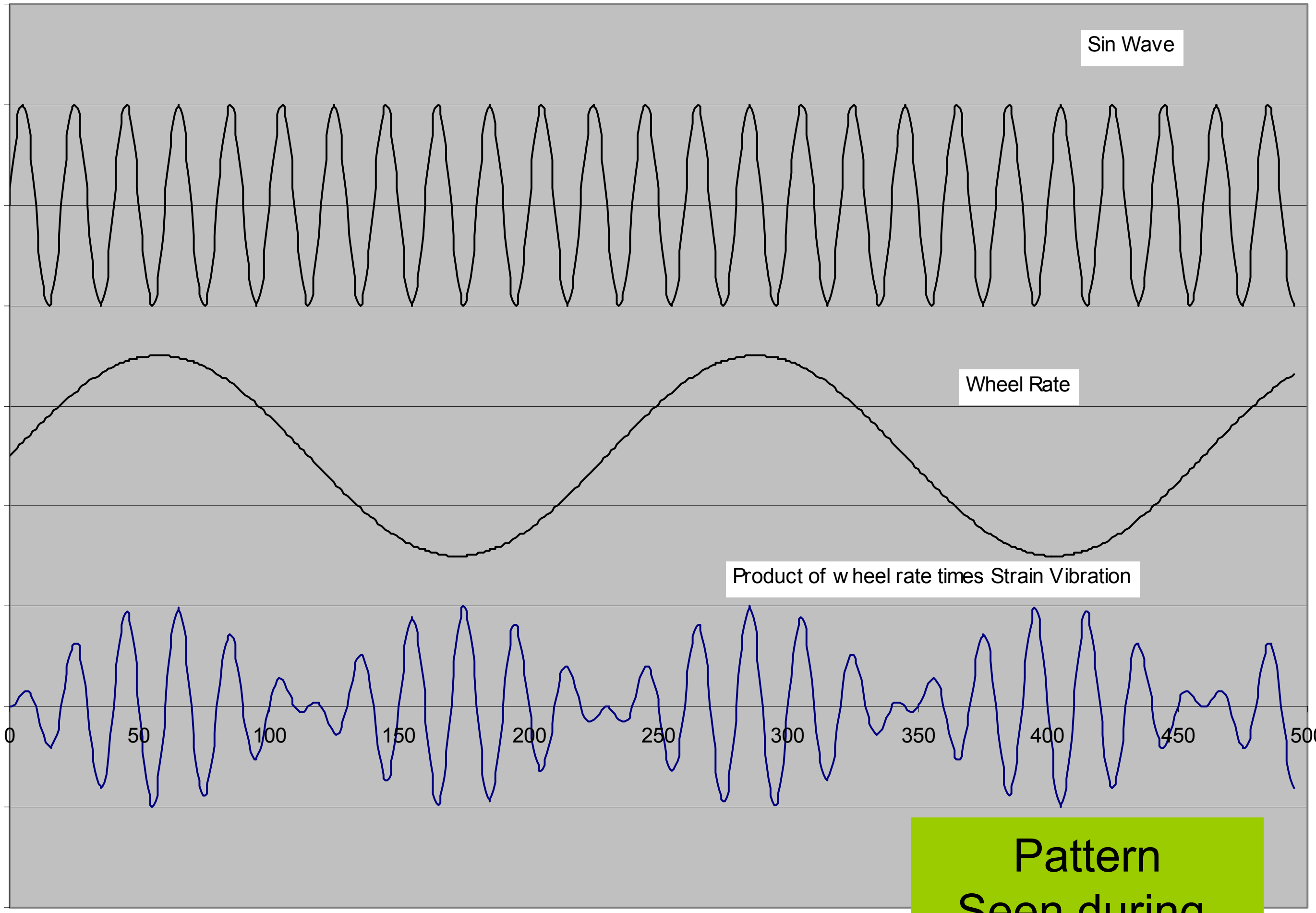
Bending In-Plane



Bending Out-of-Plane

- In The First Days Of Testing Large Oscillations At ~ 187 Hz Were Observed
- The Question Was Whether This Oscillation Was In The Plane Of The Disc Or Out Of The Plane
- The Effect Of Out Of Plane Bending Being Modulated By Wheel Rotation Rate Is Investigated In The Next Series Of Slides
- Later In The Testing Program Strain Gages Were Added To Spoke 3 (Diametrically Opposed To The Initial Instrumented Spoke 6) And Demonstrated The Out-Of-Plane Behavior

Wheel Rate Modulation



Pattern Seen during Braking in BOP Strain

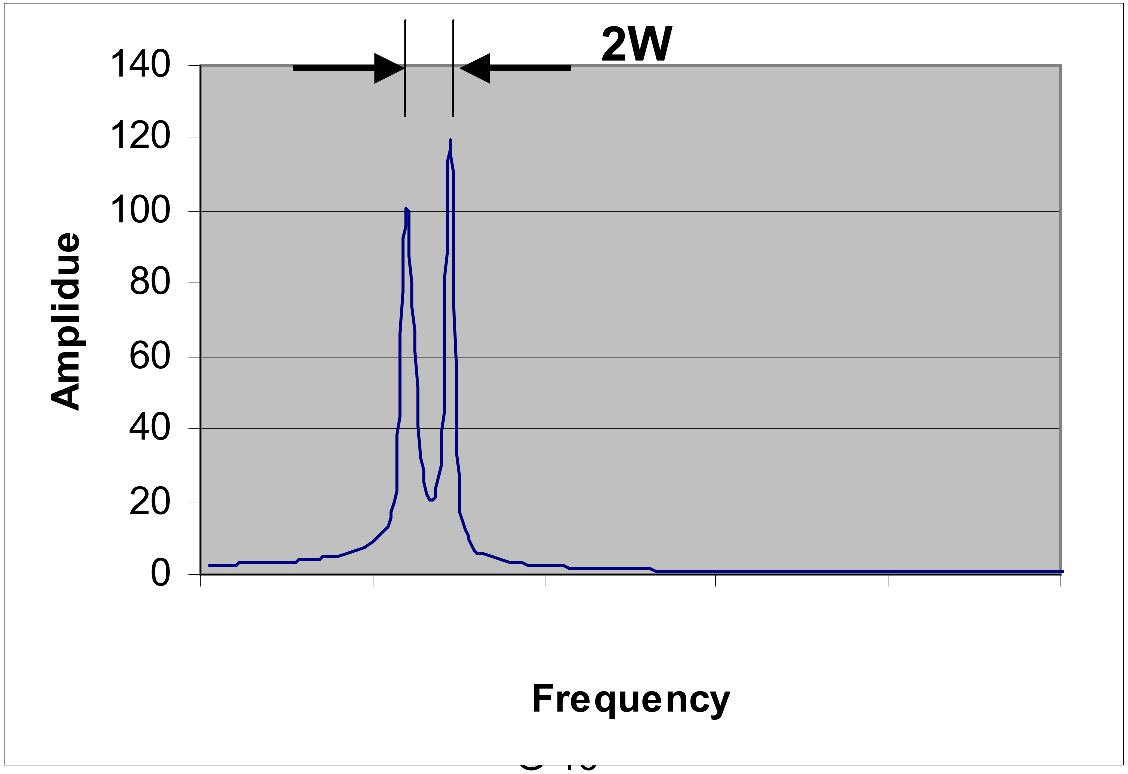
Frequency Domain Analysis of Modulated BOP Strain

Sin(2πFt)*Sin(2πWt)

$$=-0.5*\text{Cos}\{2\pi(F+W)t\}+0.5*\text{Cos}\{2\pi(F-W)t\}$$

F = Strain Signal Frequency

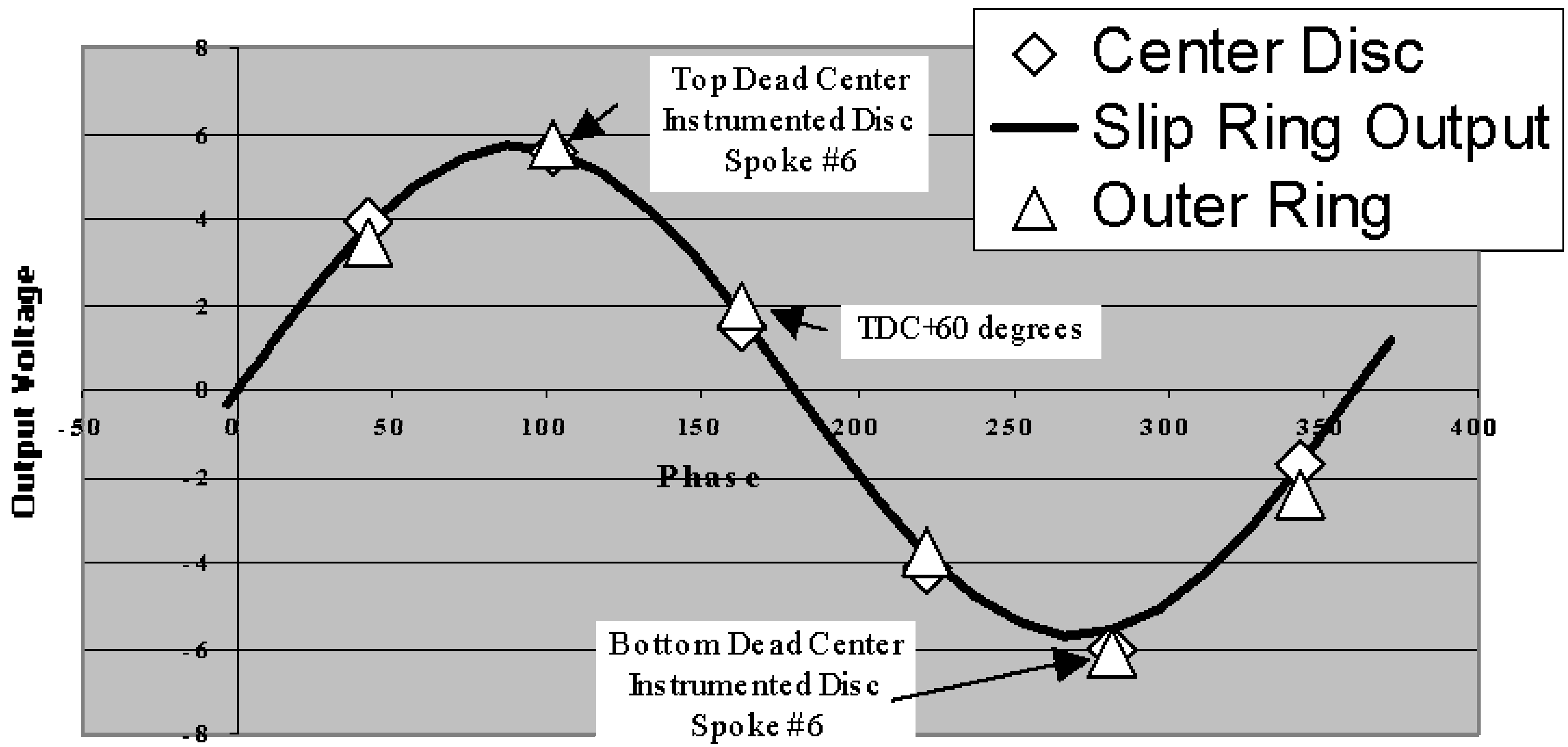
W = Wheel Rate

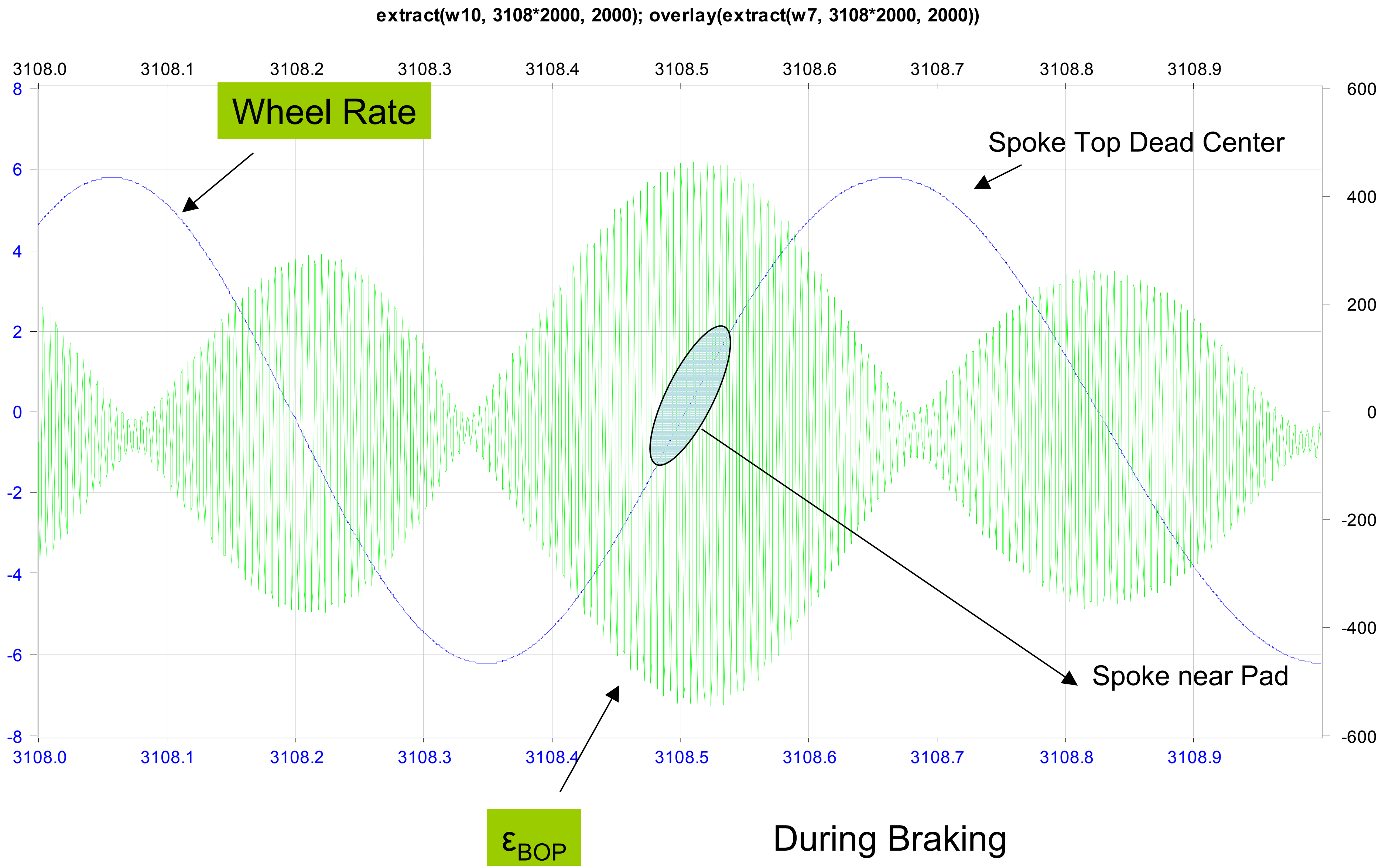


Spoke Location

- The Slip Ring Used To Transfer Signals From The Rotating Axle And Disc Contains A Sine Wave Generator (One Cycle Per Wheel Revolution)
- A Test Was Performed To Determine The Phase Of This Signal With The Position Of The Instrumented Spoke
- This Information Is Important In Determining The Axis Of Rotation Of The Disc
- Results Are Shown In The Next Slide

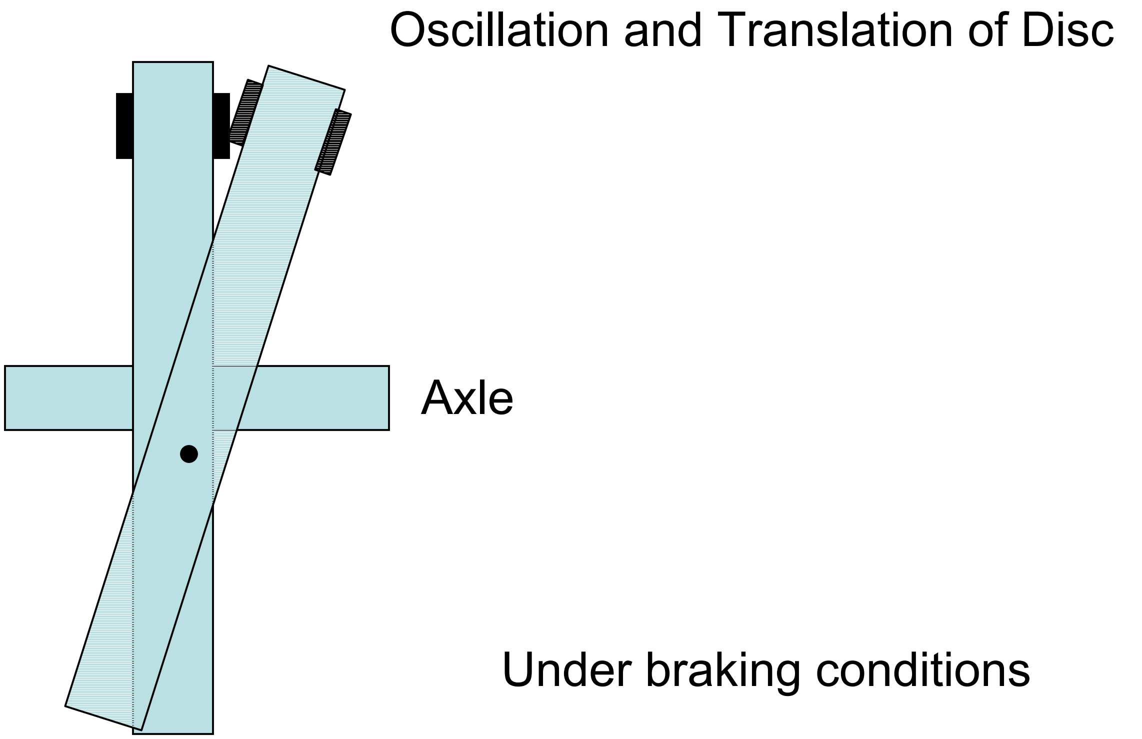
Instrumented Spoke Phase Based on Wheel Position





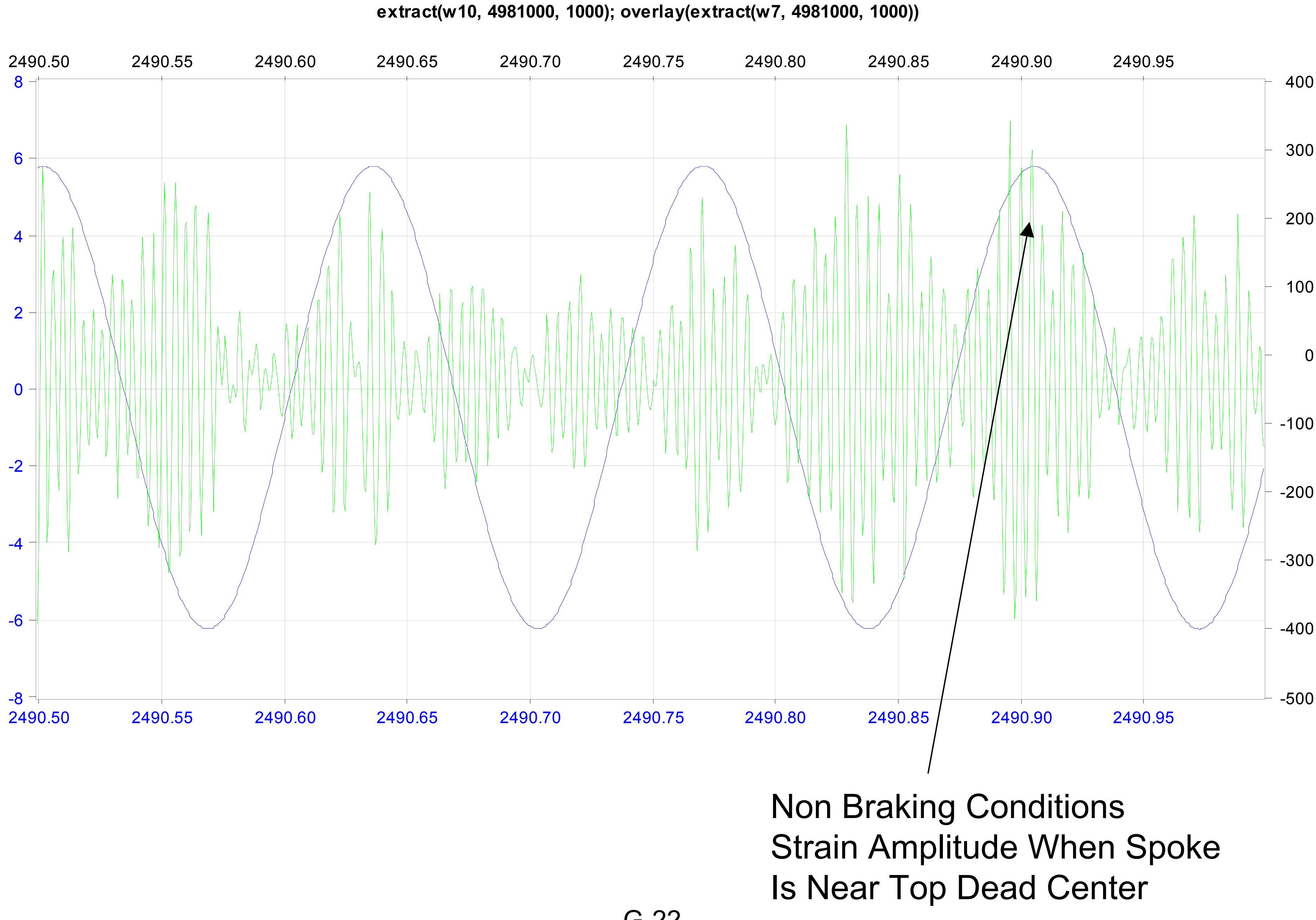
extract(w10, 3108*2000, 2000); overlay(extract(w7, 3108*2000, 2000))
Wheel Rate
Spoke Top Dead Center
Spoke near Pad
ε_{BOP}
During Braking
3108.0
3108.1
3108.2
3108.3
3108.4
3108.5
3108.6
3108.7
3108.8
3108.9
8
6
4
2
0
-2
-4
-6
-8
600
400
200
0
-200
-400
-600

Look Down on Disc

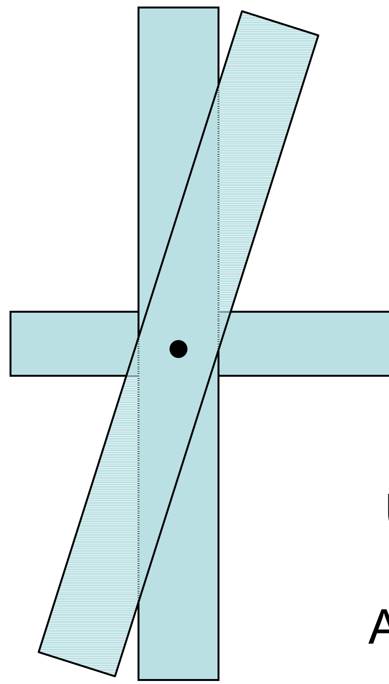


Caliper Displacement

- The Amplitude Of The BOP Oscillation During Braking Was Estimated By Observing The Amplitude Of The Lateral Acceleration Of Brake Pad
- Acceleration Level = 20 G's =$D\omega^2$
- Frequency= 192.4 Hz = 1,209 Radians Per Second
- Displacement = .005 Inches


extract(w10, 4981000, 1000); overlay(extract(w7, 4981000, 1000))
2490.50
2490.55
2490.60
2490.65
2490.70
2490.75
2490.80
2490.85
2490.90
2490.95
8
6
4
2
0
-2
-4
-6
-8
400
300
200
100
0
-100
-200
-300
-400
-500
Non Braking Conditions
Strain Amplitude When Spoke
Is Near Top Dead Center

Look from Front



Oscillation of Disc

Axle

Under Non-braking Conditions
More Pure Rotation
Appears Rotation Axis Is Mainly
Horizontal

Out-of-Plane Bending (BOP) Strains

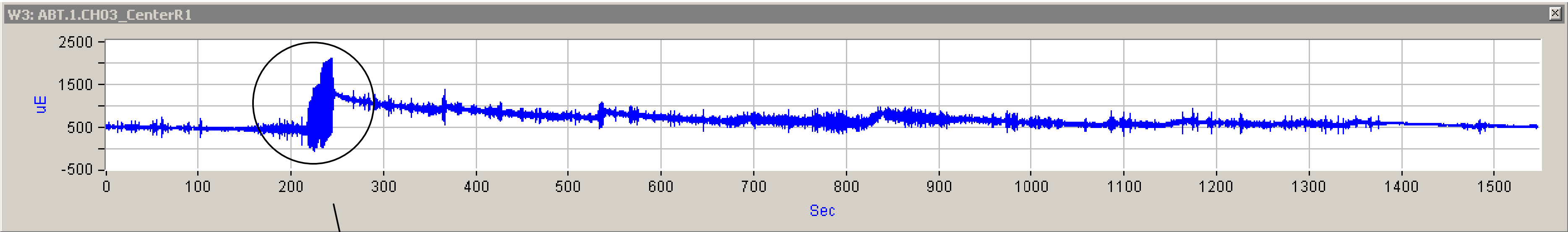
BOP Strain

- Large BOP Strain
  - *Condition 1* Input From Vertical Acceleration Observed On The Outer Bearing Housing Leads To A “Ring-out” At ~230 Hz In The BOP Mode
  - *Condition 2* During Braking With Instrumented Axle In Lead – Leads To Sustained Oscillation On The BOP Mode At ~187 Hz – Since This Occurs During Braking, Mean Strain Values Are Increasing
- Both May Contribute To Fatigue Damage Of The Spoke

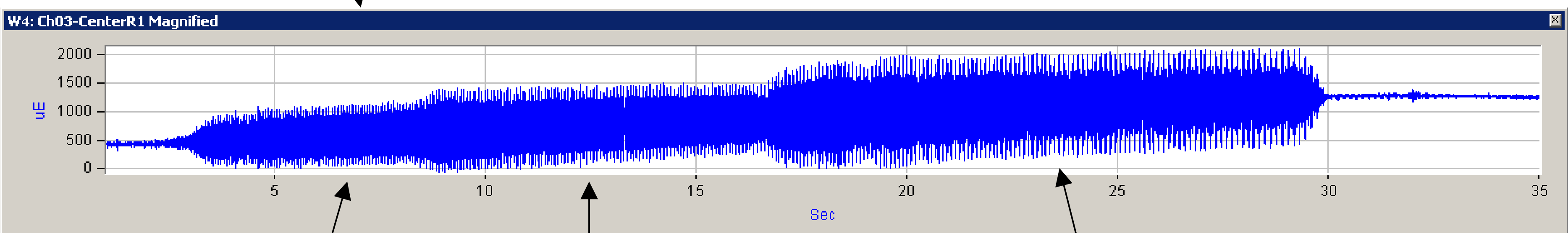
Sustained Oscillations and Track Related Oscillations

- Track Related Inputs Occur Continuously
- Track Related Responses (e.g. BOP Strain) Are Continuous But May Be Small During A Great Deal Of The Test
- The Sustained Oscillations Occur Infrequently During The Test But Produce A Large Number Of Oscillations
- During Sustained Oscillations, Response Is The Combined Effect Of Track Related Response And The Oscillations Induced By Braking

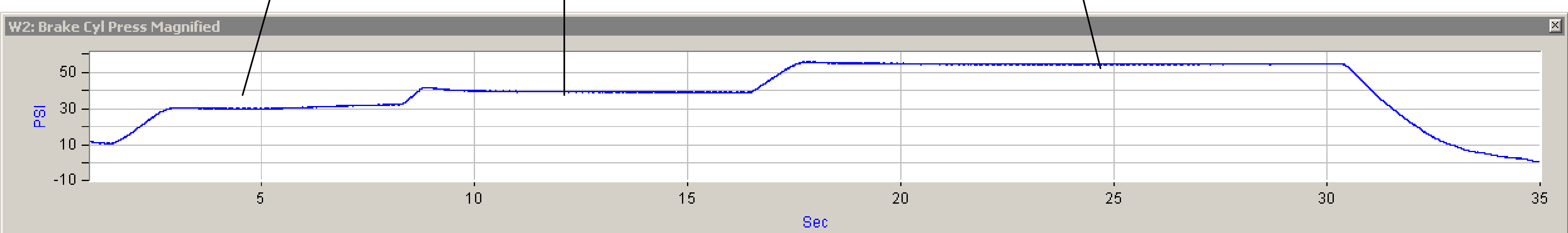
Example of Large BOP Strain During Braking



Center R1



Brake Cylinder Pressure



Note: The relationship of BOP Strain and Brake Cylinder Pressure

Sustained Oscillation Data

- First Task Was To Identify Location Of Sustained Oscillations And Characterize General Behavior
- Simple 3 Parameter Model
  - Mean Stress At Beginning Of Sustained Oscillation Period
  - Mean Stress At End Of Sustained Oscillation Period
  - Maximum Alternating Strain During Sustained Oscillation Period
- More Detailed Analysis Is Required To Investigate The Fatigue Implications Of These Oscillations

Table G.2. Summary Of Significant Sustained BOP Oscillations During Braking

Date	Direction	Instrumented Axle Leading or Trailing	Number of sustained events	Number of Brake Applications	Range of Brake Cylinder Pressures PSI	
16-May	North	Trailing	0	103		
17-May	South	Leading	7	76	31	45
26-May	North	Leading	11	82	30	40
27-May	South	Trailing	0	98		
17-Jun	North	Leading	24	147	23	55
18-Jun	South	Leading	9	95	35	56
		Total	51	601		

Terms Used to Describe Sustained Oscillations

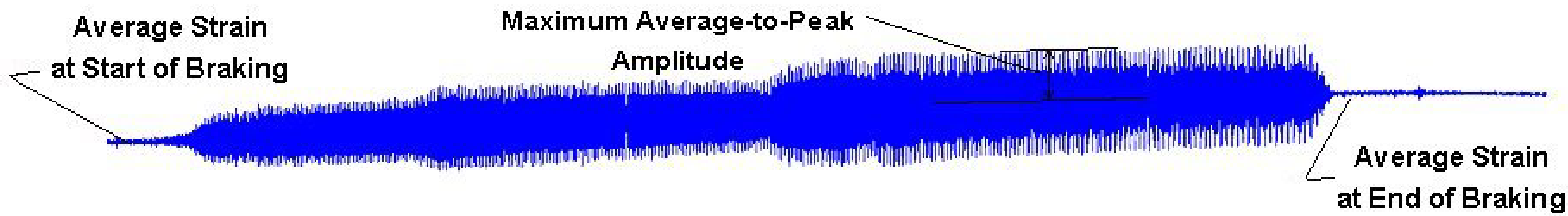


Table G.3. Significant Sustained Oscillations During Braking - May 17, 2005

17-May Bos-Was 7in CD Instrumented Axle Leading

Geographic Location	File	Time Span in the file (secs)	Time Duraction in Secs	Max Avg.-to-Peak Strain	Avg. Strain @ Start	Avg. Strain @ End	Speed (mph)	Brake Cyl Press	Temp at Start F	Temp at End F	Peak Temp F
1685 SW of MP E17	File17	218 to 246	28	850 uE	445	1329	101	45 psi	136.7	184.6	229.0
190 SW of MP AN13	File19	142 to 164	22	711.5 uE	350	887	103	35 psi	116.0	163.5	189.9
Near N. Philadelphia	File19	3107 to 3114	7	502 uE	10.6	32.3	14	45 psi	183.3	187.7	193.0
516 SW of MP AP25	File20	1251 to 1257	6	622.5 uE	476	659	94	36 psi	109.9	122.6	172.8
2303 NE of MP AP65	File21	1204 to 1224	20	700 uE	785	1368	110	40 psi	127.5	186.4	242.2
947 NE of MP AP71	File21	1475 to 1507	32	591 uE	950	1702	119	37 psi	172.3	227.3	283.1
1573 W of MP AP91	File21	2392 to 2404	12	502 uE	617	886	70	32 psi	131.4	136.7	181.5
471 SW of MP AP79 Gunpow	File21	2019 to 2022	3	576 uE	875	958	123	31 psi	160.9	161.8	171.9

Table G.4. Significant Sustained Oscillations During Braking - May 26, 2005

26-May Was-Bos 7in CD Instrumented Axle Leading

Geographic Location	File	Time Span in the file (secs)	Time Duractio n in Secs	Max Avg.-to-Peak Strain	Avg. Strain @ Start	Avg. Strain @ End	Speed (mph)	Brake Cyl Press	Temp at Start F	Temp at End F	Peak Temp F
1429 SW of MP AN11	File05	2323 to 2339	16	706.5 uE	701	1142	103 mph	40 psi	107.3	134.1	161.8
15 NW of MP E13	File07	418 to 423	5	482.5 uE	393	503	64.26 mph	32 psi	82.6	102.9	137.6
2139 NE of MP E17	File08	157 to 177	20	665 uE	432	869	77 mph	34 psi	93.2	117.8	145.9
195 SW of MP MN59	File09	202 to 206	4	262 uE	353	453	64.69 mph	30 psi	77.4	90.1	140.7
642 E of MP AB84	File12	400 to 430	30	792.5 uE	257	1129	122 mph	35 psi	74.3	126.2	162.6
1108 E of MP AB89	File12	600 to 632	32	784 uE	697	1617	89.25 mph	36 psi	134.1	186.8	217.2
1240 E of MP AB116	File13	479 to 485	6	540.5 uE	734	873	79 mph	32 psi	129.2	138.9	156.9
1936 NE of MP AB158	File15	984 to 1028	44	971.5 uE	391	1764	150.2 mph	40 psi	85.3	185.9	222.9
2230 S of MP AB179	File15	1579 to 1596	17	795.5 uE	650	1301	137 mph	38 psi	109	128.8	161.8
1939 SW of MP AB204	File17	114 to 119	5	766 uE	409	657	130 mph	33 psi	80	83.5	96.7
1732 NE of MP AB216	File17	451 to 473	22	542 uE	678	1124	83.8 mph	36 psi	87.5	145.5	187.3

Table G.5. Significant Sustained Oscillations During Braking - June 17, 2005

Geographic Location	File	Time Span in the file (secs)	Time Dur in Secs	Max Avg.-to-Peak Strain	Values for pk and valley [uE]	Avg. Strain @ Start	Avg. Strain @ End	Speed (mph)	Brake Cyl Press	Temp at Start F	Temp at End F	Peak Temp F
2089 NE of MP AP4	File10	206.5 to 209	3.5	531.5	675 to 1738	1282	1348	85	46	169.2	212.2	242.1
980 NE of MP MN21	File19	348 to 355	7	335	203 to 873	488	694	89	42	143.3	145.9	179.7
1627 NE of MP MN25	File21	151 to 165	14	327	261 to 915	528	766	73	32	152.5	158.6	181
772 E of MP MN28	File21	310 to 314	4	316	296 to 928	611	646	67	29	158.6	158.6	169.2
2599 E of MP MN45	File23	164 to 169	5	185.5	455 to 826	604	677	69	23	146.8	147.2	155.6
582 SW of MP MN59	File24	264 to 270	6	276.5	319 to 872	478	611	68	31	130.1	134	179.3
1163 W of MP MN64	File25	227 to 236	9	288	288 to 864	470	633	70	28	136.7	138.9	156.4
1530 SW of MP MN68	File25	490 to 499	9	314	335 to 963	528	704	74	30	144.6	145.9	157.8
49 E of MP MN69	File25	556 to 568	12	394.5	352 to 1141	665	861	72	34	149	162.6	178.4
717 NE of MP MN70	File25	631 to 640	9	333.5	538 to 1205	750	930	71	32	168.7	170.5	188.9
1022 E of MP AB99	File29	121 to 132	11	658	167 to 1483	756	1035	120	44	144.6	148.5	170.1
1768 E of MP AB102	File29	244 to 250	6	290	592 to 1172	770	922	85	35	164.8	163	180.6
1525 NE of MP AB115	File30	561 to 575	14	1010	-261 to 1759	580	1038	81	43	138.4	147.6	167.9
No GPS	File31	92 to 98	6	525.5	515 to 1566	984	1081	83	41	190.3	190.7	204.3
No GPS	File31	166 to 172	6	403	807 to 1613	1172	1280	78	31	203.9	203.9	221.9
821 SE of MP AB125	File32	334 to 338	4	255.5	743 to 1254	938	1005	66	29	204.8	204.8	213.6
639 SE of MP AB126	File32	387 to 393	6	658	486 to 1802	1004	1176	71	41	211.4	211.4	215.3
2129 SE of MP AB128	File33	72 to 78	6	899	445 to 2243	1142	1486	94	44	214.9	232	266.3
29 NE of MP AB131	File34	90 to 110	20	378.5	915 to 1672	1218	1520	95	37	224.5	236.4	250.5
2136 SW of MP AB138	File34	411 to 426	15	719	408 to 1846	1015	1413	90	40	189.4	242.6	245.2
673 SW of MP AB140	File35	70 to 90	20	749	731 to 2229	1272	1710	92	51	221	276.4	278.2
464 W of MP AB143	File36	131 to 144	13	1138.5	366 to 2643	1170	1686	107	50	222.3	227.2	247
2455 NE of MP AB158	File37	46 to 93	47	1371.5	-361 to 2382	658	2202	148	55	144.1	310.7	330
2579 NE of MP AB160	File38	546 to 557	11	590.5	308 to 1489	520	996	141	33	130.5	134	179.3

Table G.6. Significant Sustained Oscillations During Braking – June 18, 2005

Geographic Location	File	Time Span in the file (secs)	Time Dur in Secs	Max Avg.-to-Peak Strain	Values for pk and valley [uE]	Avg. Strain @ Start	Avg. Strain @ End	Speed (mph)	Brake Cyl Press	Temp at Start F	Temp at End F	Peak Temp F
2396 NE of MP AB202	File03	476 to 498	22	947.5	387 to 2282	1309	1918	116	56	100.6	253.5	252.7
2619 S of MP AB178	File05	530 to 551	21	1226	-367 to 2085	438	1483	130	52	115.6	244.3	243.4
691 SW of MP AB170	File06	242 to 258	16	558.5	768 to 1885	971	1406	113	35	169.2	198.2	225
4 SW of MP AB162	File06	503 to 540	37	1200.5	-214 to 2187	650	2154	150	54	145.4	266.3	298.8
1222 SW of MP AB159	File07	32 to 56	24	1132	540 to 2804	1491	2315	120	54	249.6	301.4	327.8
732 SW of MP AB156	File07	153 to 180	27	835	1051 to 2721	1719	2512	120	52	282.5	314.6	341.9
784 SW of MP AN13	File22	211 to 226	15	1128.5	-687 to 1570	285	925	110	55	107.2	156	199.9
1211 SW of MP AN19	File22	446 to 453	7	1171.5	-442 to 1901	643	938	120	51	143.3	148.5	179.3
1748 SW of MP AN55	File24	578 to 595	17	1454.5	196 to 3105	1466	1974	133	56	226.7	261.9	325.6

Outer Discs versus Center Discs

- Sustained Oscillations Were Observed On The Outer And Center Discs During Test On May 17, Phase 1 Test
- When The Sustained Oscillations Were Observed On One Disc, They Were Also Observed On The Other
- The Magnitude Of The Sustained Oscillations On The Center Disc Was 2.9 to 3.4 Times The Maximum Peak-To-Peak Oscillations Found On The Center Discs
- The Duration Of The Oscillations On The Outer Discs Was The Same As That On The Center Discs
- The Oscillations Were Out Of Phase By 12 Degrees Which Corresponds To The 12 Degrees Offset Of The Instrumented Spokes On The Outer And Center Discs

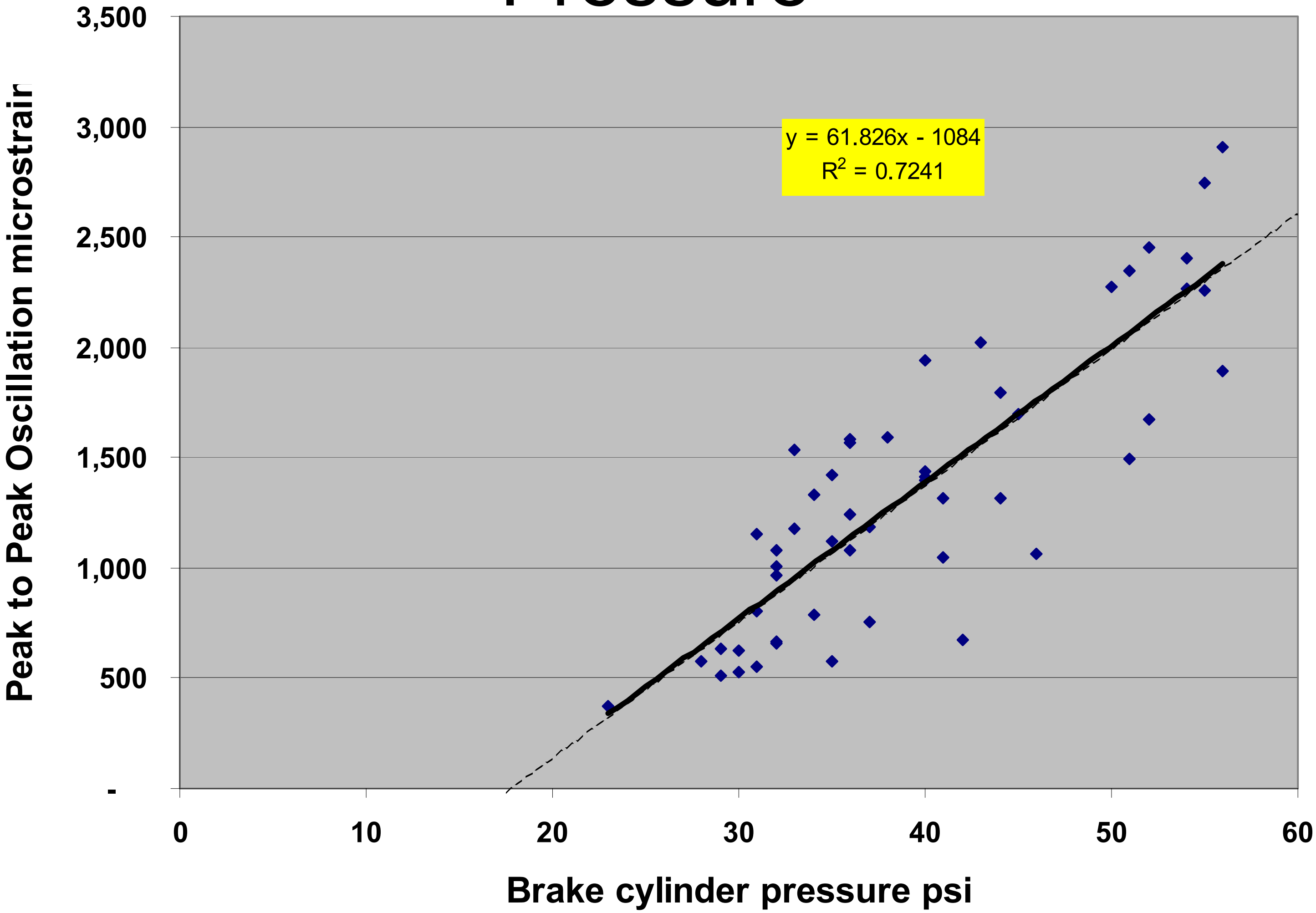
Sustained Oscillations On The Outer Discs

		Time Span in the file	Time Duration In Secs	Max Pk-to-Pk	Ratio of Center to Outer Disc Peak-to-peak
1685 SW of MP E17	File17	218 to 246 secs	28	587	2.90
190 SW of MP AN13	File19	142 to 164 secs	22	498	2.86
516 SW of MP AP25	File20	1251 to 1257 secs	6	385	3.23
2303 NE of MP AP65	File21	1204 to 1224 secs	20	508	2.76
947 NE of MP AP71	File21	1475 to 1507 secs	32	452	2.62
1573 W of MP AP91	File21	2392 to 2404 secs	12	299	3.36
471 SW of MP AP79 Gunpow	File21	2019 to 2022 secs	3	391	2.95

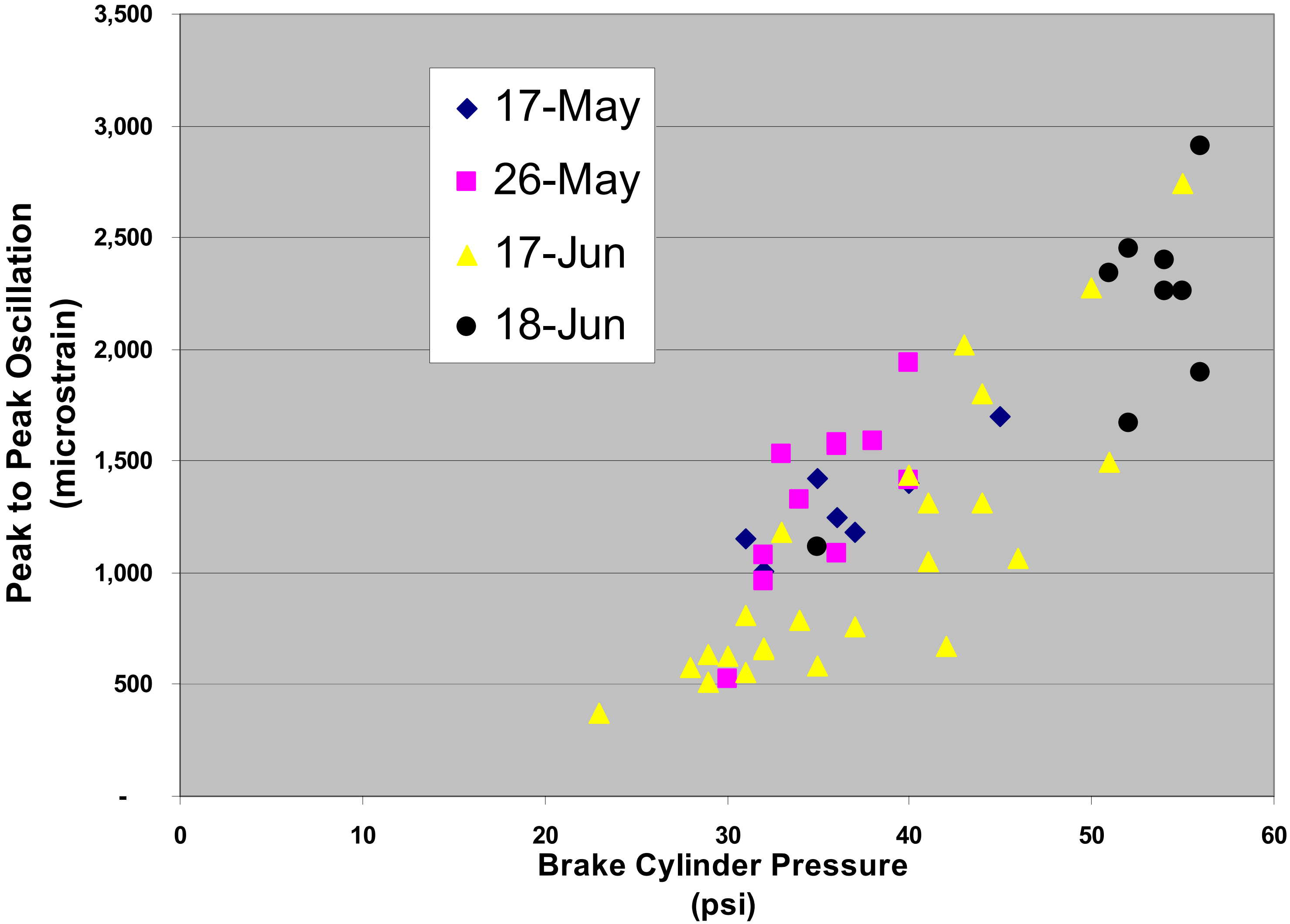
Influence of Brake Cylinder Pressure on Sustained Oscillations

- Based on the Tables
- Cross Plot - Maximum Strained Bop (peak-to-peak) vs Brake Cylinder Pressure

Sustained Oscillations Peak BOP Strain vs Brake Cylinder Pressure



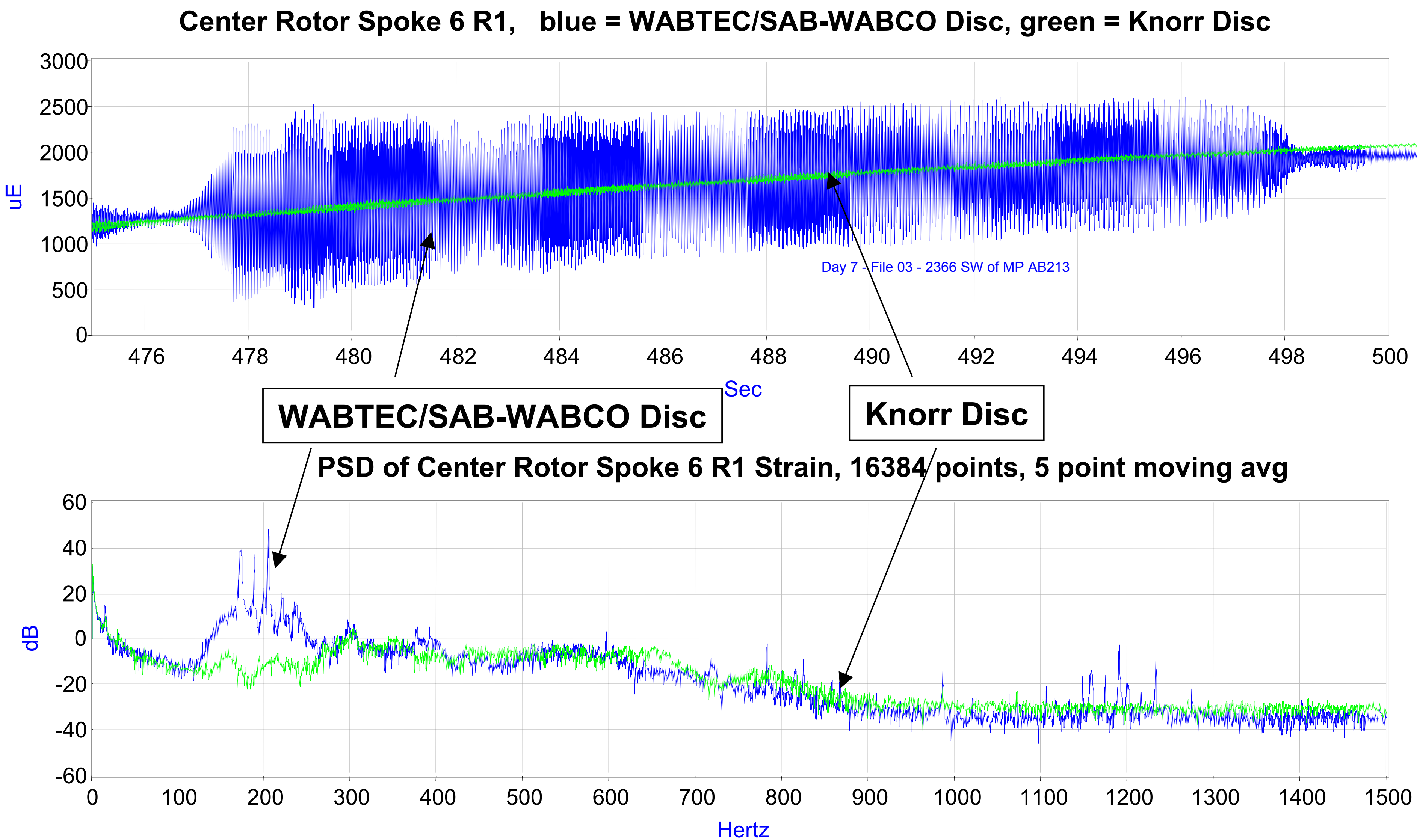
Sustained Oscillations
Peak BOP Strain vs Brake Cylinder Pressure



Sustained BOP Oscillations in Braking

- 51 Occurrences of Sustained BOP Oscillations
- Total Duration – 774 Seconds
- Only When the Instrumented Axle was in the Lead

Day 7 – File 03



Center Rotor Spoke 6 R1, blue = WABTEC/SAB-WABCO Disc, green = Knorr Disc
3000
2500
2000
1500
1000
500
0
uE
476
478
480
482
484
486
488
490
492
494
496
498
500
Sec
Day 7 - File 03 - 2366 SW of MP AB213
WABTEC/SAB-WABCO Disc
Knorr Disc
PSD of Center Rotor Spoke 6 R1 Strain, 16384 points, 5 point moving avg
60
40
20
0
-20
-40
-60
dB
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Hertz

Relationship of BOP Strain to Acceleration Difference

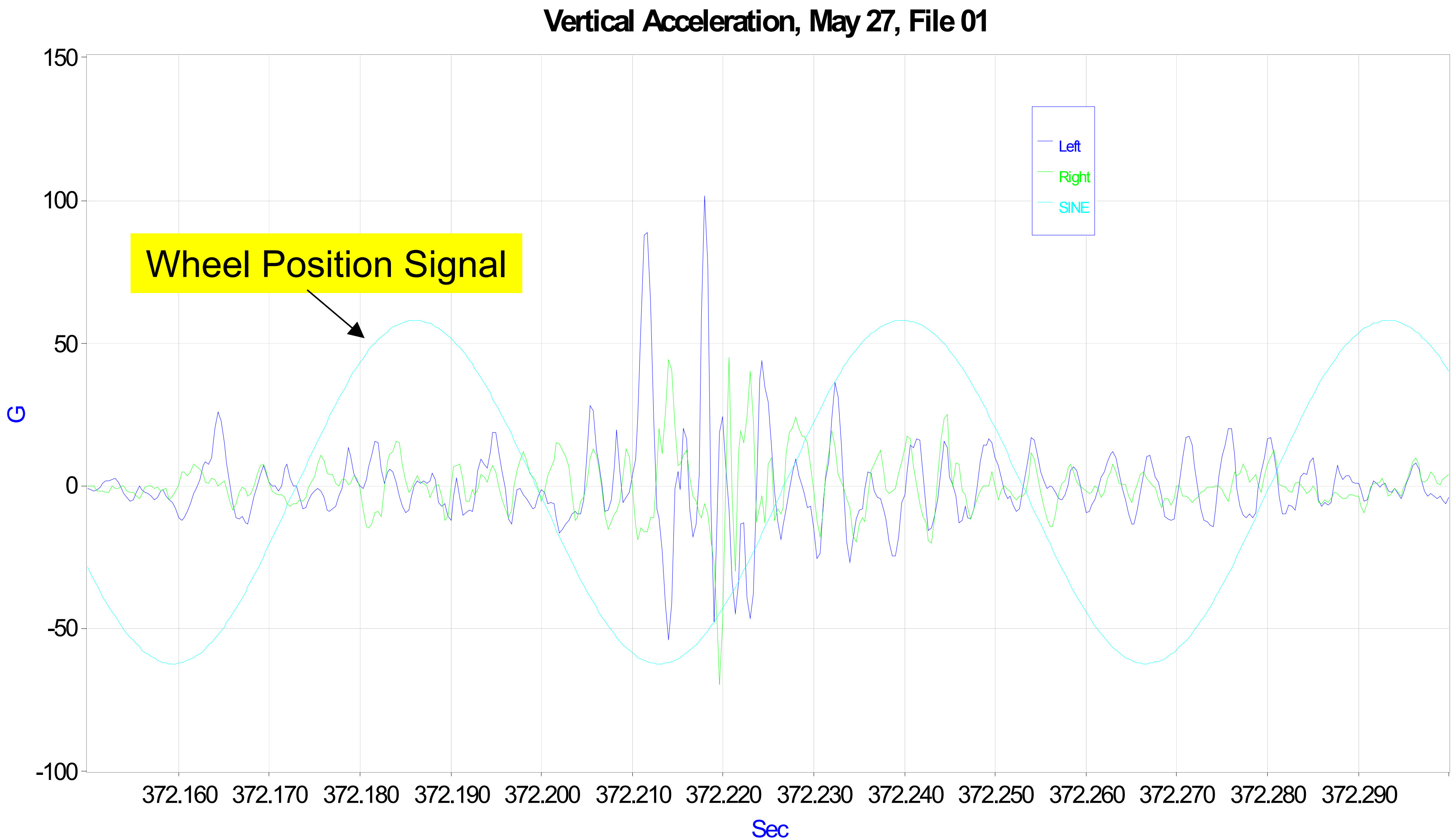
Relationship of BOP Strain to Acceleration Difference

- Acceleration Difference Is Related To The BOP Strain Observed During Testing
- For A Single Acceleration Difference Peak, the BOP Strain is ~7.5 με/G.
- Sometimes The Acceleration Difference Has Multiple Large Peaks Within A Half Wheel Revolution
- Bombardier Requested That Two Specific Events Be Reviewed

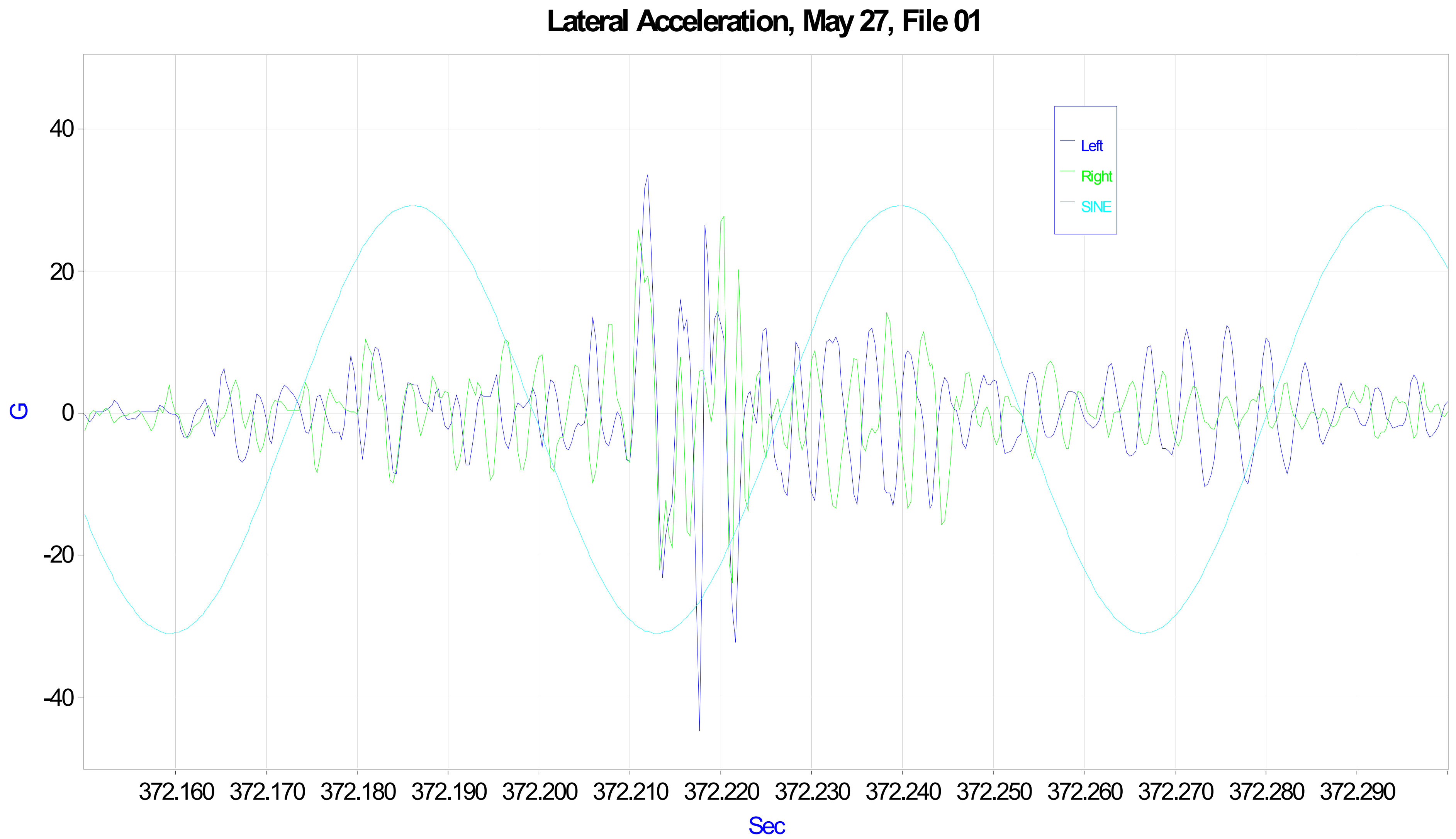
Two Cases

- Case 1
  - May 27 (File 1 @ ~ 372 seconds)
  - Peak Acceleration Difference – 102 g's
  - BOP Magnitude Response – ~2,200 $\mu\varepsilon$
  - Minimum BOP Strain -2258 $\mu\varepsilon$
  - Maximum BOP Strain +2051$\mu\varepsilon$
- Case 2
  - June 17 (File 24 @ ~ 85 seconds)
  - Peak Acceleration Difference – 189 g's
  - BOP Magnitude Response – ~1,000 $\mu\varepsilon$
  - Minimum BOP Strain -1033 $\mu\varepsilon$
  - Maximum BOP Strain +889$\mu\varepsilon$

Case 1 Right and Left Acceleration

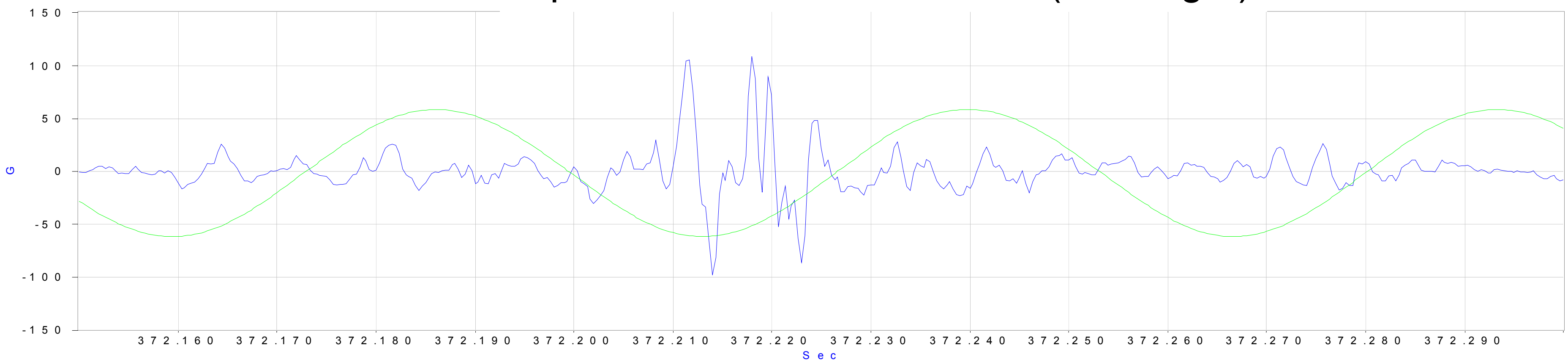


Case 1 Lateral Acceleration

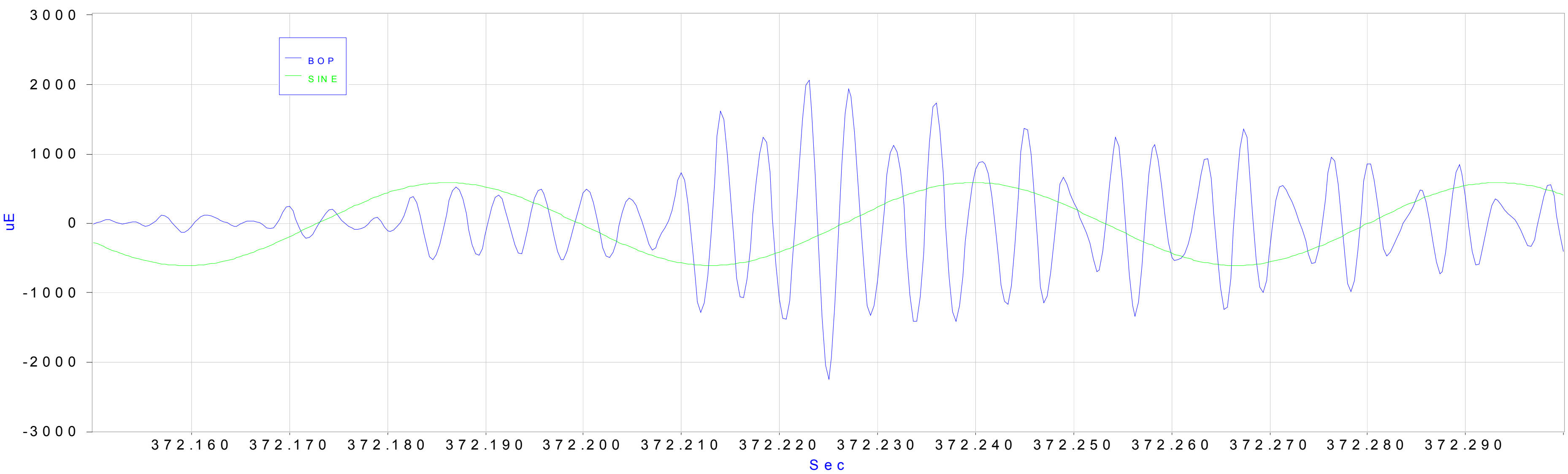


Case 1 May 27

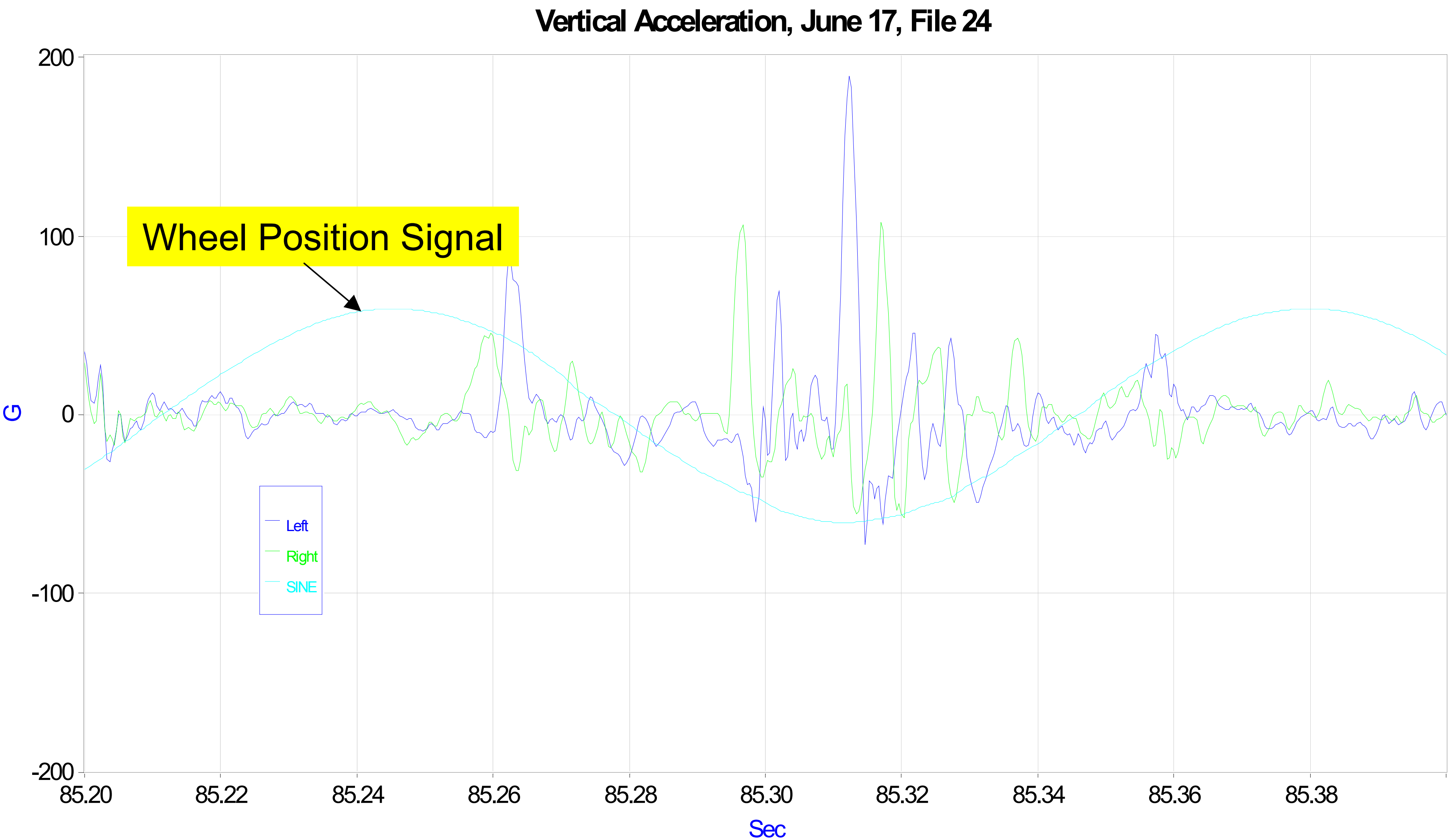
Input Acceleration Difference (Left-Right)



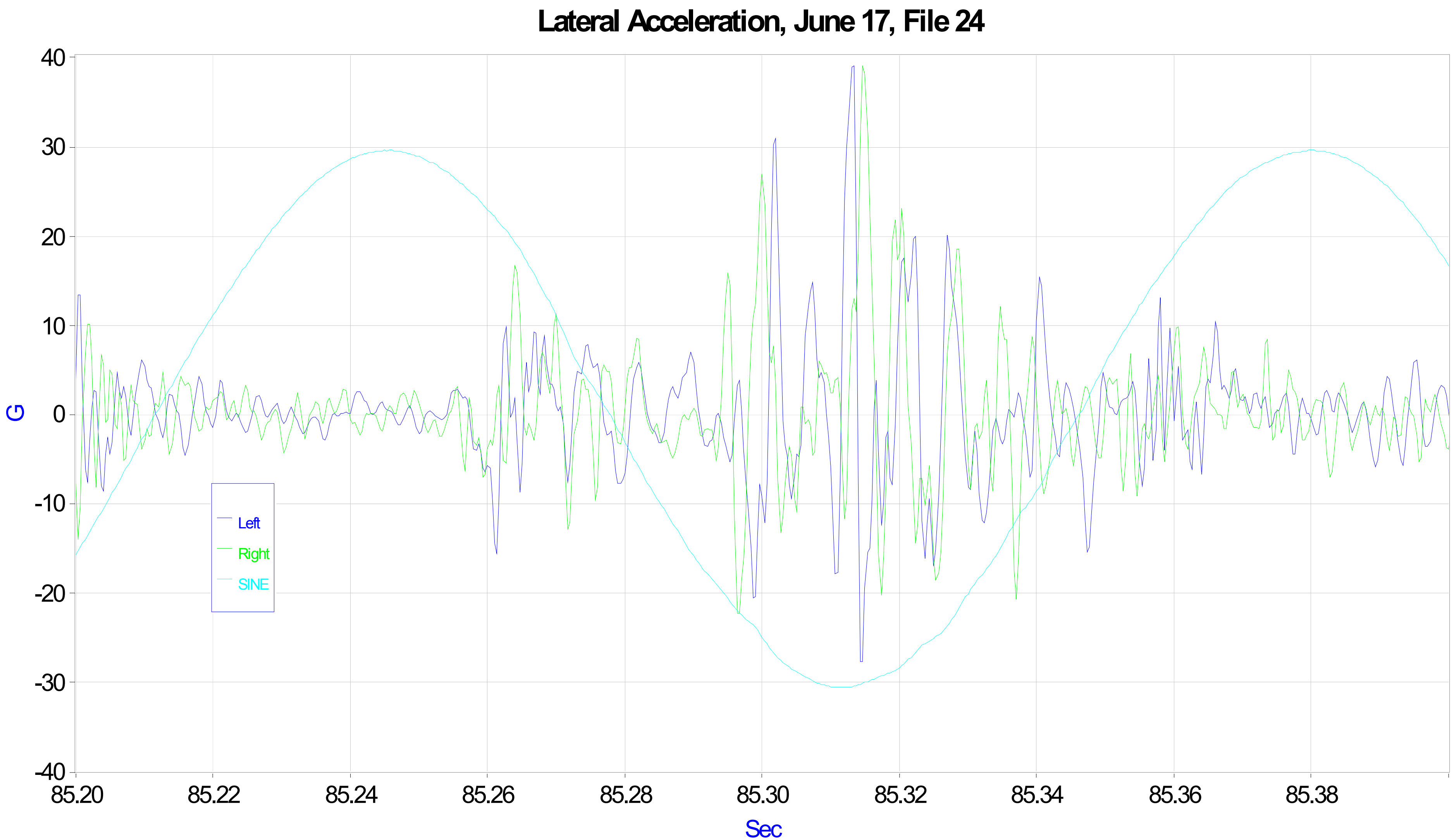
Output BOP Strain



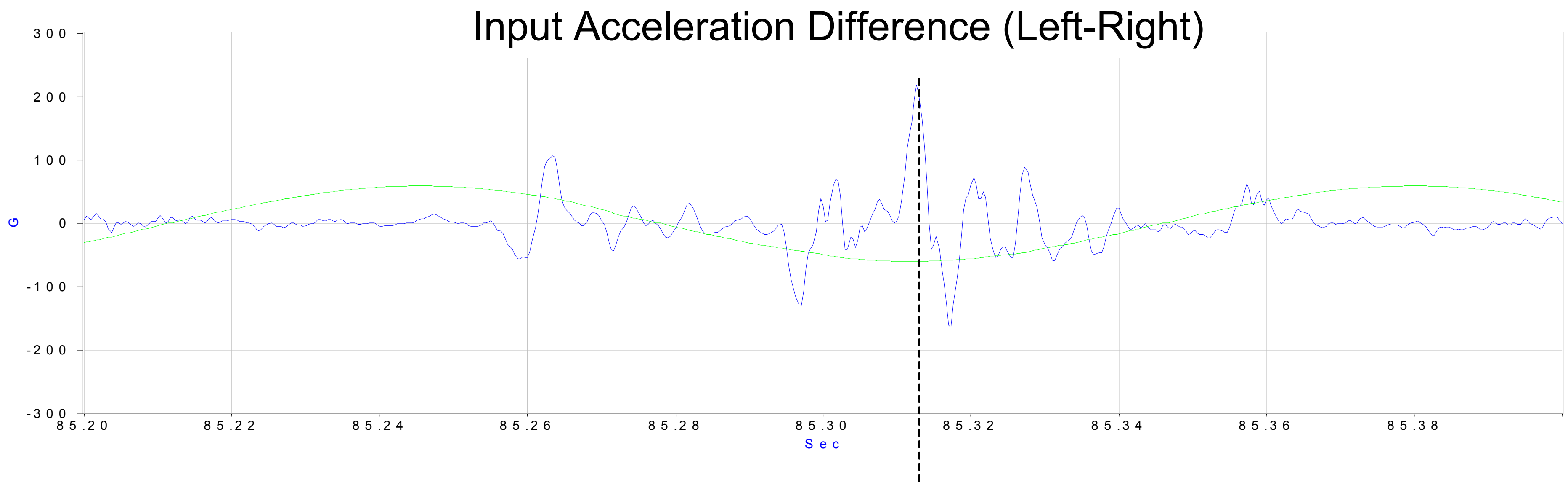
Case 2 Right and Left Acceleration

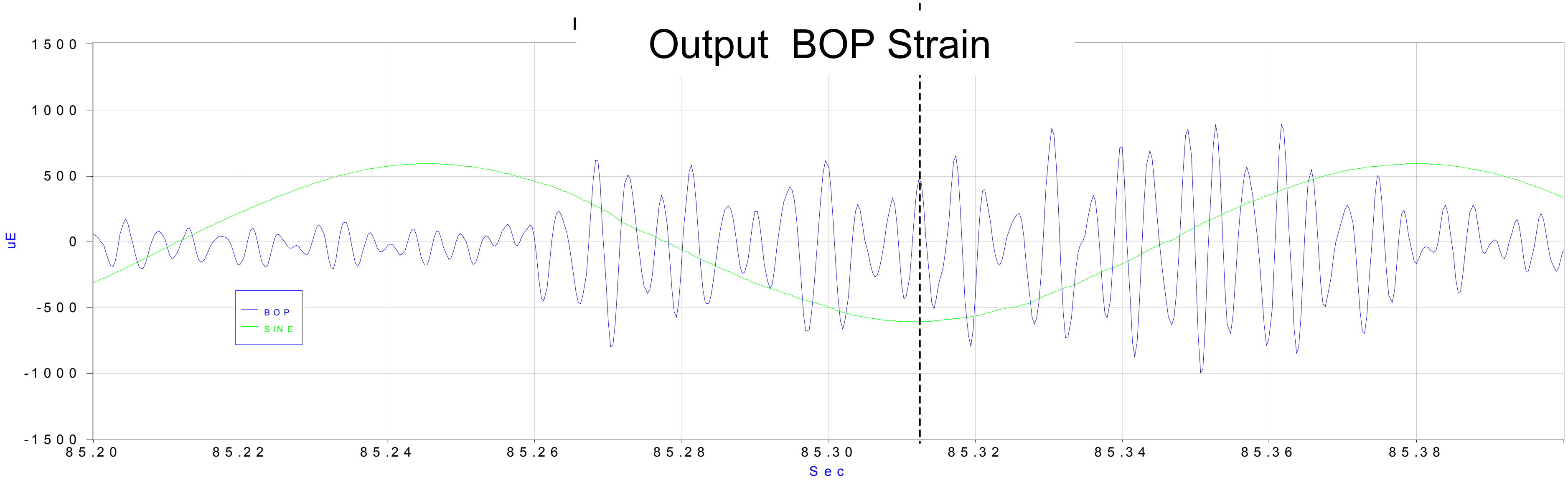


Case 2 Lateral Acceleration

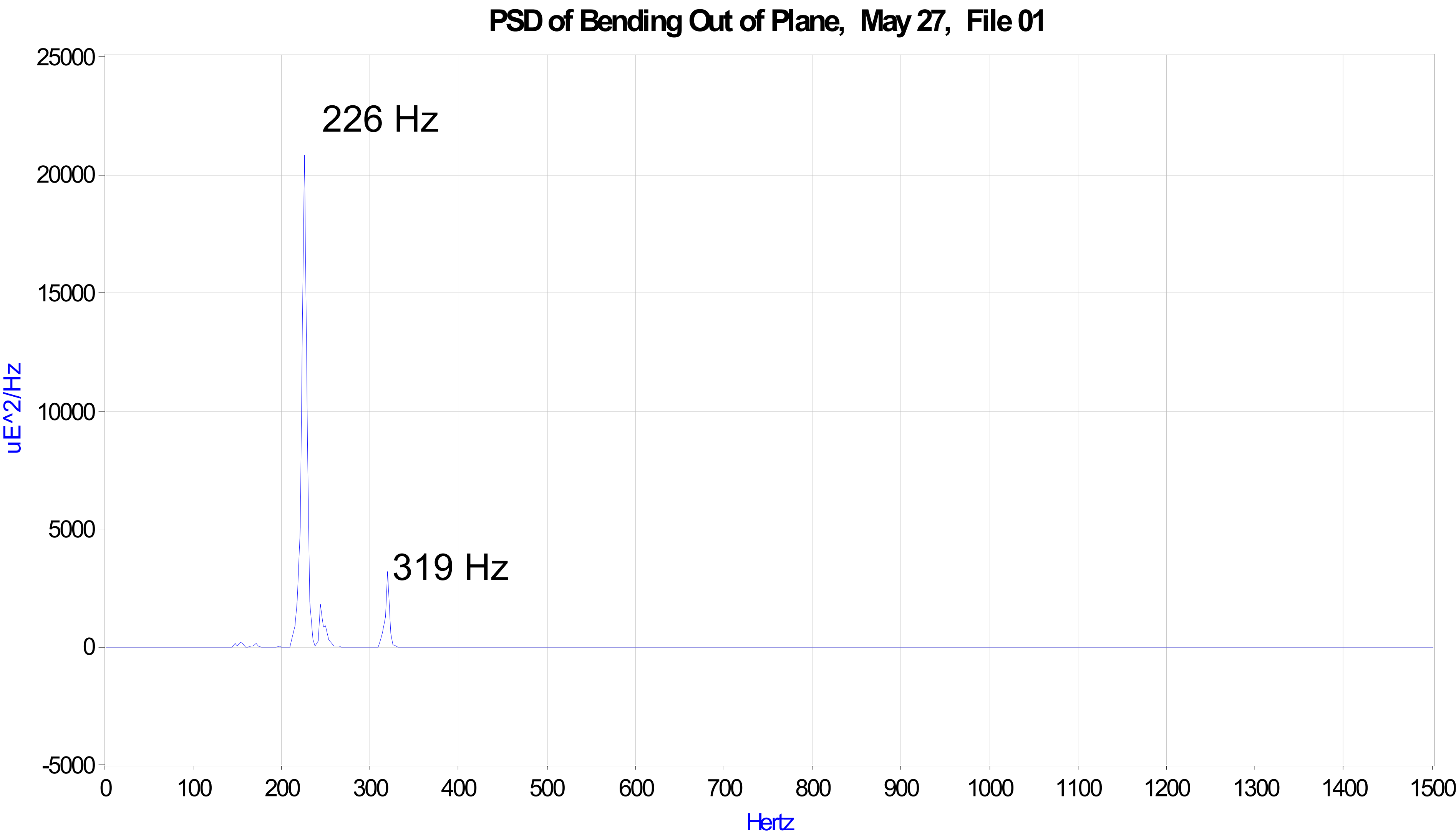


Case 2 June 17

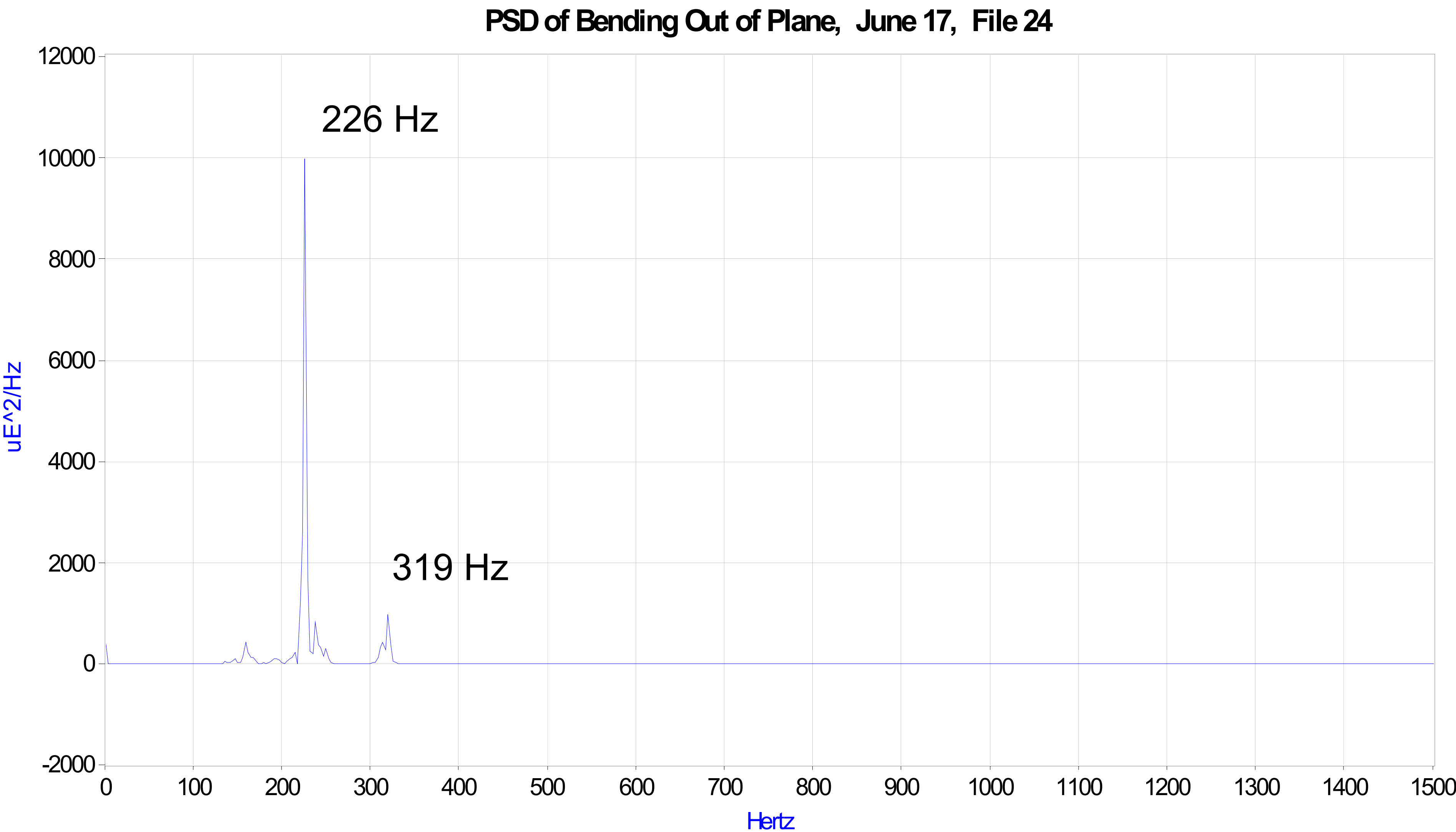




PSD Of BOP Strain, Case 1



PSD Of BOP Strain, Case 2



Observations

- The Largest Peak in the Spectrum of the BOP Strain is Observed at 227 Hz
- The Second Largest Peak in the Spectrum of the BOP Strain is Observed at 319 Hz
- The PSD Level of the Largest Peak at 227 Hz is 10 times the Level of the Second Largest Peak at 319 Hz

Theory

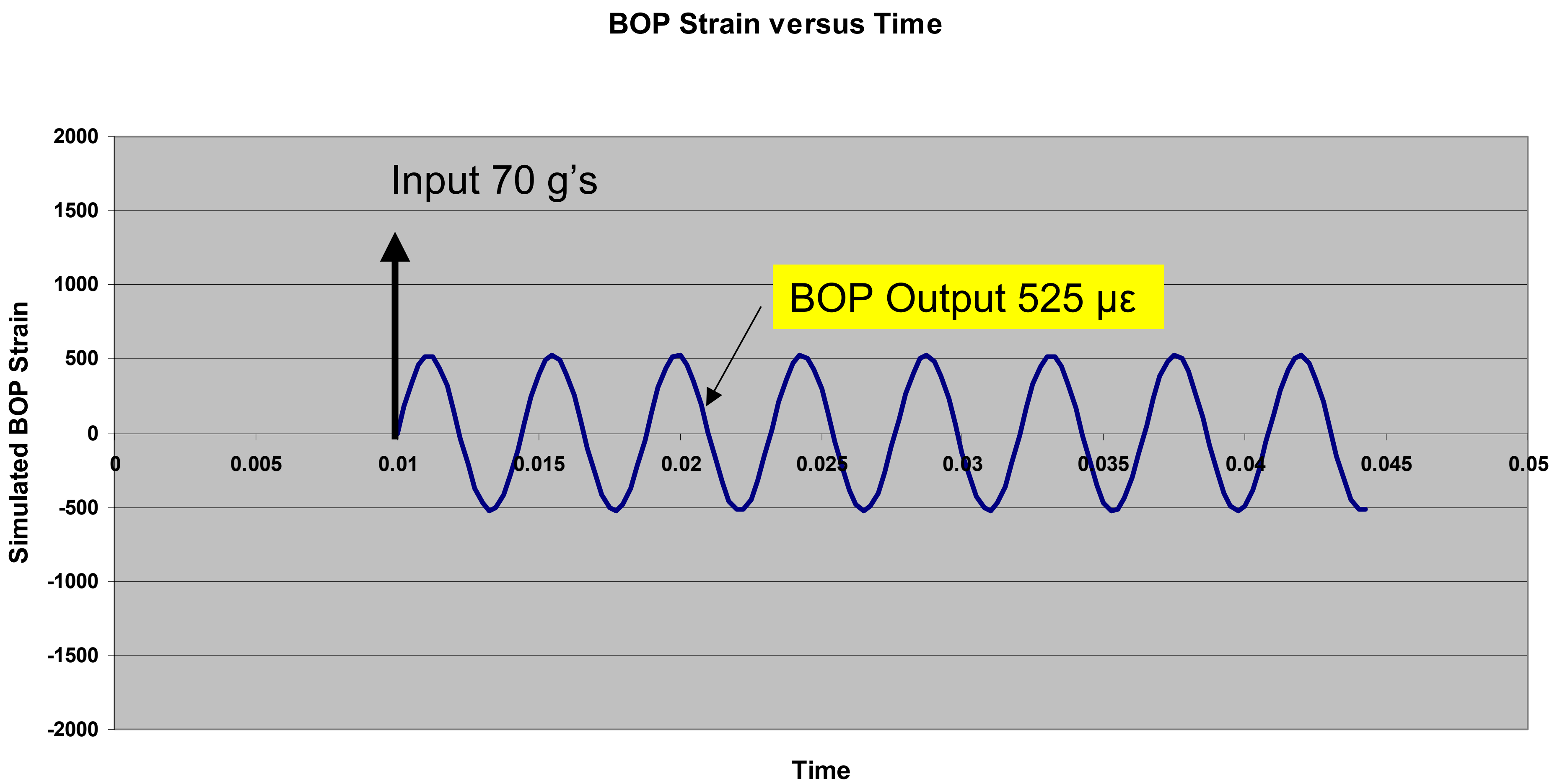
- A Possible Cause For BOP Strains Not Being Proportional To Large Peak Acceleration Differences Is That The Results Of Two Accelerations Peaks Do Not Add Arithmetically But Add Vectorially
- This Allows For Both Constructive And Destructive Interference In BOP Strain Response
- The Following Slides Provide A Conceptual Description Of This Effect

Terminology

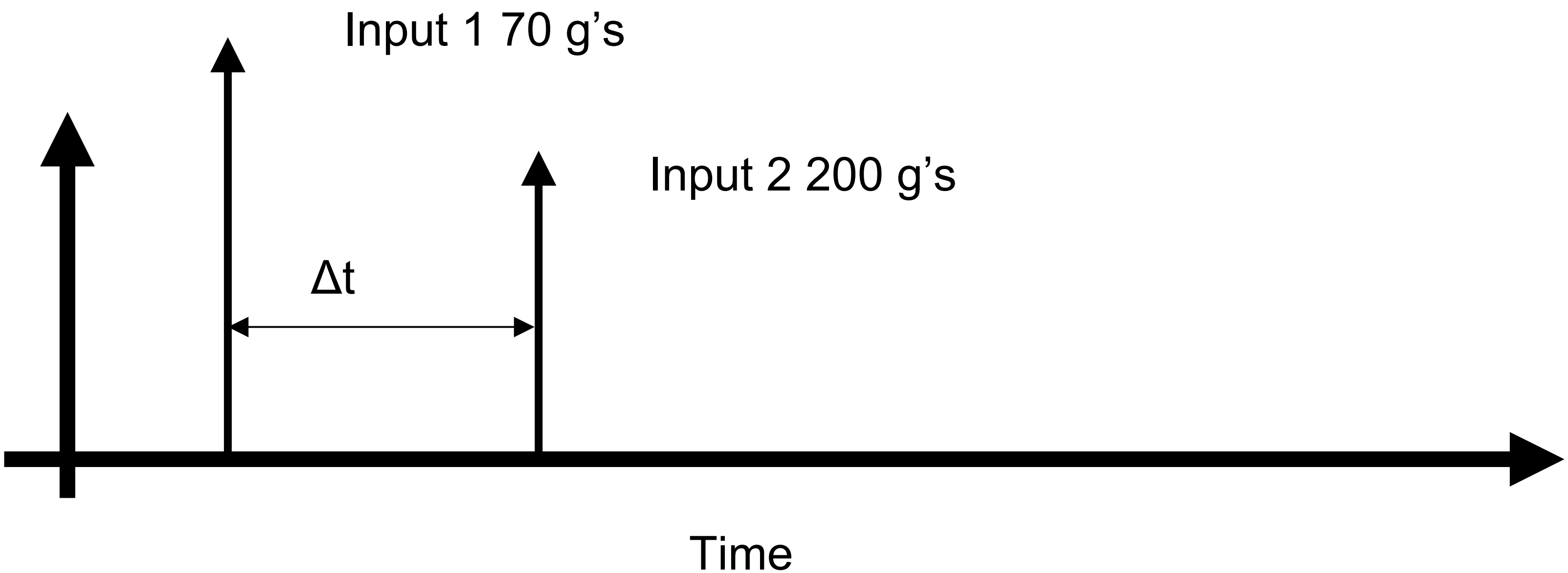
- Interference Constructively
  - When superposition leads to a maximum possible intensity
- Interference Destructively
  - When superposition leads to zero intensity
- Interference
  - Between the limits of Interference Constructively and Interference Destructively

Reference: The Physics of Vibrations and Waves
H.J. Pain

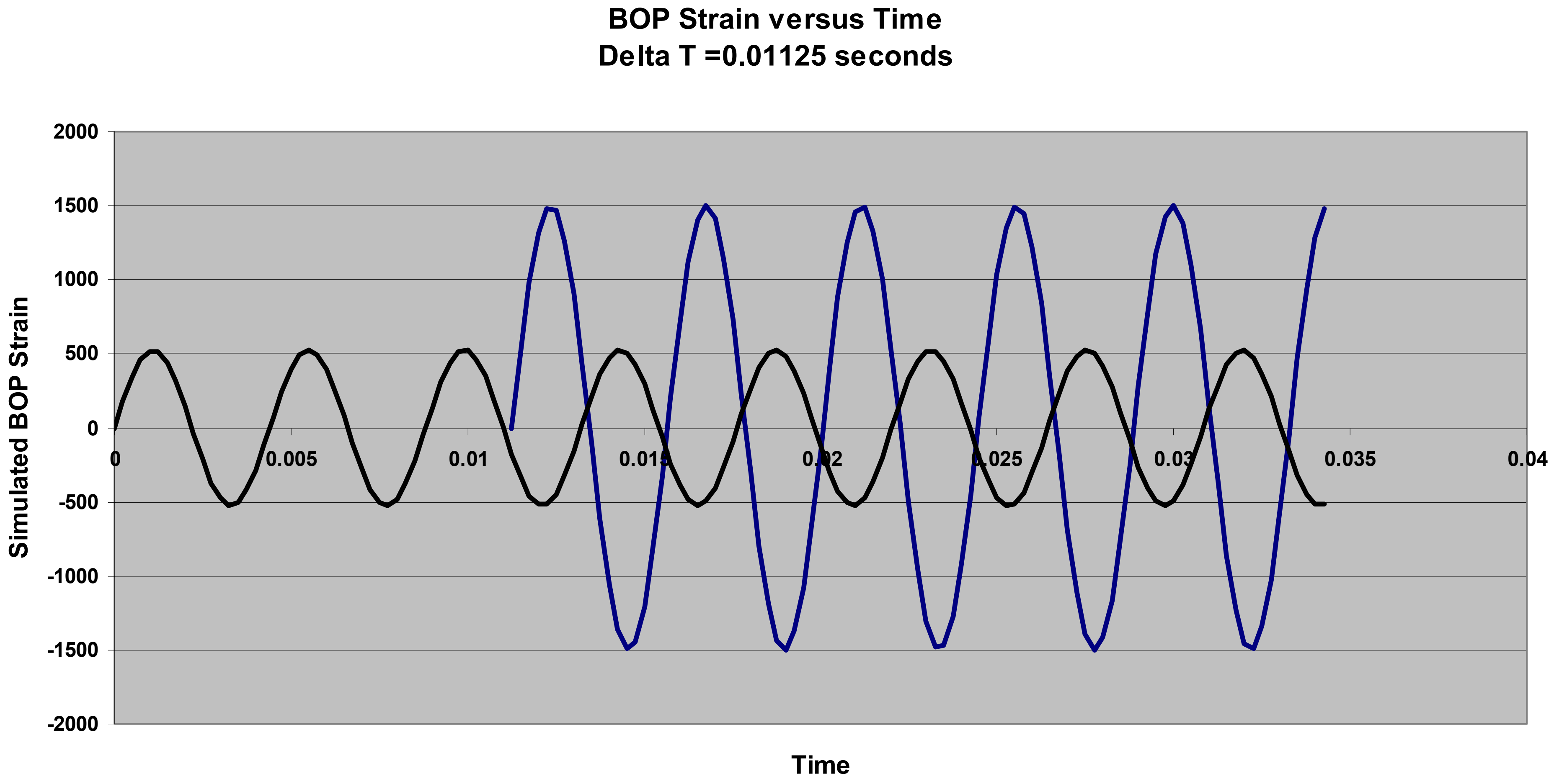
Theory


BOP Strain versus Time
Input 70 g's
BOP Output 525 με
Simulated BOP Strain
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Time

Two Inputs

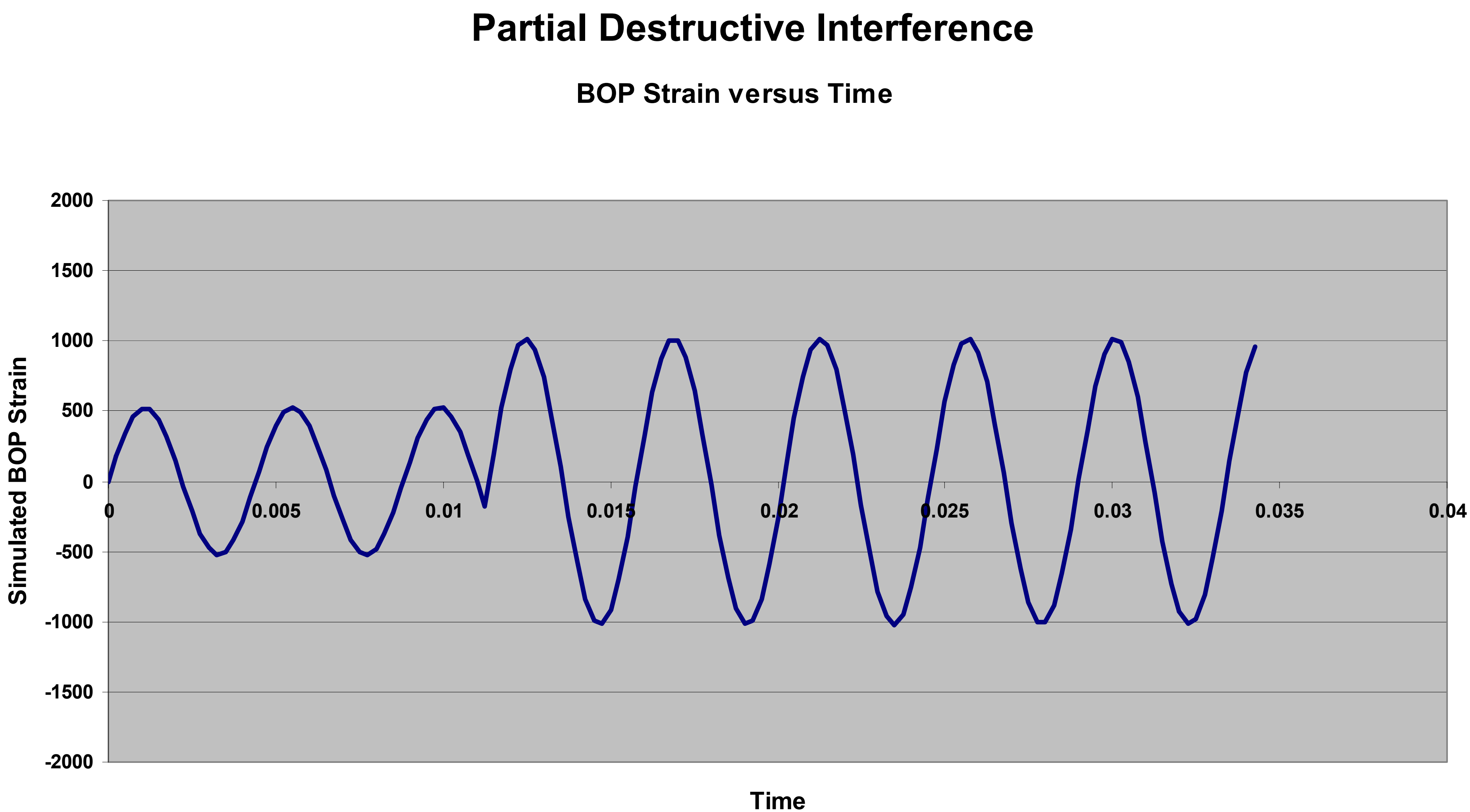


Example 1

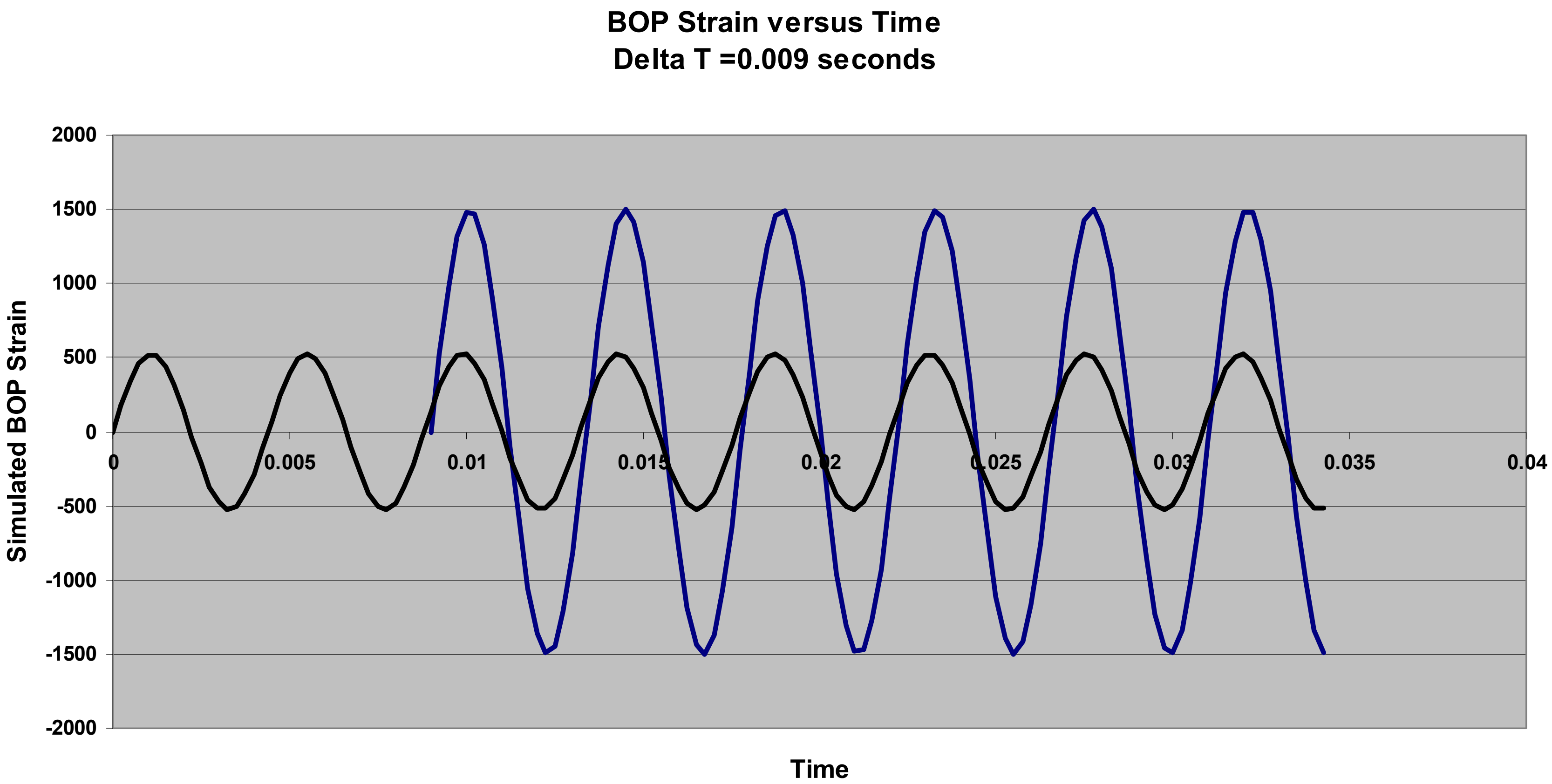


BOP Strain versus Time
Delta T =0.01125 seconds
2000
1500
1000
500
0
-500
-1000
-1500
-2000
Simulated BOP Strain
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
Time

Example 1 Combined BOP Strain From The Two Inputs

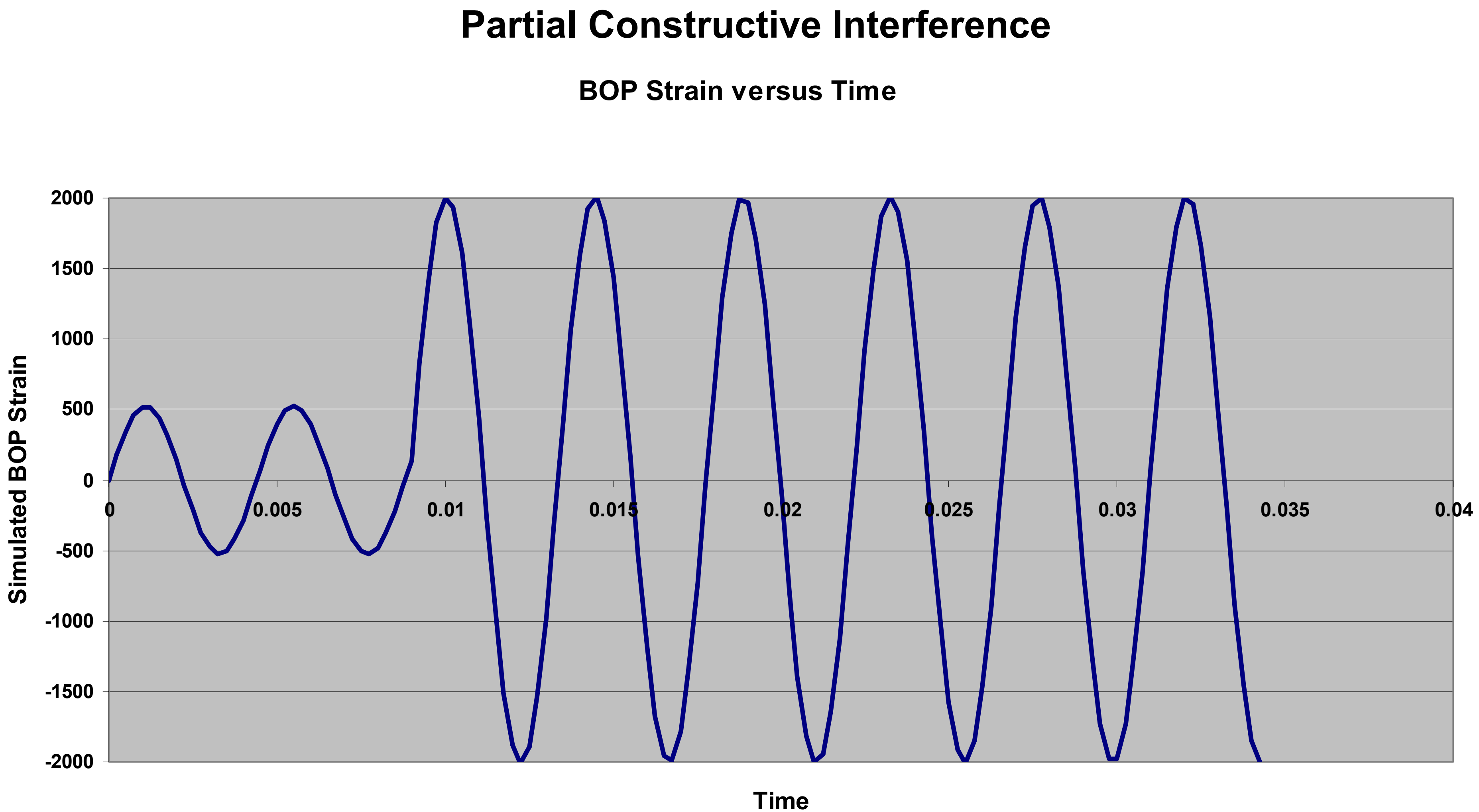


Example 2



BOP Strain versus Time
Delta T =0.009 seconds
Simulated BOP Strain
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
Time

Example 2 Combined BOP Strain From The Two Inputs



Estimate of Fatigue Effects and Goodman Plots

Fatigue

- Process In Which Damage Accumulates Due To The Repetitive Application Of Loads
- Strains Due To These Loads Are Well Below The Yield Strain of the Material
- Fatigue Consists of:
  - Crack initiation
  - Crack propagation
  - Final Fracture
- Spoke Cracks In WABTEC/SAB-WABCO Disc May Be Influenced By Fatigue

ASTM Definition

- Fatigue Life Is The Number Of Cycles Of Stress Or Strain Of A Specific Character That A Given Specimen Sustains Before Failure Of A Specific Nature Occurs
- Fatigue Strength Is The Hypothetical Value Of Stress At Failure For Exacting N Cycles
- Fatigue Limit, S_f , Is The Limiting Value Of Median Fatigue Strength As N Becomes Very Large

SN Curve

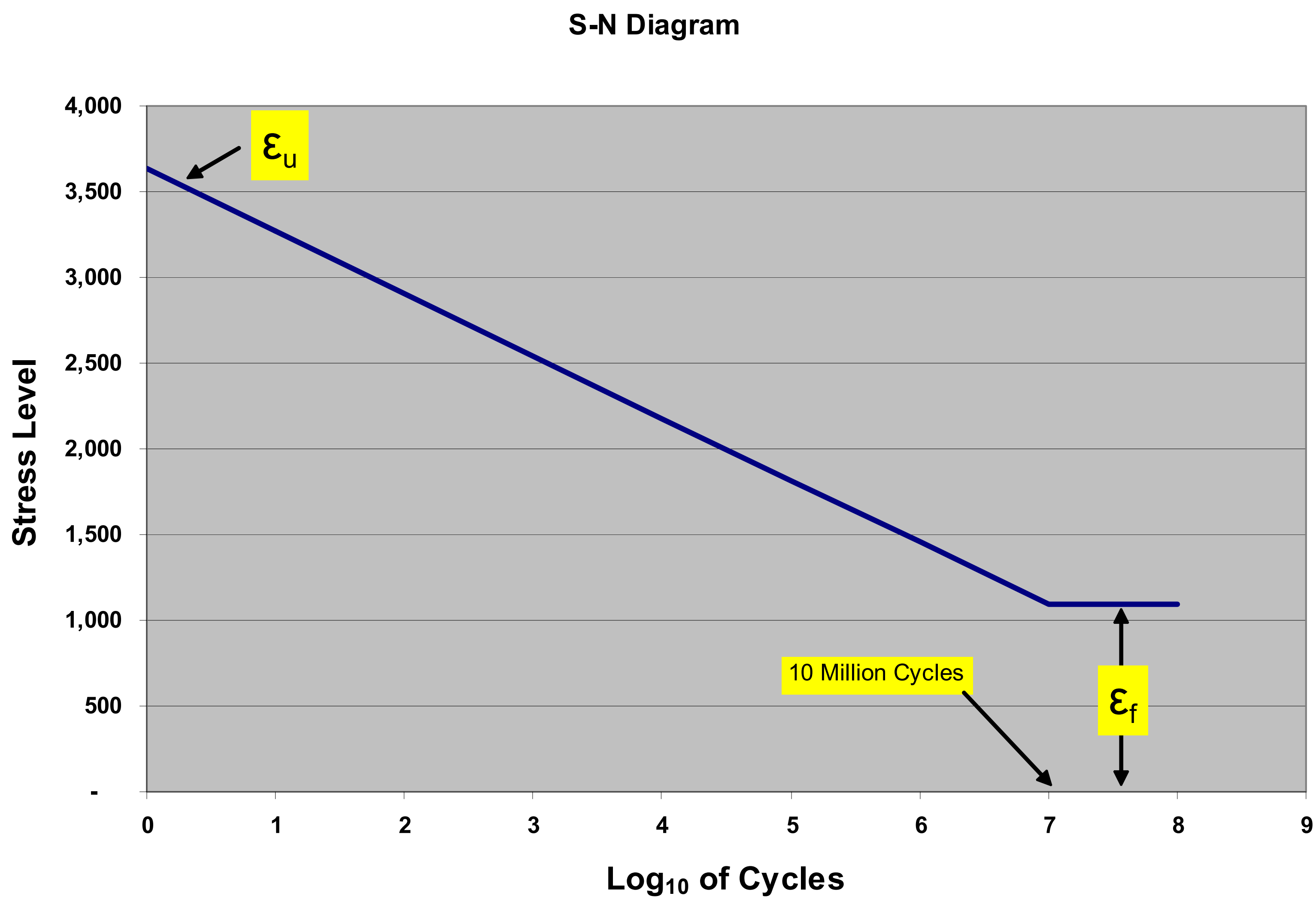

S-N Diagram
Stress Level
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
-
0
1
2
3
4
5
6
7
8
9
Log10 of Cycles
εu
εf
10 Million Cycles

Table G.7. Key Stress/Strain Values for WABTEC/SAB-WABCO Disc

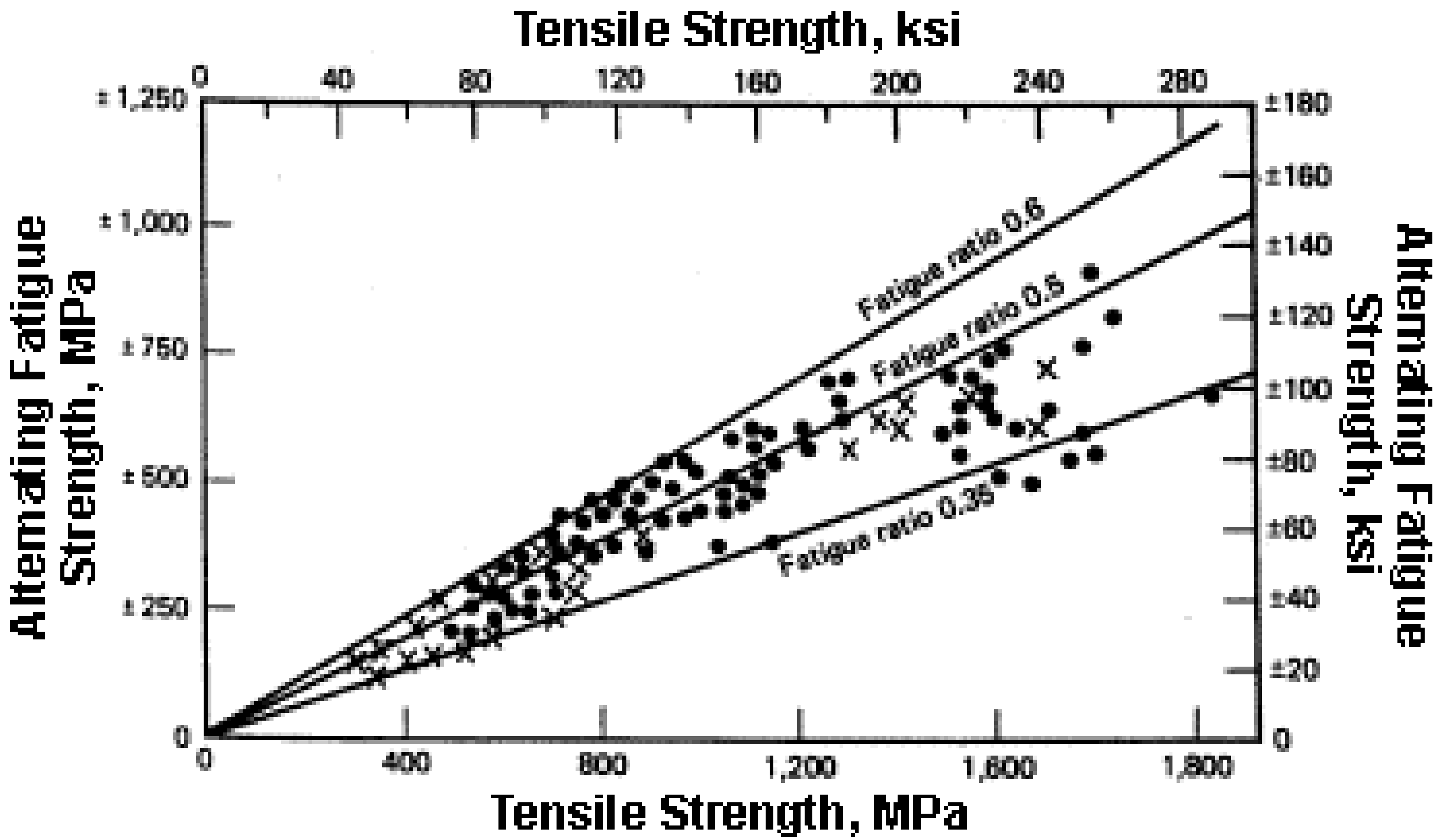
WABTEC/SAB-WABCO Disc					
Value	**Stress Mpa**	**Stress PSI**	**Compared to Ultimate**	**Micro-Strain**	**Source**
Young's Modulus	**210,345**	**30,500,000**			**Steel**
Ultimate Strength	**752**	**109,000**	**100%**	**3,574**	**SHTL**
Yield Strength	**550**	**79,750**	**73%**	**2,615**	**SHTL**
Endurance Limit	**226**	**32,700**	**30%**	**1,072**	**30% Ultimate**
Pre-Strain (press on)	**84**	**12,200**	**11%**	**400**	**see Appendix H**
Pre-Strain (as built)	**126**	**18,300**	**17%**	**600**	**see Appendix H**
Pre-Strain (Total New)	**210**	**30,500**	**28%**	**1,000**	**see Appendix H**
True Fracture Stress (European)	**1,232**	**178,689**	**164%**	**5,859**	**SHTL**
True Fracture Stress (USA)	**1,059**	**153,521**	**141%**	**5,033**	**SHTL**

Table G.8. Key Stress/Strain Values for Knorr Disc

Value	Stress (MPa)	Stress (PSI)	Comparison to "Ultimate"	Micro-Strain	Source
Young's Modulus	210,000	30,450,000	-	-	SWL
Ultimate Strength	1,050	152,250	100%	5,000	N10193
Yield Strength	900	130,500	86%	4,286	N10193
Endurance Limit	300	43,500	29%	1,429	SWL
Pre-Strain (Press On)	112	16,230	11%	533	see Appendix J

Provided by Knorr-Bremse

Typical Data



http://www.fatiguecalculator.com/

Other Factors May Lower Fatigue Ratio

- Environment
  - Water
  - Sea Water
- Corrosion Fatigue Effects
- Casting Irregularities

Environment

Metal Fatigue in Engineering
H.O. Fuchs and R.I. Stephens

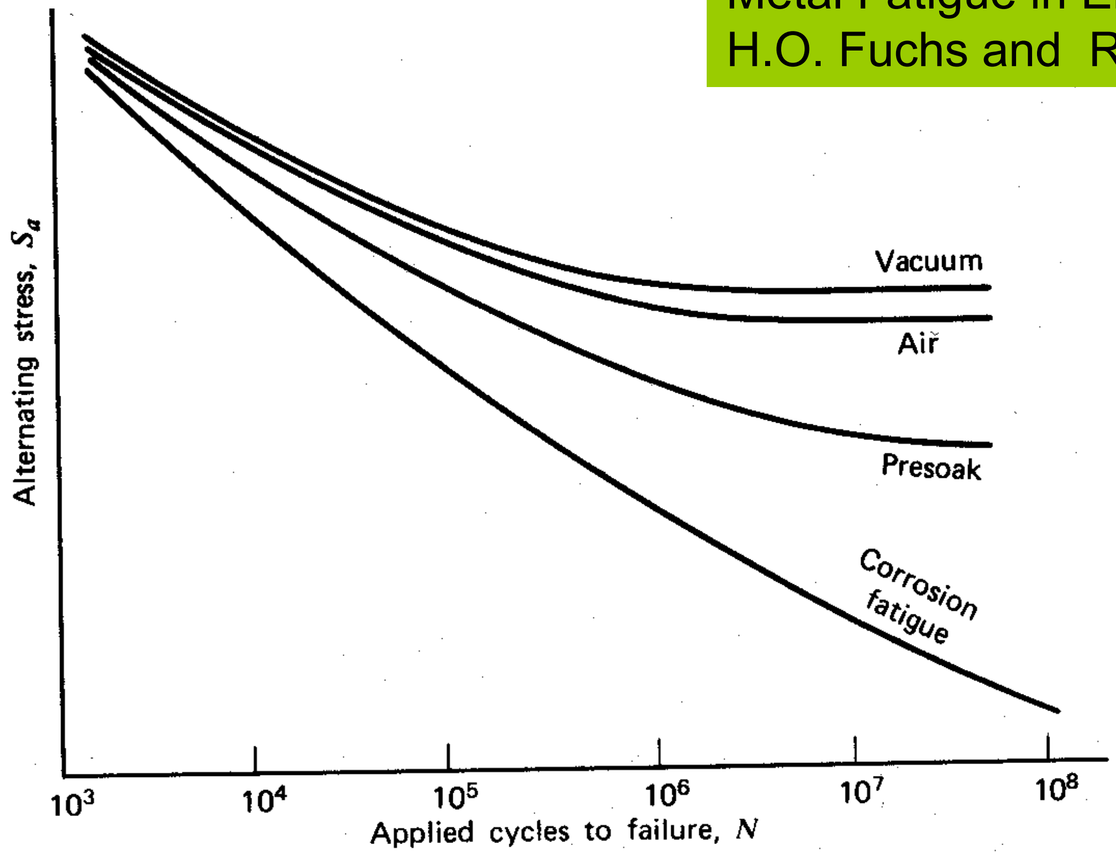


FIGURE 11.3 Relative fatigue behavior under various environmental conditions.

Combined Stress

- Load Conditions
  - S_a = Alternating Strain (zero-to-peak)
  - S_m= Mean Strain
- Material Properties
  - Su = Ultimate Strain
  - Sy = Ultimate Strain
  - Sf = Ultimate Strain
- Mean Stress has a substantial influence on fatigue behavior

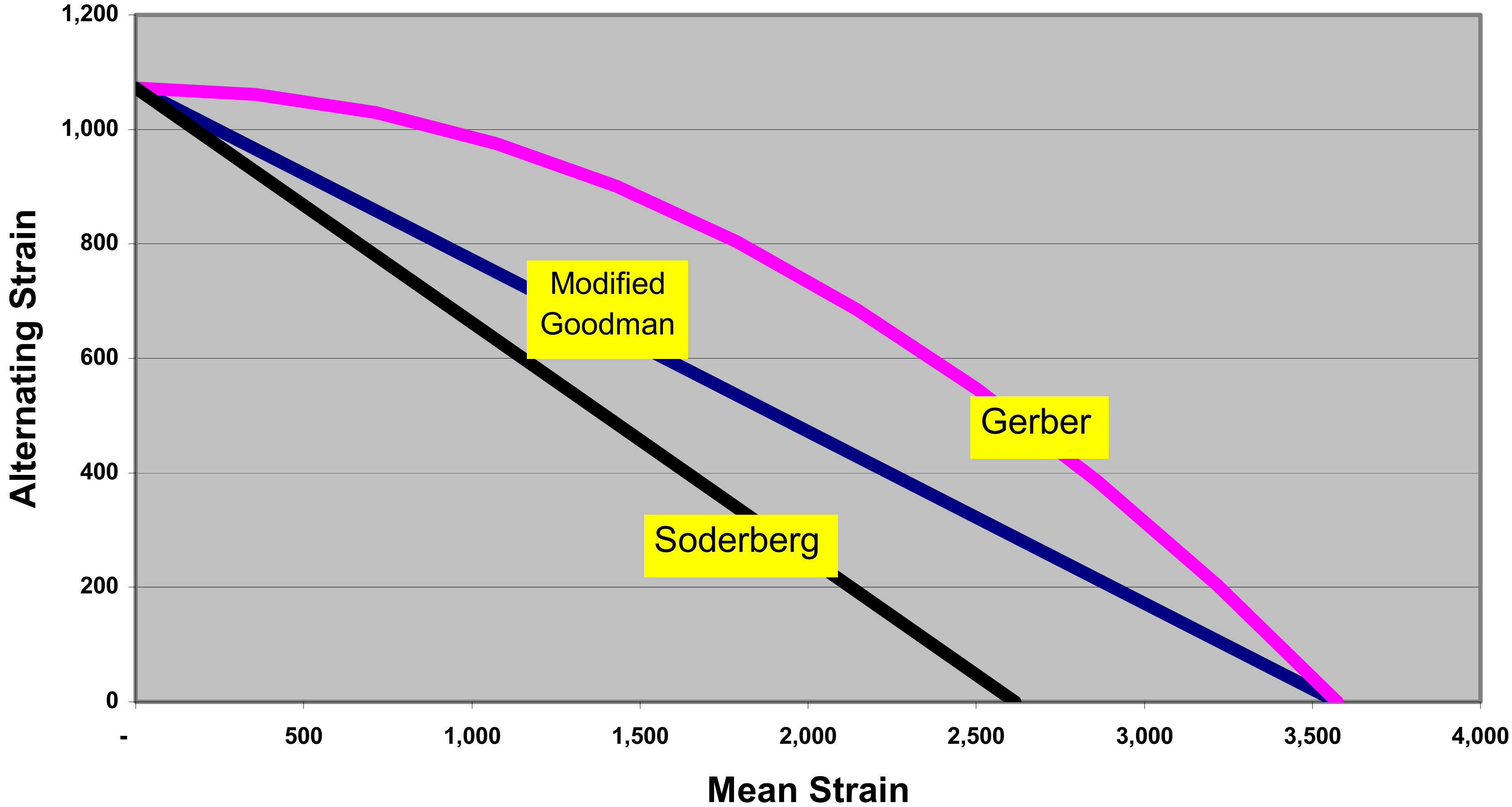
Mean Strain/Alternating Strain Models

- Modified Goodman $$\frac{S_a}{S_f} + \frac{S_m}{S_u} = 1$$

- Gerber $$\frac{S_a}{S_f} + \left(\frac{S_m}{S_u}\right)^2 = 1$$

- Soderberg $$\frac{S_a}{S_f} + \frac{S_m}{S_y} = 1$$

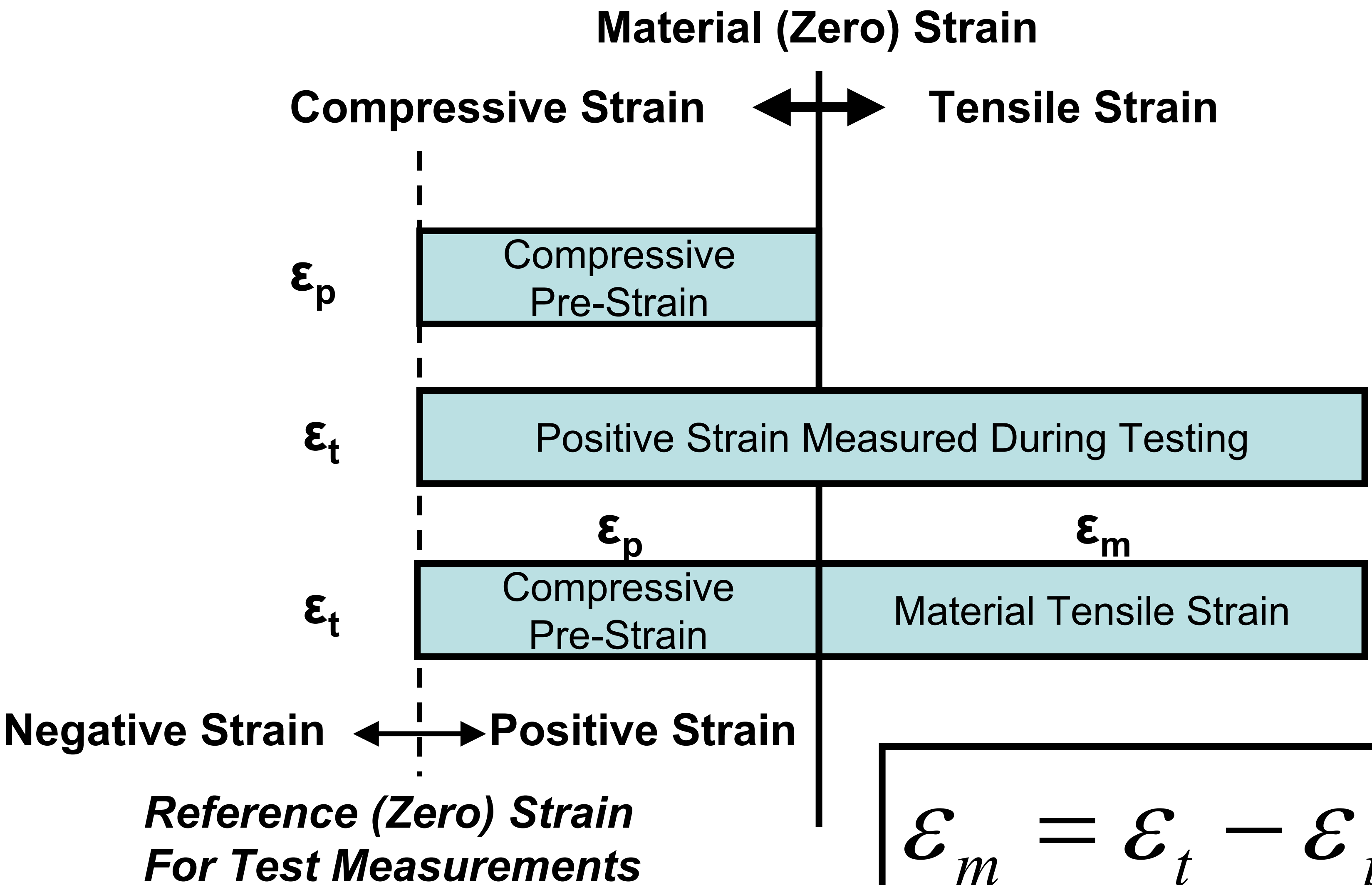
Combined and Alternating Strain



Strain In Spoke

- Pre-stress (Strain) Due To Manufacturing
- Pre-stress (Strain) Due To Hub Interference Fit
- Tensile Strain Due To Friction Ring Expansion
- Bending Out-Of-Plane Strain

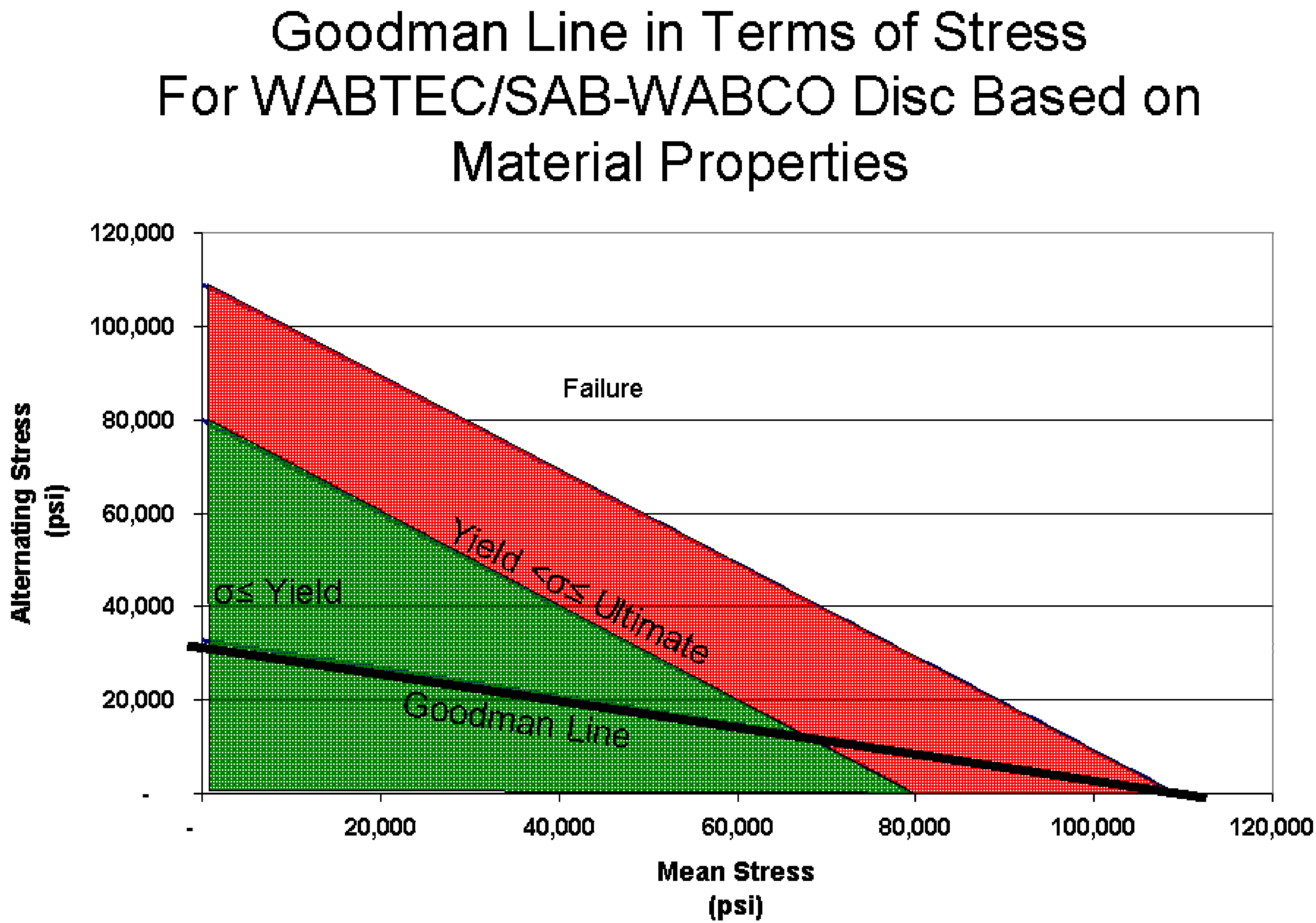
Compressive Pre-Strain Concept



$$\boxed{\varepsilon_m = \varepsilon_t - \varepsilon_p}$$

Mean And Alternating Strain

- A Fatigue Prospective Of The Test Data Requires Simultaneous Tabulation Of Mean Strain (Thermal Effect) And Alternating Strain (BOP)
- A Modified Goodman Line Based On Fatigue Limit Of 30% Ultimate Strain Was Used For This Exercise
- This Is Not Intended As A Fatigue Analysis When K Factors Would Be Required But An Exercise To Determine Where In The Data Significant Combinations Of Mean And Alternating Strains Occur
- The Mean (Tensile Strain) Must Account For The Pre-strain In The Spokes
- Based On Test Of Disc During Press-on Operations And Cutting Of Spokes On Disc Removed From Service, A Value Of 1,000 Micro-strain Is Used For The Pre-stress In The Spoke

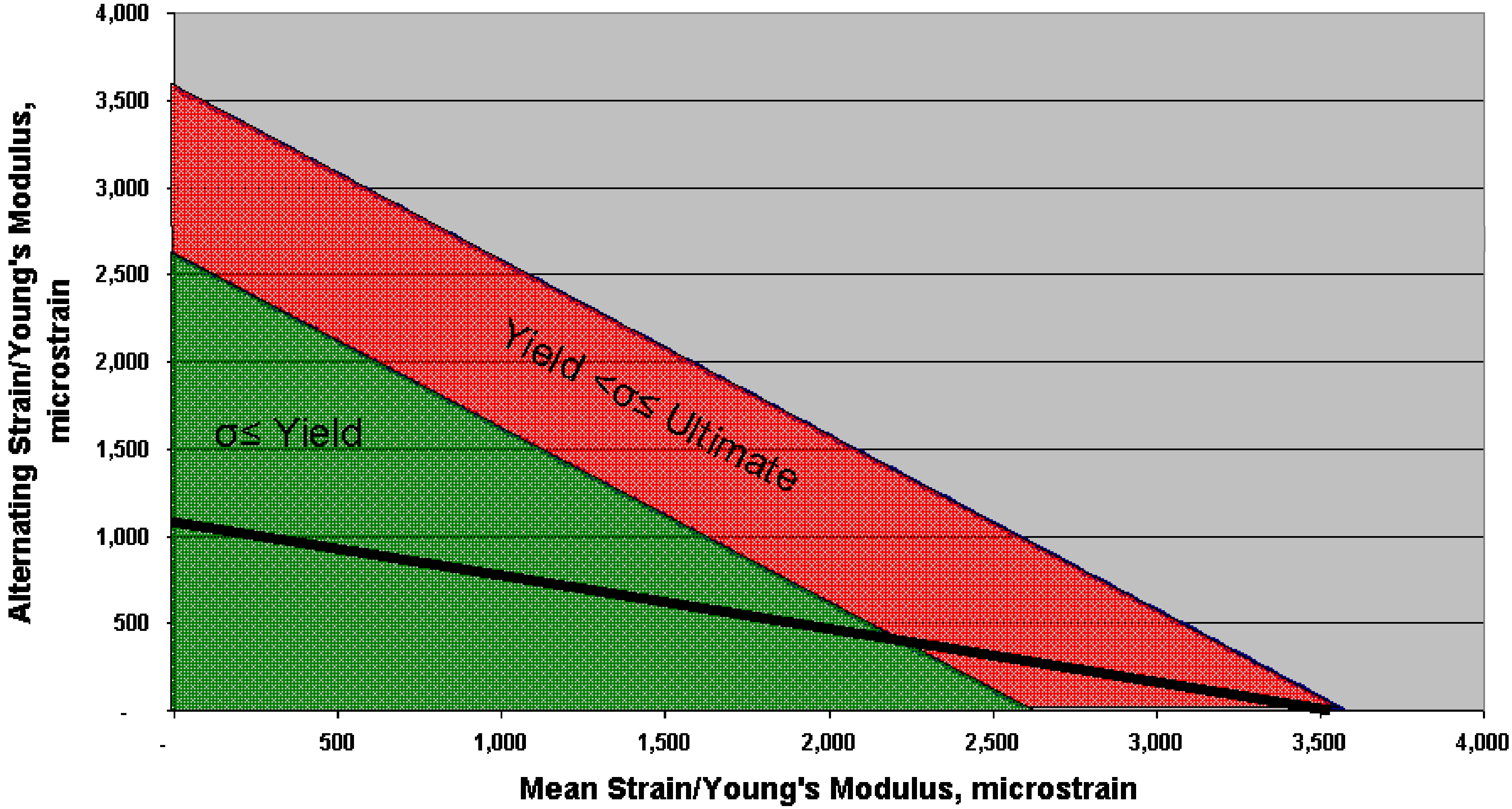


Goodman Line in Terms of Stress
For WABTEC/SAB-WABCO Disc Based on
Material Properties
120,000
100,000
80,000
60,000
40,000
20,000
-
Alternating Stress
(psi)
Failure
Yield <σ≤ Ultimate
σ≤ Yield
Goodman Line
-
20,000
40,000
60,000
80,000
100,000
120,000
Mean Stress
(psi)

Transform The “Goodman Plot” From Stress to Strain

- Formulated Goodman Line In Terms Of Stress
- Transform To Strain By Dividing By Young’s Modulus, E
- Indicated Where The Linear Stress-Strain Relationship Exists In The Mean Versus Alternating Plane; Denoted by Green on Plots
- Indicated Where The Non-Linear Relationship Exists In The Mean Versus Alternating Plane (In Excess of Yield Stress, But Less than ultimate Stress); Denoted by Red on Plots

Goodman Line in Terms of Strain For WABTEC/SAB-WABCO Disc Based on Material Properties



Checked on Test Data

- After The Data Was Processed, Checked That All Data Points Fell In The “Green Zone” (Area of Linear Stress-Strain Relationship).
- Only Cases That Approached “Red Zone” Were Those Where Vertical Impact Observed During Brake Application Where High Mean Strain Due to Heating of Disc Observed.

A Counting Method

- Calculate Mean Strain Minus 1000 Micro Strain
- Calculate BOP Strain Required To Be Above Or Near Goodman Line
- Calculate BOP Strain
- Check If BOP Strain Is Near The Goodman Line
- If Yes, Calculate Cycles And Time Duration
- Record Mean Strain, Alternating Strain, Brake Pressure, Number Of Cycles And Time Duration

Table G.9. Count of Cycles Near Limits

Goodman Plots Cycles

		WABTEC/SAB-WABCO Disc Axle 1								Knorr Disc Axle 2	
		Center Disc				Outer Disc				Center Disc	
		Spoke 3		Spoke 6		Spoke 3		Spoke 6		Spoke 6	
	Date	NB	B	NB	B	NB	B	NB	B	NB	B
Phase 1	16-May	n/a	n/a	4.5	0	n/a	n/a	5.5	0	n/a	n/a
	17-May	n/a	n/a	11.5	55	n/a	n/a	1	0	n/a	n/a
Phase 2	26-May	12	14	9	20	n/a	n/a	n/a	n/a	n/a	n/a
	27-May	6.5	0	10.5	0	n/a	n/a	n/a	n/a	n/a	n/a
Phase 3	17-Jun	2	2754	5	3156.5	n/a	n/a	n/a	n/a	0	0
	18-Jun	5	7074	6	6947	n/a	n/a	n/a	n/a	0	0

n/a Test Plan did not include this measurement

B Braking

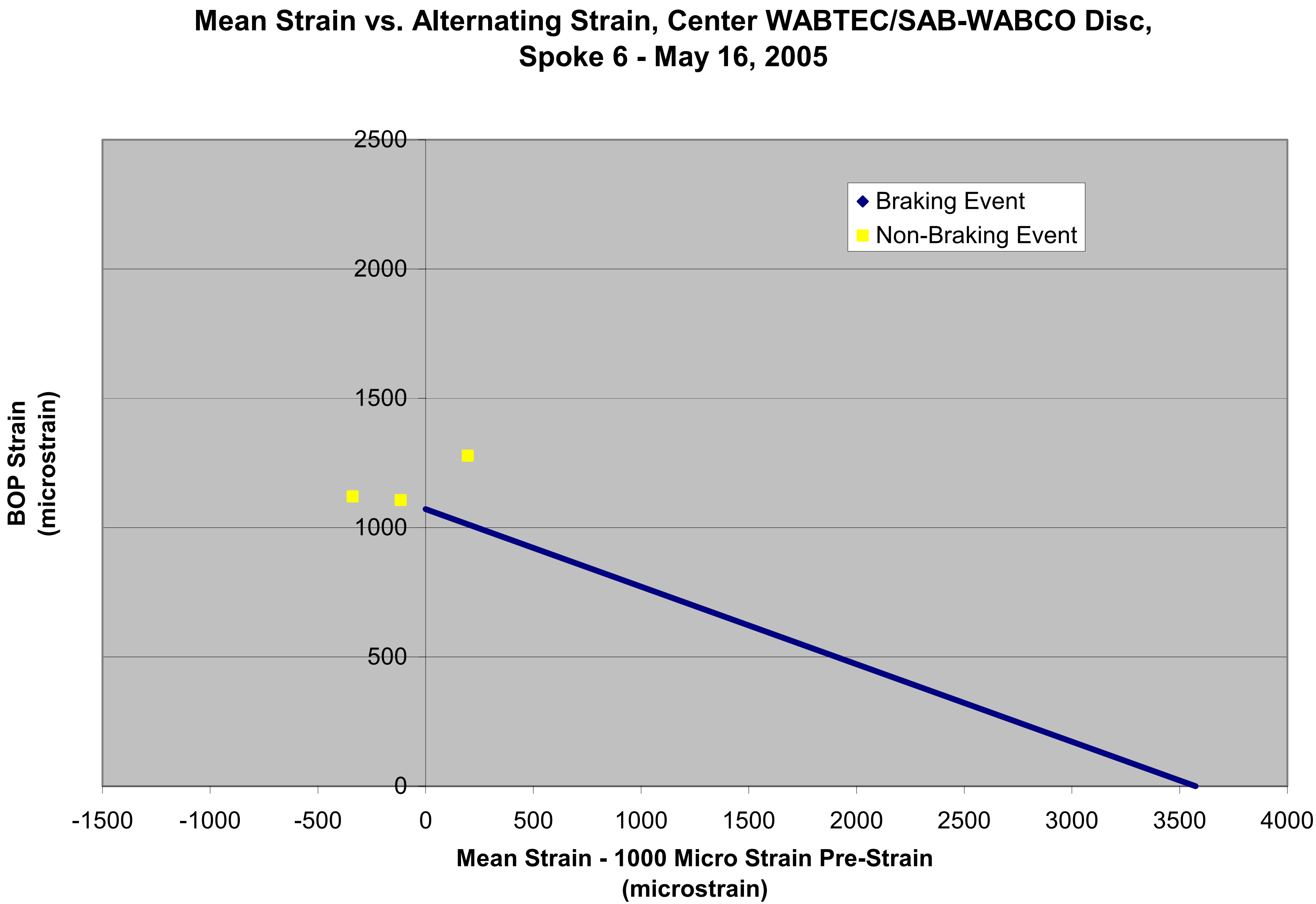
NB Not Braking

Figures Included

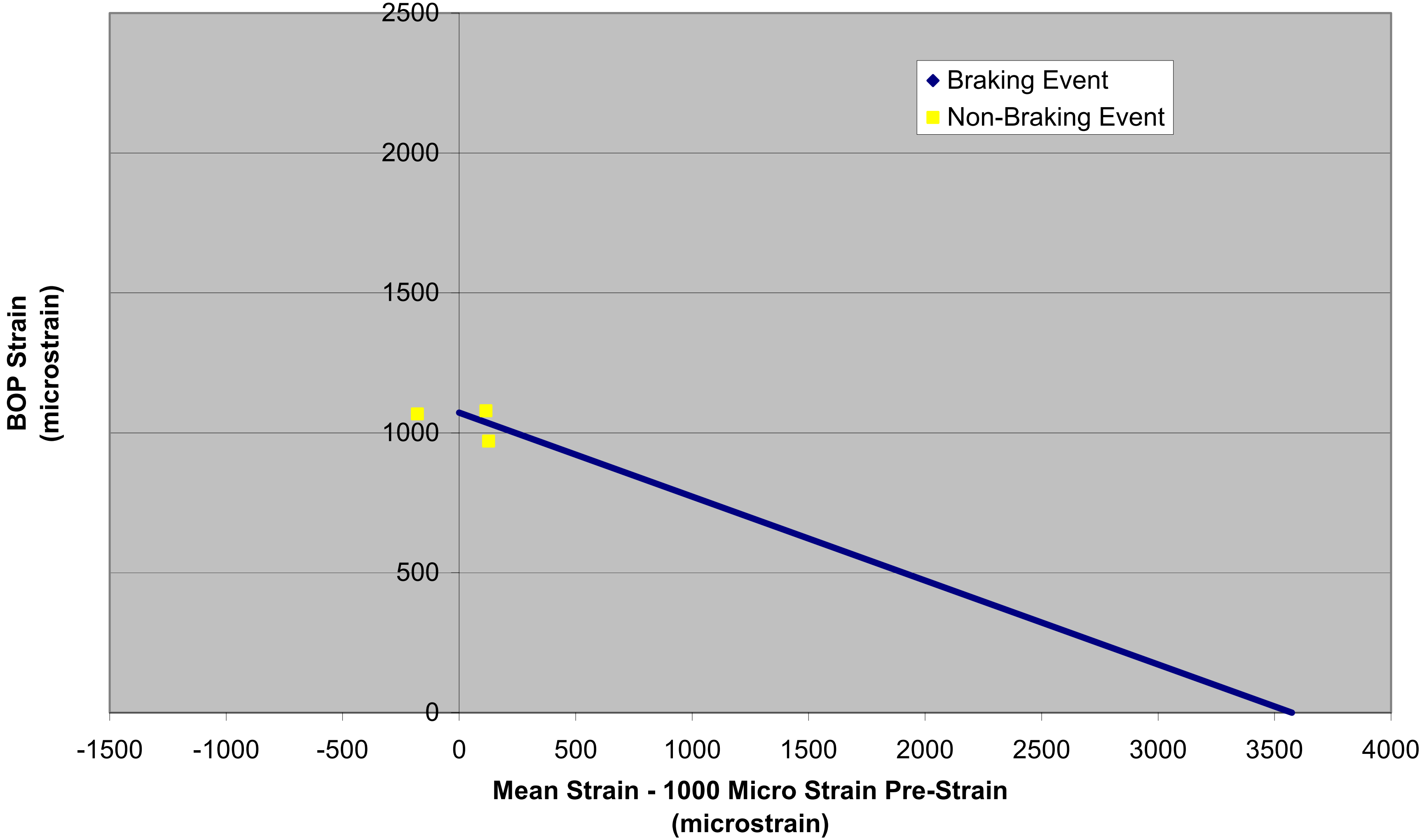
- Phase 1
  - Center Disc Spoke 6
  - Outer Disc Spoke 6
- Phase 2
  - Center Disc Spoke 6
  - Outer Disc Spoke 6
  - Center Disc Spoke 3
  - Outer Disc Spoke 3
- Phase 3
  - Center Disc Spoke 6
  - Outer Disc Spoke 6
  - Center Disc Spoke 3
  - Outer Disc Spoke 3

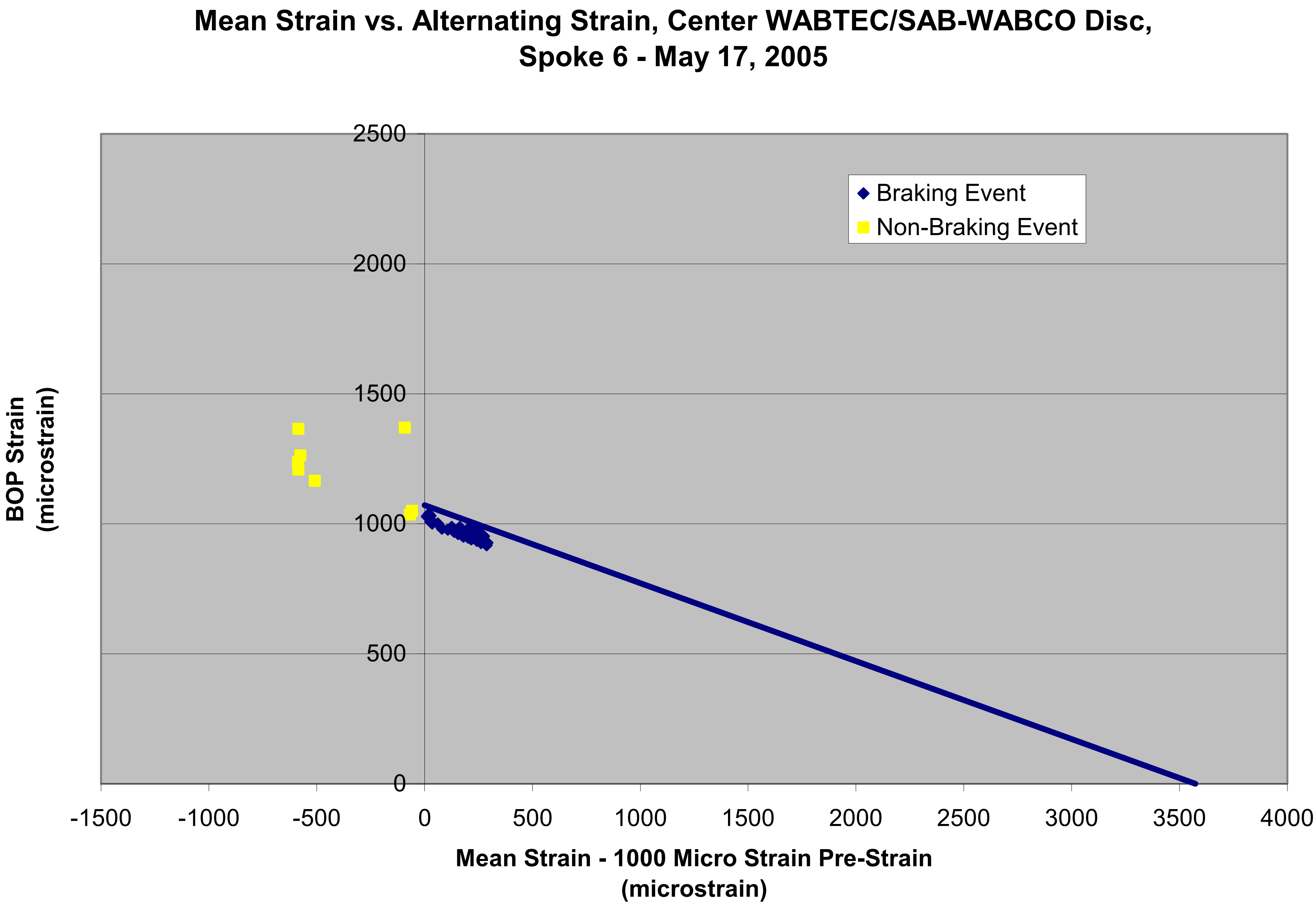
Note:

- These figures are based on occurrences of combinations of BOP and mean strains that approach the Goodman line used in the analysis
- A single point in the figures may represent a single cycle or many cycles
- The above table shows the cumulative number of cycles


Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc,
Spoke 6 - May 16, 2005
BOP Strain
(microstrain)
2500
2000
1500
1000
500
0
Braking Event
Non-Braking Event
-1500
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000
Mean Strain - 1000 Micro Strain Pre-Strain
(microstrain)

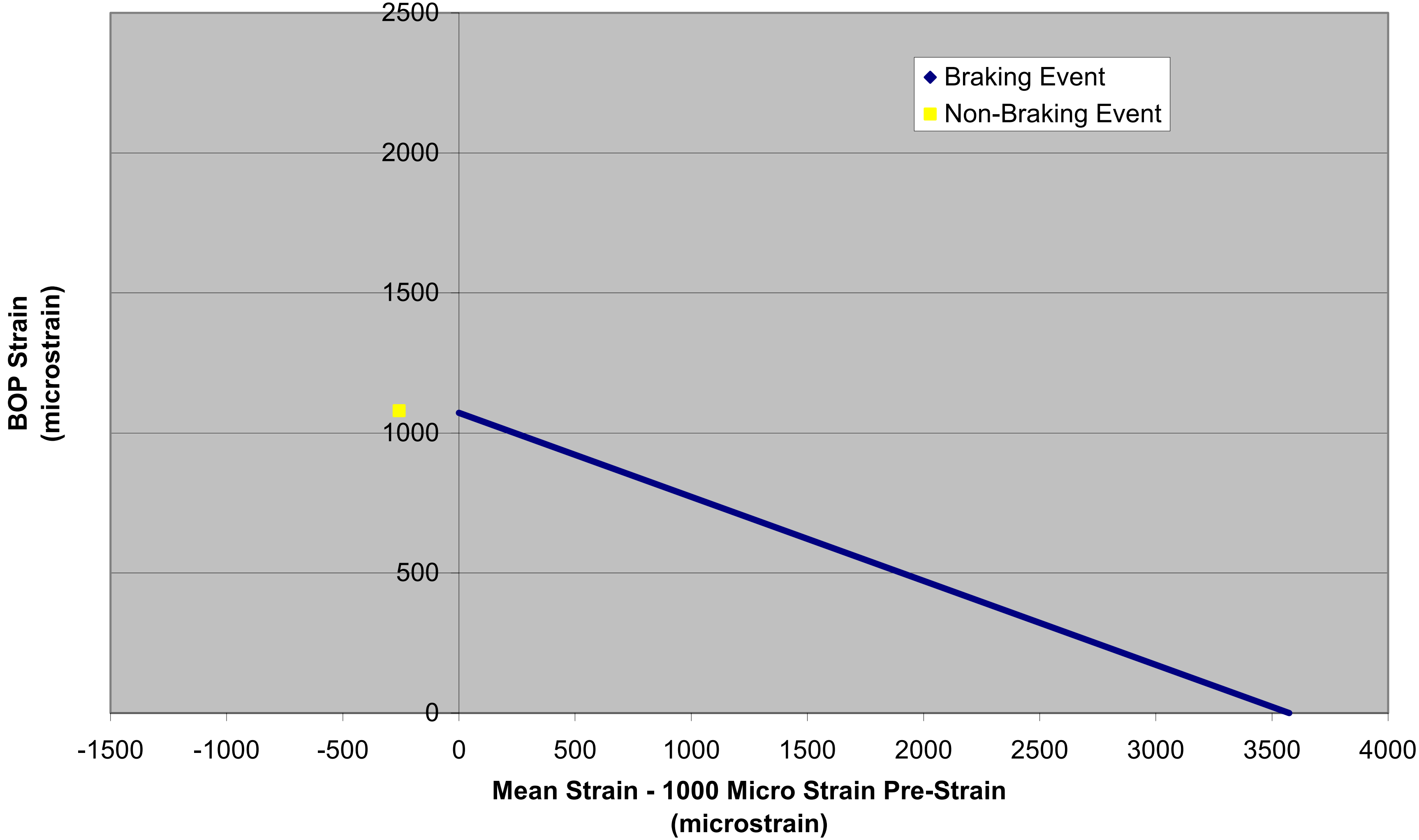
Mean Strain vs. Alternating Strain, Outer WABTEC/SAB-WABCO Disc, Spoke 6 - May 16, 2005



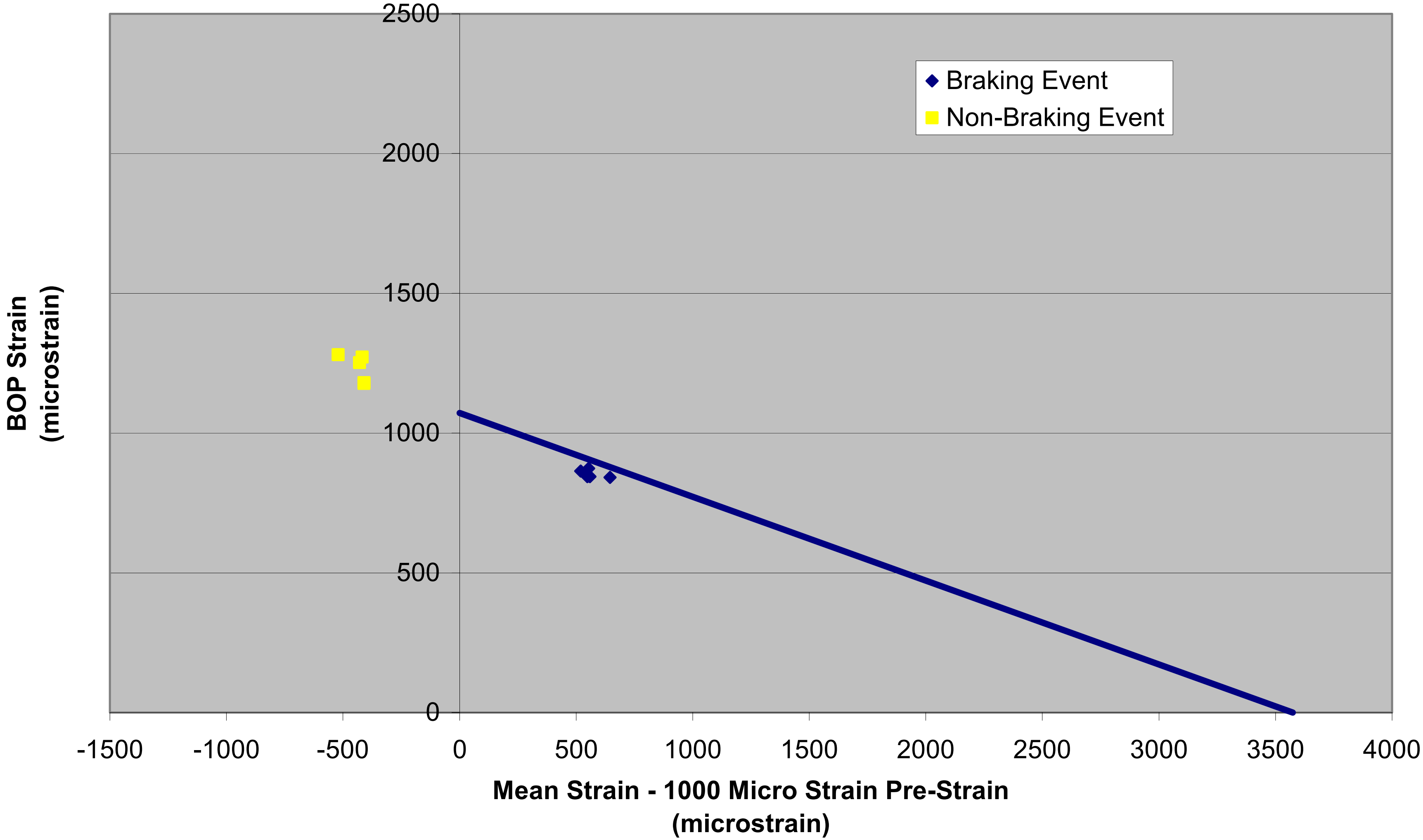


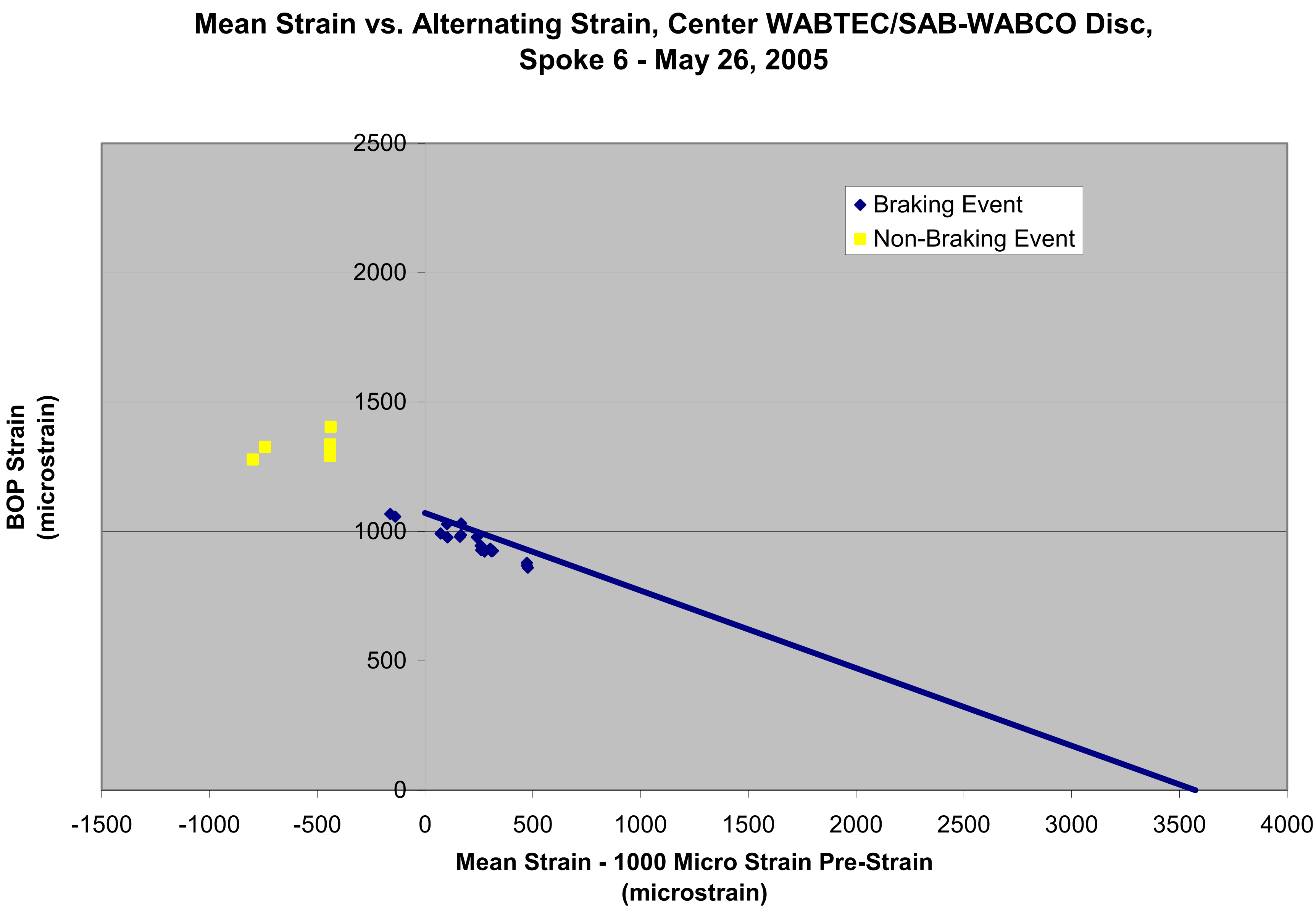
Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc,
Spoke 6 - May 17, 2005
Braking Event
Non-Braking Event
BOP Strain
(microstrain)
2500
2000
1500
1000
500
0
-1500
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000
Mean Strain - 1000 Micro Strain Pre-Strain
(microstrain)

Mean Strain vs. Alternating Strain, Outer WABTEC/SAB-WABCO Disc, Spoke 6 - May 17, 2005

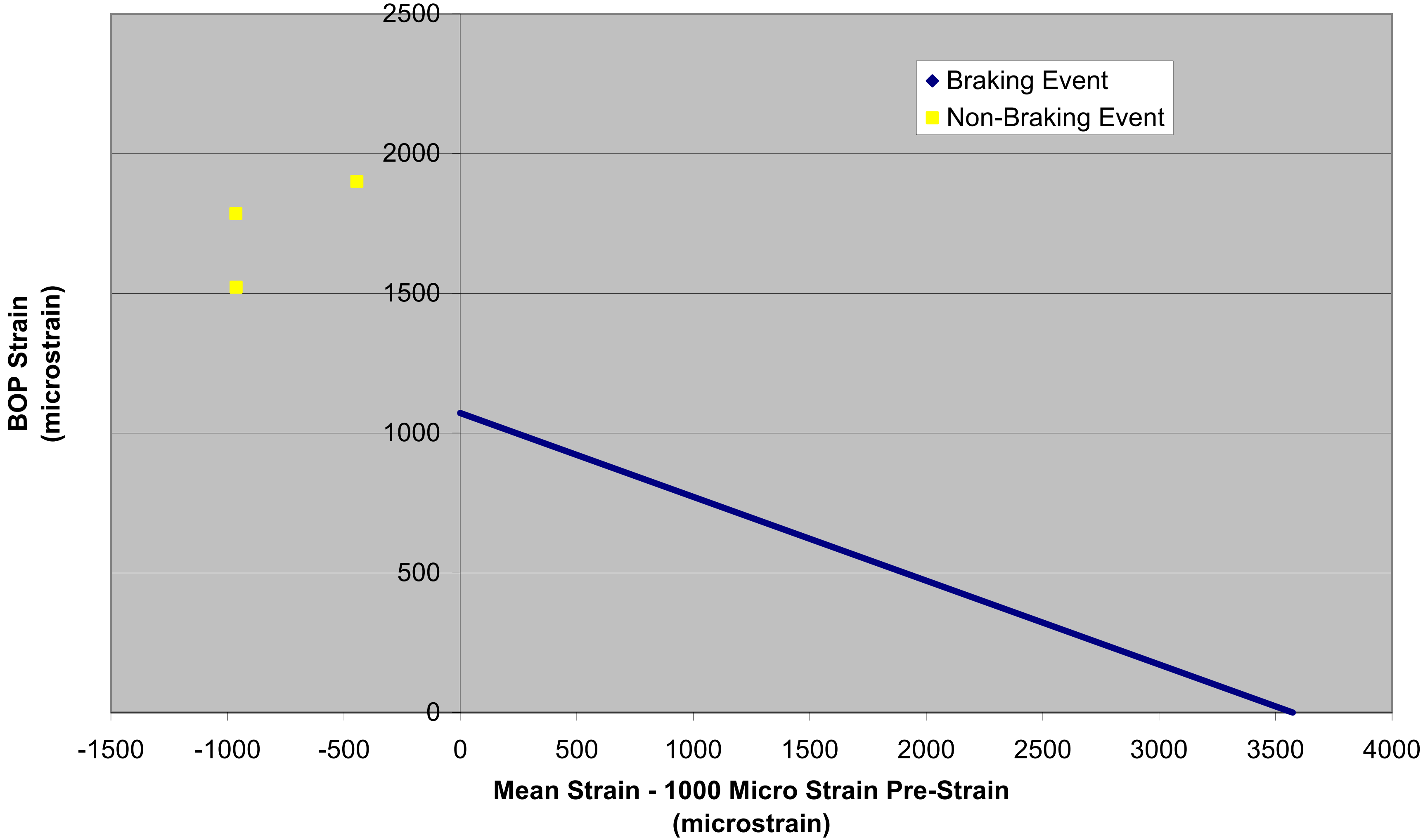


Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc, Spoke 3 - May 26, 2005

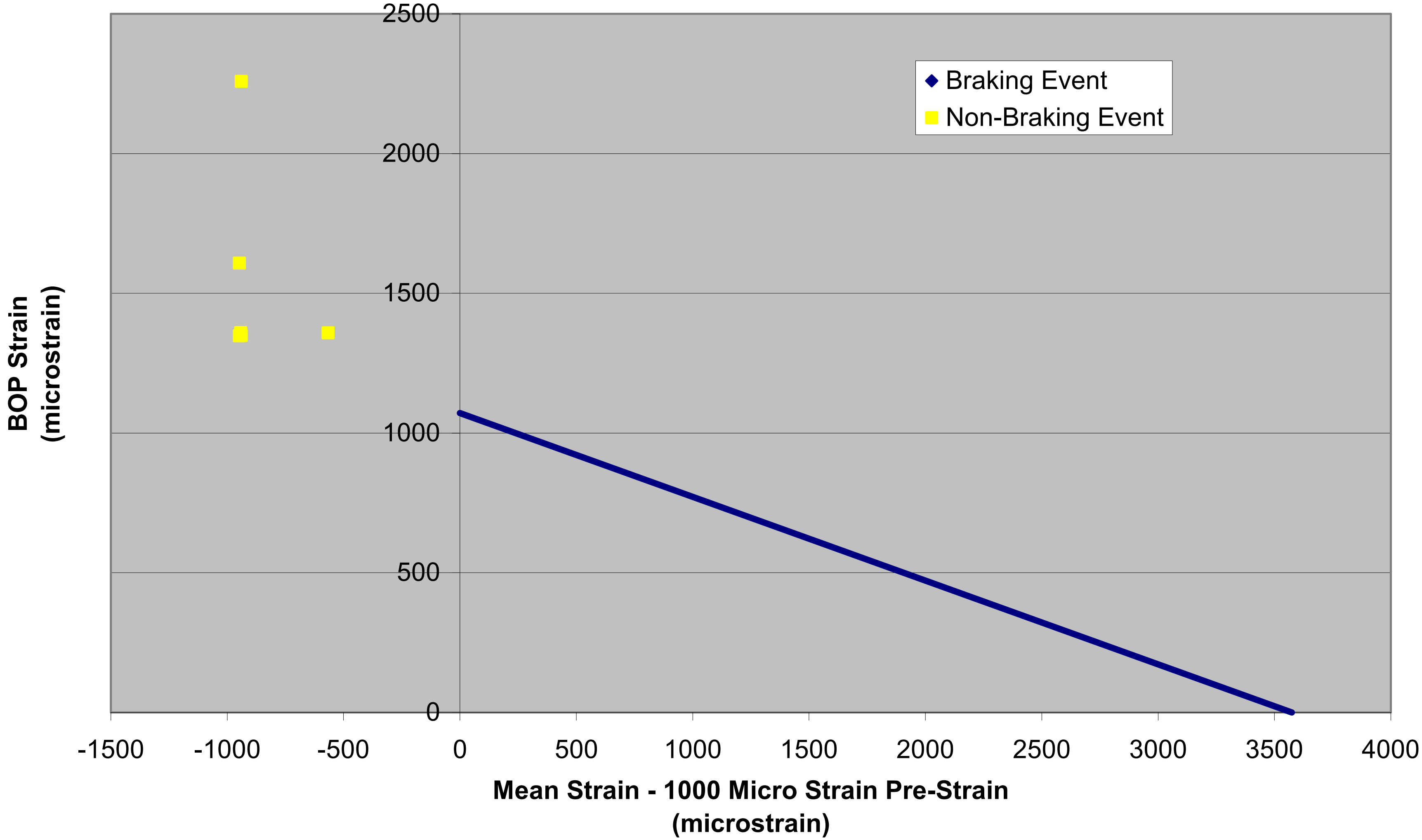


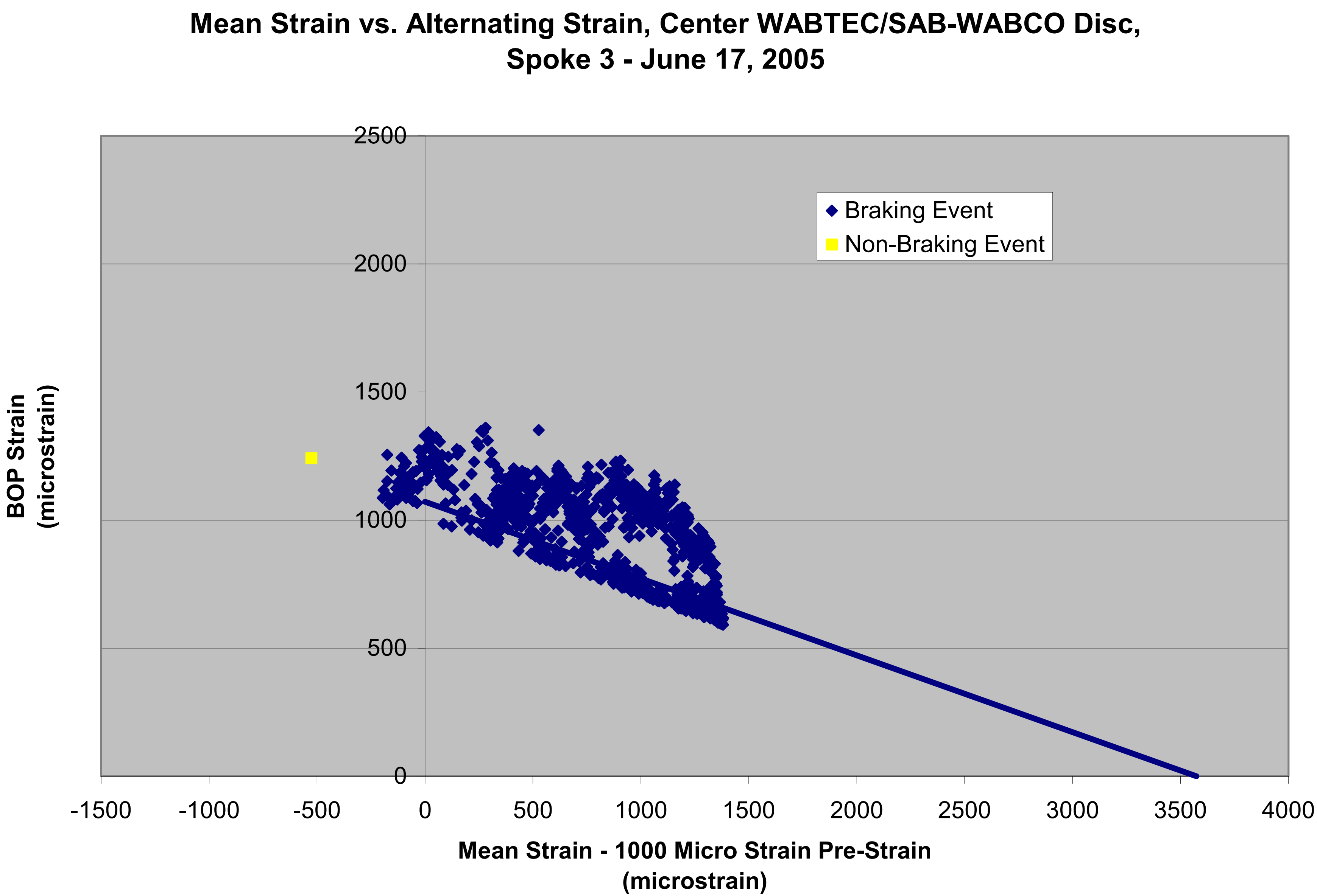

Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc, Spoke 6 - May 26, 2005
BOP Strain (microstrain)
Mean Strain - 1000 Micro Strain Pre-Strain (microstrain)
Braking Event
Non-Braking Event
2500
2000
1500
1000
500
0
-1500
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000

Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc, Spoke 3 - May 27, 2005

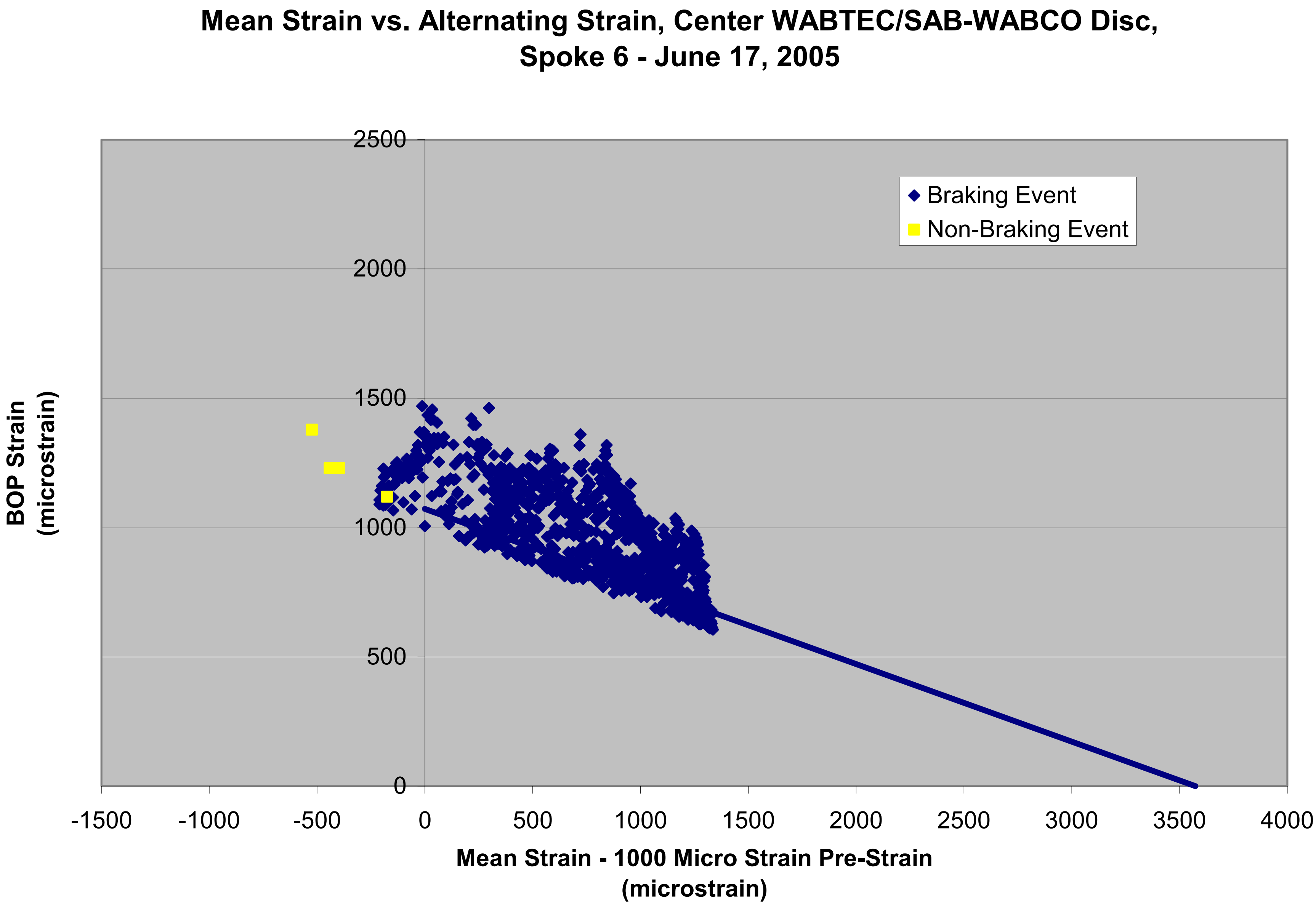


Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc, Spoke 6 - May 27, 2005

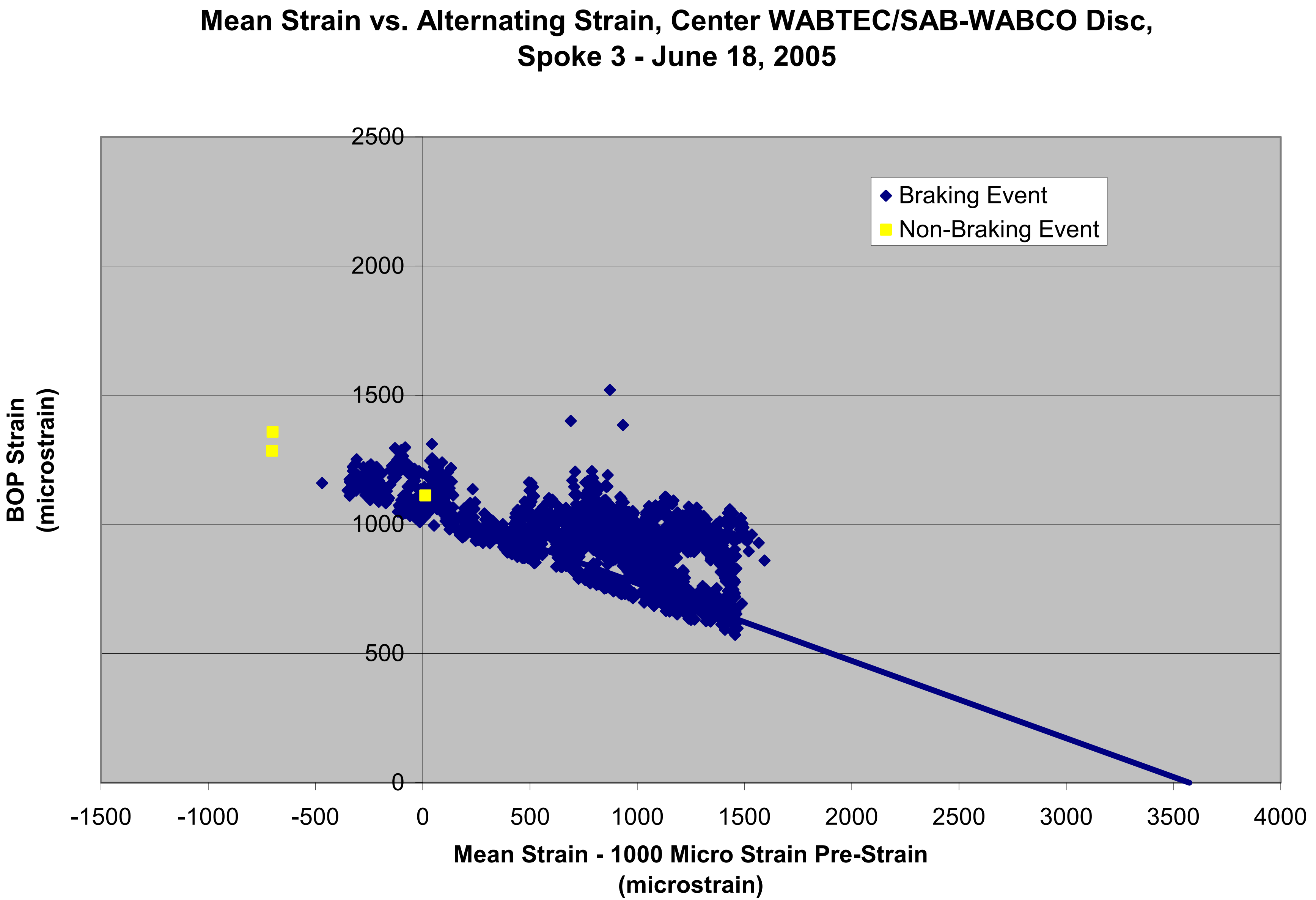




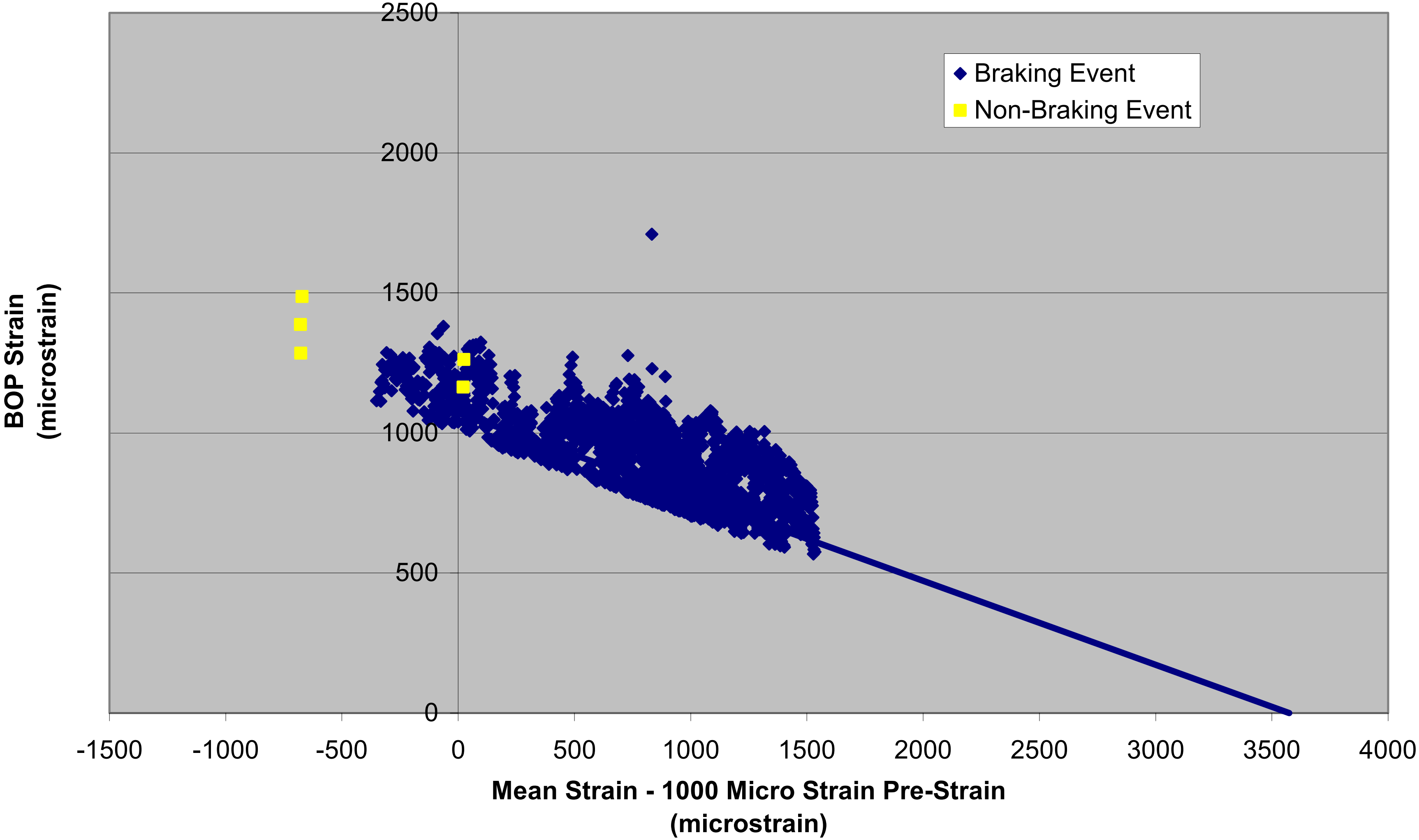
Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc,
Spoke 3 - June 17, 2005
Braking Event
Non-Braking Event
BOP Strain
(microstrain)
2500
2000
1500
1000
500
0
-1500
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000
Mean Strain - 1000 Micro Strain Pre-Strain
(microstrain)



Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc,
Spoke 6 - June 17, 2005
BOP Strain
(microstrain)
2500
2000
1500
1000
500
0
Braking Event
Non-Braking Event
-1500
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000
Mean Strain - 1000 Micro Strain Pre-Strain
(microstrain)


Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc,
Spoke 3 - June 18, 2005
Braking Event
Non-Braking Event
BOP Strain
(microstrain)
0
500
1000
1500
2000
2500
-1500
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000
Mean Strain - 1000 Micro Strain Pre-Strain
(microstrain)

Mean Strain vs. Alternating Strain, Center WABTEC/SAB-WABCO Disc, Spoke 6 - June 18, 2005



Knorr Disc

- In No Case Did The Knorr Disc Have A Combination Of Mean Strain And BOP Microstrain Levels That Meets The Level Of The Analysis Approach
- This Included Non Braking And Braking Events

Summary

- Thermal Strains Build-up Quickly, But Have A Long Decay (Time Constant Of 7 Minutes Or More) – Levels Up To 2,500 Micro Strain
- Sustained BOP Vibration In Braking Produces Largest Strain Observed In Test At ~187 Hz (Only Observed In Lead Axle Cases)
- Caliper Participates In This Vibration
- Shorter Bursts Of BOP Vibration Occur Throughout Testing And May Be Related To Vertical Acceleration Of Wheelset
- Vertical Acceleration On Bearing About 3 Times Lateral Acceleration
- BOP Strain Can Have Amplitudes Of 1,500 Micro strain
- Combined Tensile And BOP Strain Can Be In The Range Of 2,700 (TBR) Micro strain Tension Taking Into Account 1,000 Micro strain Pre Strain
- Yielding Occurs At 2,850 Micro strain (Based On Amtrak Provided Laboratory Test Results)
- The Pre-stress Levels Were Examined For 2 WABTEC/SAB-WABCO Disc (Small Sample) And One Knorr Disc During Press On