“Can Tilting Pad Bearings Whirl?”

Talmadge D. Ward Jr.
Duke Energy Florida

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ABSTRACT

Intermittent Fluid Film Instability was observed on a GE 7A6 80 MW generator with tilting pad bearings which caused high vibration and sub-synchronous frequencies. Direct shaft vibration as measured by proximeter probes was above 10 mils. Cause was determined to be a combination of excessing bearing clearance, excessive pad pre-load and misalignment.

Background

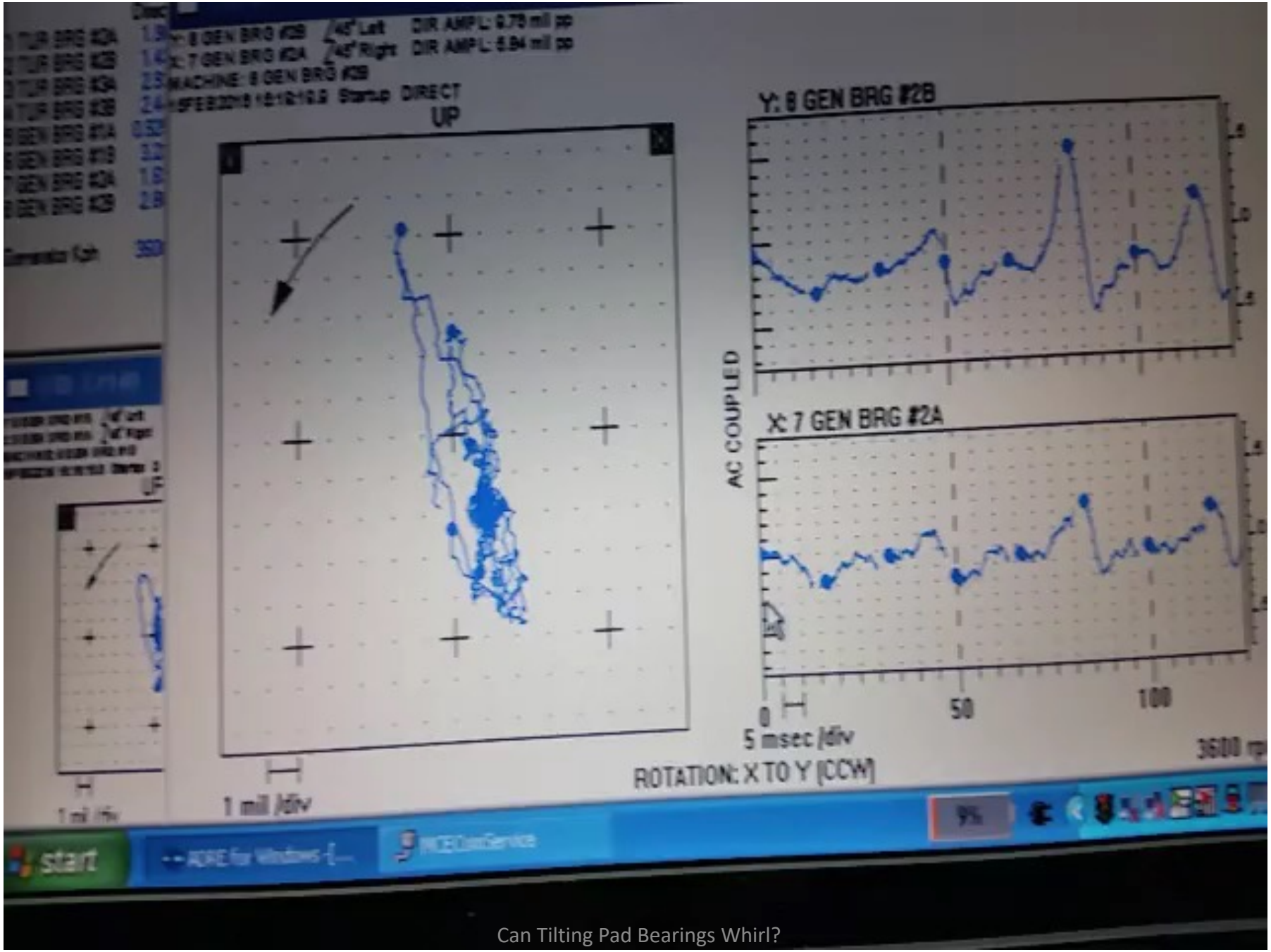
This particular generator has been in operation since 1992 with no indication of fluid film instabilities. Four GE 7EA gas turbines with 7A6 generators were installed at that time and none have shown signs or symptoms of issues other than the occasional need to field balance the generator rotor. These units have both a Bently Nevada 3300 system using 2 orthogonal prox probes on each of the five bearings and a vibration protection system using Metrix 5485C high temperature velocity transducers. Operation has been typical for peaking combustion turbine units and routine scheduled minor and major outages have been performed. Both Generator bearings have 5 tilting pads, load on center and are of the single axis tilting variety.

Event

On February 15, 2016 at approximately 1500 hours I was walking between units 7 and 9 and noticed that the concrete pad was vibrating significantly. The vibration lasted only about 4 seconds and stopped only to restart about 8 seconds later. This cycle was observed several times and so I walked to unit 9 and the vibration became stronger. I entered the Non-Drive End (NDE) housing of the generator and the vibration of the structural was very high during the 4 seconds and then dissipated. Next, I checked the Bently 3300 panel and found that the Drive End (DE) vibration was modulating between 1 mil and 7 mils while the NDE was modulating between 2 mils and 10 mils – full scale range. Next, I installed a Bently Nevada ADRE system to capture the Orbit data. The orbits were stable during the “quite period” and greatly disturbed during the excited period.

Event (cont)

The installed vibration protection system, which uses transducers mounted on the bearing housings at TDC, showed very little increase in vibration during the events. This is likely due to the low frequency energy of the sub-synchronous problem and the inherent filtering of the velocity transducer. As a result, this unit had begun this abnormal behavior and excessive vibration pattern several weeks before, however It generated no vibration alarms by the protection system and so went unnoticed by operations. This emphases the need for prox probe monitoring systems, a gap in some monitoring strategies and the need for periodic local observation of critical equipment


UP
1 mil /div
Y: 8 GEN BRG #2B
X: 7 GEN BRG #2A
AC COUPLED
0
50
100
5 msec /div
ROTATION: X TO Y (CCW)
3600 rpm

Babbit As A Bearing Material

Invented by Isaac Babbitt (born July 26, 1799) in 1839. Called it a white metal alloy with excellent bearing properties. The original formula was 89.3% tin, 7.1% antimony and 3.6% copper. This alloy is still used today and sold as ASTM B-23 Grade 2 Babbitt, aka "Genuine Babbitt".

History Of Tilt Pad Bearings

Albert Kingsbury pioneered the tilting pad bearing for thrust bearing applications. His success is legendary. Consider reading the article of published in the October 2003 Sound and Vibration magazine https://www.kingsbury.com/pdf/albert_kingsbury.pdf

After his thrust bearing success in vertical machines the same concept was applied to radial bearings. Opinion – Without Mr. Babbit and Mr. Kingsbury machinery reliability would be very poor. They changed the world.

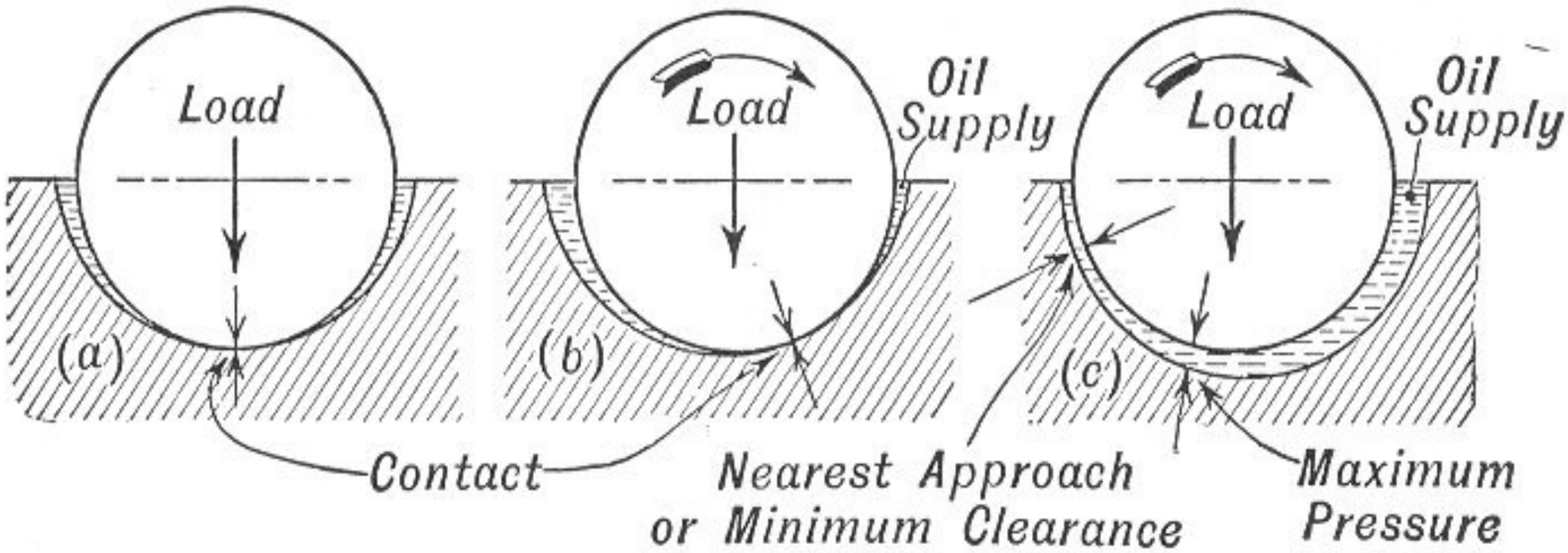
Why They Work

Tilting pads, in either thrust or radial applications, work because the segments allow heated oil to escape and fresh cooler oil to enter the clearance gap. This doesn't allow the oil to circulate continuously in the clearance gap thus breaking up or stopping the sub-synchronous flow and forces that cause Whirl and Whip. Each pad segment also produces a force that lifts the shaft surface away from the bearing surface, just like radial bearings.

The oil wedge is critical to reliability of these bearings and diagnostics is best performed by prox probes, not casing sensors. Understanding the shaft centerline movement with load and speed help us identify overall bearing health and find misalignment as well as other issues.

Oil Wedge

The oil wedge is key to the babbit bearing performance. Many think that, with proper lubrication, a correctly designed babbit bearing has almost infinite life, unlike rolling element bearings.



FROM - Tilting Pad Bearing Overview - http://wiki.vintagemachinery.org/BabbittWhatIsIt.ashx

Important Term

Preload – Basically the difference of shaft radius and pad radius. This causes the pad to rock or tilt when the oil wedge is present.

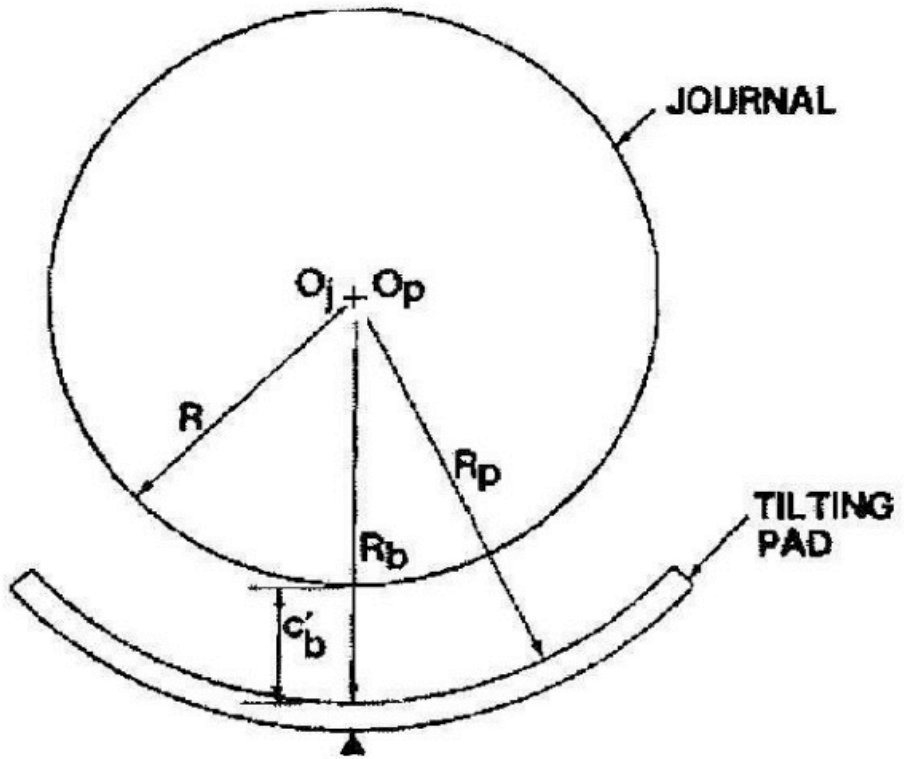
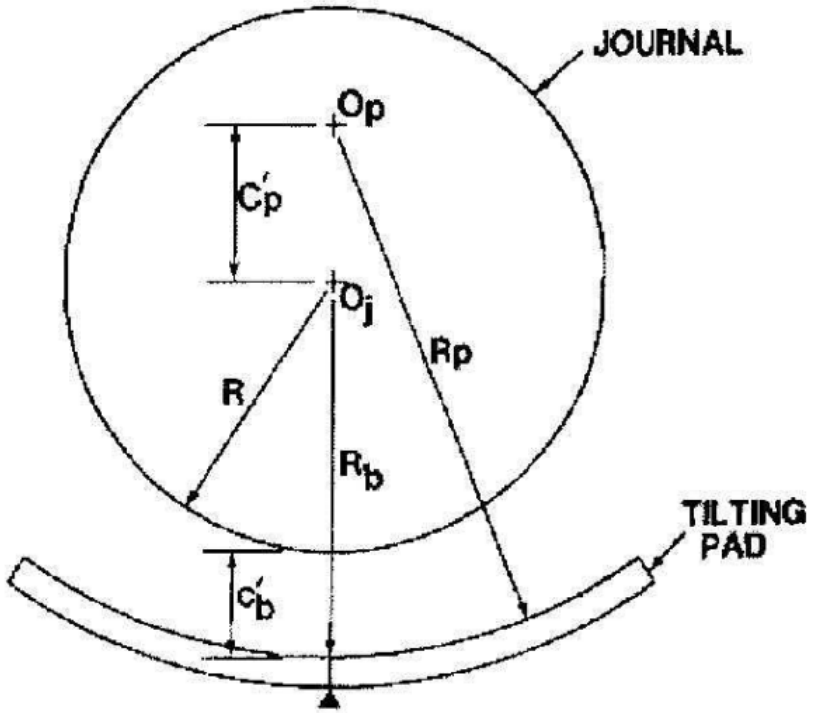


Figure 14. Zero Preloaded Tilting Pad.



$R_b = R + c'_b$

$R_p = R + c'_p$

PRELOAD, $m = 1 - c'_b/c'_p$

TYPICAL m = .2 to .6
(20% to 60%)

c'_b = ASSEMBLED BEARING CLEARANCE

c'_p = PAD CLEARANCE

Figure 15. Preloaded Tilting Pad.

Figures from Nicholas, 23rd Turbo Symposium

Tilt Pad Advantages:

Damping and Stability – designs can be alter to compensate for rotor design issues by shifting rotor critical speeds or reducing the amplification factor to reach an acceptable vibration level.

Disadvantages – Complexity, cost, and a much more involved repair processes.

Whirl and Whip

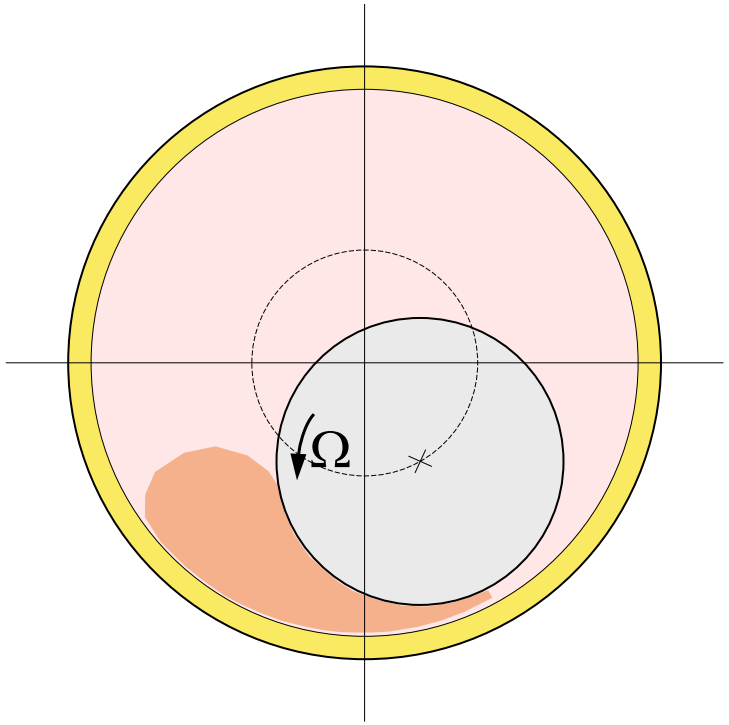
Whirl is more common than Whip and is caused by the rotation velocity of the oil within the annular clearance created by the shaft journal and bearing inside diameter. It tends to be seen at a fraction of shaft speed – 0.42 to 0.48% and can generate very high and destructive forces. Whip occurs when the sub-synchronous frequency coincides with a rotor critical and is both highly destructive and rare.

See Article by Jim Berry - https://www.machinerylubrication.com/Read/754/oil-whirl-whip

Tangential Force

- In a ***properly*** **loaded bearing**, **the tangential force is low**

- For a **rotor *improperly* loaded**, as speed increases, tangential forces become stronger while spring and damping forces do not. **High tangential forces generate fluid instability**



Click to animate

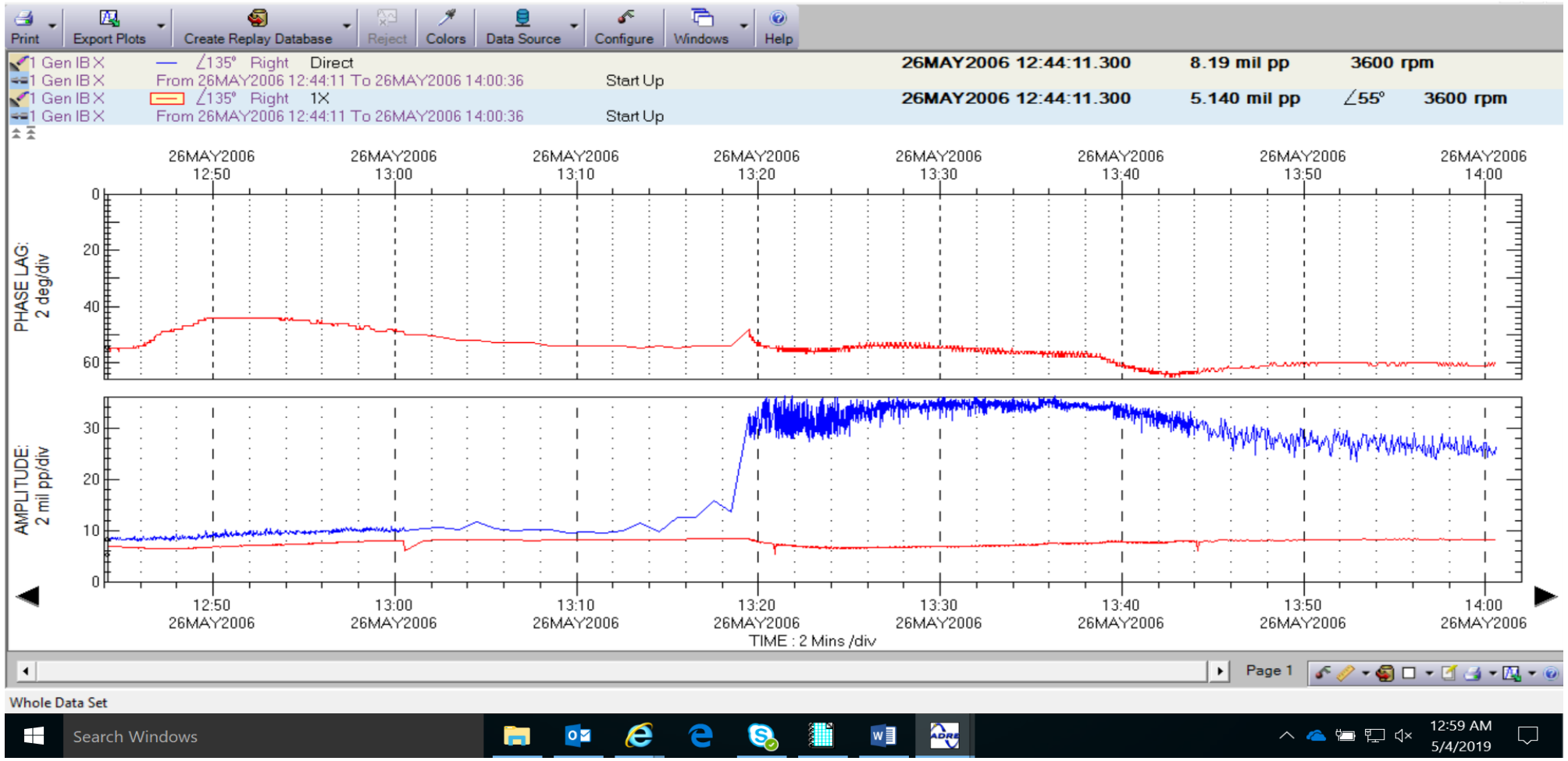
Example of Elliptical Bearing Whirl

GE 7EA with misalignment

May 26, 2006

35 mils

Shook the control room 250 ft. away.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Export Plots
Create Replay Database
Reject
Colors
Data Source
Configure
Windows
Help
1 Gen IB X ∠135° Right Direct
From 26MAY2006 12:44:11 To 26MAY2006 14:00:36 Start Up
26MAY2006 12:44:11.300 8.19 mil pp 3600 rpm
1 Gen IB X ∠135° Right 1X
From 26MAY2006 12:44:11 To 26MAY2006 14:00:36 Start Up
26MAY2006 12:44:11.300 5.140 mil pp ∠55° 3600 rpm
26MAY2006 12:50
26MAY2006 13:00
26MAY2006 13:10
26MAY2006 13:20
26MAY2006 13:30
26MAY2006 13:40
26MAY2006 13:50
26MAY2006 14:00
PHASE LAG: 2 deg/div
0
20
40
60
AMPLITUDE: 2 mil pp/div
30
20
10
0
12:50 26MAY2006
13:00 26MAY2006
13:10 26MAY2006
13:20 26MAY2006
13:30 26MAY2006
13:40 26MAY2006
13:50 26MAY2006
14:00 26MAY2006
TIME : 2 Mins /div
Page 1
Whole Data Set
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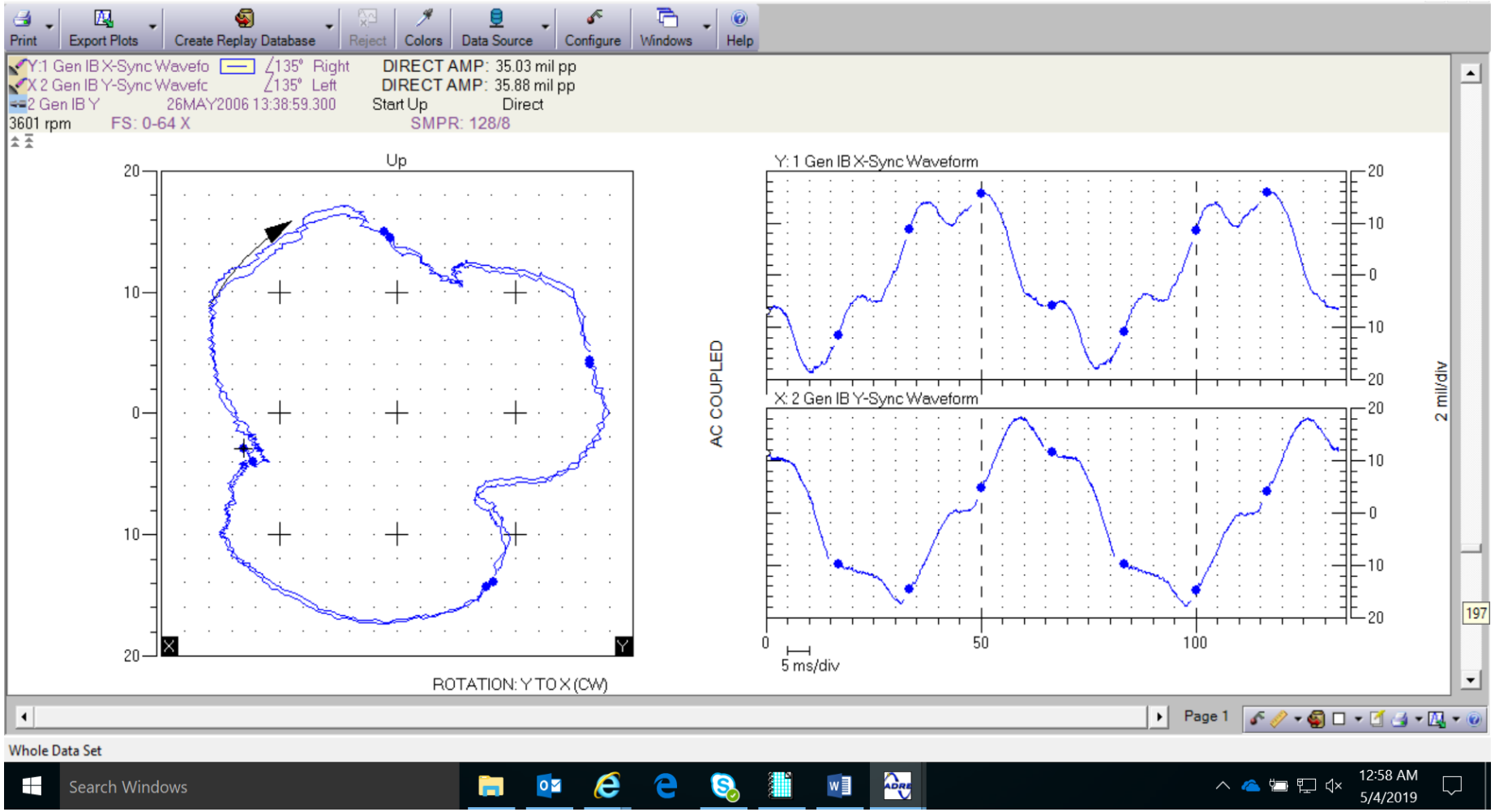
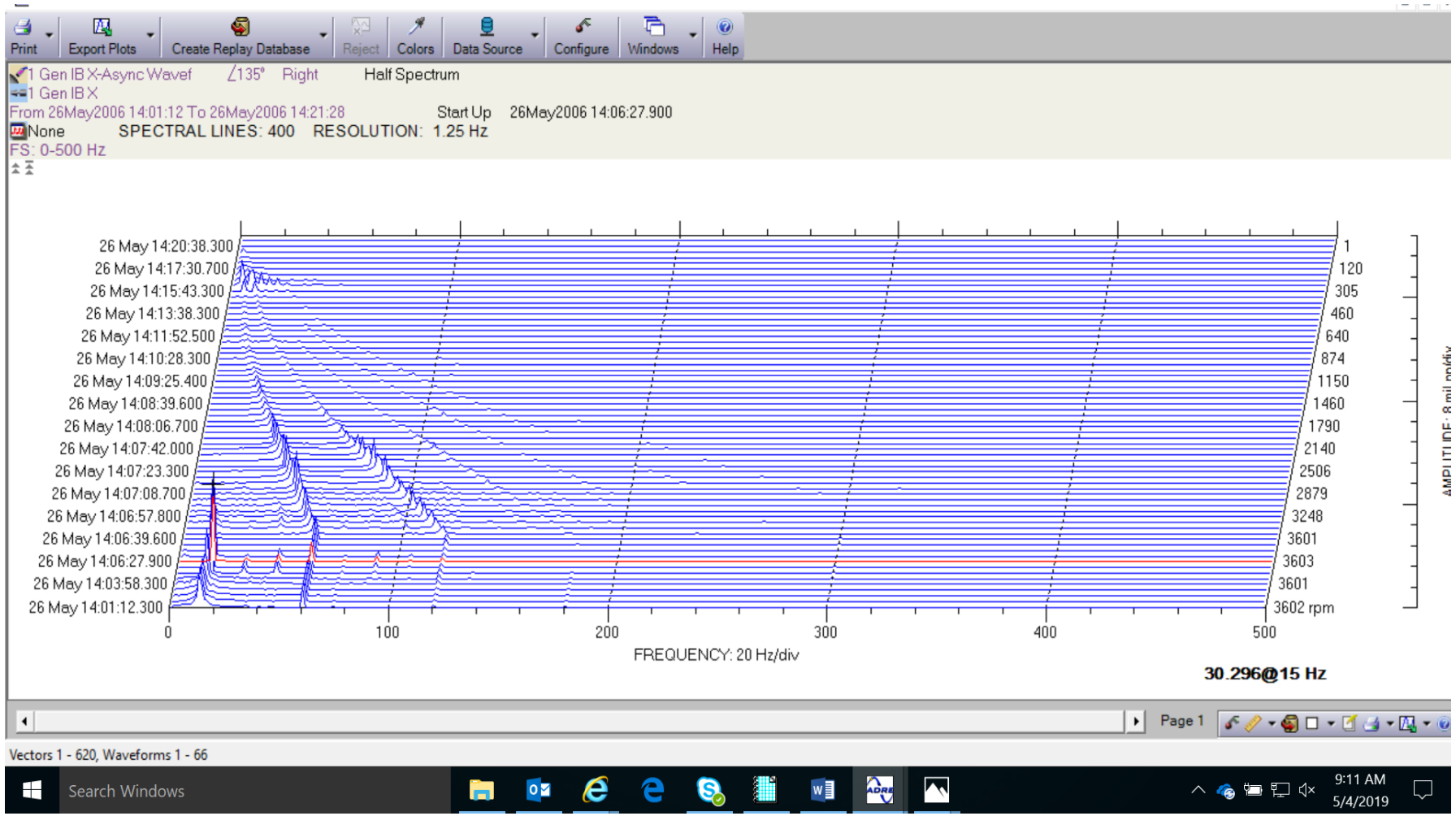
12:59 AM
5/4/2019


Print
Export Plots
Create Replay Database
Reject
Colors
Data Source
Configure
Windows
Help
Y:1 Gen IB X-Sync Wavefo
X 2 Gen IB Y-Sync Wavefc
2 Gen IB Y
3601 rpm
FS: 0-64 X
135° Right
135° Left
26MAY2006 13:38:59.300
DIRECT AMP: 35.03 mil pp
DIRECT AMP: 35.88 mil pp
Start Up
Direct
SMPR: 128/8
Up
ROTATION: Y TO X (CW)
Y: 1 Gen IB X-Sync Waveform
X: 2 Gen IB Y-Sync Waveform
AC COUPLED
2 mil/div
5 ms/div
Page 1
Whole Data Set
Search Windows
12:58 AM
5/4/2019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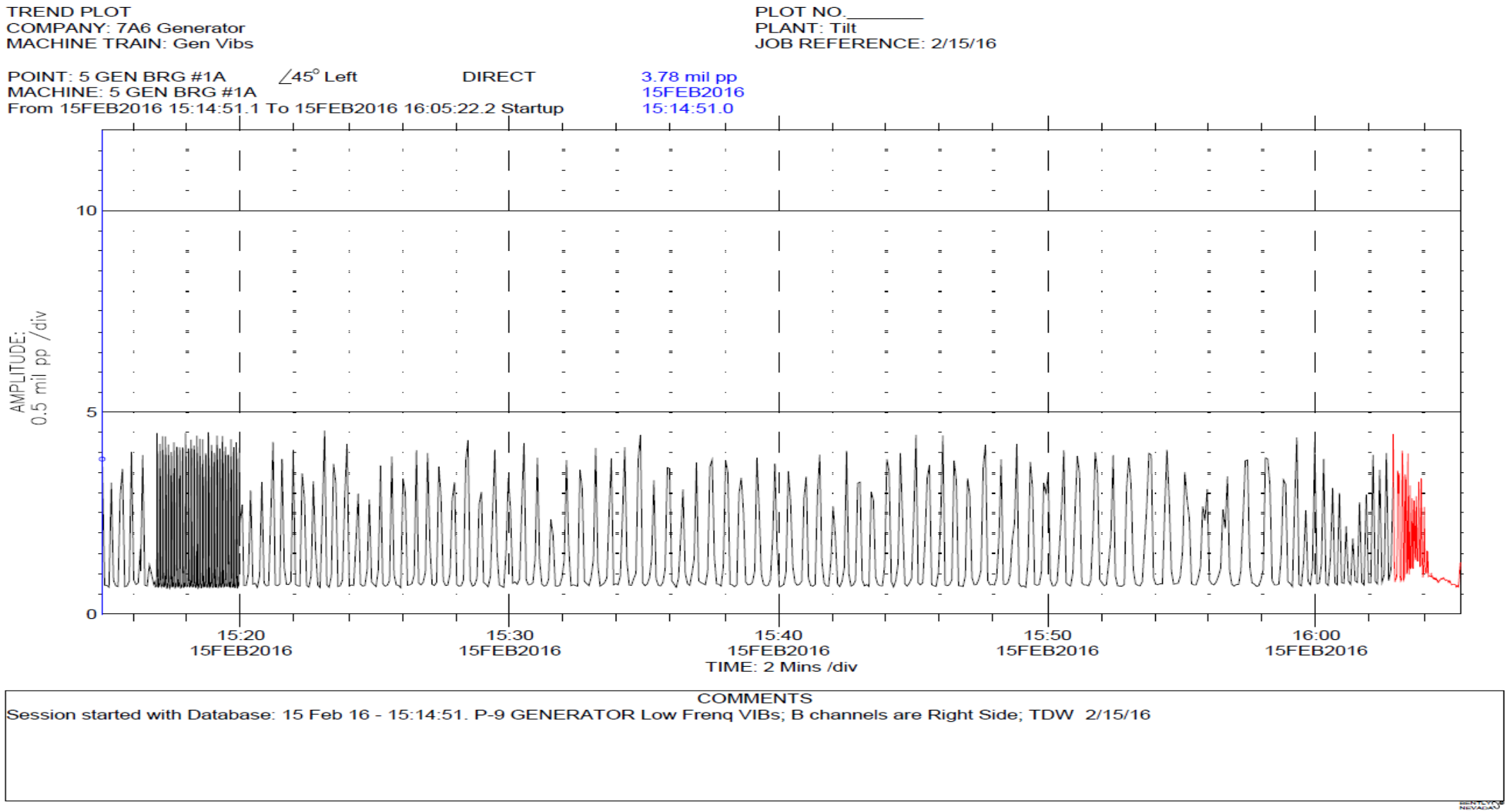
Export Plots
Create Replay Database
Reject
Colors
Data Source
Configure
Windows
Help
1 Gen IB X-Async Wavef ∠135° Right Half Spectrum
1 Gen IB X
From 26May2006 14:01:12 To 26May2006 14:21:28 Start Up 26May2006 14:06:27.900
None SPECTRAL LINES: 400 RESOLUTION: 1.25 Hz
FS: 0-500 Hz
26 May 14:20:38.300
26 May 14:17:30.700
26 May 14:15:43.300
26 May 14:13:38.300
26 May 14:11:52.500
26 May 14:10:28.300
26 May 14:09:25.400
26 May 14:08:39.600
26 May 14:08:06.700
26 May 14:07:42.000
26 May 14:07:23.300
26 May 14:07:08.700
26 May 14:06:57.800
26 May 14:06:39.600
26 May 14:06:27.900
26 May 14:03:58.300
26 May 14:01:12.300
1
120
305
460
640
874
1150
1460
1790
2140
2506
2879
3248
3601
3603
3601
3602 rpm
0
100
200
300
400
500
FREQUENCY: 20 Hz/div
30.296@15 Hz
Page 1
Vectors 1 - 620, Waveforms 1 - 66
Search Windows
9:11 AM
5/4/2019

Diagnostic Steps

My initial theory was a fluid film instability based on previous experience with a GE 7B gas turbine that displayed similar intermittent “Shakes the Earth” vibration some 10 years prior. However, following the easiest and cheapest approach to diagnostics and correction, other causes were considered. Top of this list is a rotor rub at the air or oil deflectors of the generator bearings. Looking at the Polar data this seemed reasonable. We considered oil temperature as a contributing cause but the running temperature was well within the normal range for this and other units. In fact it usually ran at the top end of the temperature range. Cold oil is considered a contributor to Whirl and Whip but this was not our condition. Unbalance was not considered a possible cause since the vibration levels were low during the quiet periods. Pad flutter was also considered however we found little diagnostic information to help this pursue this theory.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MACHINE TRAIN: Gen Vibs
PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16
POINT: 5 GEN BRG #1A
MACHINE: 5 GEN BRG #1A
From 15FEB2016 15:14:51.1 To 15FEB2016 16:05:22.2 Startup
∠45° Left
DIRECT
3.78 mil pp
15FEB2016
15:14:51.0
AMPLITUDE:
0.5 mil pp /div
10
5
0
15:20
15FEB2016
15:30
15FEB2016
15:40
15FEB2016
15:50
15FEB2016
16:00
15FEB2016
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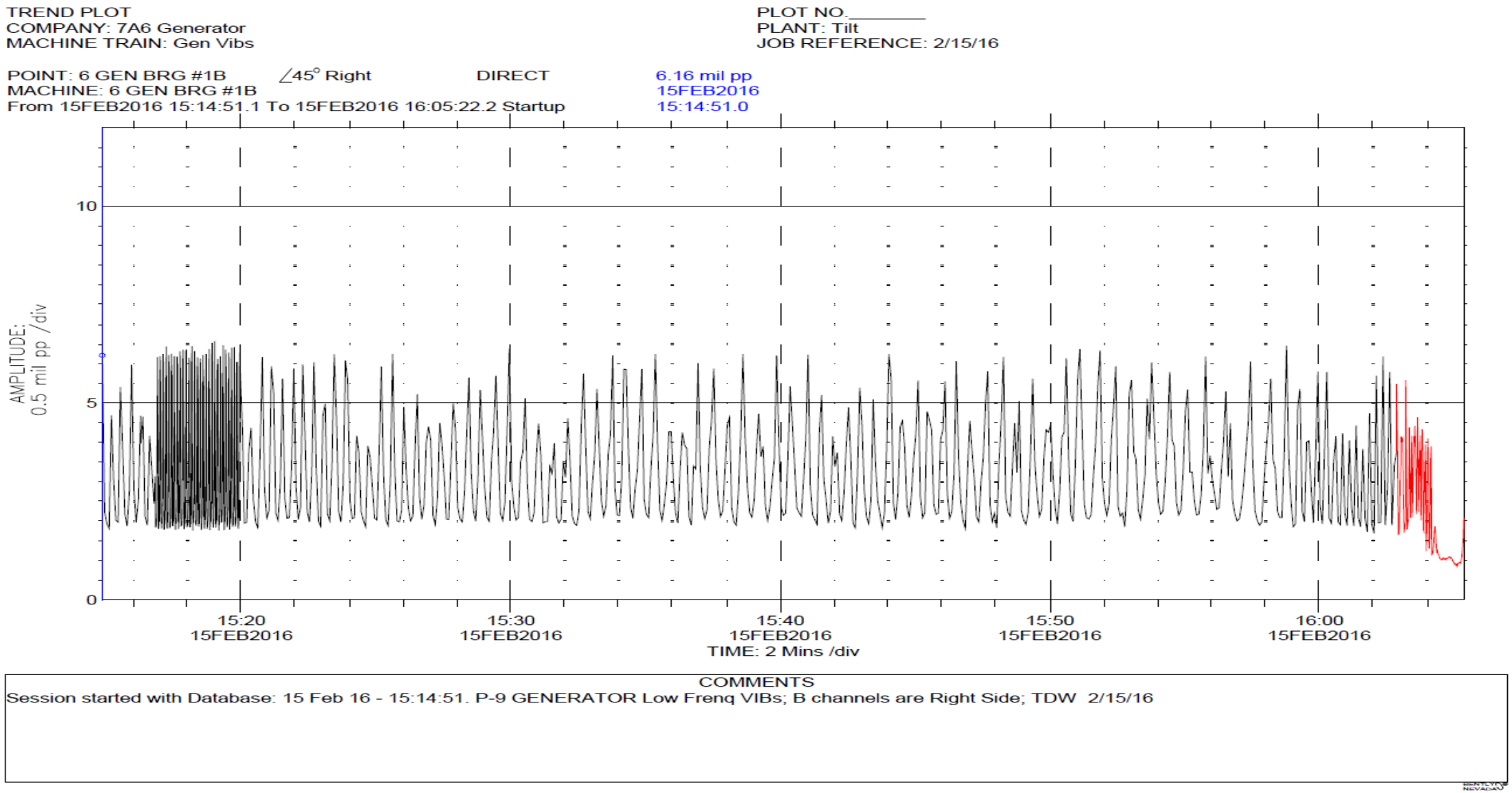
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COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs
PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16
POINT: 6 GEN BRG #1B ∠45° Right DIRECT
MACHINE: 6 GEN BRG #1B
From 15FEB2016 15:14:51.1 To 15FEB2016 16:05:22.2 Startup
6.16 mil pp
15FEB2016
15:14:51.0
AMPLITUDE:
0.5 mil pp /div
10
5
0
15:20
15FEB2016
15:30
15FEB2016
15:40
15FEB2016
15:50
15FEB2016
16:00
15FEB2016
TIME: 2 Mins /div
COMMENTS
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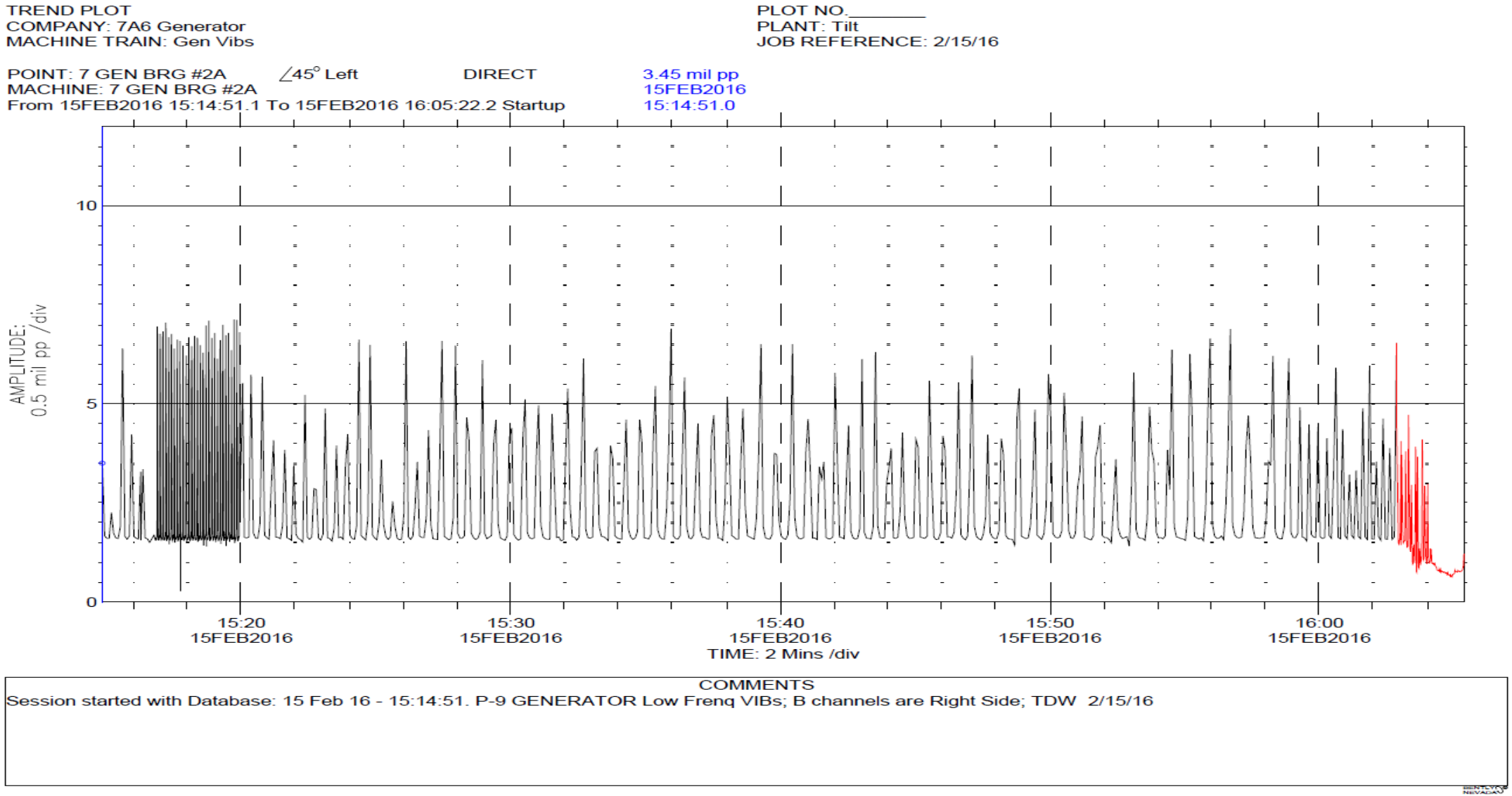
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MACHINE TRAIN: Gen Vibs
PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16
POINT: 7 GEN BRG #2A
MACHINE: 7 GEN BRG #2A
From 15FEB2016 15:14:51.1 To 15FEB2016 16:05:22.2 Startup
∠45° Left
DIRECT
3.45 mil pp
15FEB2016
15:14:51.0
AMPLITUDE:
0.5 mil pp /div
10
5
0
15:20
15FEB2016
15:30
15FEB2016
15:40
15FEB2016
15:50
15FEB2016
16:00
15FEB2016
TIME: 2 Mins /div
COMMENTS
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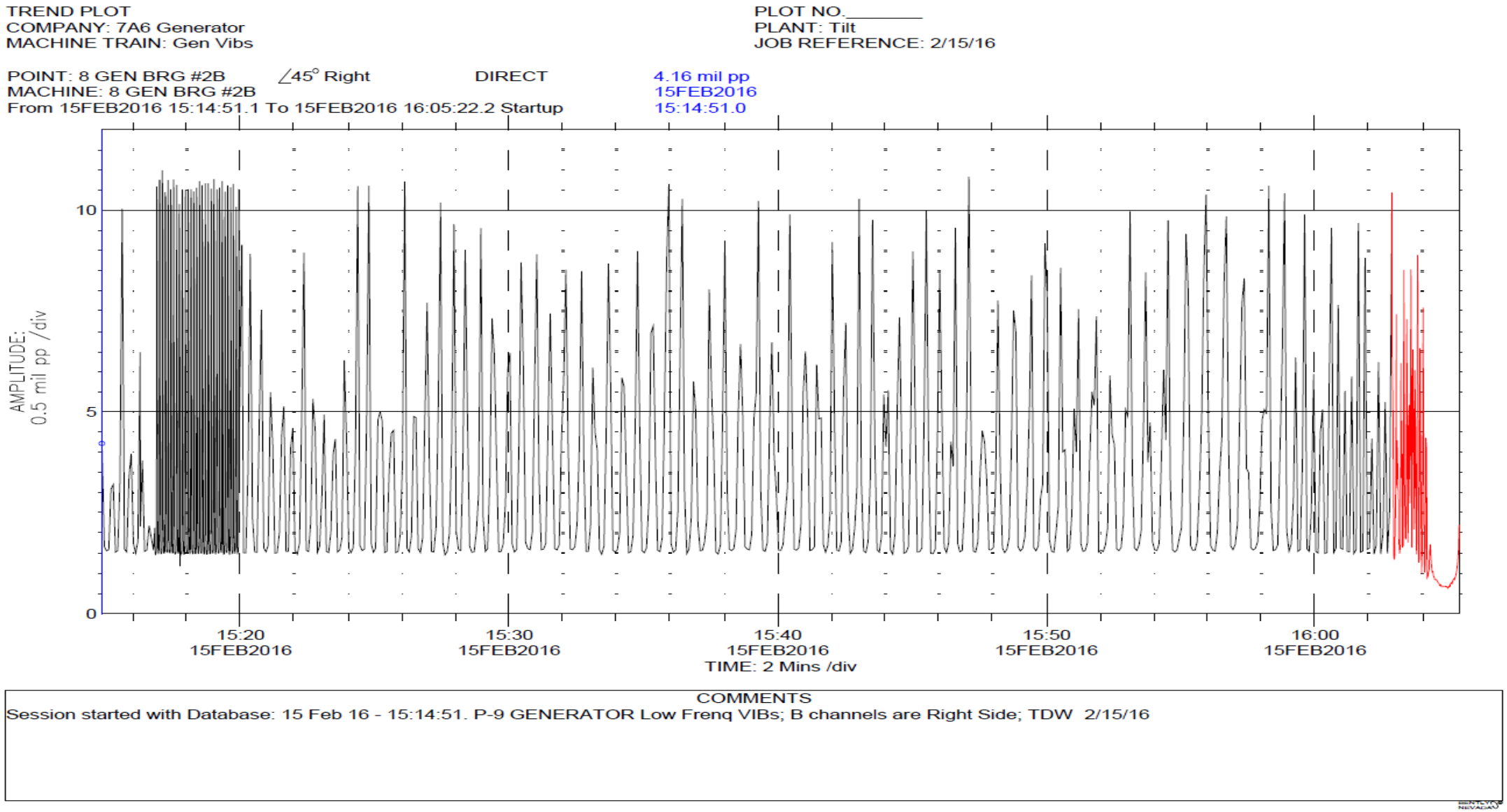
TREND PLOT
COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs
PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16
POINT: 8 GEN BRG #2B ∠45° Right DIRECT
MACHINE: 8 GEN BRG #2B
From 15FEB2016 15:14:51.1 To 15FEB2016 16:05:22.2 Startup
4.16 mil pp
15FEB2016
15:14:51.0
AMPLITUDE:
0.5 mil pp /div
10
5
0
15:20
15FEB2016
15:30
15FEB2016
15:40
15FEB2016
15:50
15FEB2016
16:00
15FEB2016
TIME: 2 Mins /div
COMMENTS
Session started with Database: 15 Feb 16 - 15:14:51. P-9 GENERATOR Low Frenq VIBs; B channels are Right Side; TDW 2/15/16

POLAR PLOT
COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs

PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16

POINT: 5 GEN BRG #1A ∠45° Left 1X UNCOMP 1.06∠167° @3600 rpm
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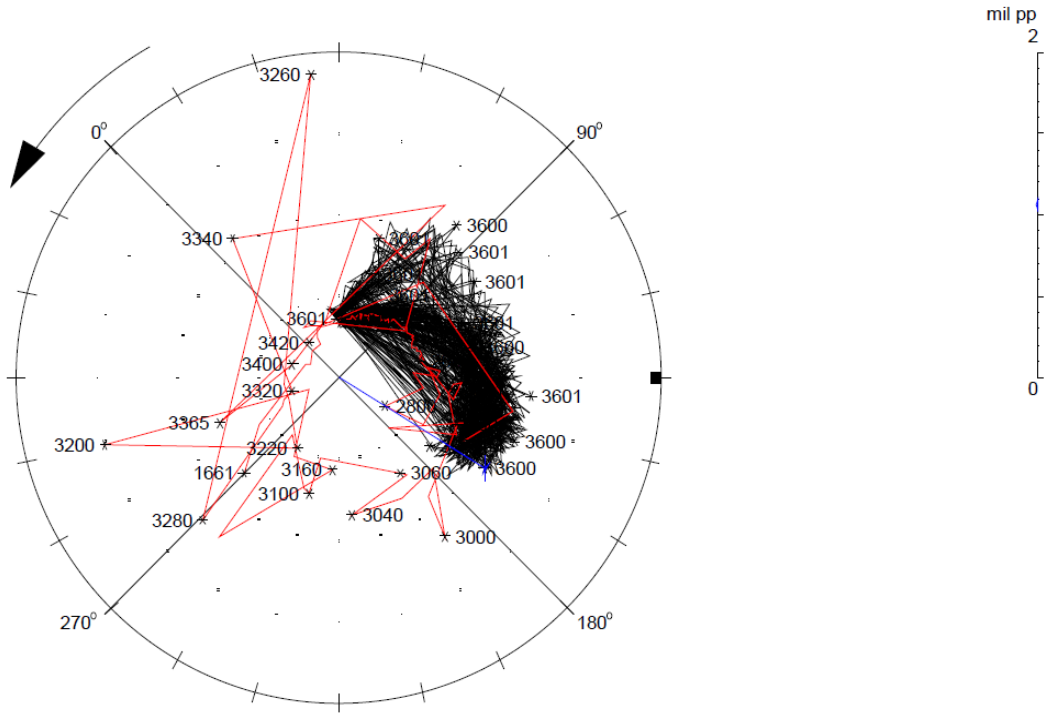

2 mil pp FULL SCALE

CCW ROTATION

COMMENTS
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POLAR PLOT
COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs

PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16

POINT: 6 GEN BRG #1B ∠45° Right 1X UNCOMP 2.10∠151° @3600 rpm
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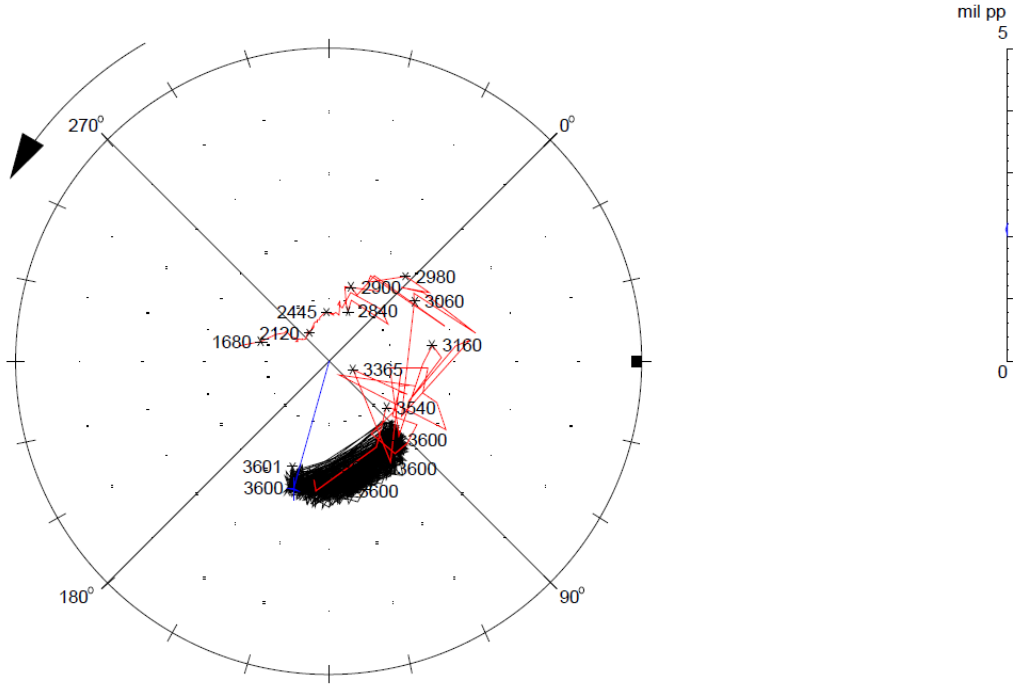

5 mil pp FULL SCALE

CCW ROTATION

COMMENTS
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POLAR PLOT
COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs

PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16

POINT: 7 GEN BRG #2A ∠45° Left 1X UNCOMP 0.267∠270° @3600 rpm
MACHINE: 7 GEN BRG #2A
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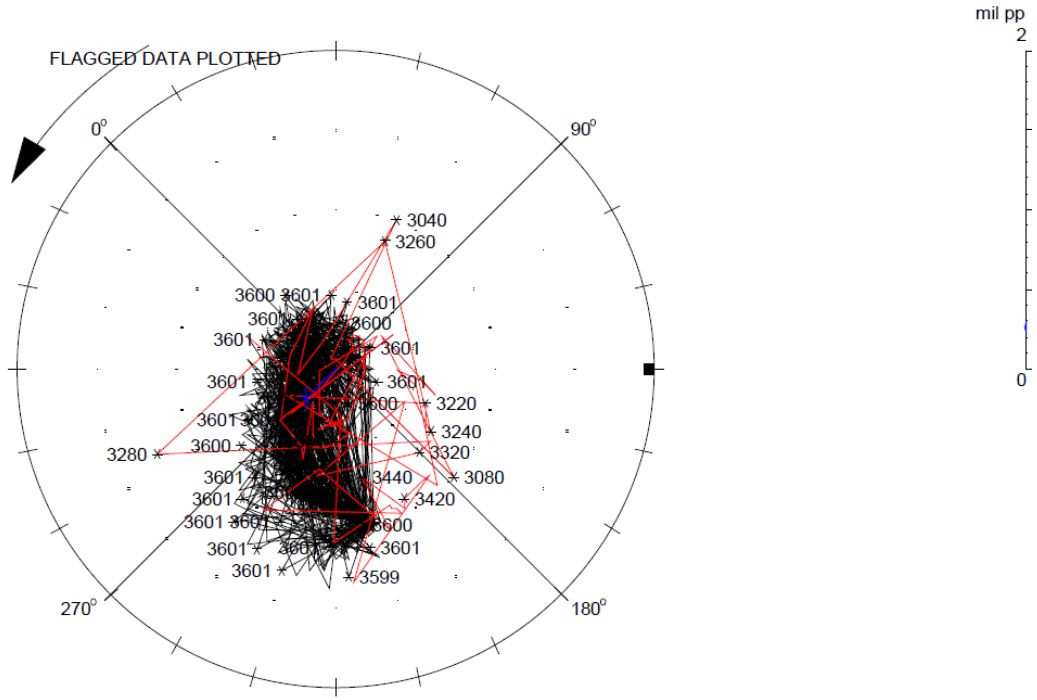

2 mil pp FULL SCALE

CCW ROTATION

COMMENTS
Session started with Database: 15 Feb 16 - 15:14:51. P-9 GENERATOR Low Freq VIBs; B channels are Right Side; TDW 2/15/16

POLAR PLOT
COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs

PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16

POINT: 8 GEN BRG #2B ∠45° Right 1X UNCOMP 2.00∠345° @3600 rpm
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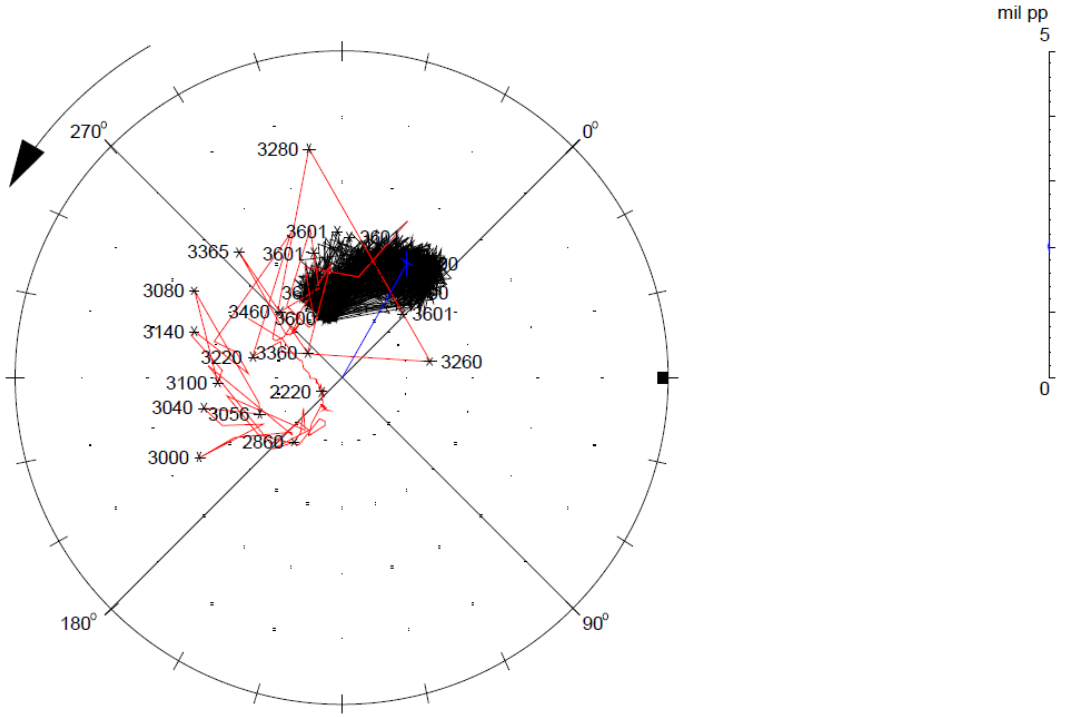

5 mil pp FULL SCALE

CCW ROTATION

COMMENTS
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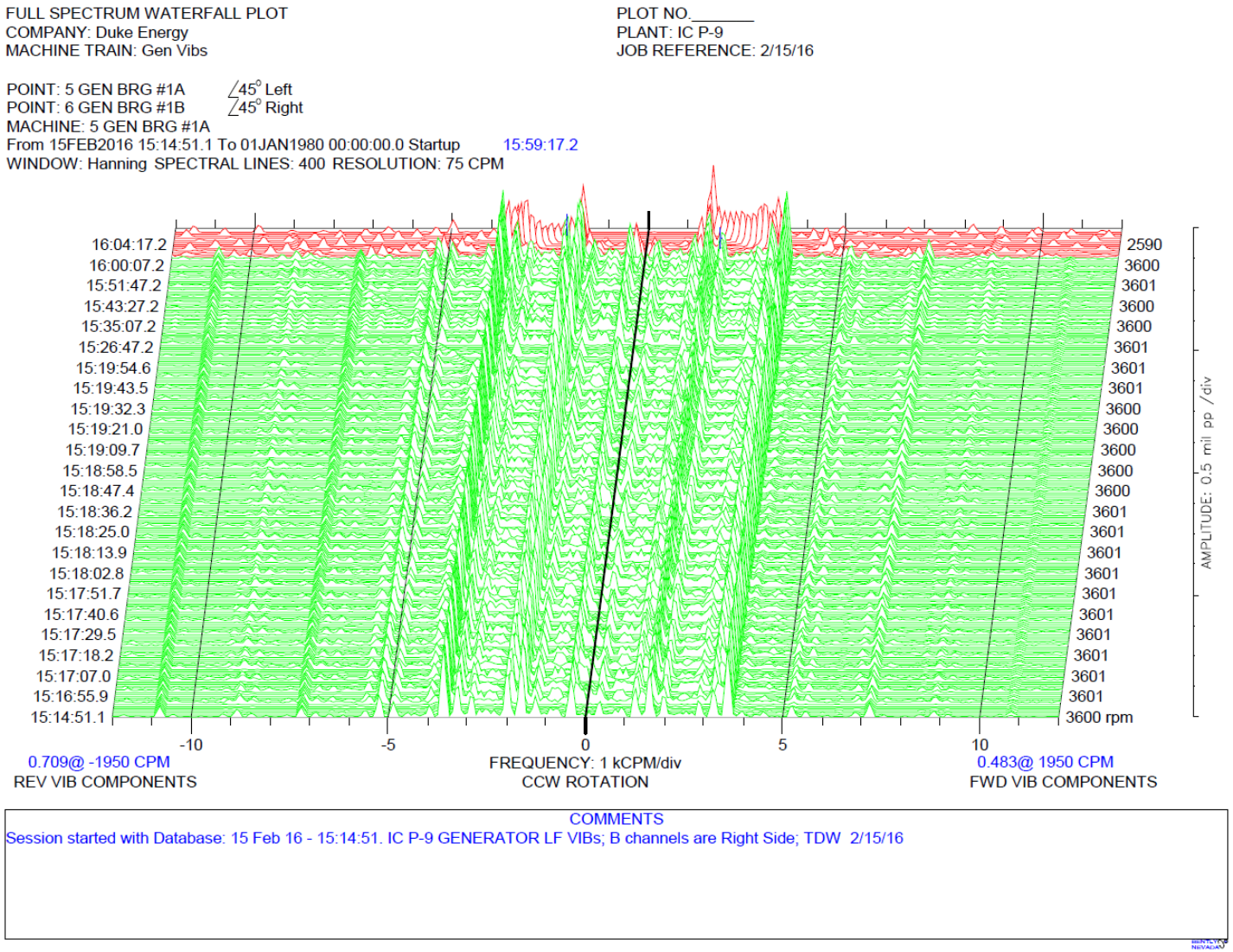
FULL SPECTRUM WATERFALL PLOT
COMPANY: Duke Energy
MACHINE TRAIN: Gen Vibs
PLOT NO._____
PLANT: IC P-9
JOB REFERENCE: 2/15/16
POINT: 5 GEN BRG #1A ∠45° Left
POINT: 6 GEN BRG #1B ∠45° Right
MACHINE: 5 GEN BRG #1A
From 15FEB2016 15:14:51.1 To 01JAN1980 00:00:00.0 Startup 15:59:17.2
WINDOW: Hanning SPECTRAL LINES: 400 RESOLUTION: 75 CPM
16:04:17.2
16:00:07.2
15:51:47.2
15:43:27.2
15:35:07.2
15:26:47.2
15:19:54.6
15:19:43.5
15:19:32.3
15:19:21.0
15:19:09.7
15:18:58.5
15:18:47.4
15:18:36.2
15:18:25.0
15:18:13.9
15:18:02.8
15:17:51.7
15:17:40.6
15:17:29.5
15:17:18.2
15:17:07.0
15:16:55.9
15:14:51.1
2590
3600
3601
3600
3600
3601
3601
3601
3601
3600
3600
3600
3600
3600
3601
3601
3601
3601
3601
3601
3601
3601
3601
3601
3600 rpm
AMPLITUDE: 0.5 mil pp /div
-10
-5
0
5
10
0.709@ -1950 CPM
REV VIB COMPONENTS
FREQUENCY: 1 kCPM/div
CCW ROTATION
0.483@ 1950 CPM
FWD VIB COMPONENTS
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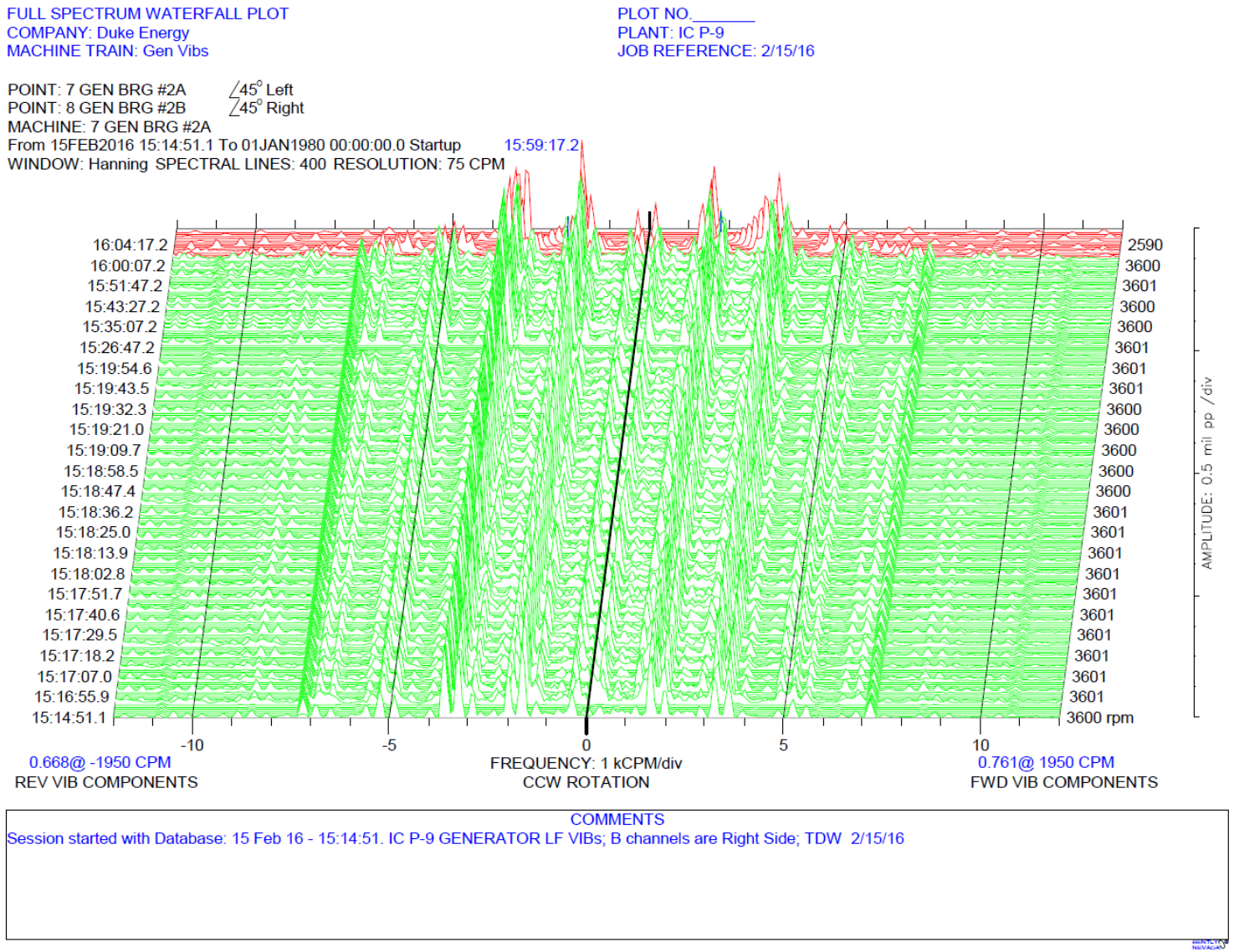
FULL SPECTRUM WATERFALL PLOT
COMPANY: Duke Energy
MACHINE TRAIN: Gen Vibs
PLOT NO._____
PLANT: IC P-9
JOB REFERENCE: 2/15/16
POINT: 7 GEN BRG #2A ∠45° Left
POINT: 8 GEN BRG #2B ∠45° Right
MACHINE: 7 GEN BRG #2A
From 15FEB2016 15:14:51.1 To 01JAN1980 00:00:00.0 Startup
15:59:17.2
WINDOW: Hanning SPECTRAL LINES: 400 RESOLUTION: 75 CPM
16:04:17.2
16:00:07.2
15:51:47.2
15:43:27.2
15:35:07.2
15:26:47.2
15:19:54.6
15:19:43.5
15:19:32.3
15:19:21.0
15:19:09.7
15:18:58.5
15:18:47.4
15:18:36.2
15:18:25.0
15:18:13.9
15:18:02.8
15:17:51.7
15:17:40.6
15:17:29.5
15:17:18.2
15:17:07.0
15:16:55.9
15:14:51.1
2590
3600
3601
3600
3600
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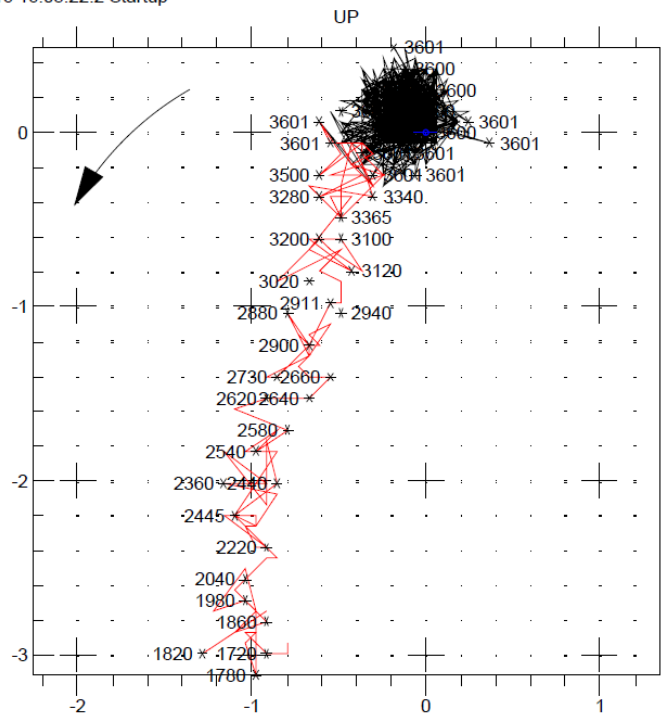
3601
3601
3600
3600
3600
3600
3600
3601
3601
3601
3601
3601
3601
3601
3601
3601
3600 rpm
AMPLITUDE: 0.5 mil pp /div
-10
-5
0
5
10
0.668@ -1950 CPM
REV VIB COMPONENTS
FREQUENCY: 1 kCPM/div
CCW ROTATION
0.761@ 1950 CPM
FWD VIB COMPONENTS
COMMENTS
Session started with Database: 15 Feb 16 - 15:14:51. IC P-9 GENERATOR LF VIBs; B channels are Right Side; TDW 2/15/16

SHAFT AVERAGE CENTERLINE PLOT
COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs

PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16

POINT: 5 GEN BRG #1A ∠45° Left REF: -9.38 Volts 0
POINT: 6 GEN BRG #1B ∠45° Right REF: -9.31 Volts 0
MACHINE: 5 GEN BRG #1A (0, 0) 3600
From 15FEB2016 15:14:51.1 To 15FEB2016 16:05:22.2 Startup
(not orbit or polar plot)



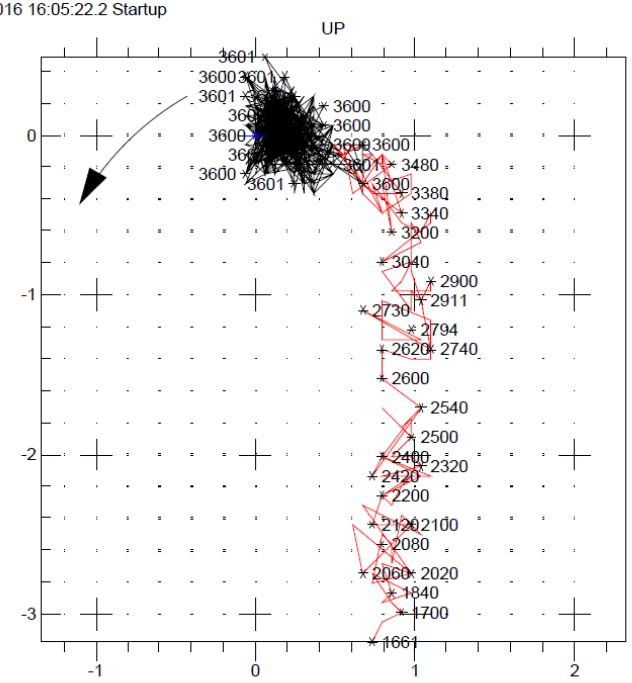
0.2 mil /div

COMMENTS
Session started with Database: 15 Feb 16 - 15:14:51. P-9 GENERATOR Low Frenq VIBs; B channels are Right Side; TDW 2/15/16

SHAFT AVERAGE CENTERLINE PLOT
COMPANY: 7A6 Generator
MACHINE TRAIN: Gen Vibs

PLOT NO._____
PLANT: Tilt
JOB REFERENCE: 2/15/16

POINT: 7 GEN BRG #2A ∠45° Left REF: -9.24 Volts 0
POINT: 8 GEN BRG #2B ∠45° Right REF: -9.09 Volts 0
MACHINE: 7 GEN BRG #2A (0, 0) 3600
From 15FEB2016 15:14:51.1 To 15FEB2016 16:05:22.2 Startup
(not orbit or polar plot)



0.2 mil /div

COMMENTS
Session started with Database: 15 Feb 16 - 15:14:51. P-9 GENERATOR Low Freq VIBs; B channels are Right Side; TDW 2/15/16

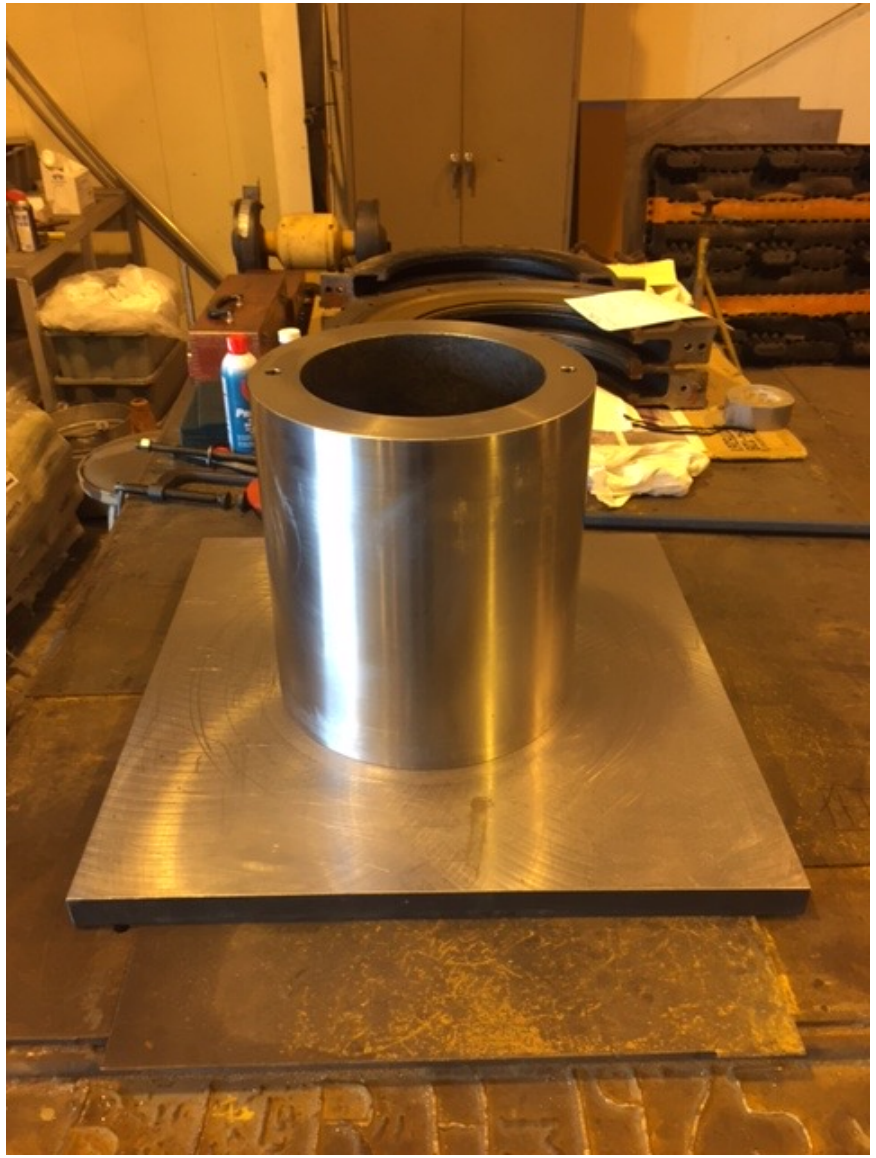
Outage Inspection Results

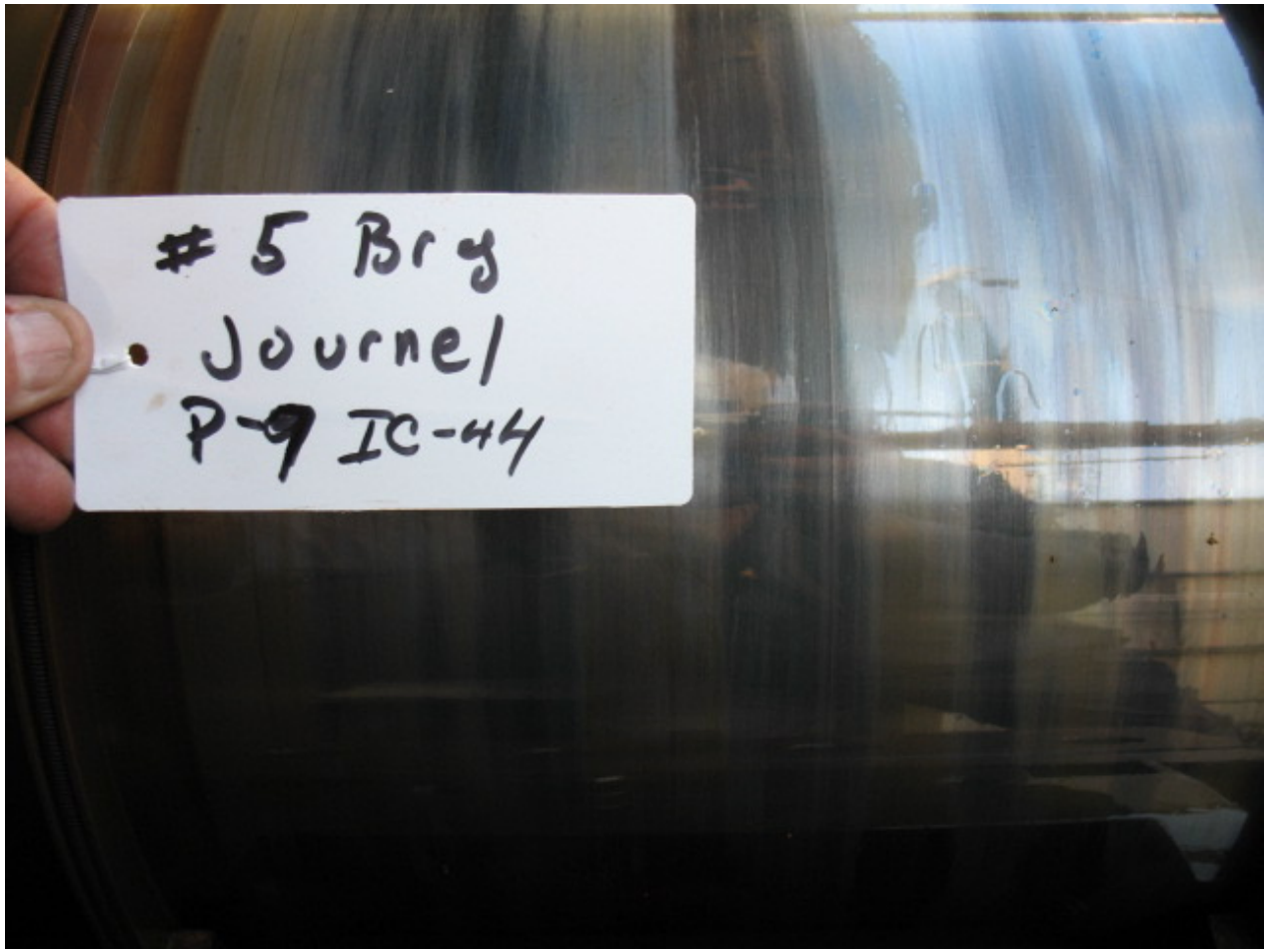
The unit was inspected the following day and in fact the NDE air seal was rubbing more than 180 degrees around and included both 90 degree left and right locations. These rubs were cleared and the unit retested however no change was observed. The unit was placed in a “Last On and First Off” operating scheme to minimize the potential damage. Numerous meetings and discussions were had with staff, vendors and experts during the following weeks to confirm a diagnosis and develop a plan. This plan would include capturing as found alignment and bearing data. During this time the unit remained in service and it was noted that the excited period was lasting longer and the quiet period was getting shorter. The possibility of no quiet period was then realized.

Inspection Results

Alignment - The Turbine to Generator alignment was found out of spec by 122 mils with the generator high and 132 to the right with the coupling faces open 6 mils at the bottom. Final alignment was Gen 6 mils high and “Fair” on horizontal and 11 mils open at the top.

Bearings - Radial clearances were checked using a Bearing Mandrel and found to be 28 mils instead of 21 mils, oversized by 7 mils. The “Preload” was also out of spec.




#5 Brg
Journel
P-9 IC-44


IC-44
P-9
#5 Brg
U/H


IC-44
P-9
#5 Brg
U/H

Corrections Made

All parameters were restored to within GE specification and the unit reassembled for testing

Post Maintenance Test

The unit was started and brought to full load. The generator vibration was well within limits and no instability was observed

Other Industry Experience

Since this sub-synchronous event another GE 7A6 generator at the Sheridan Road plant in NJ, operated by Calpine, suffered a similar problem (May of 2018). Using the knowledge gained on Unit 9 their contractor, TOPS, quickly diagnosed and then solved the issue.

In the future I would recommend only an alignment check and correction as a first step to ensure that the Generator drive end bearing is sufficiently loaded.

Questions?