APPENDIX J

Laboratory Testing

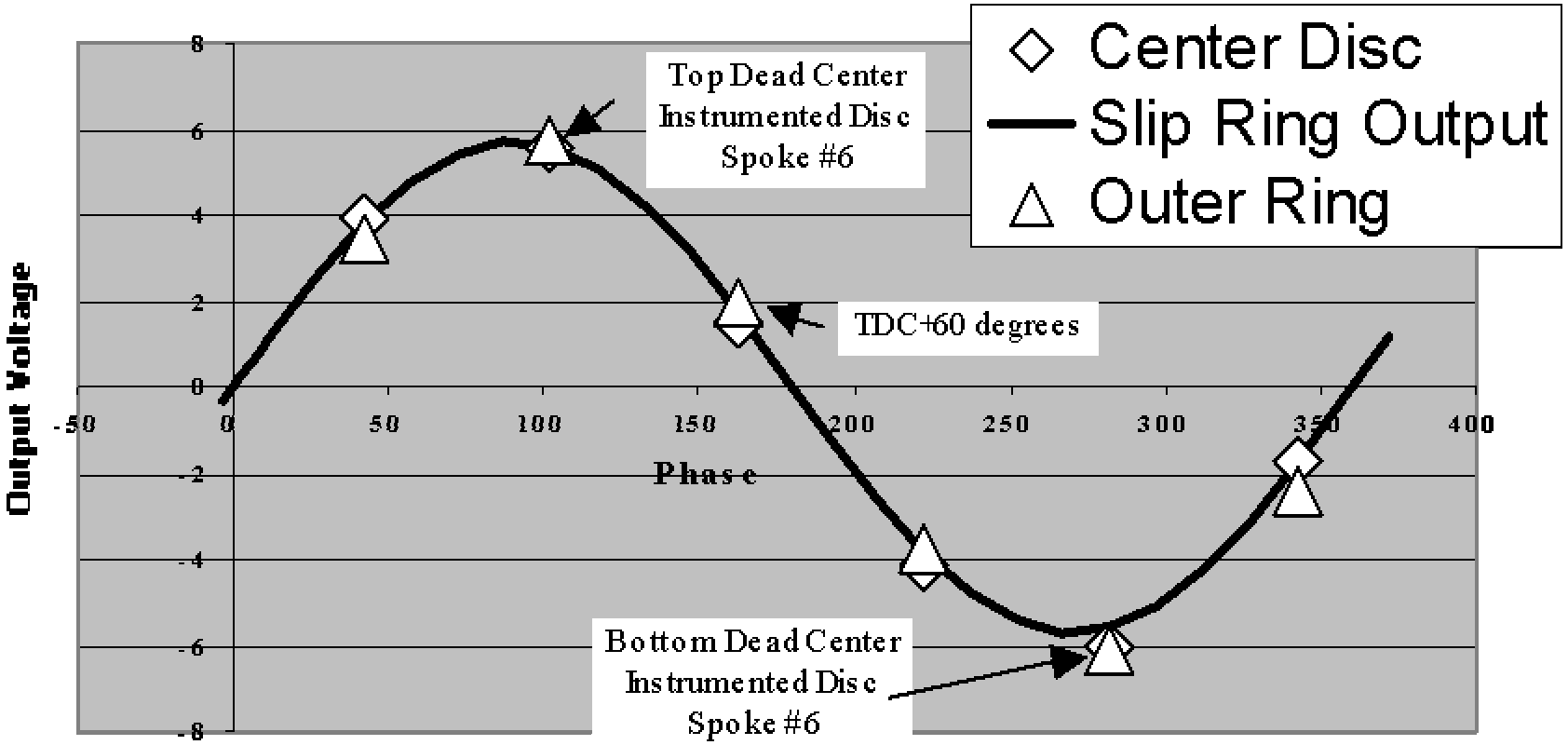
Appendix J
Part A

Resolver Synchronization and Spreader Bar Test

Resolver Synchronization

- Rotate axle in defined direction
- Record Slip Ring resolver sine wave output
- Record spoke position
- Use resolver sine wave to determine angular position of instrumented spoke when BOP strain is near zero and when BOP strain has large amplitude to identify plane

Instrumented Spoke Phase Based on Wheel Position



Spreader Bar Test

- Place hydraulic ram and load cell between the center brake disc and the outer brake disc at the outer circumference of the discs.
- Apply a spreading force normal to the discs in turn at a radial position in line with each spoke of the center disc, and in line with each spoke of the outer disc.
- Record strain from each spoke for each spreading force application.

Force Applied at the Outer Perimeter of the Disc Friction Ring: 5.75 inches out from the inner radius of the friction ring
8 3/8 inches out from the hub
Force Applied Between the Center Disc and the Outer Disc in each case

Center Disc		Strains Measured on Center Disc Spoke				Strains Measured on Outer Disc Spoke			
Spoke at which Force Applied	Force Applied [lb]	Strain F1	Strain F2	Strain R1	Strain R2	Strai n F1	Strain F2	Strain R1	Strain R2
6	-400	-10.4	-7.2	-73.5	56.3	-7.7	-12.3	53.2	-53.4
6	-504	-10.5	-7.1	-89.3	72.4	-7.9	-12.6	67.7	-65.5
1	-505	-9	-11.9	-53.9	30.8	-6.9	-12.8	38.5	-45.2
2	-510	-13.5	-11.6	-12.9	-13.4	-8.9	-14.2	-12.4	-10.1
3	-502	-10.6	-12	23	-48	-5.8	-13.5	-40.3	16.2
4	-503	-13.2	-8	-1.2	-22.4	-6.9	-10.3	-27.6	2.2
5	-504	-11.7	-4.9	-53.8	32.5	-9.4	-9.6	23.8	-33.6
6	-508	-8.6	-5.9	-89.1	74.1	-5.1	-9	67.1	-64.1

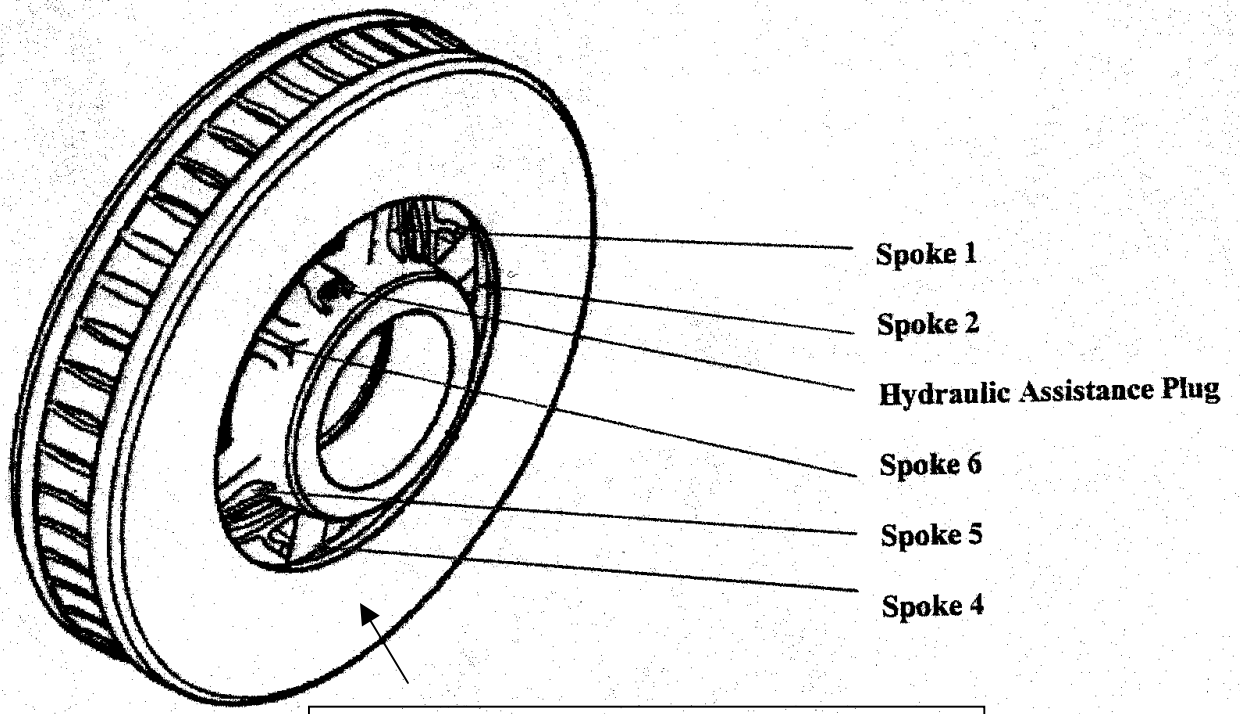
Appendix J
Part B

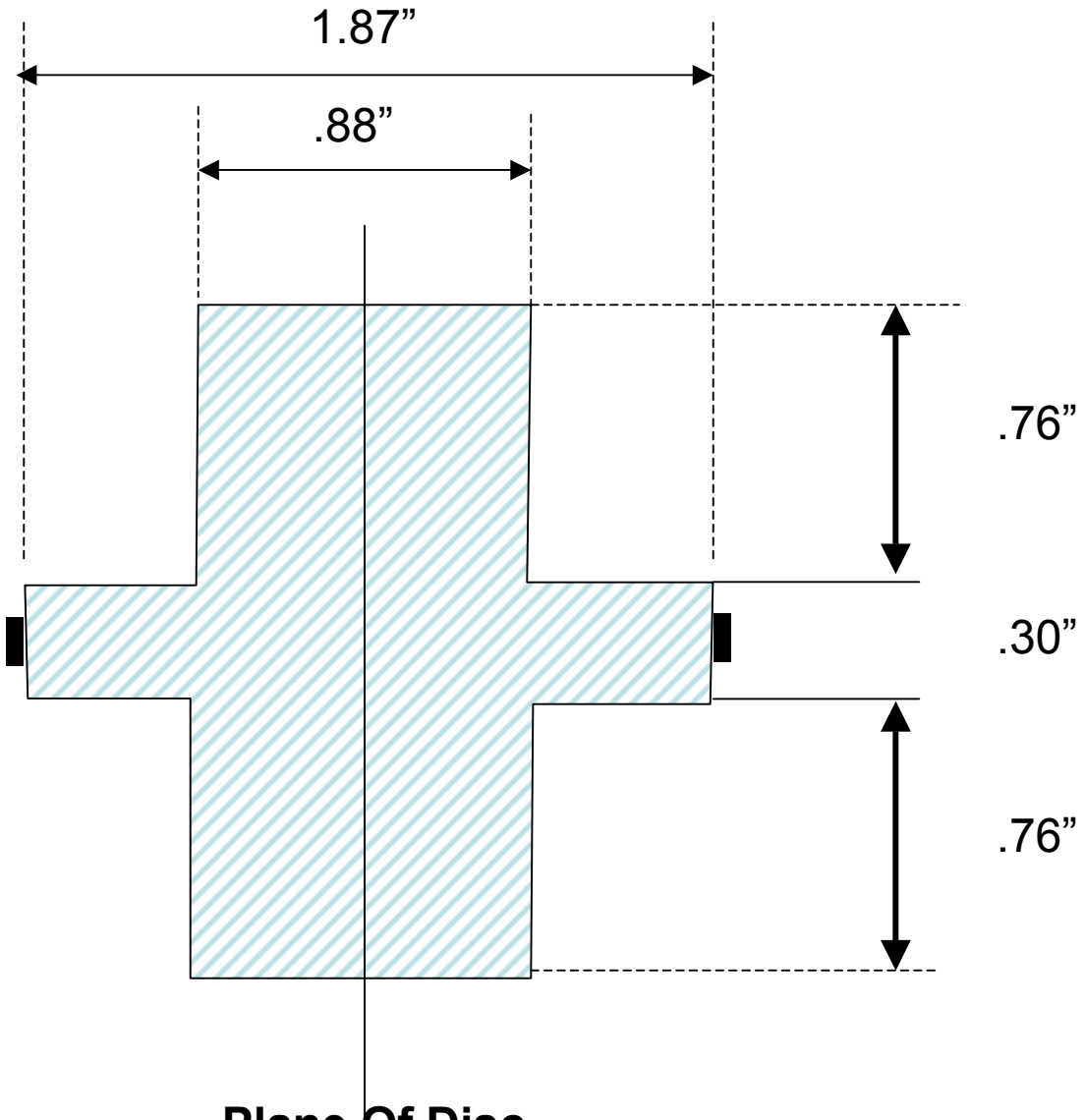
Residual Strains

Residual Strain Tests

- Performed By Mike Tomas (AMTRAK)
- Three Discs Examined
  1. WABTEC/SAB-WABCO Disc After Press Off Operation and After Spokes Cut
  2. Knorr Disc After Press On Operation
  3. WABTEC/SAB-WABCO Disc with Two (2) Cracked Spokes After Spokes Cut
- Strain Gages On Spokes In The R1 And R2 Positions

Spoke Naming Convention





WABTEC/SAB-WABCO Disc

J-Part B-4

Table J.B.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

Disc 1 WABTEC/SAB-WABCO

- Interference Fit Parameters
  - Allowable .009 to .012”
  - Press Force 27 to 84 Tons

- Disc 1
  - Interference Fit .0097”
  - Press Force 54 Tons

Information from Volpe

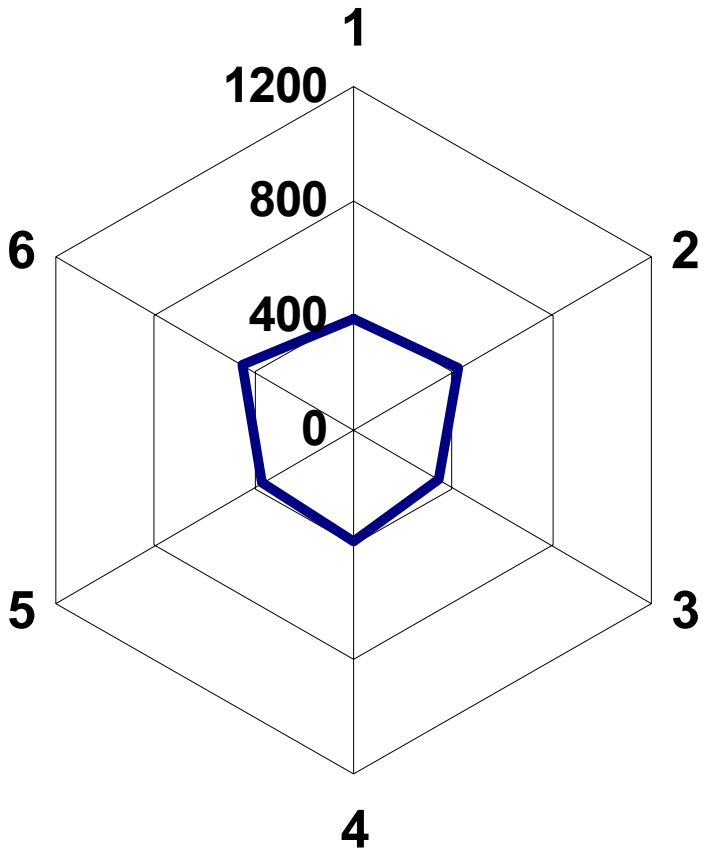
Key Values

- $E=30.5\ 10^6$ psi
- Cross Sectional Area Of Spoke At Strain Gage Location 1.9 in^2
- Negative Strains Indicate A Reduction In Compressive Pre-Strain

Table J.B.2. WABTEC/SAB-WABCO Disc 1 Pre-Strain, Disc Removal

WABTEC/SAB-WABCO Disc - Good condition with approximately 1,500 to 2,000 miles service. Disc removed from axle 4 on car 3534, May 28, 2005. Press off operation.					
	Nut side	Other-side			
Spoke	Resultant Strain		Resultant Average Strain	Resultant Bending Strain	Estimate Force in Spoke (kips)
1	-330	-436	-383	53	22.2
2	-356	-480	-418	62	24.2
3	-400	-295	-348	-52.5	20.1
4	-392	-374	-383	-9	22.2
5	-364	-360	-362	-2	21.0
6	-348	-541	-445	96.5	25.8
		Average	-390	25	23

WABTEC/SAB-WABCO Disc 1 Press Off Operation

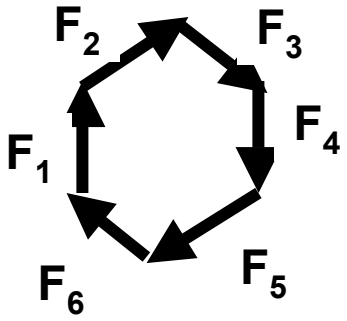


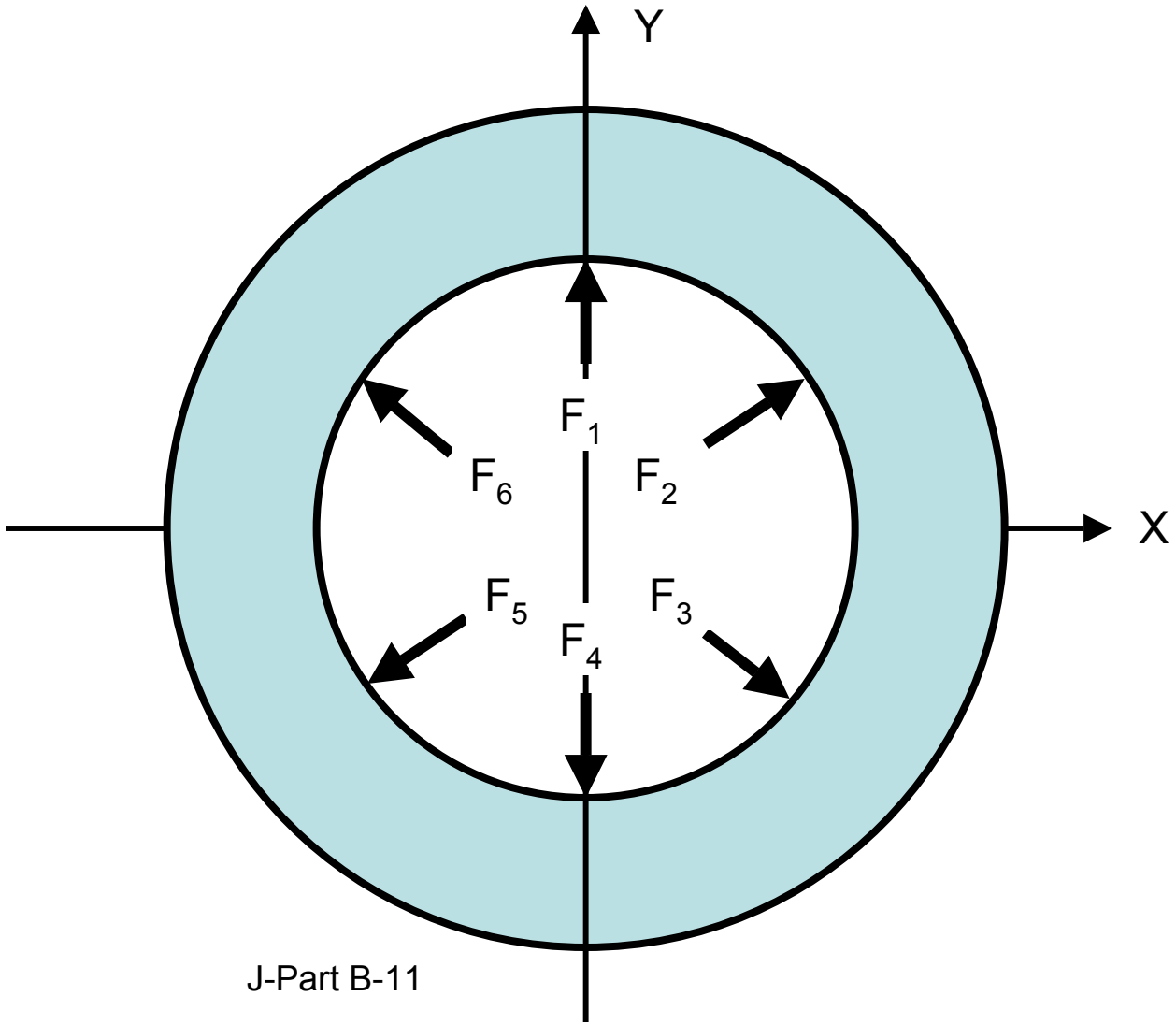
Test Of Observed Pre Strain Reduction

- Assume:
  - Pre-strain Produces Only Compressive Force Along The Axis Of The Spoke
  - This Force Can Be Estimated By The Mean Observed Strain (Average Of The Right And Left Strain Gages) Times The Cross Section Area Of Section
  - The 6 Forces Acting On The Friction Disc Should Be In Equilibrium

Spoke Forces on Friction Rings

$$\sum_{1}^{6} F_i = 0$$





Summation of Spoke Forces

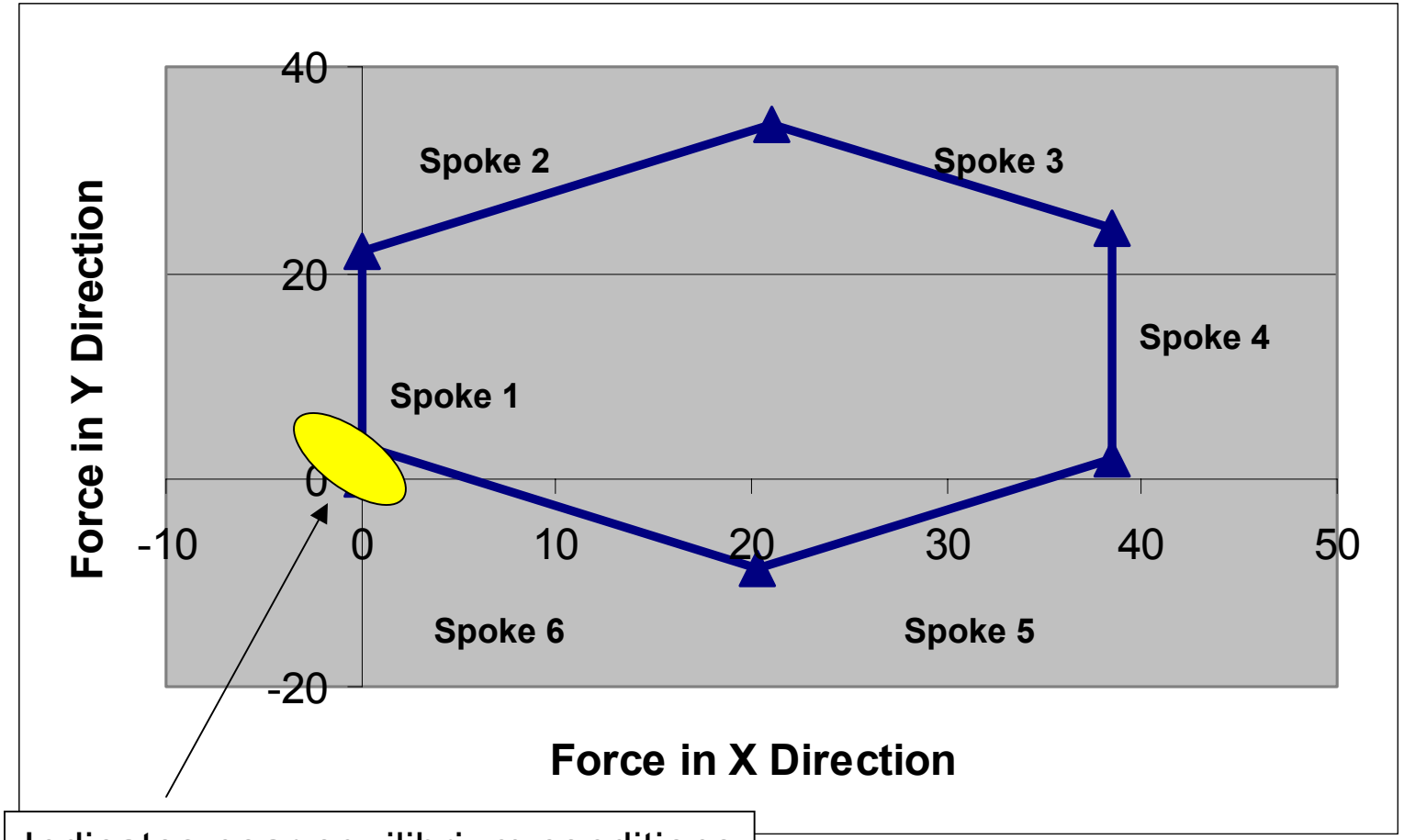
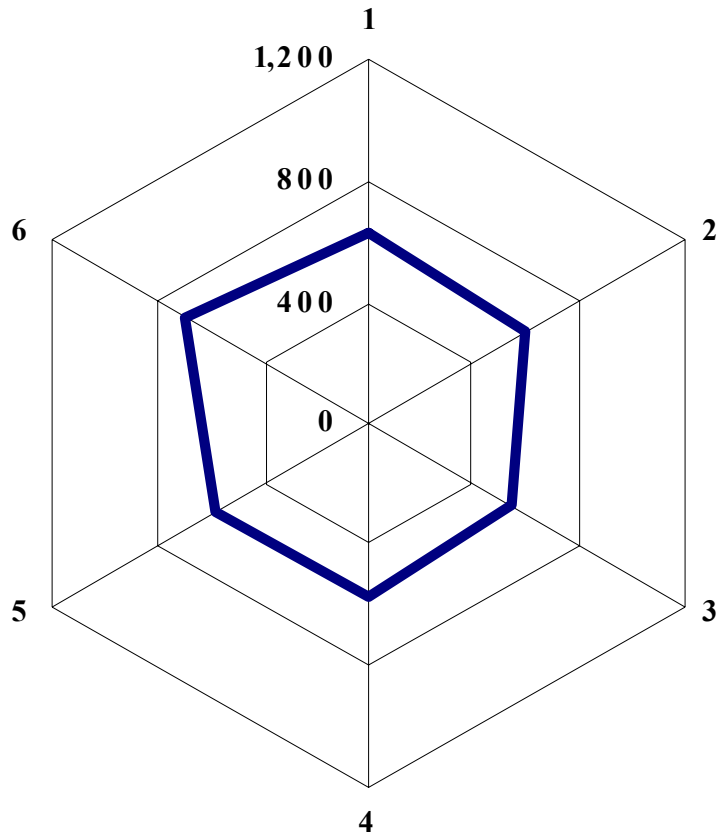


Table J.B.3. WABTEC/SAB-WABCO Disc 1 Pre-Strain, Spoke Cutting

Spokes Cut to relieve any Pre- Stress. WABTEC/SAB-WABCO Disc - Good condition with approximately 1,500 to 2,000 miles service. Disc removed from axle 4 on car 3534, May 28, 2005					
	Nut side	Other-side	Resultant Average Strain	Resultant Bending Strain	Estimate Force in Spoke (lbs)
Spoke	Resultant Strain				
1	-602	-650	-626	24	36.3
2	-567	-630	-599	31.5	34.7
3	-613	-455	-534	-79	30.9
4	-694	-444	-569	-125	33.0
5	-697	-467	-582	-115	33.7
6	-656	-725	-691	34.5	40.0
		Average	-600	-38	35

WABTEC/SAB-WABCO Disc 1 Spokes Cut



J-Part B-14

Spoke Force Summation
Disc 1

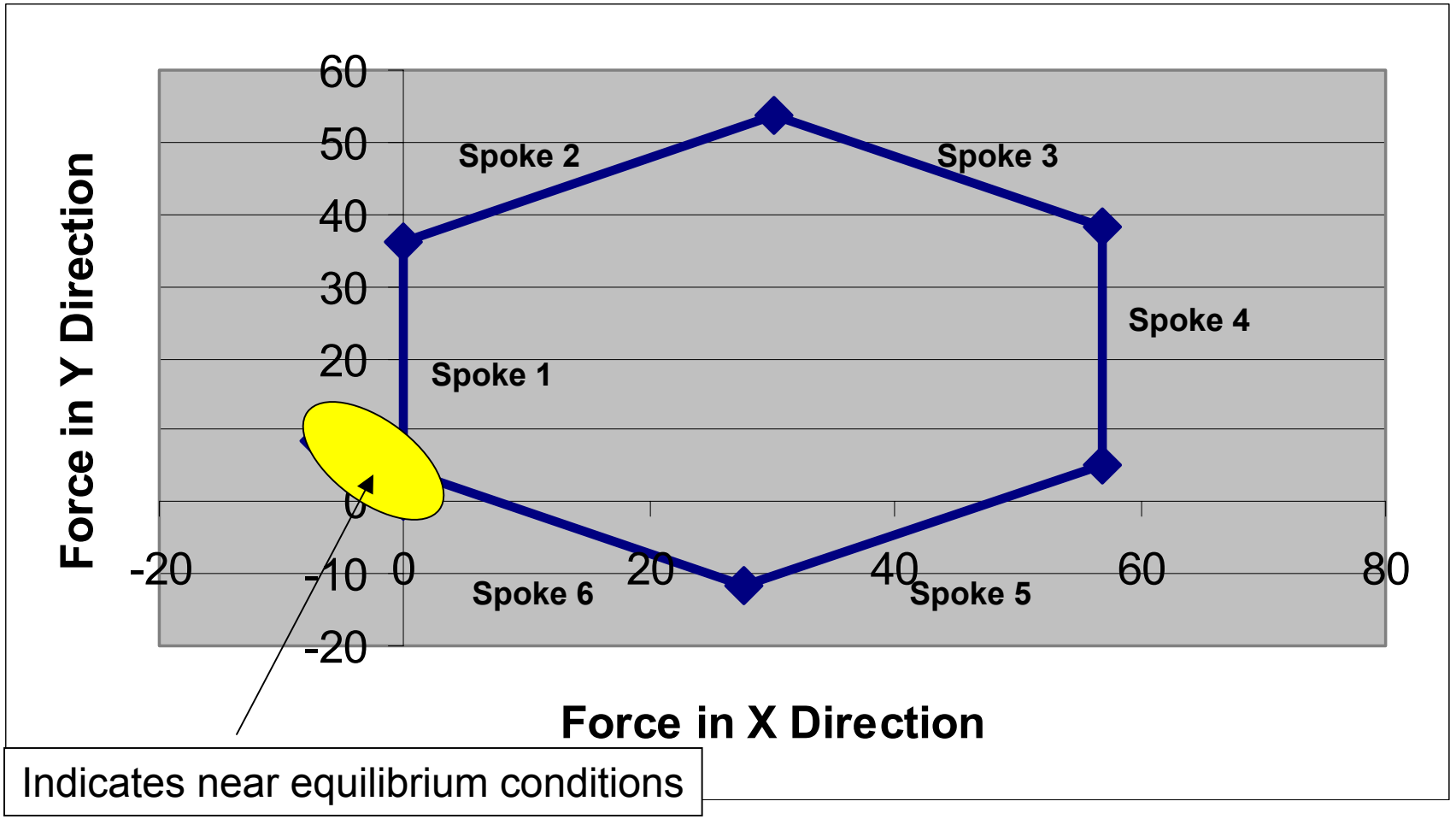
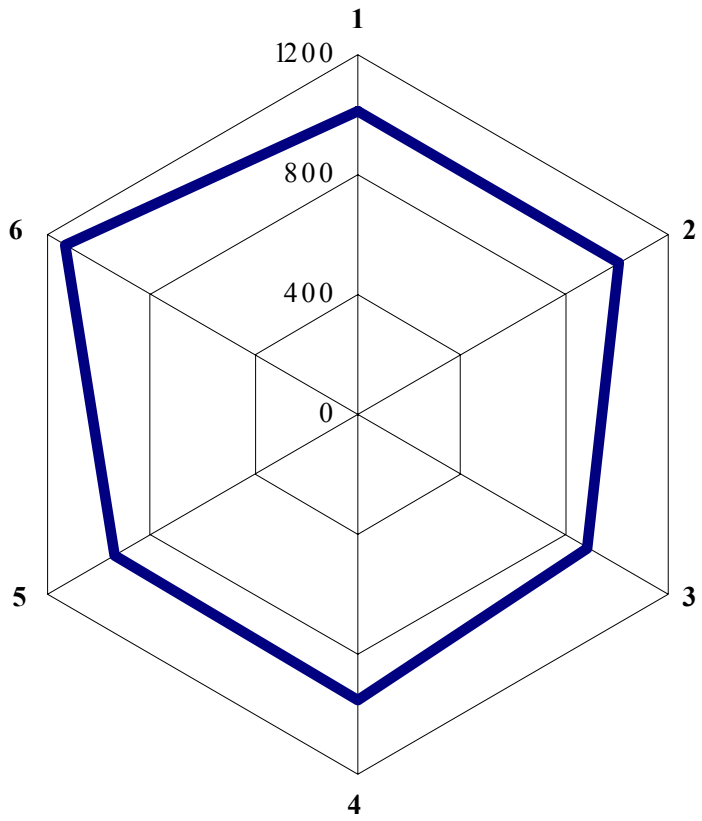


Table J.B.4. WABTEC/SAB-WABCO Disc 1 Pre-Strain, Disc Removal & Disc Cutting

Combined Residual Strain (both compressive)					
	Nut side	Other-side	Resultant Average Strain	Resultant Bending Strain	Estimate Force in Spoke (lbs)
Spoke	Resultant Strain				
1	-932	-1,086	-1,009	77	58
2	-923	-1,110	-1,017	94	59
3	-1,013	-750	-882	-132	51
4	-1,086	-818	-952	-134	55
5	-1,061	-827	-944	-117	55
6	-1,004	-1,266	-1,135	131	66
		Average	-990	-14	57

Disc 1
Combined Relieved Strain



Disc 1 Combined

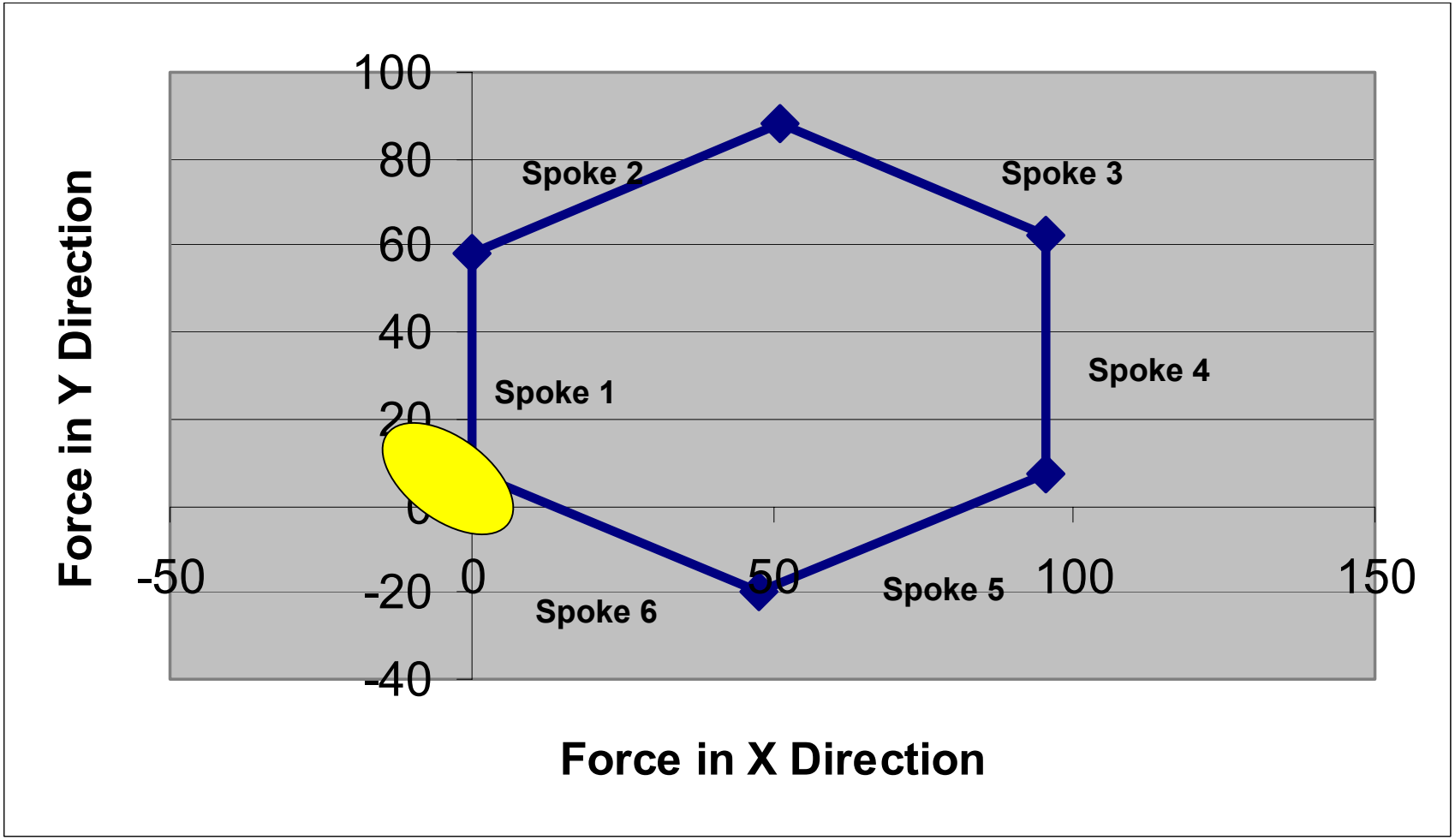
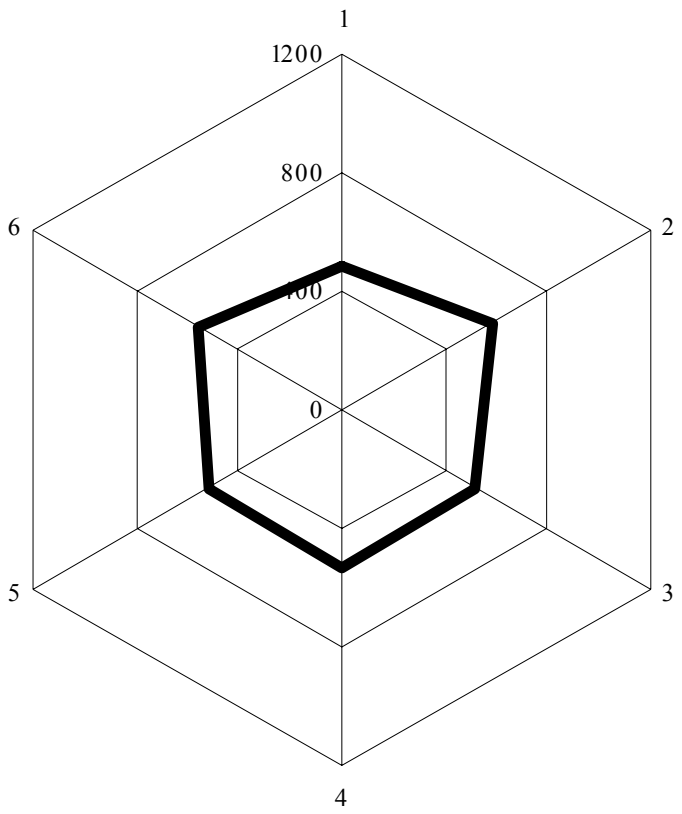


Table J.B.5. Knorr Disc 2 Pre-Strain, Disc Installation

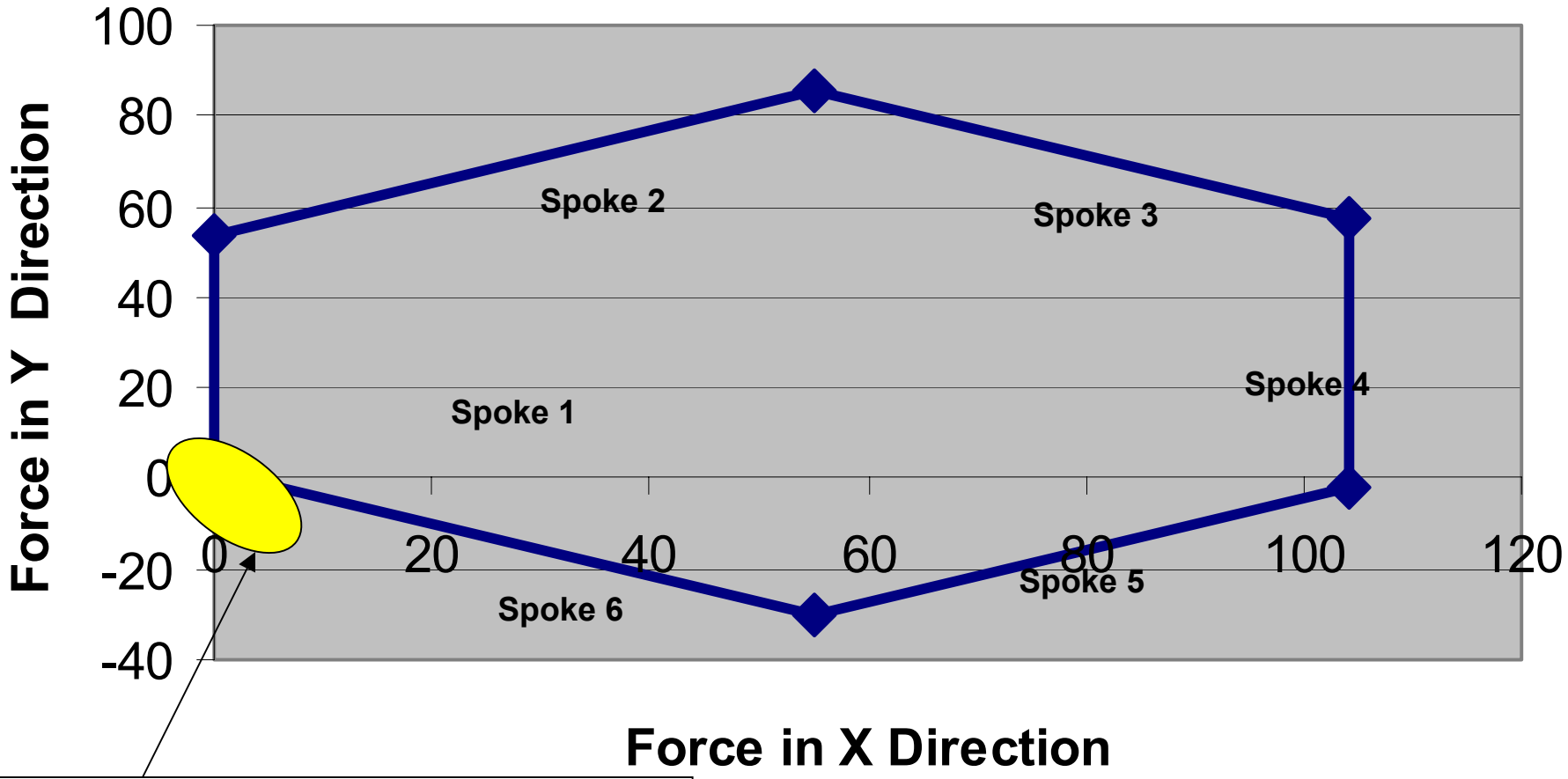
Knorr Press On					
	Nut side	Other-side	Resultant Average Strain	Resultant Bending Strain	Estimate Force in Spoke (lbs)
Spoke	Resultant Strain				
1	-491	-484	-488	-3.5	54
2	-637	-524	-581	-56.5	64
3	-503	-530	-517	13.5	57
4	-460	-612	-536	76	59
5	-513	-524	-519	5.5	57
6	-531	-585	-558	27	61
Average			-533	10	59

Knorr Disc
Disc 2



J-Part B-20

Knorr Disc
Disc 2



Disc 2 Knorr

Photo Courtesy of J. Gordon, Volpe National Transportation Center

Spoke Strain Gage on Knorr Disc

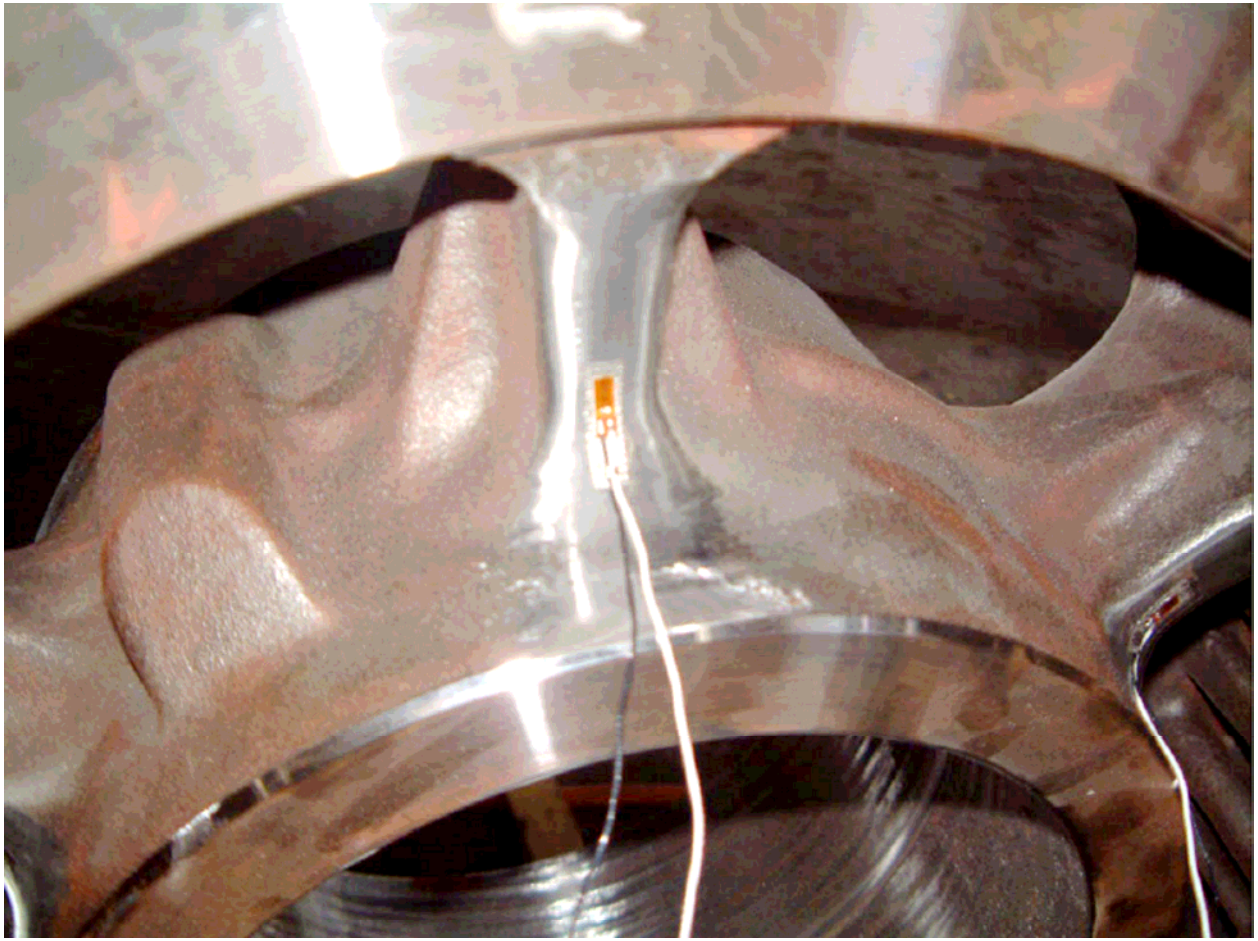


Photo Courtesy of J. Gordon, Volpe National Transportation Center

Spoke Strain Gage on Knorr Disc

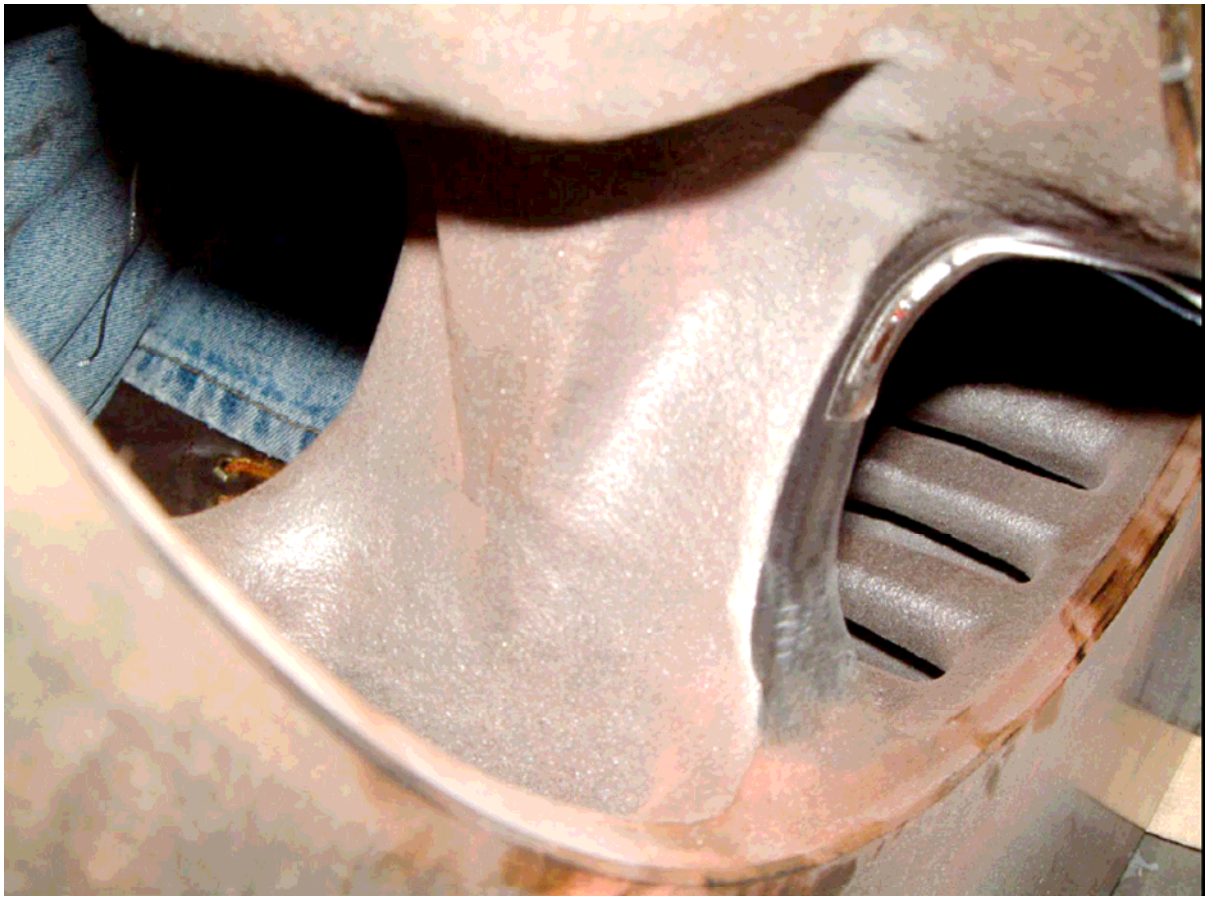


Photo Courtesy of J. Gordon, Volpe National Transportation Center

Material Properties
Knorr Disc

- Reported by Volpe
  - Yield Strength 850-900 MPa
  - Ultimate Strength 1000-1050 MPa

  - Yield Strength 123-130 ksi
  - Ultimate Strength 145-152 ksi

Disc 3 WABTEC/SAB-WABCO Disc with Two (2) Cracked Spokes

- Cracked Spokes – No Pre-Stress
- Other Spokes –
  - Strain Levels Less Than In Disc 1 After Press Off Operation
  - Large Values Of Bending Strain

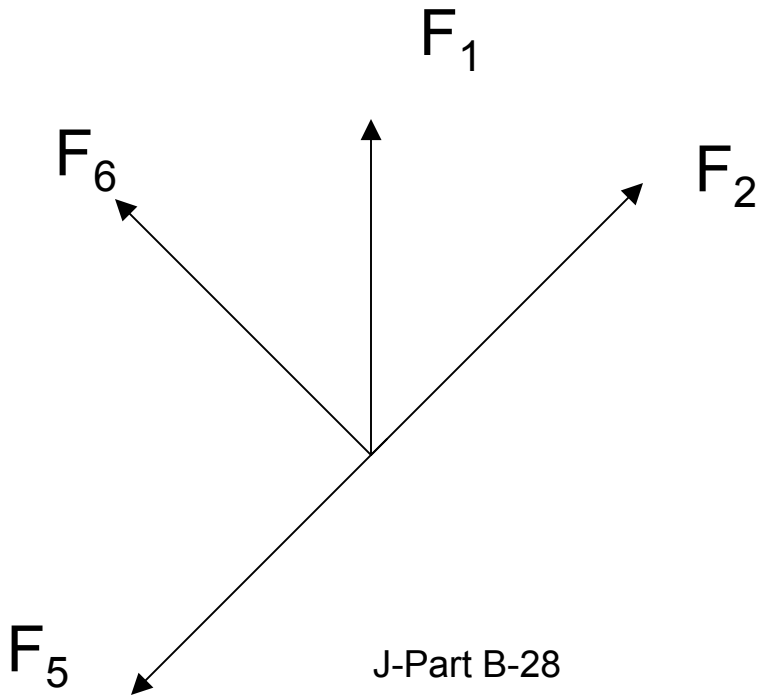
Table J.B.6. WABTEC/SAB-WABCO Disc 3 Pre-Strain, Spoke Cutting with Two Cracked Spokes

WABTEC/SAB-WABCO Disc with 2 Cracked Spokes					
	Nut side	O-side	Resultant Average Strain	Resultant Bending Strain	Estimate Force in Spoke (lbs)
Spoke	Resultant Strain				
1	N/A	-681	N/A	N/A	N/A
2	-1,219	-386	-803	-416.5	47
3	-2	31	15	-16.5	-1
4	2	N/A	N/A	N/A	N/A
5	-580	-779	-680	99.5	39
6	N/A	-474	N/A	N/A	N/A
		Average	-741	N/A	N/A

Note: Average Based on Spokes 2 and 5

Summation Of Spoke Forces

- The Equilibrium Conditions Cannot Be Met With The Two Broken Spokes Under The Assumption Stated Above



Comments

- Spokes Compressive Force Must Be Augmented With Shear Forces In The Spoke
- The Available Test Data Does Not Allow This Force To Be Calculated
- The Large Bending Strain In Spoke 2 May Indicate Shear In Spoke 2

Cracked Spoke

Photo Courtesy of M. Tomas, Amtrak

Cracked Spoke

Photo Courtesy of M. Tomas, Amtrak

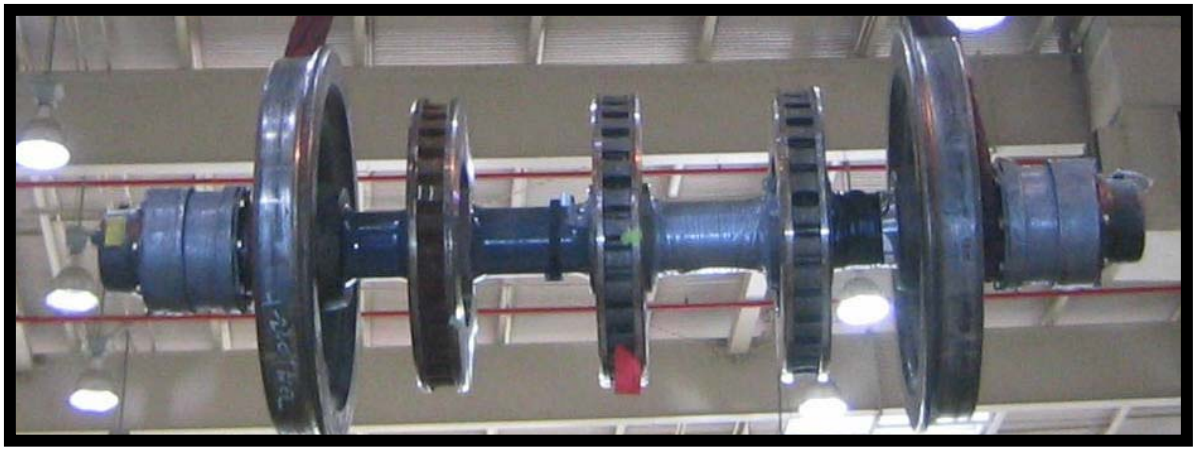
Observations

- These observations based on limited sample
  - One WABTEC/SAB-WABCO Disc (press off and cutting of spokes)
  - One WABTEC/SAB-WABCO Disc with two cracked spokes (cutting of spokes)
  - One Knorr Disc (press on)
  - Extrapolation to total population will require more samples
- WABTEC/SAB-WABCO Disc
  - Press Off Operation Relieved Strain 360 To 440 Microstrain
  - Cutting The Spokes Relieved Strain 530 To 690 Microstrain
  - Retired Disc With 2 Cracked Spokes, Showed No Pre-Strain In The Two Cracked Discs
  - Retired Disc With 2 Cracked Spokes, Showed Retained Strain Level Of 680-800 Microstrain On 2 Spokes (The Other Two Spokes Did Not Have Gage Readings On Both Sides Of Spoke, But One-sided Strain Of 475 And 680 Microstrain)
- Knorr Disc
  - Press On Operation Produced Strain Level Of 490-580 Microstrain

Appendix J
Part C

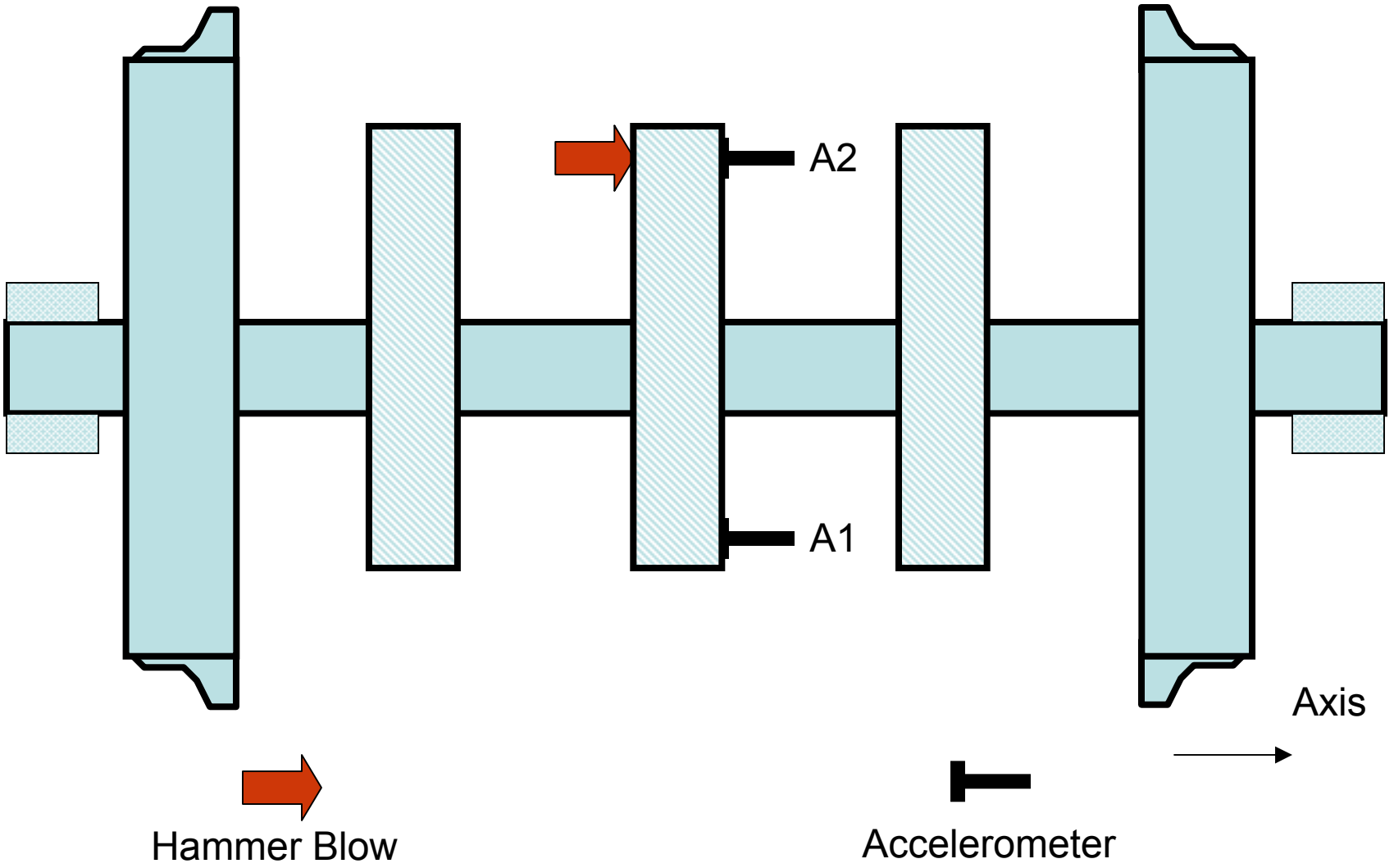
Vibration Analysis

Acela Wheelset



- Static Vibration Tests Conducted on 2 Wheelsets Using Acceleration Measurements:
  - One with WABTEC/SAB-WABCO Discs, One with Knorr Discs
  - Each Wheelset Removed from Truck, Resting on Shop Floor

Test Conditions - 1



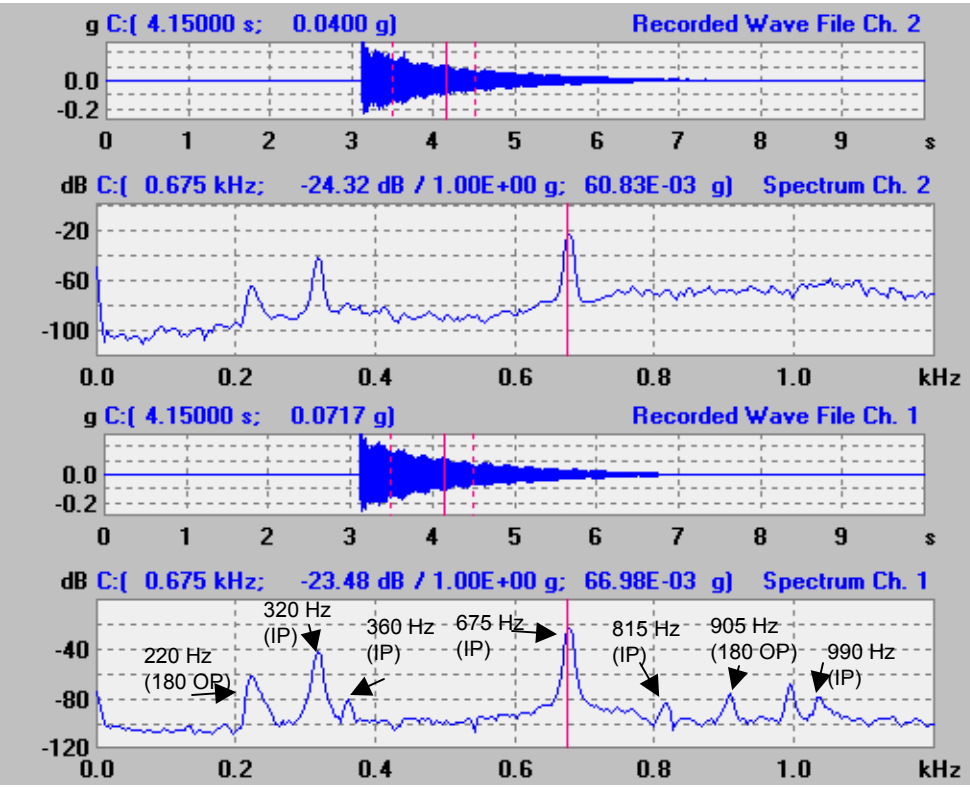
Test 1- Analysis Conditions

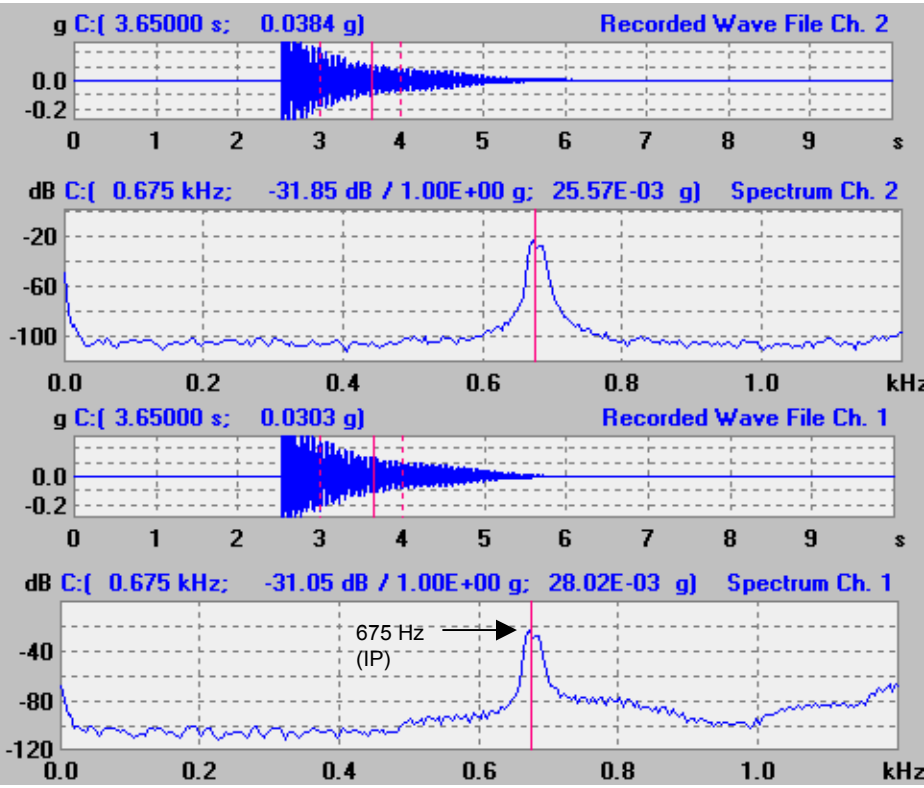
- 45 Oz Dead Blow Hammer Used For Force Input
- FFT Over One-Second Window,
  Approximately 1/2 Second After Impact
- Channel 1 - Accelerometer A1
  Channel 2 - Accelerometer A2

Vibration Analysis – Test Condition 1

WABTEC/SAB-WABCO Disc

Knorr Disc

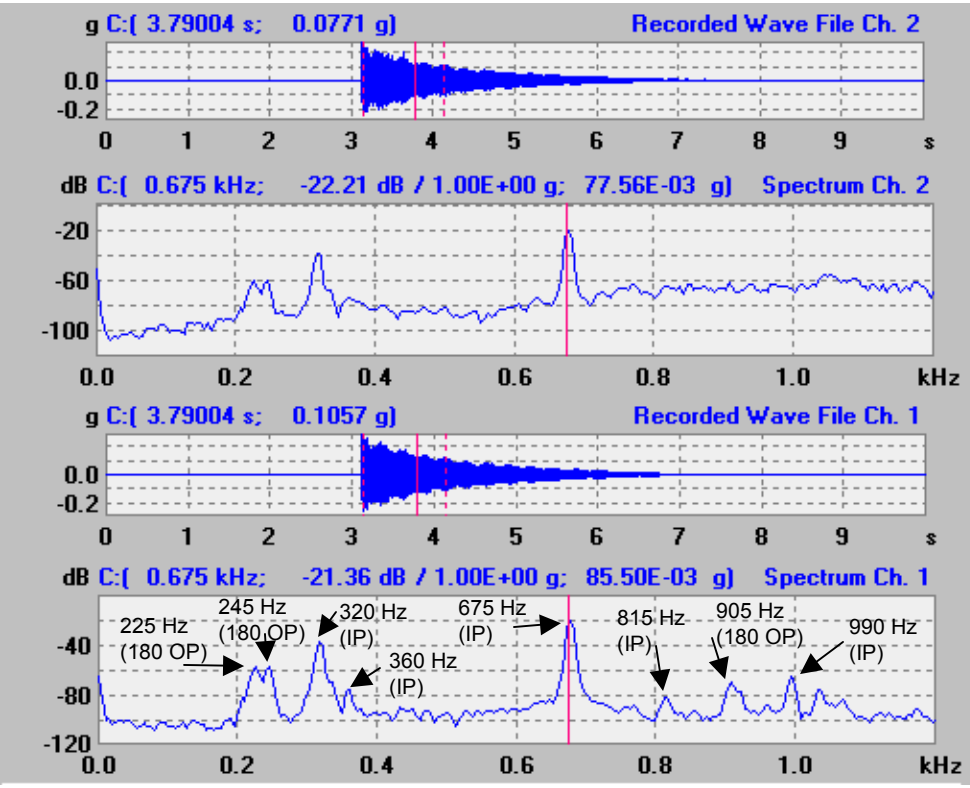


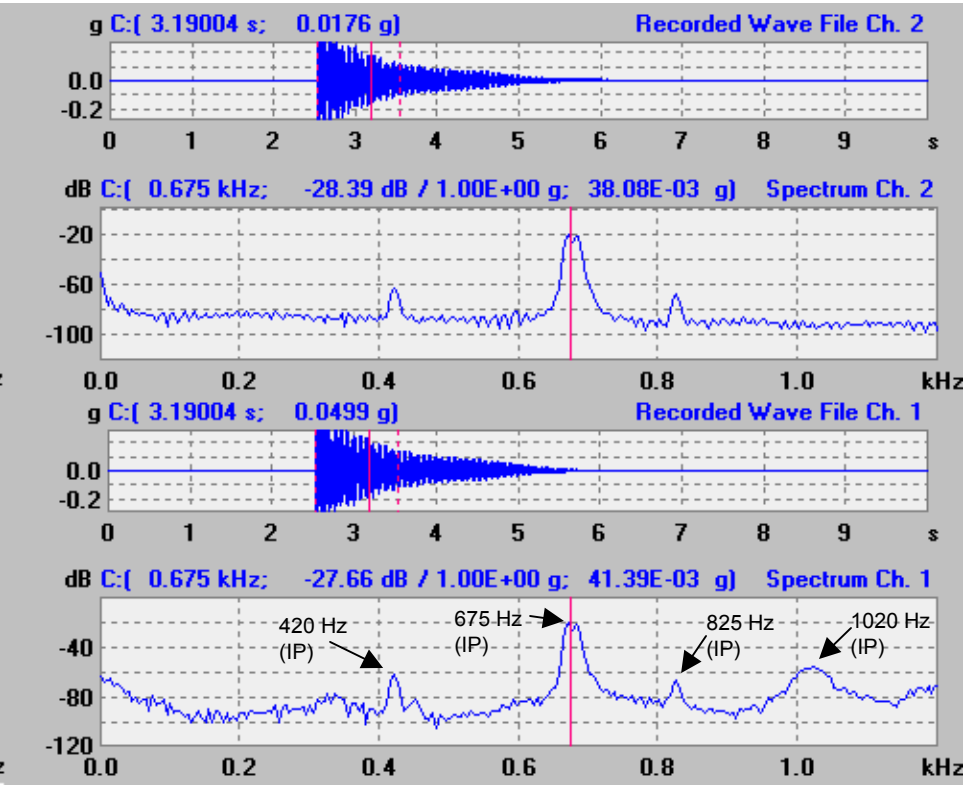


Vibration Analysis – Test Condition 1

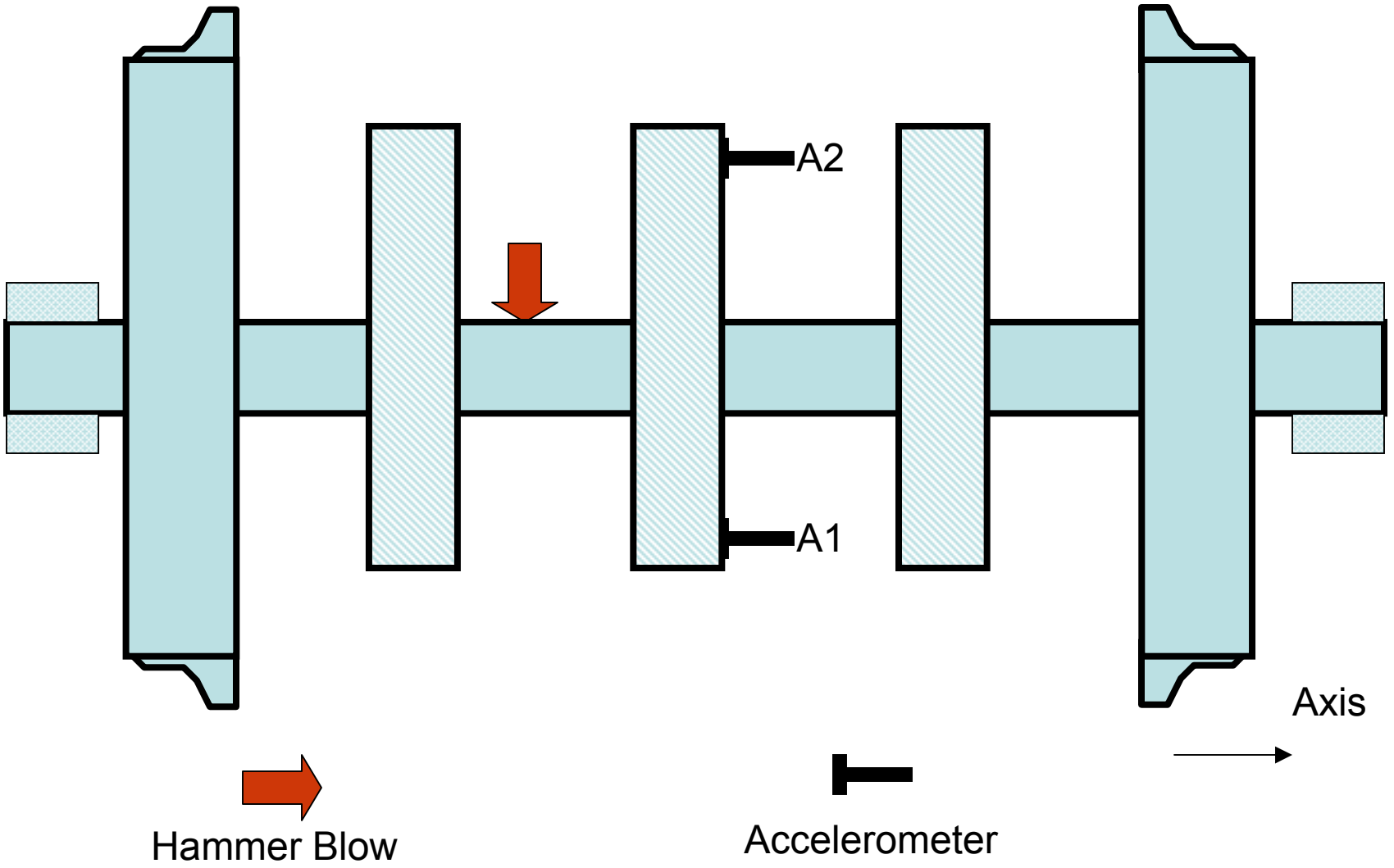
WABTEC/SAB-WABCO Disc

Knorr Disc





Test Conditions - 2



Test 2 - Analysis Conditions

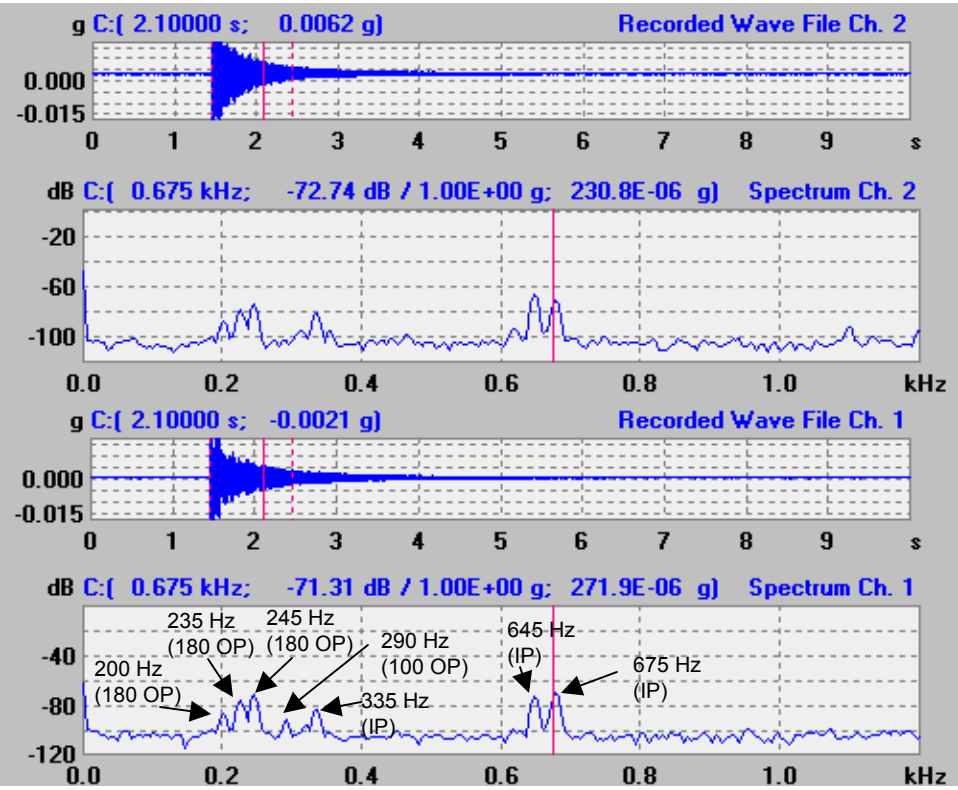
- 45 Oz Dead Blow Hammer Used For Force Input
- FFT Over One-Second Window, Right After The Impact
- Channel 1 - Accelerometer A1

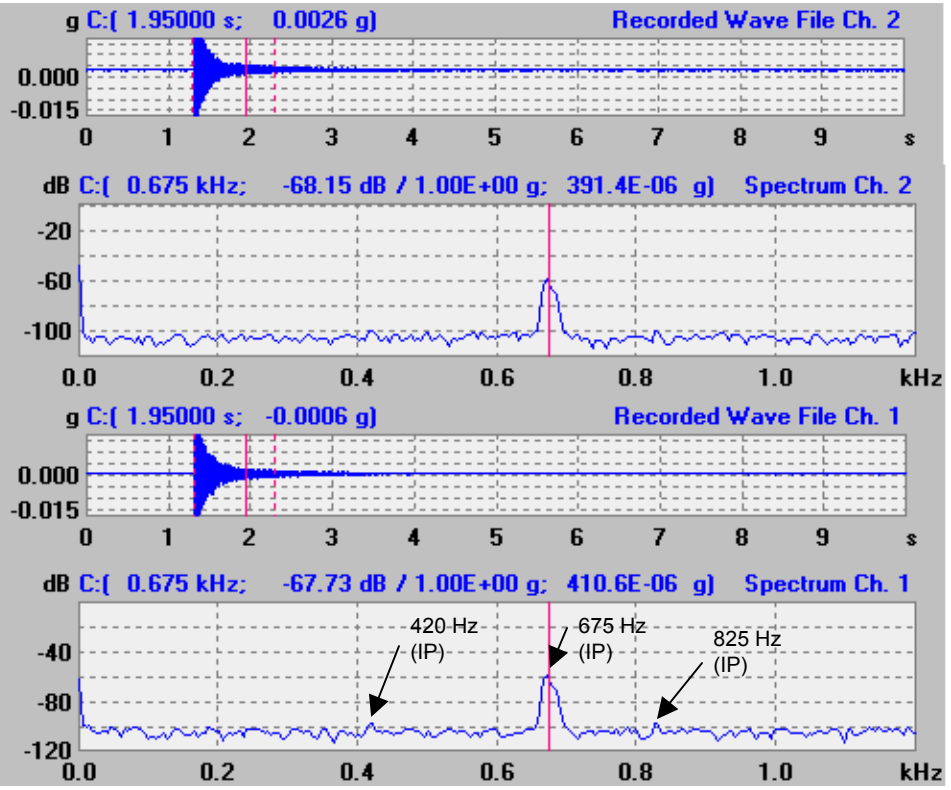
  Channel 2 - Accelerometer A2

Vibration Analysis – Test Condition 2

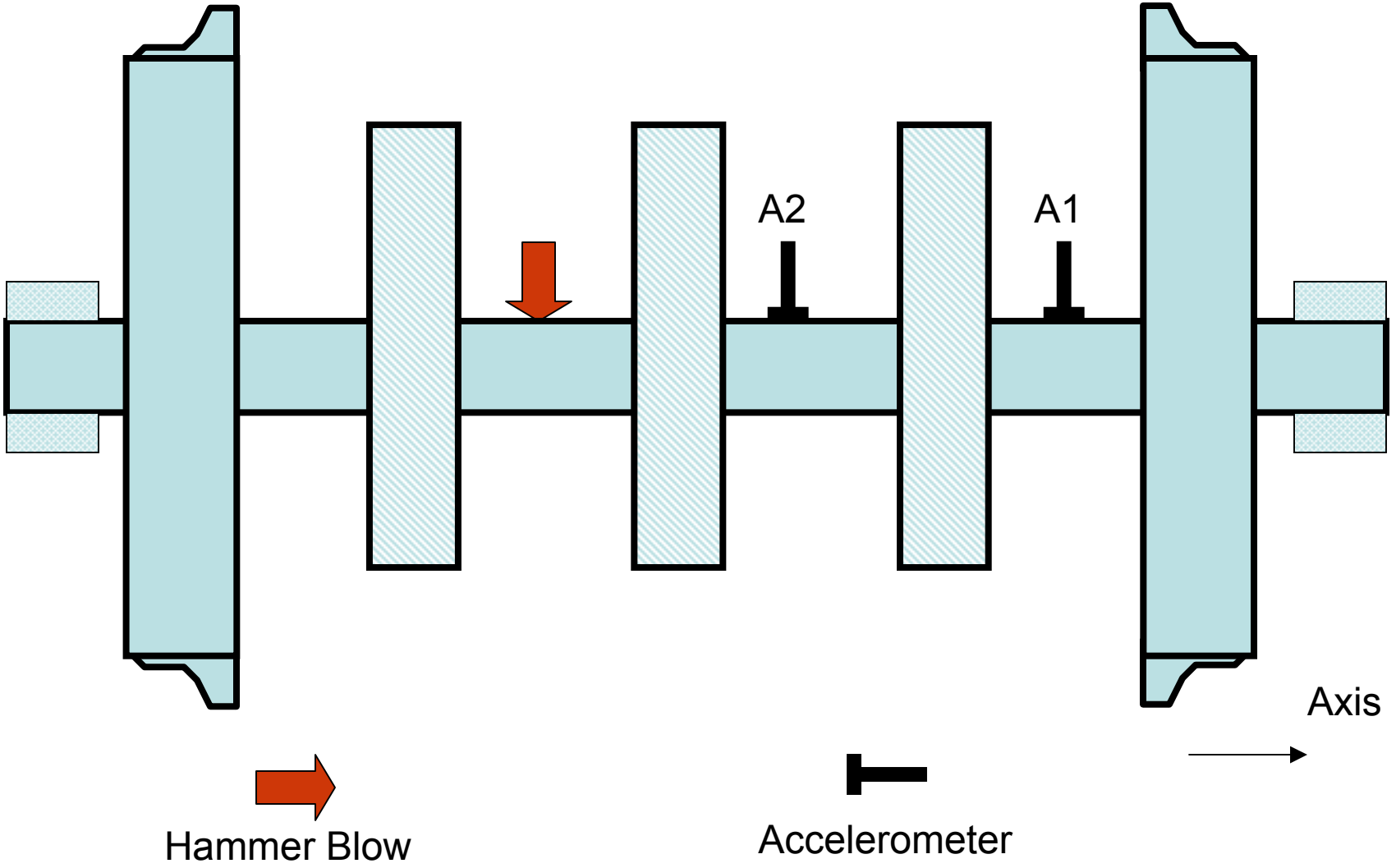
WABTEC/SAB-WABCO Disc

Knorr Disc





Test Conditions - 3



Test 3 - Analysis Conditions

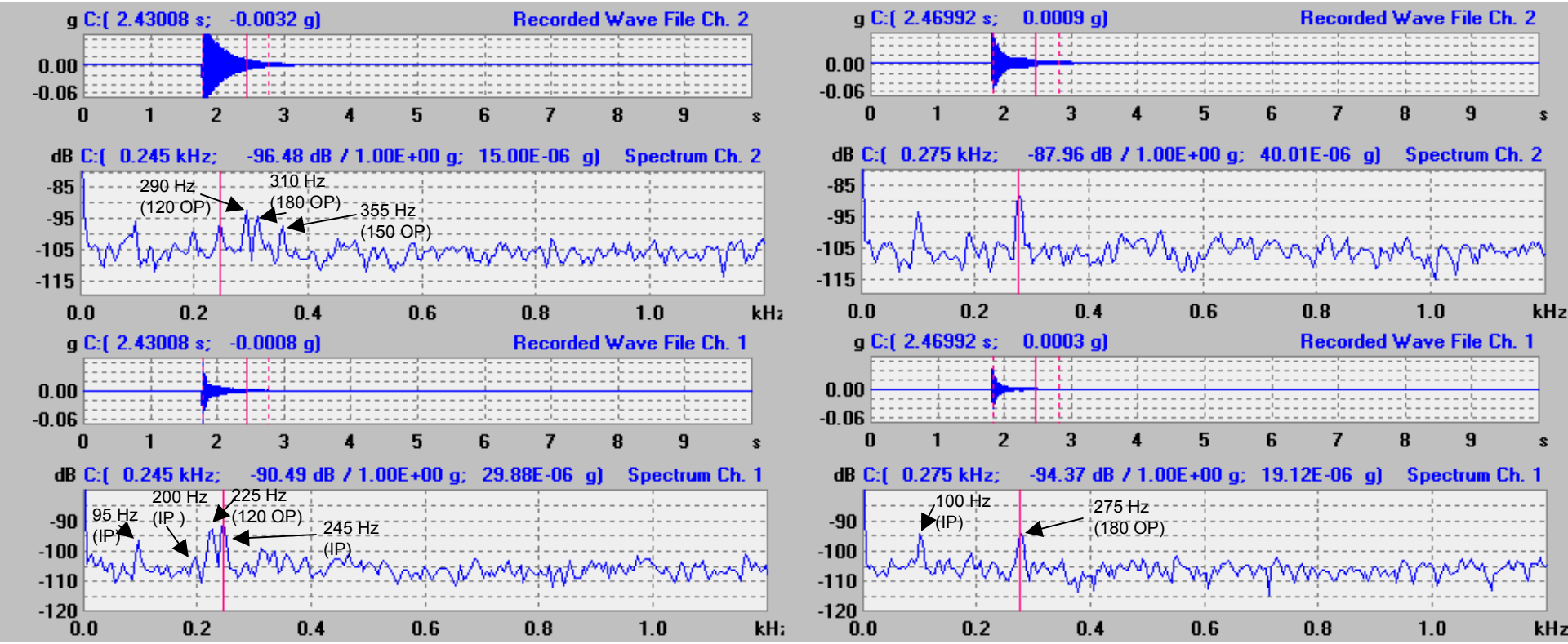
- 45 Oz Dead Blow Hammer Used For Force Input
- FFT Over One-Second Window, Right After The Impact
- Channel 1 - Accelerometer A1

  Channel 2 - Accelerometer A2

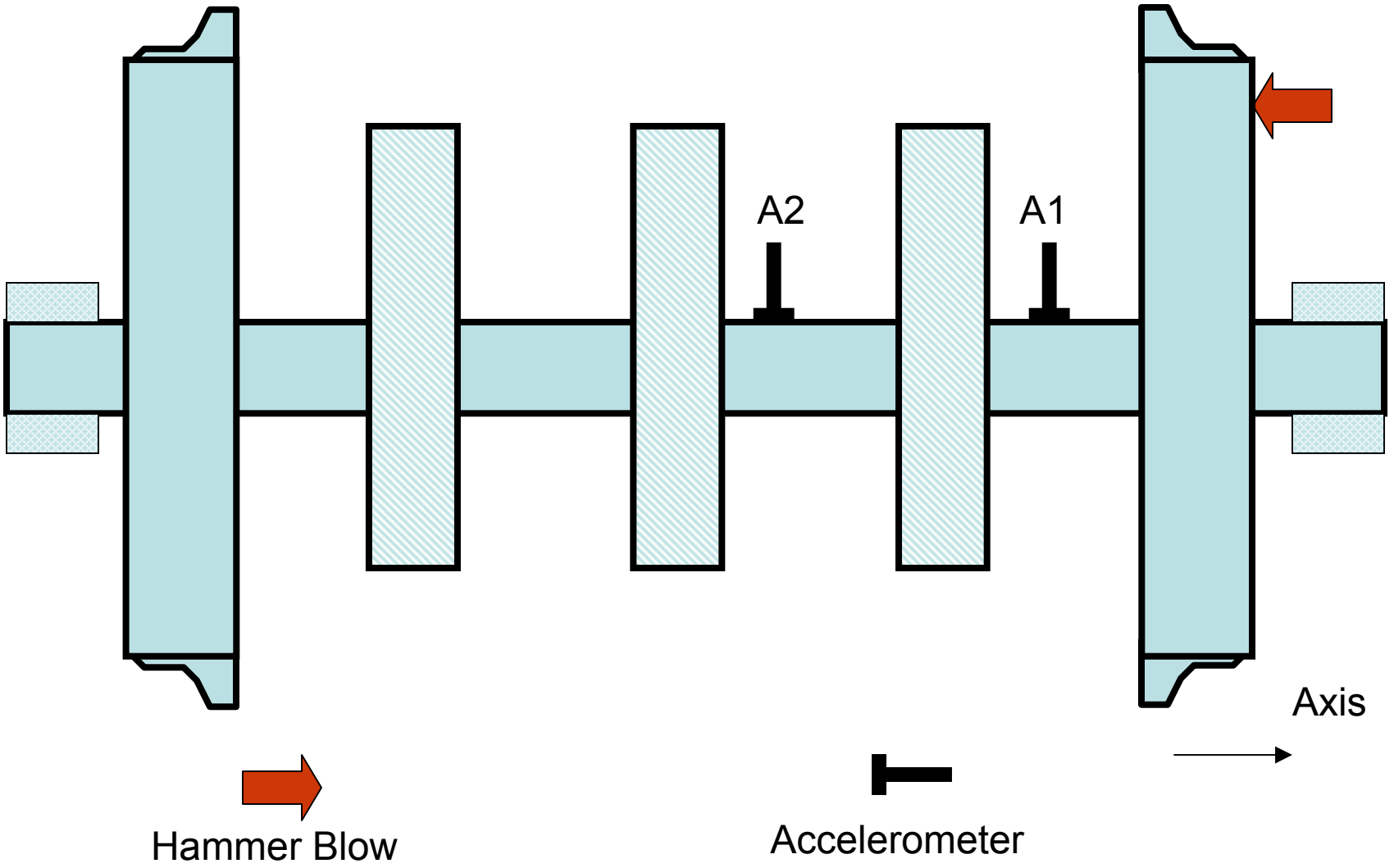
Vibration Analysis – Test Condition 3

WABTEC/SAB-WABCO Disc

Knorr Disc



Test Conditions - 4



Test 4 - Analysis Conditions

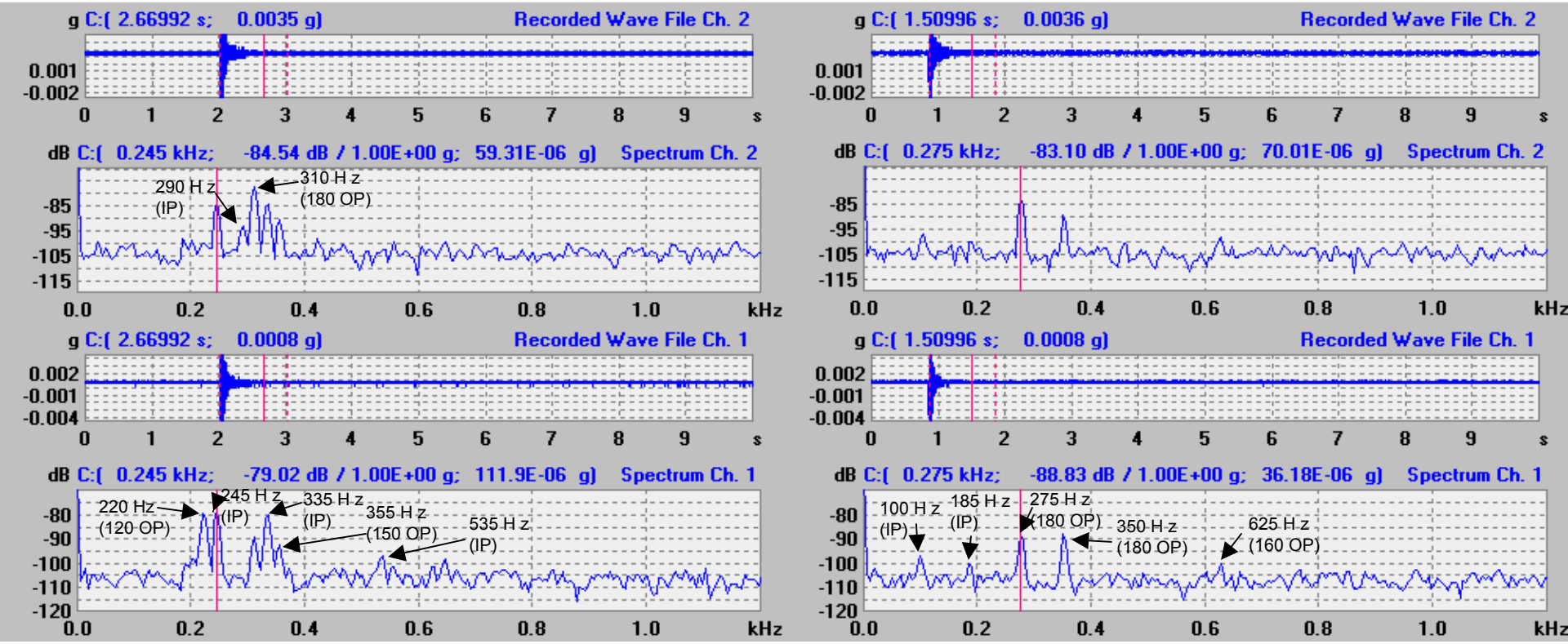
- 45 Oz Dead Blow Hammer Used For Force Input
- FFT Over One-Second Window, Right After The Impact
- Channel 1 - Accelerometer A1

  Channel 2 - Accelerometer A2

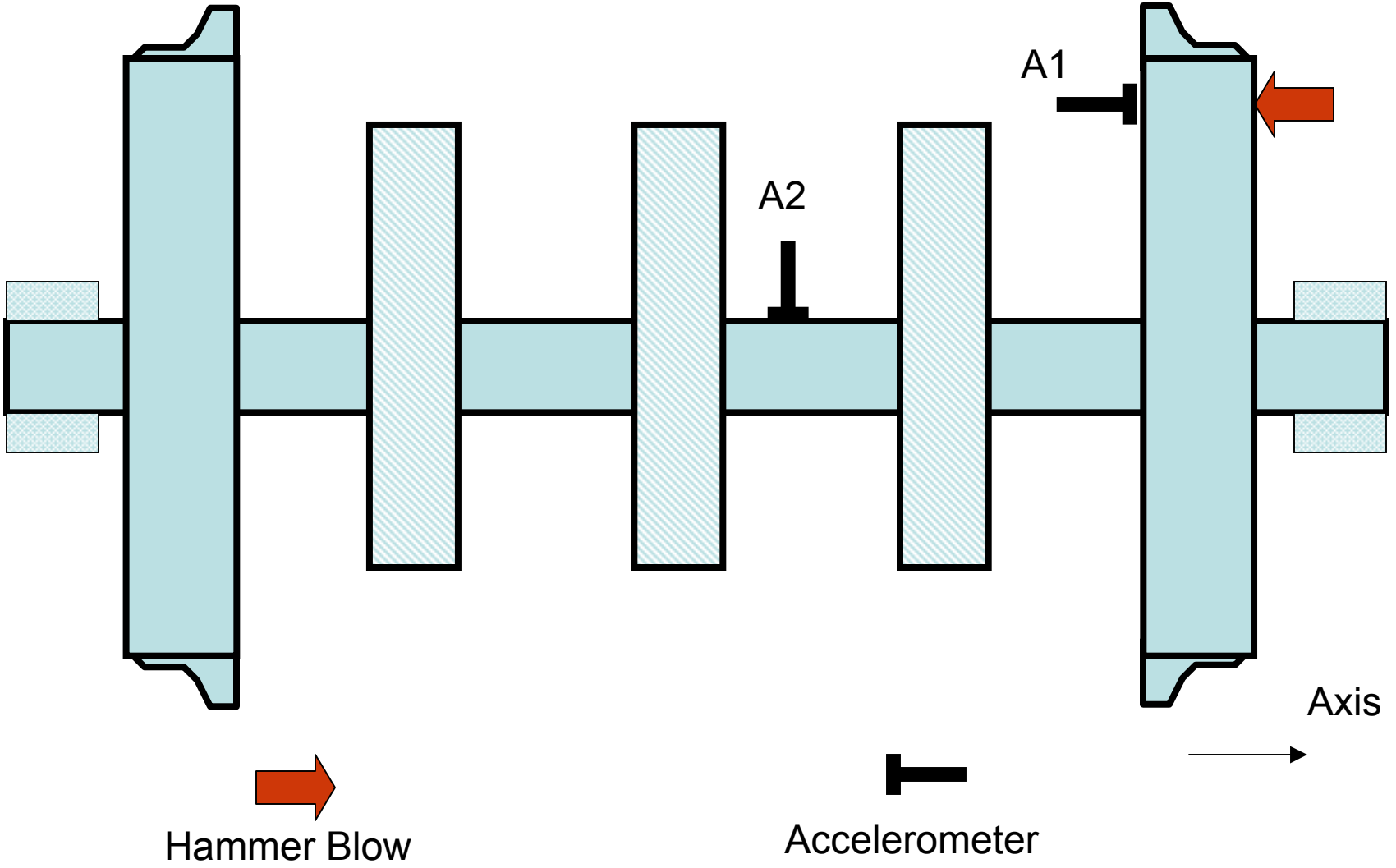
Vibration Analysis – Test Condition 4

WABTEC/SAB-WABCO Disc

Knorr Disc



Test Conditions - 5



Test 5 - Analysis Conditions

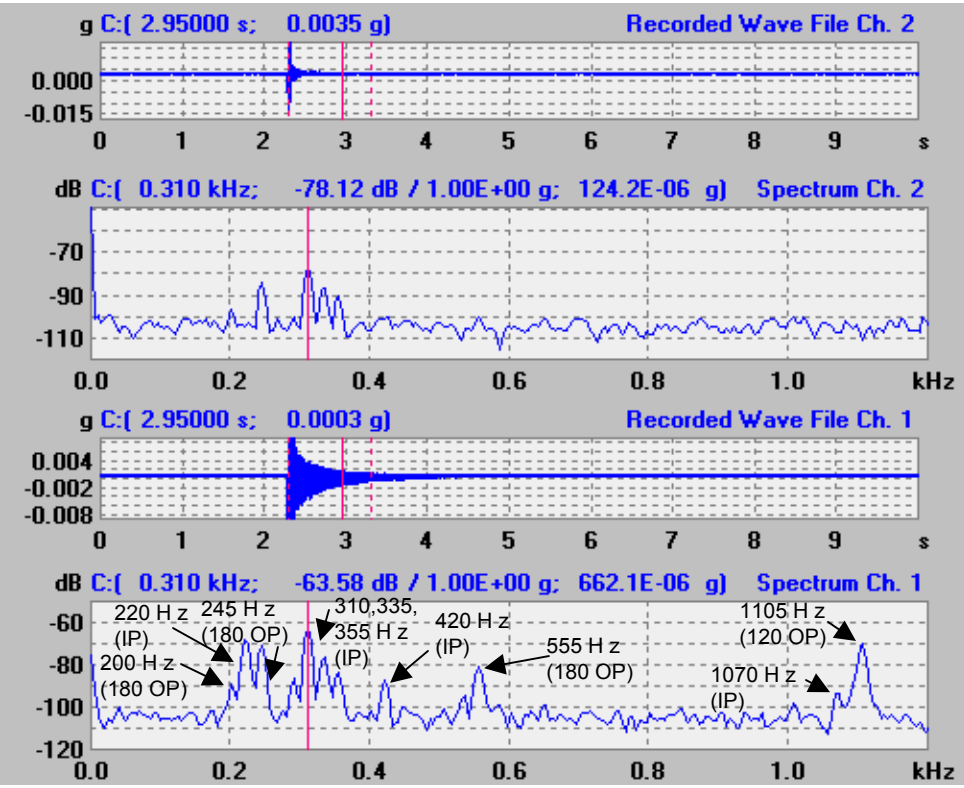
- 45 Oz Dead Blow Hammer Used For Force Input
- FFT Over One-Second Window, Right After The Impact
- Channel 1 - Accelerometer A1

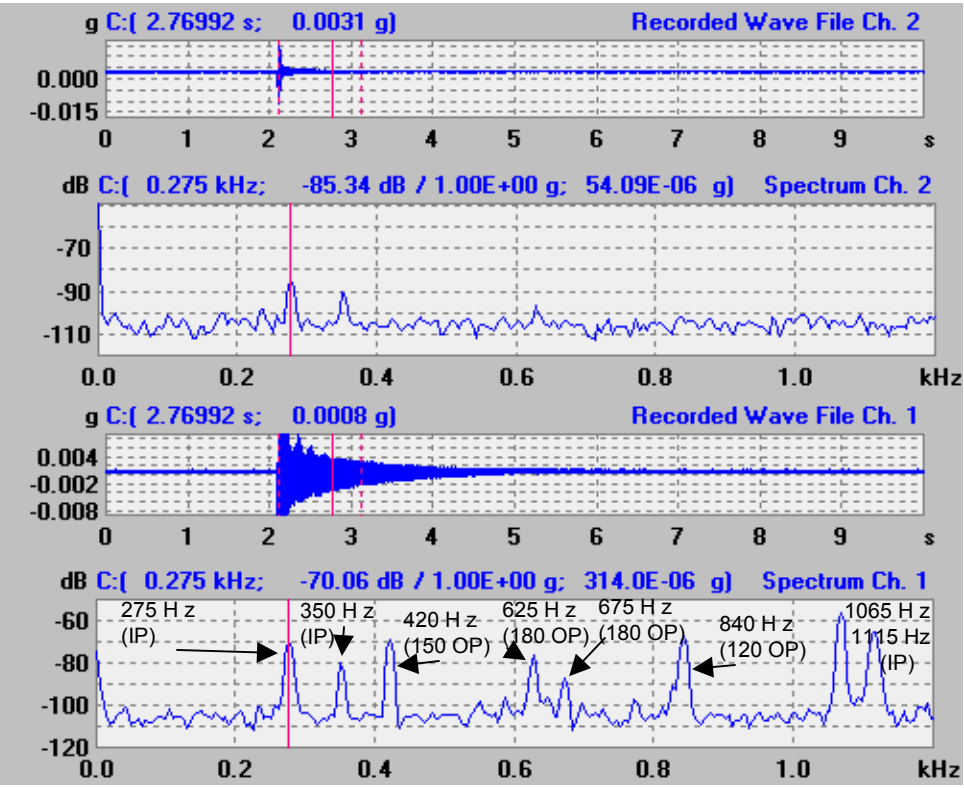
  Channel 2 - Accelerometer A2

Vibration Analysis – Test Condition 5

WABTEC/SAB-WABCO Disc

Knorr Disc





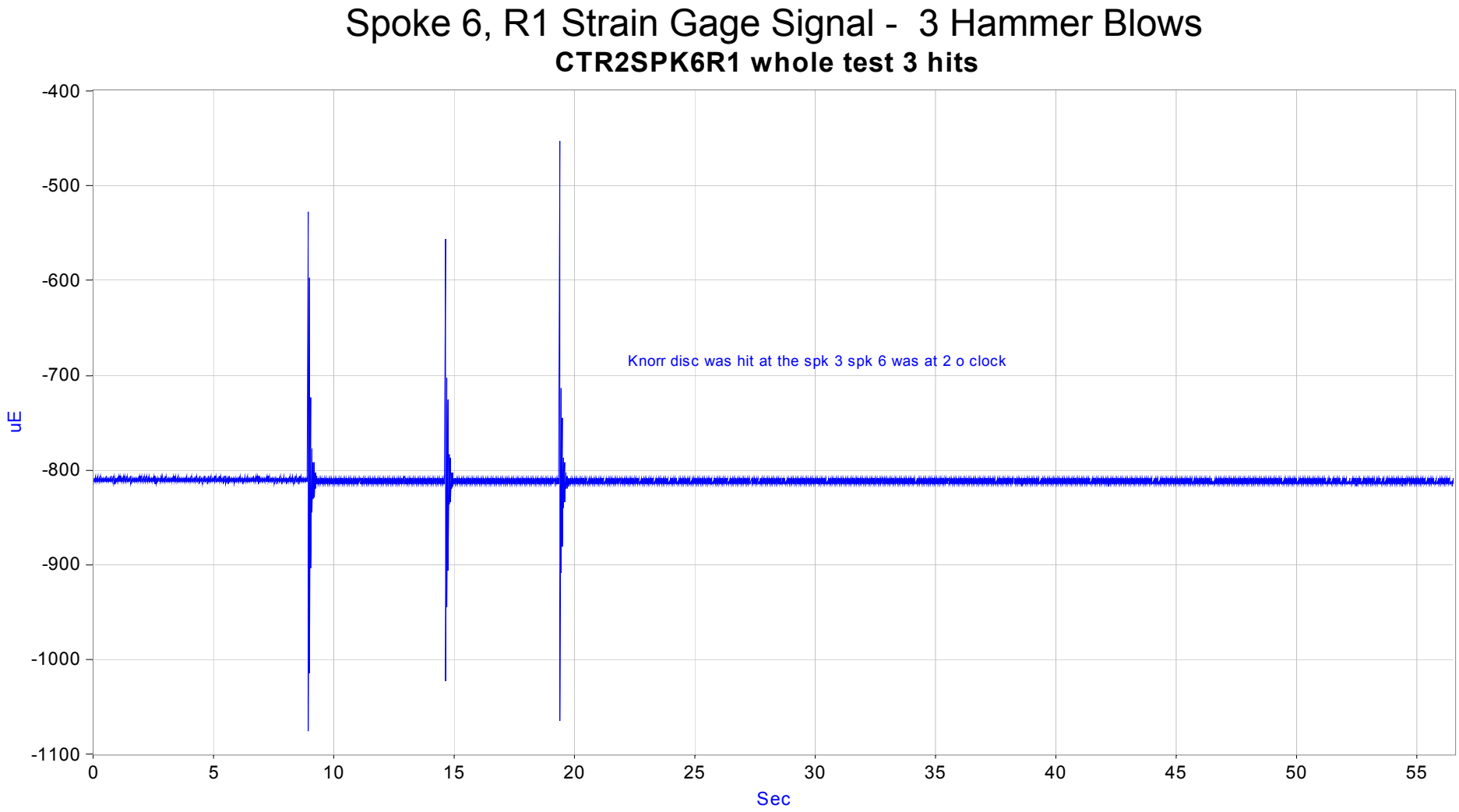
Second Vibration Test Bending Out-of-Plane (BOP) Mode for Knorr Disc

- A BOP Natural Frequency for the Knorr Disc Was Difficult to Resolve Using The Accelerometers and Hammer as Described Above
- Field Data Indicated a BOP Frequency of ~350 Hz
- A Second Method Of Investigating the BOP Frequency Was Used After Completion of Phase 3 Testing

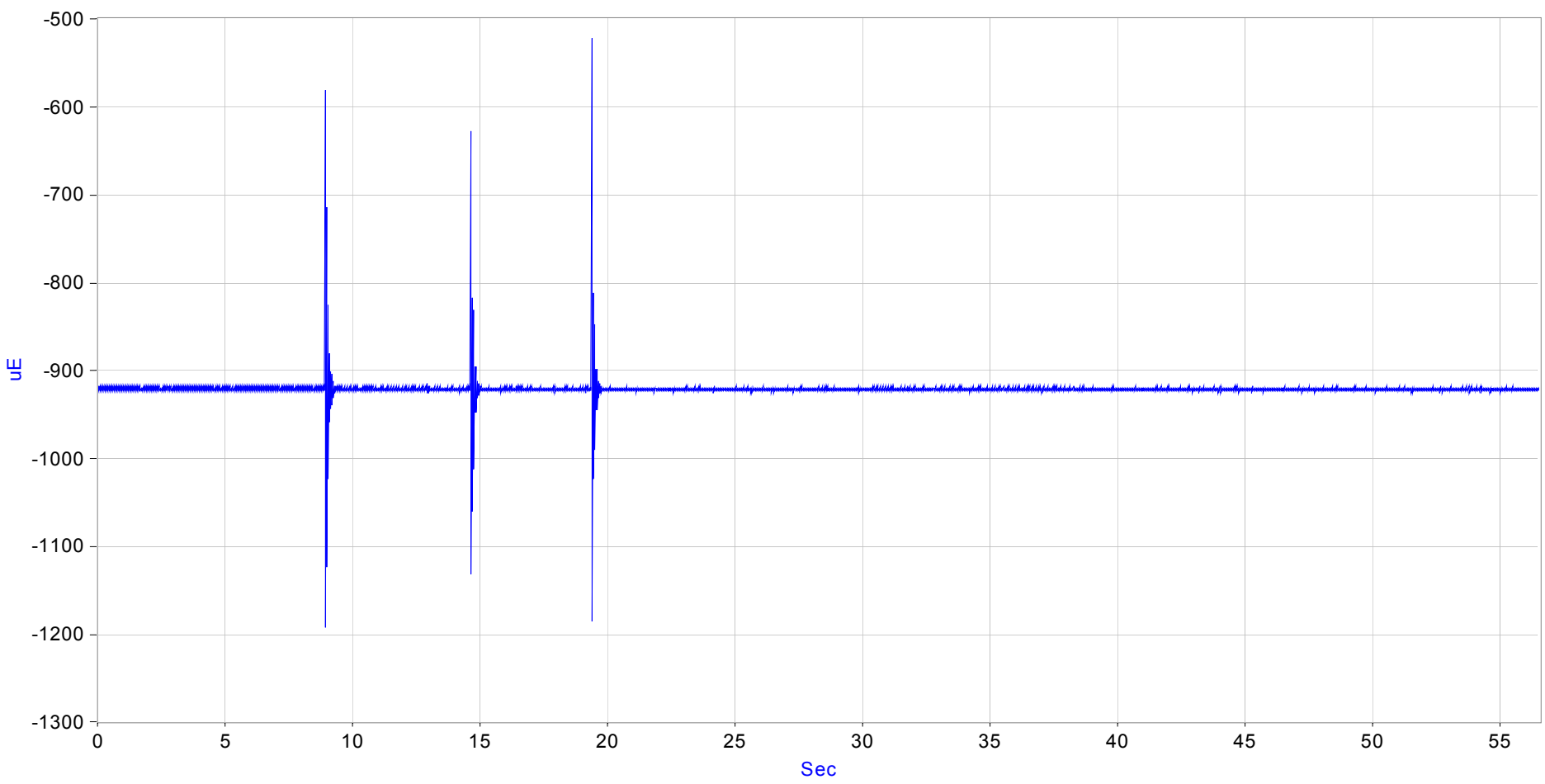
Vibration Test, Knorr Disc

- For this Test, the Strain Gages on Spokes 3 and 6 of the Center Disc of Test Axle 2 Were Used To Produce Signals For Analysis
- Test Axle 2 Was Still Installed in B-end Truck Under Coach Car 3534
- A Hammer Was Used To Excite The Disc
- Three Successive Hammer Blows, ~ 5 Seconds Apart, Were Applied to the Friction Ring at the Spoke 3 Position When Spoke 6 Was at the 2 O'Clock Position and Within The Pads
- Brakes Were Not Applied and Not Touching Disc

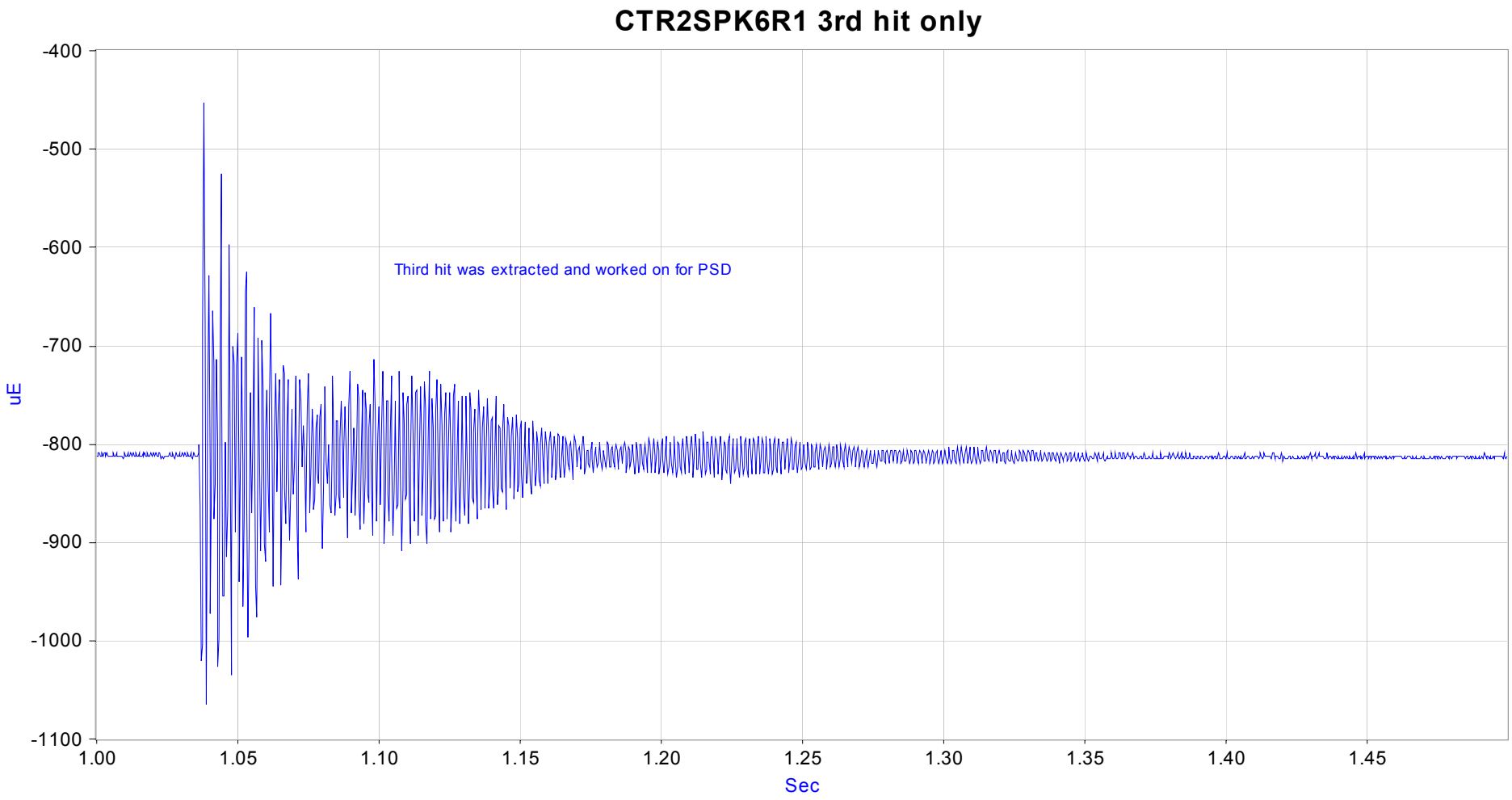
- The resulting ring out of the spoke strain gage signals is shown below



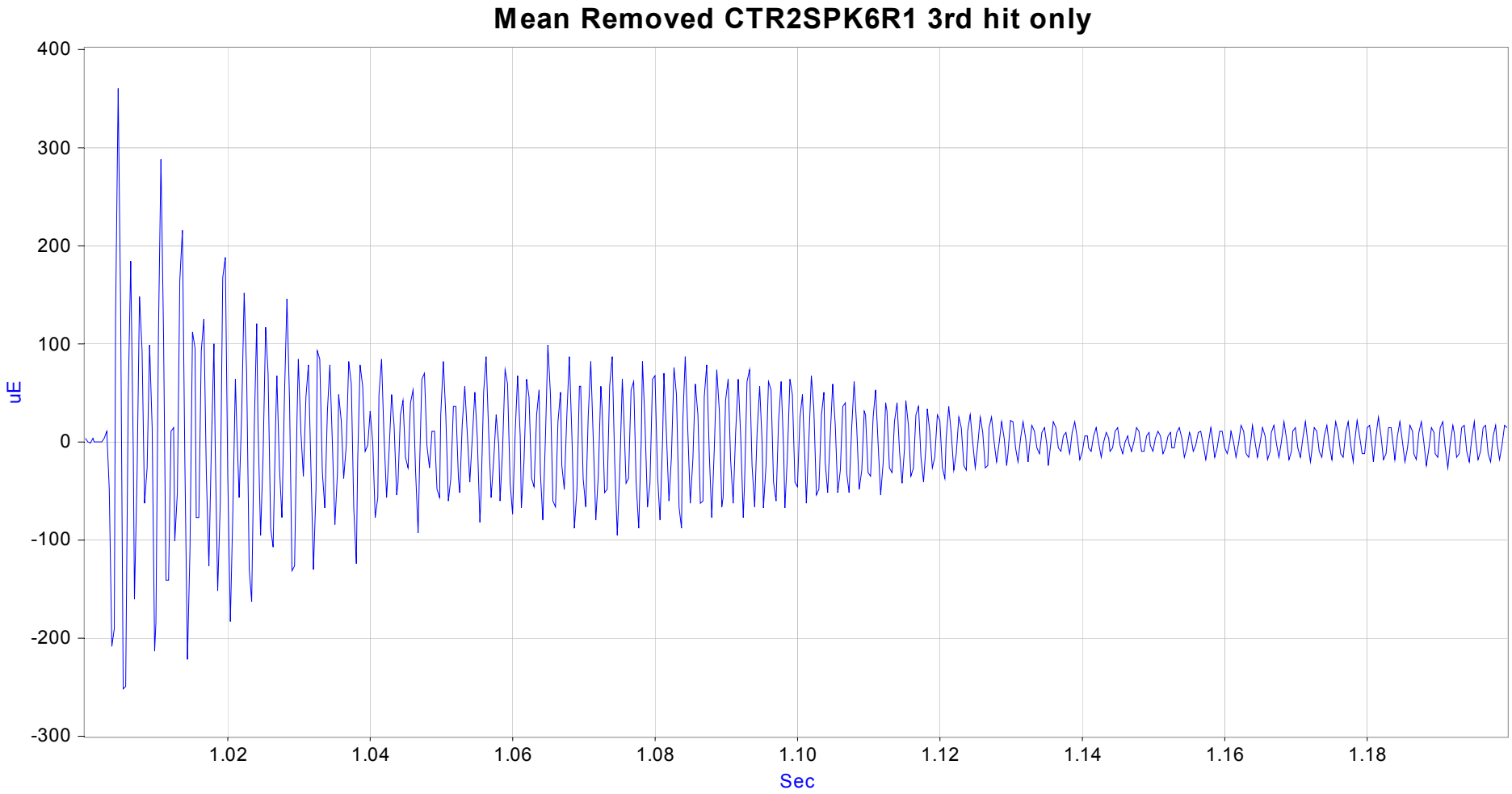
Spoke 3, R1 Strain Gage Signal - 3 Hammer Blows



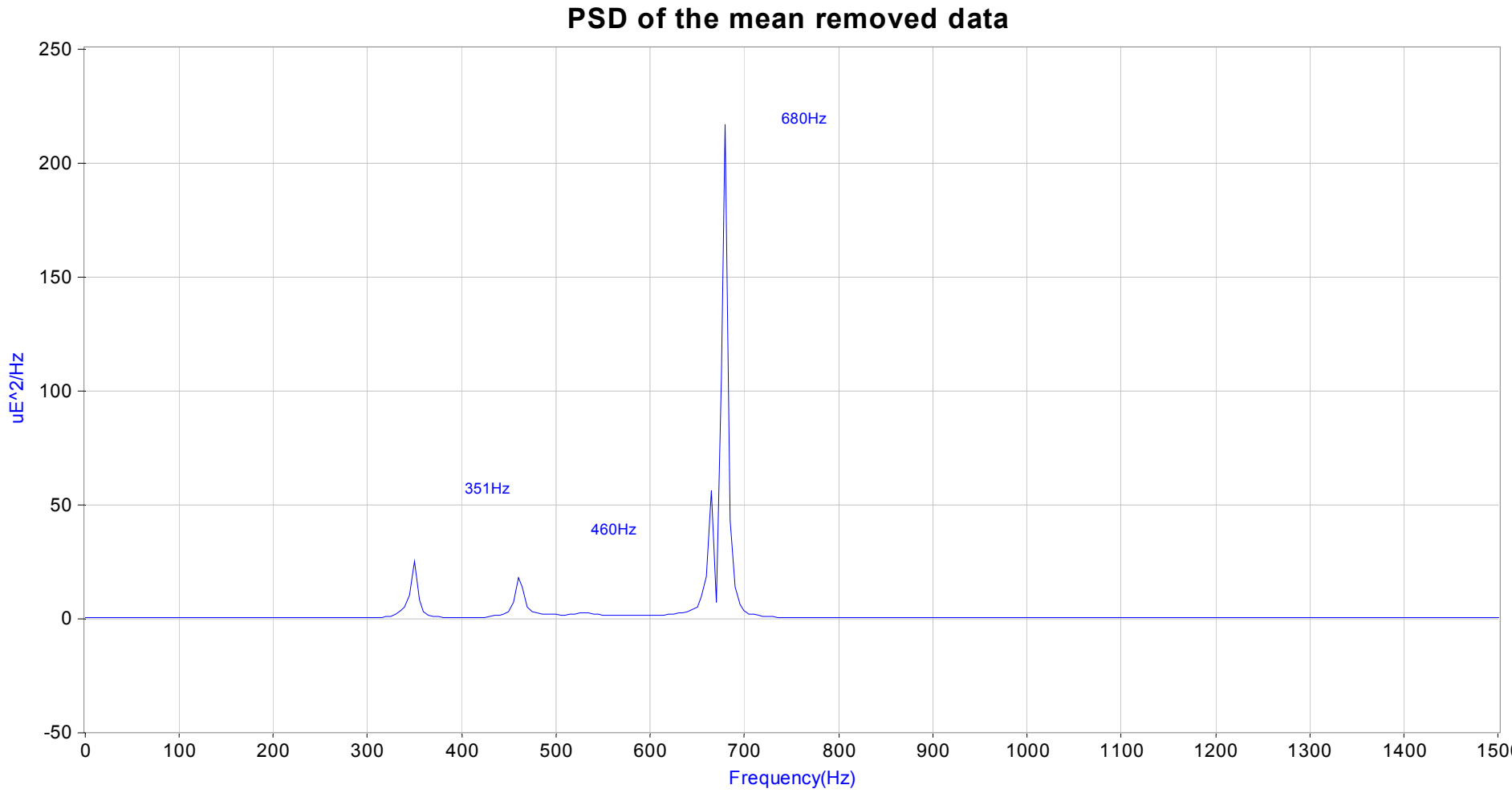
Spoke 6, R1 Strain Gage Signal after 3rd Hammer Blow



Spoke 6, R1 Strain Gage Signal, Mean Removed, after 3rd Hammer Blow

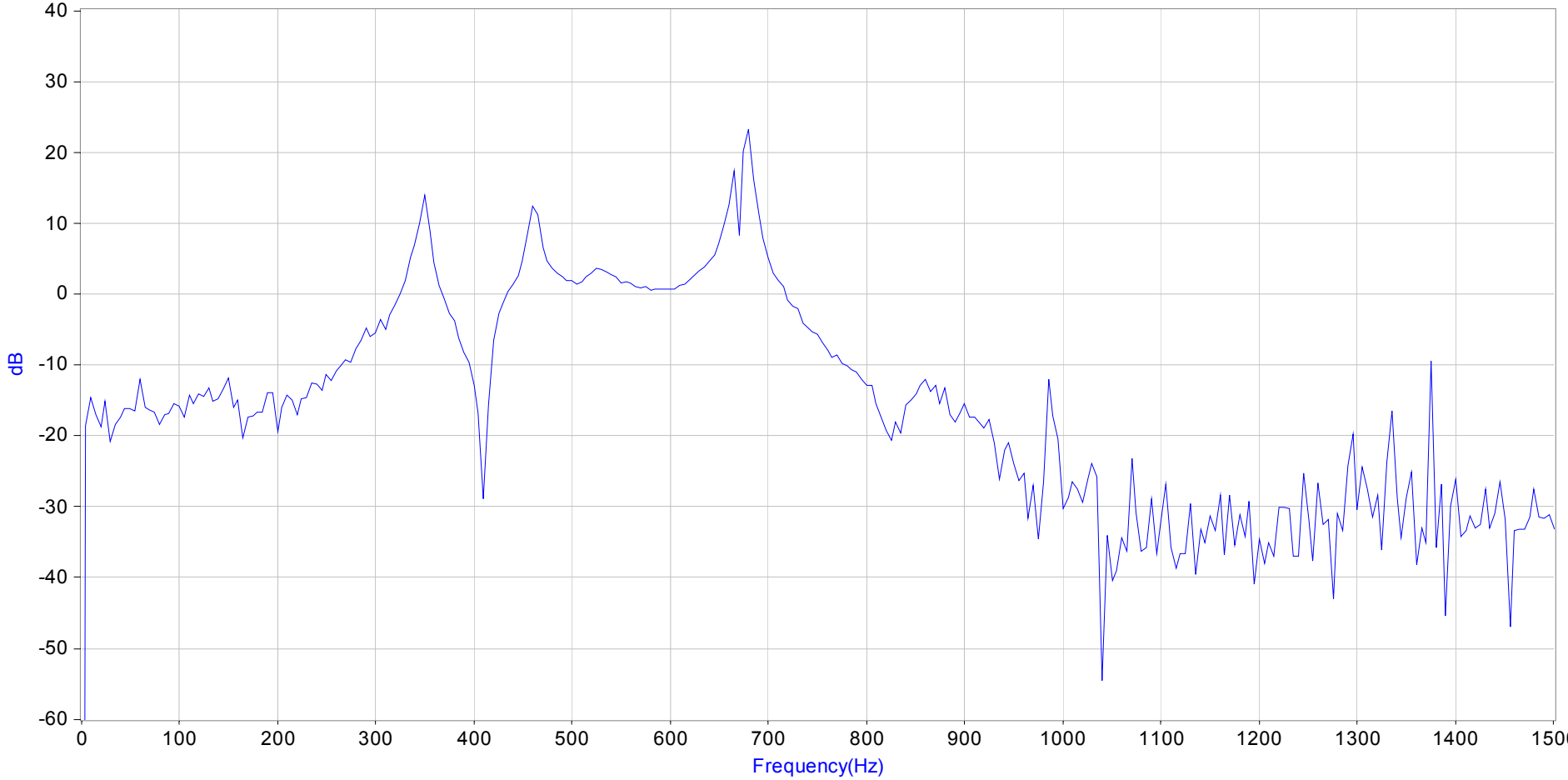


PSD of Spoke 6, R1 Strain Gage Signal, Mean Removed, after 3rd Hammer Blow

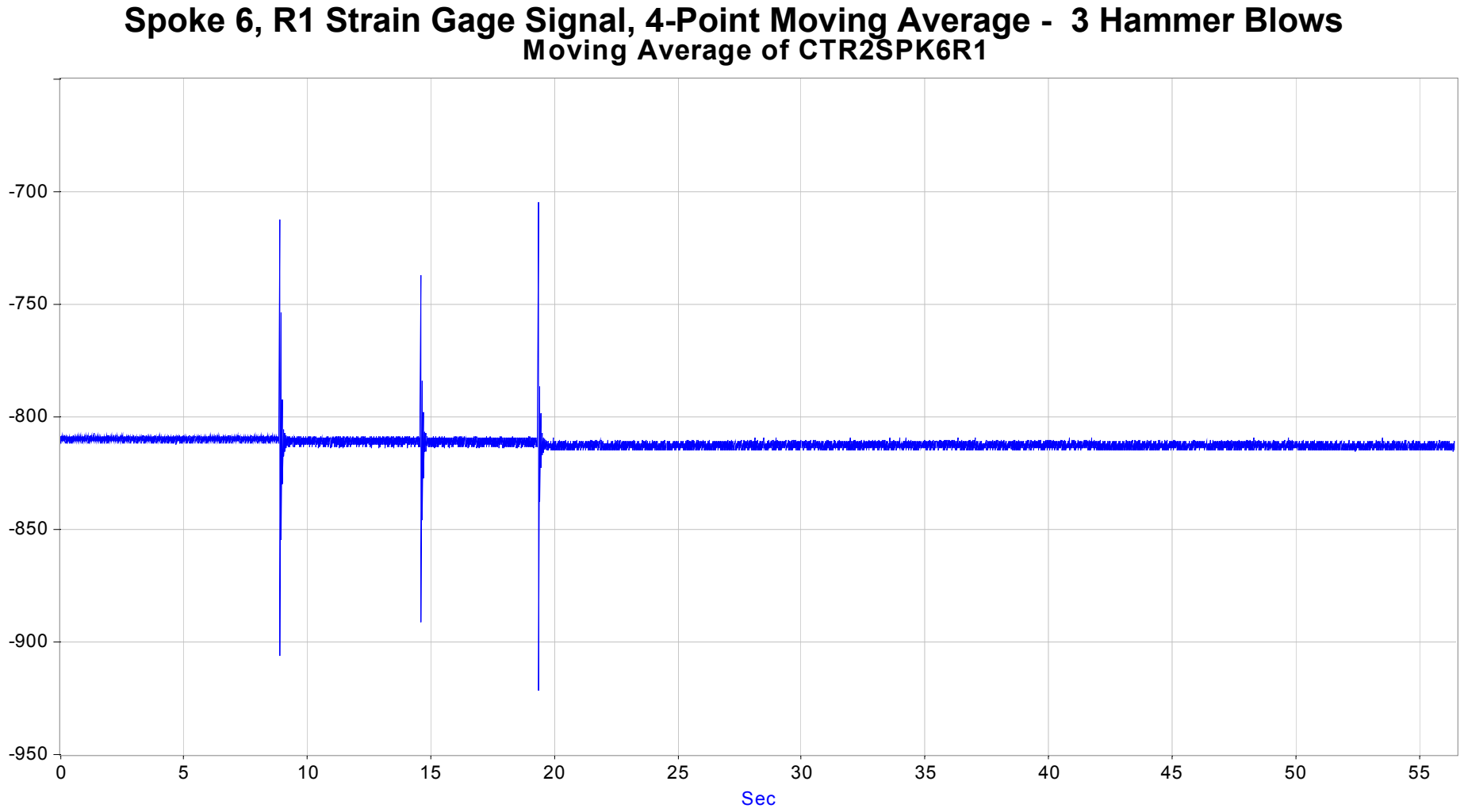


PSD (dB Scale) of Spoke 6, R1 Strain Gage Signal, Mean Removed, after 3rd Hammer Blow

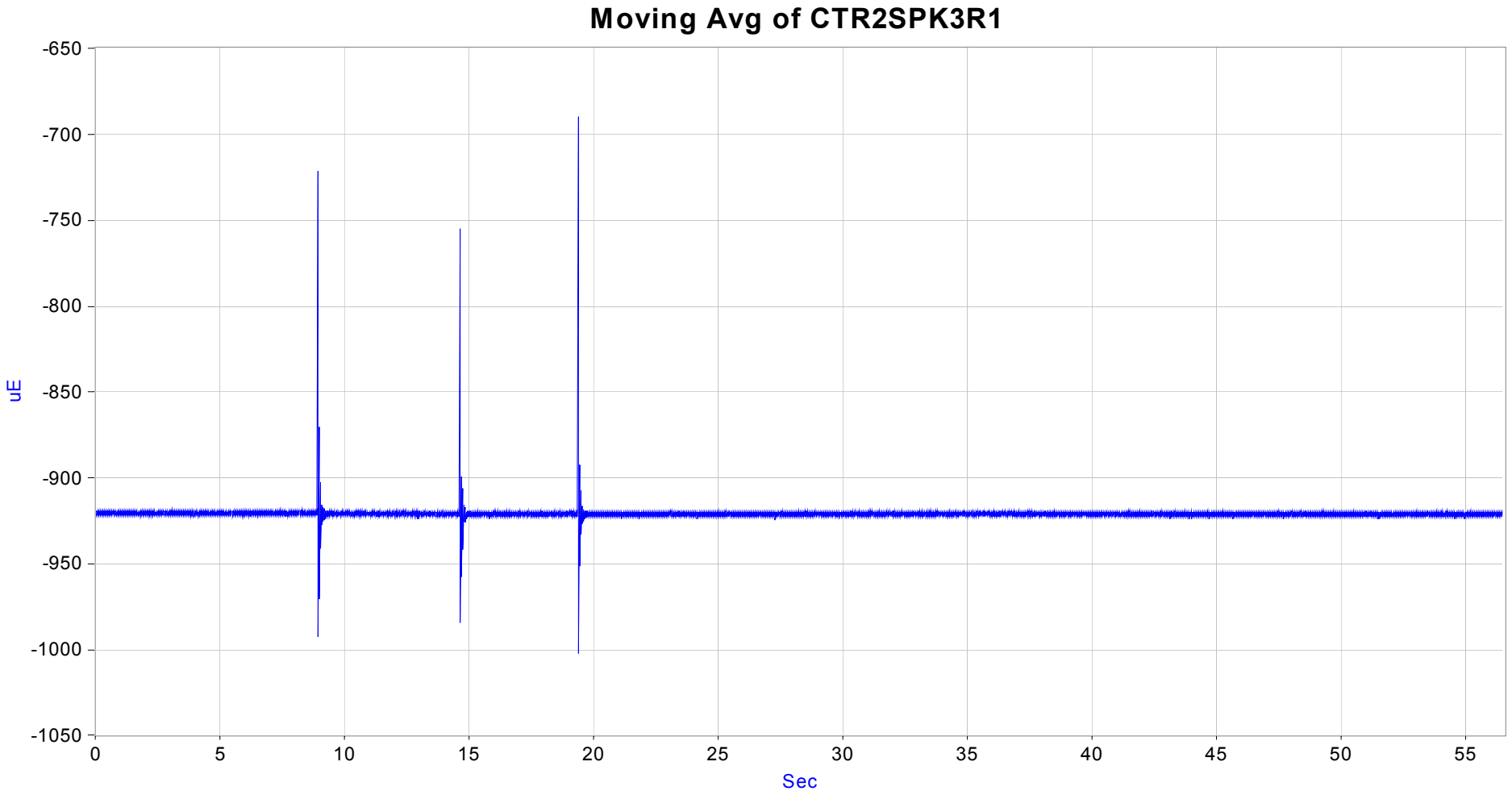
Log10(PSD)*10



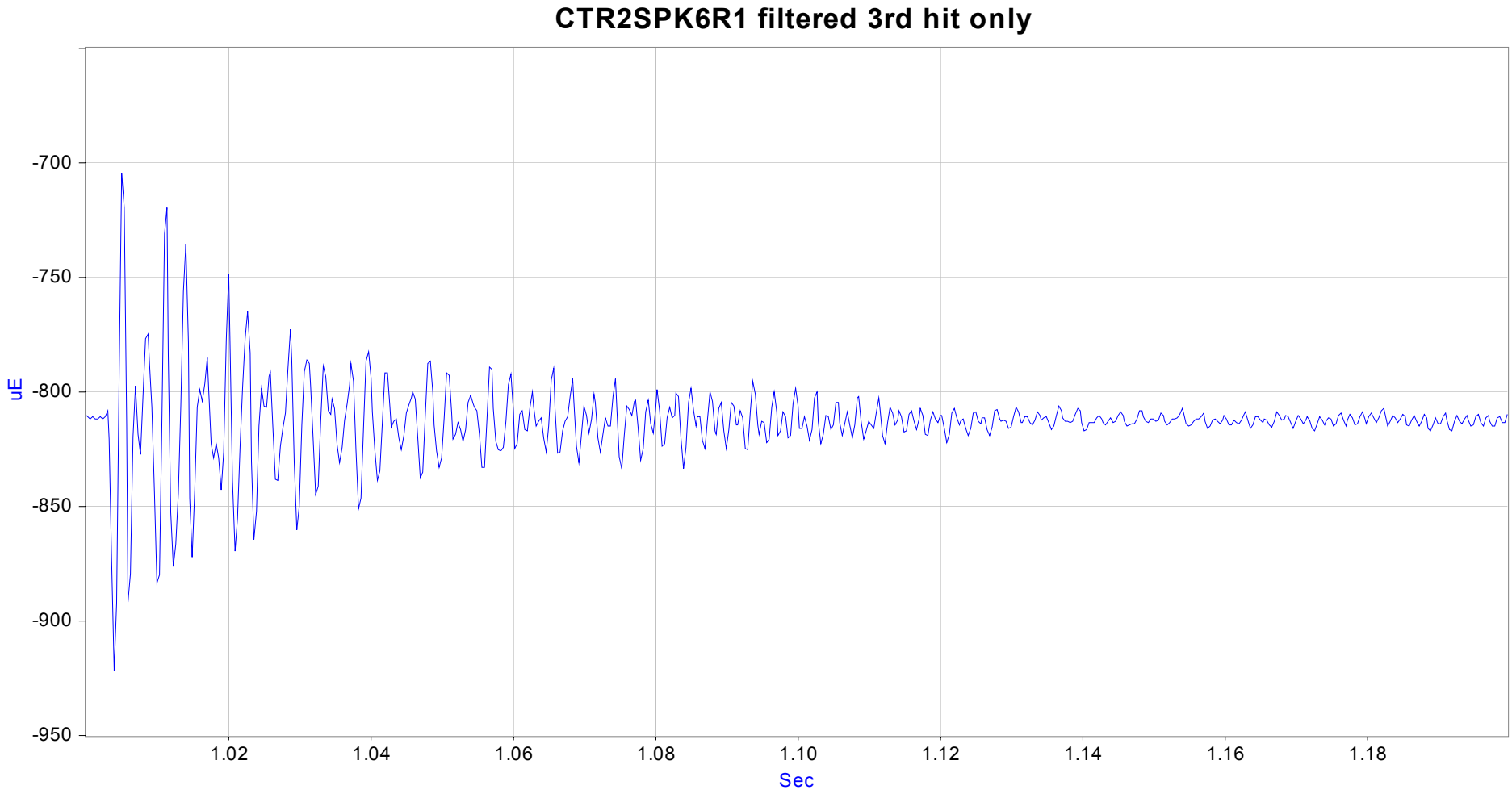
- A 4-point Moving Average Filter Was Applied to Filter Out the Dominant 680 Hz Mode and Focus on the Lower Frequency Modes



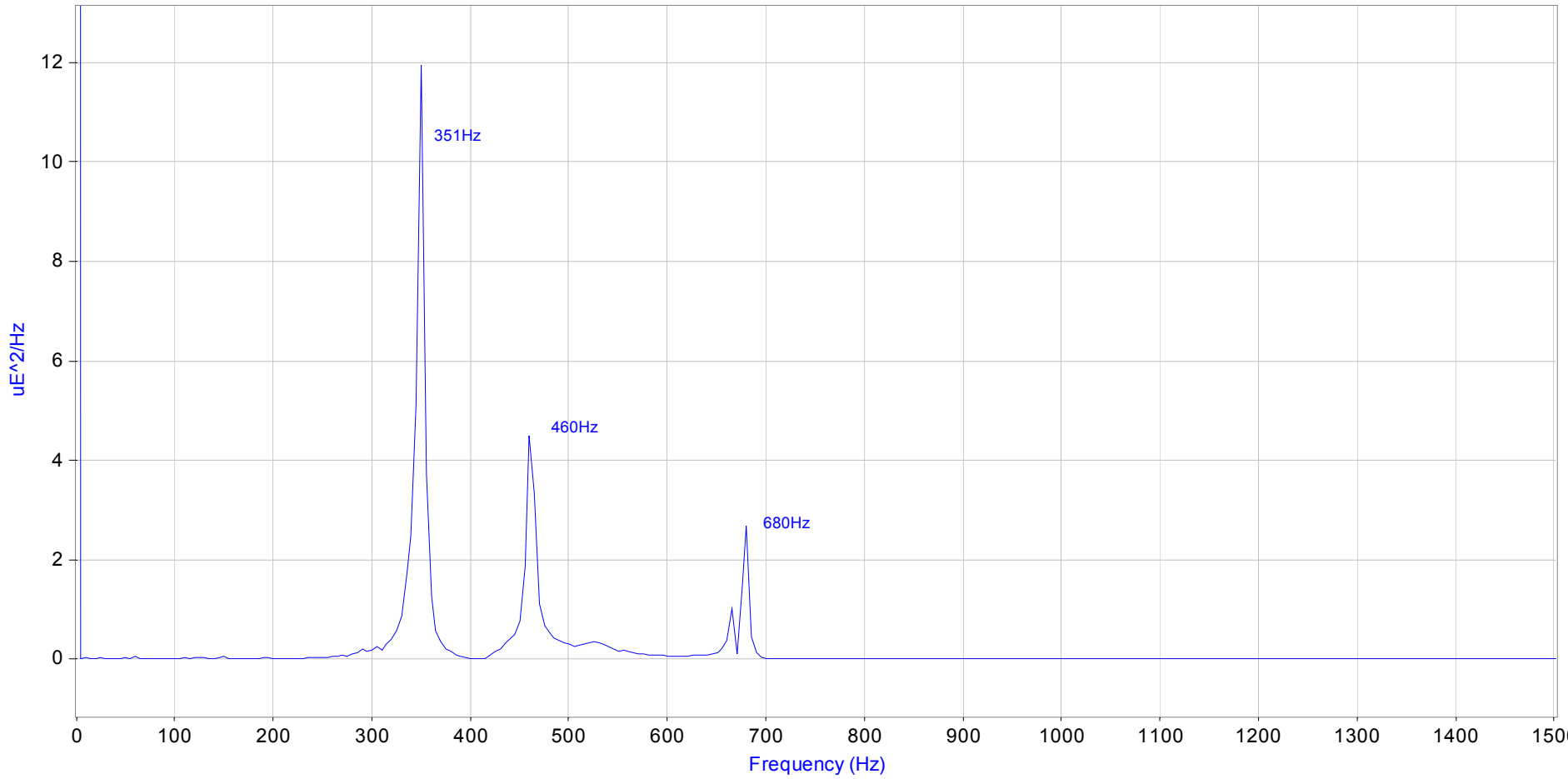
Spoke 3, R1 Strain Gage Signal, 4-Point Moving Average - 3 Hammer Blows



Spoke 6, R1 Strain Gage Signal, 4-Point Moving Average, after 3rd Hammer Blow

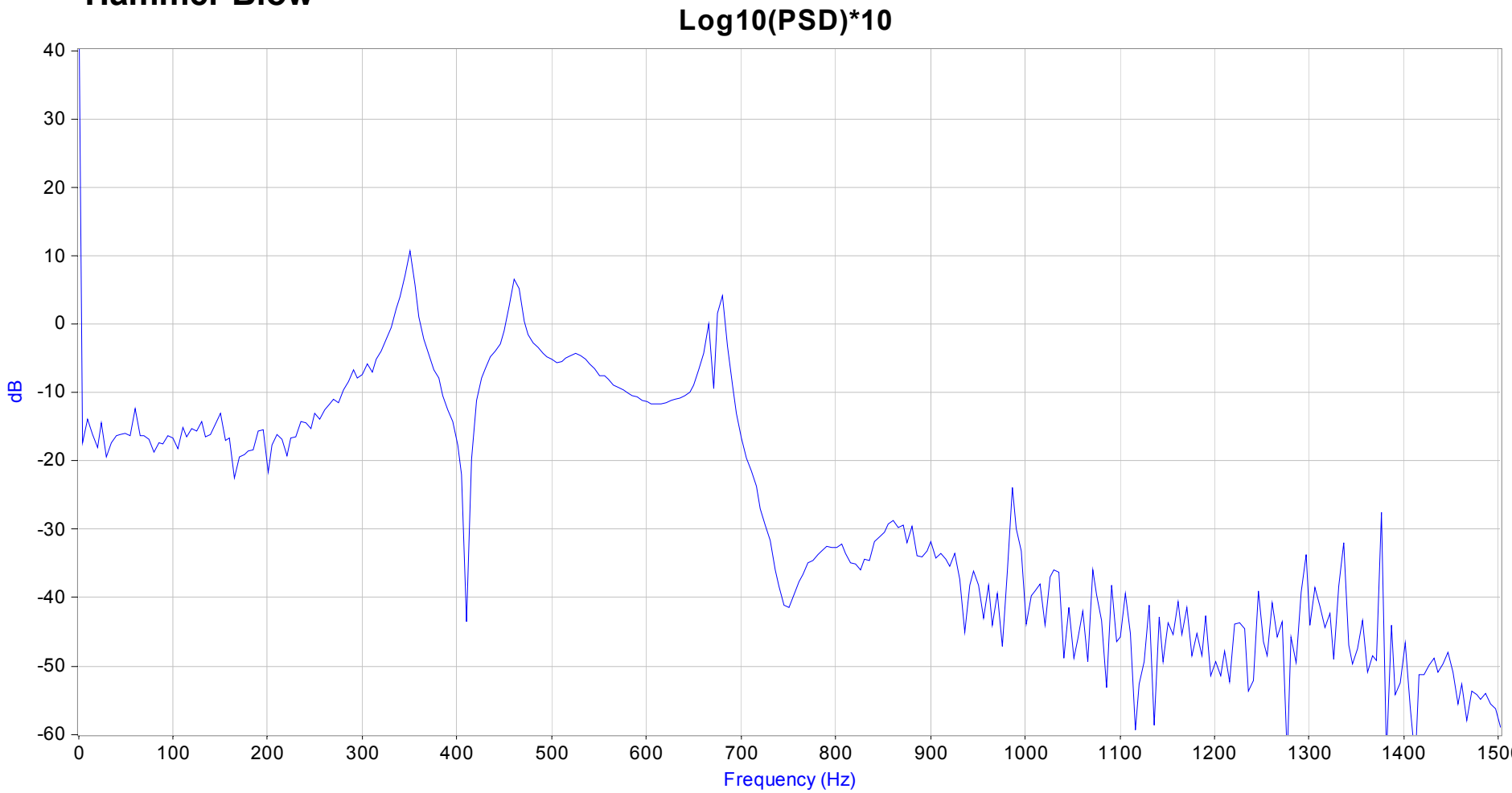


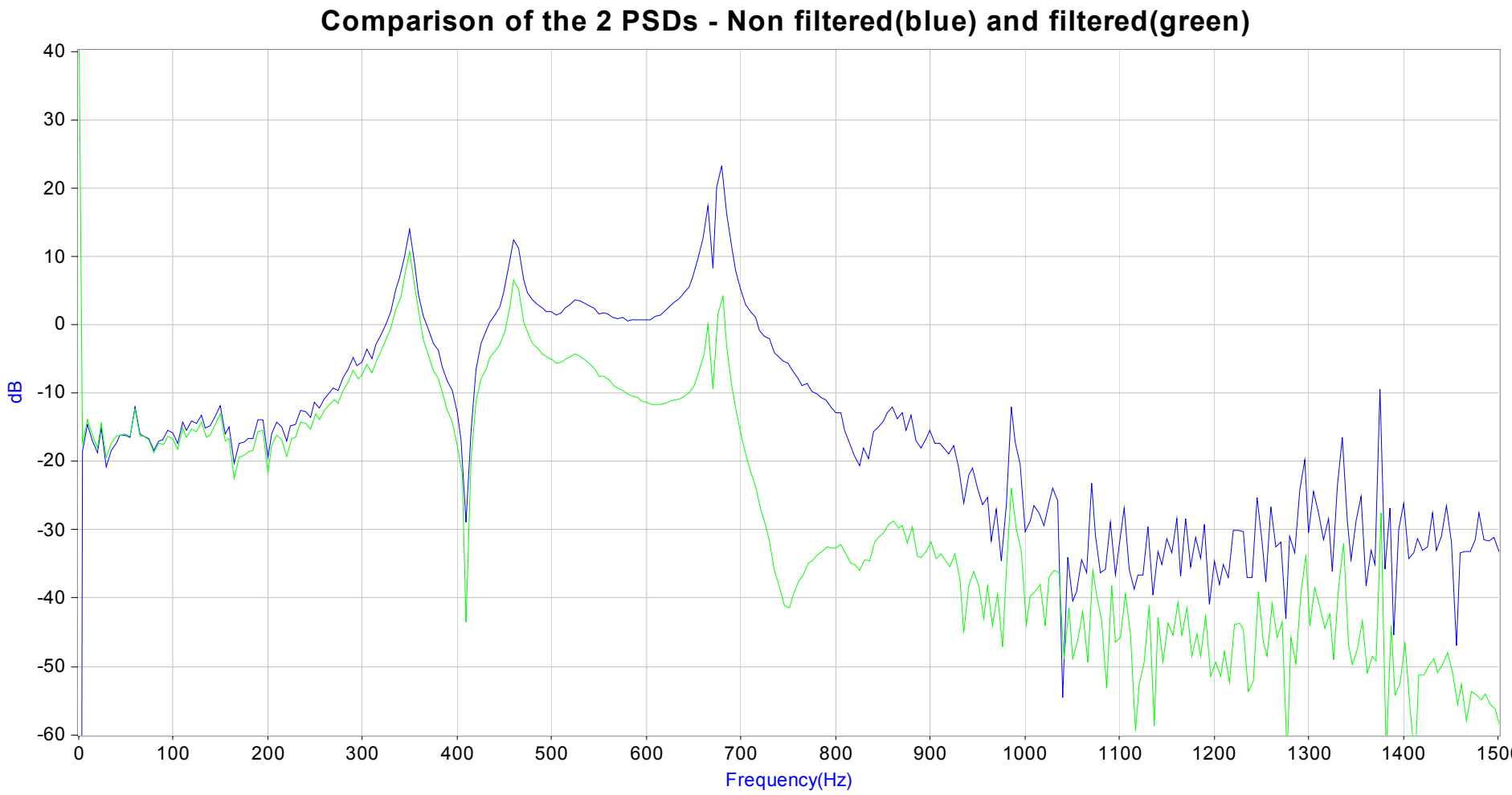
PSD of Spoke 6, R1 Strain Gage Signal, 4-Point Moving Average, after 3rd Hammer Blow

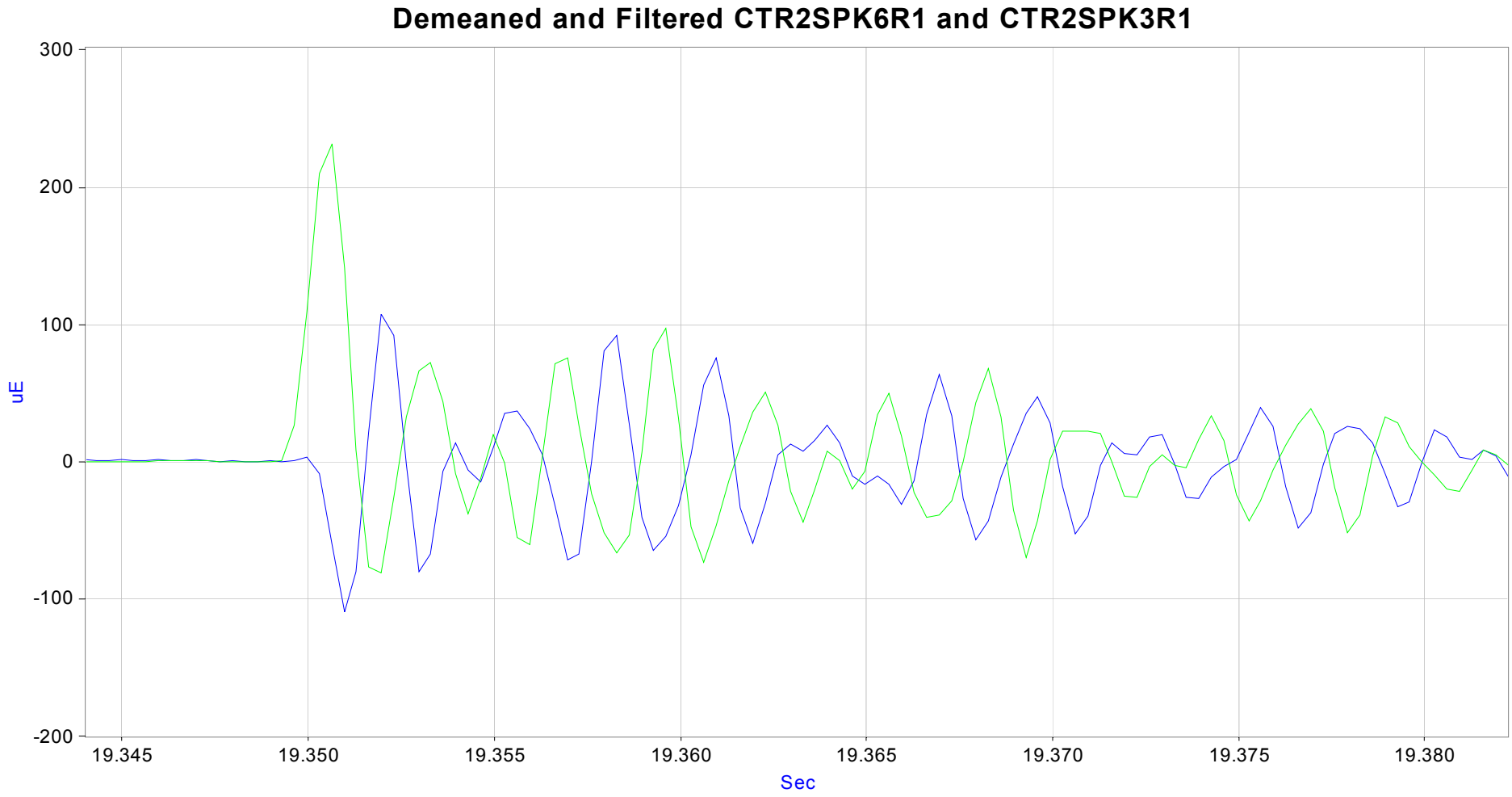


- The Knorr Disc Has A BOP Frequency At 350 Hz

PSD (dB Scale) of Spoke 6, R1 Strain Gage Signal, 4-Point Moving Average, after 3rd Hammer Blow




Comparison of the 2 PSDs - Non filtered(blue) and filtered(green)
dB
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Frequency(Hz)



- The Oscillations Seen On Spokes 3 And 6 Are Out Of Phase With Respect To Each Other