Gas Turbine Introduction and Vibration Diagnostic Basics

Timothy S Irwin, P.E. – GTSE Service Engineering Manager

MITSUBISHI HITACHI POWER SYSTEMS

Mitsubishi Hitachi Power Systems Americas, Inc.

Gas Turbine Introduction

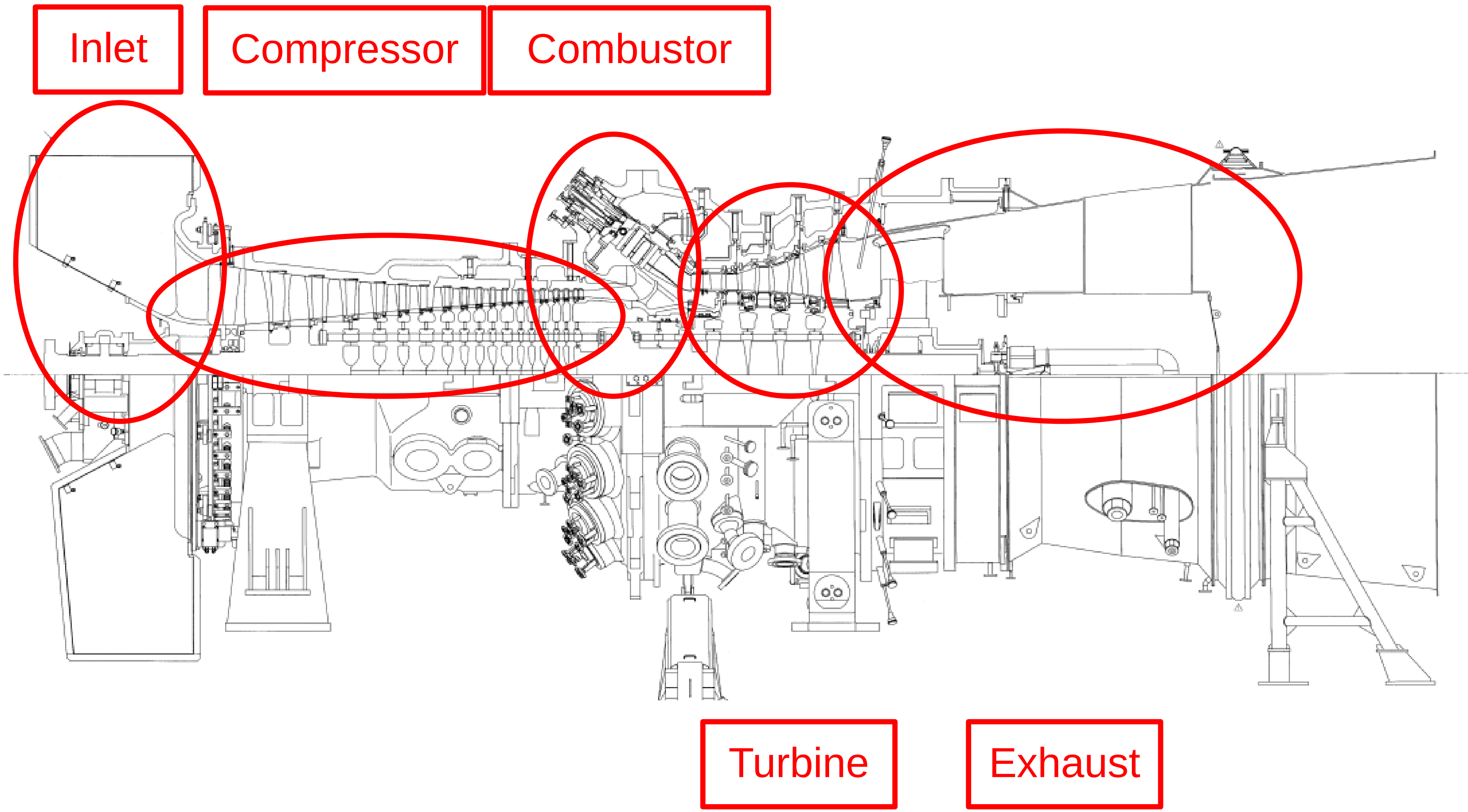
Styles of Gas Turbines

- Micro-turbines – typically produce tens to hundreds of kW. Some corporations advertise micro-turbines up to 1 MW, but that size of this style of machine is rare to date with most being in sizes less than 400 kW.
- Aero-derivative gas turbines – Typically range in size from one MW to tens of MW. There is considerable use of this technology presently being used to improve performance efficiencies of larger ‘frame’ size gas turbines.
- Large frame gas turbines – Typically range in size from just under 100MW to over 300 MW with current technology

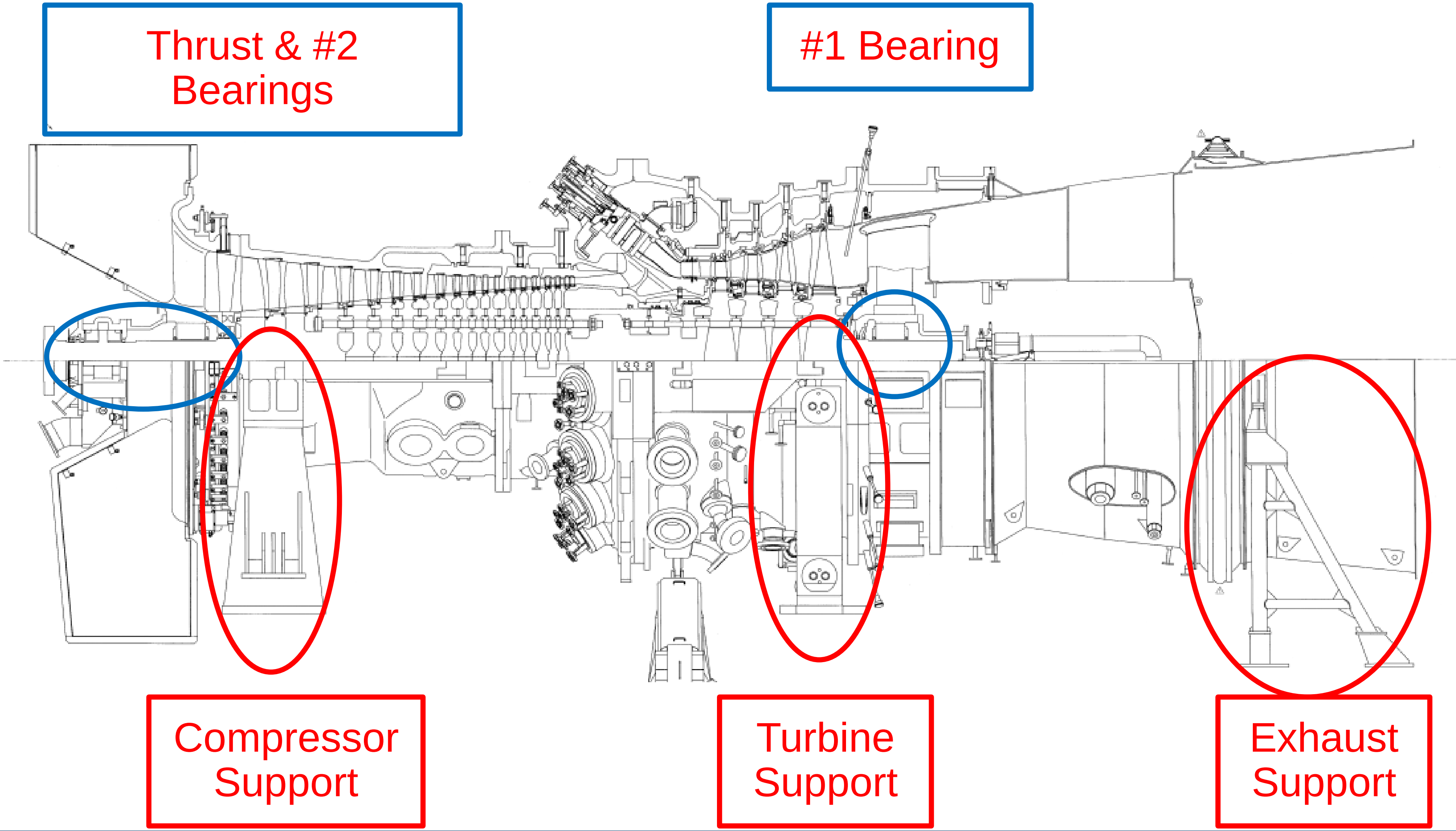
Today’s topic will be the large frame gas turbines

Gas Turbine Introduction

Gas Turbine Basics – Major Sections



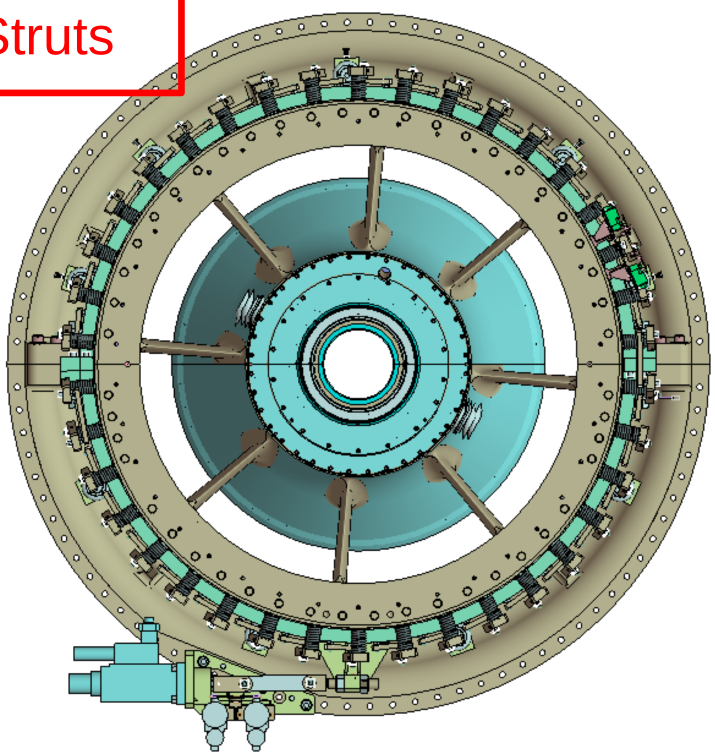
Gas Turbine Basics – Structural Support



Gas Turbine Basics – Bearing Support

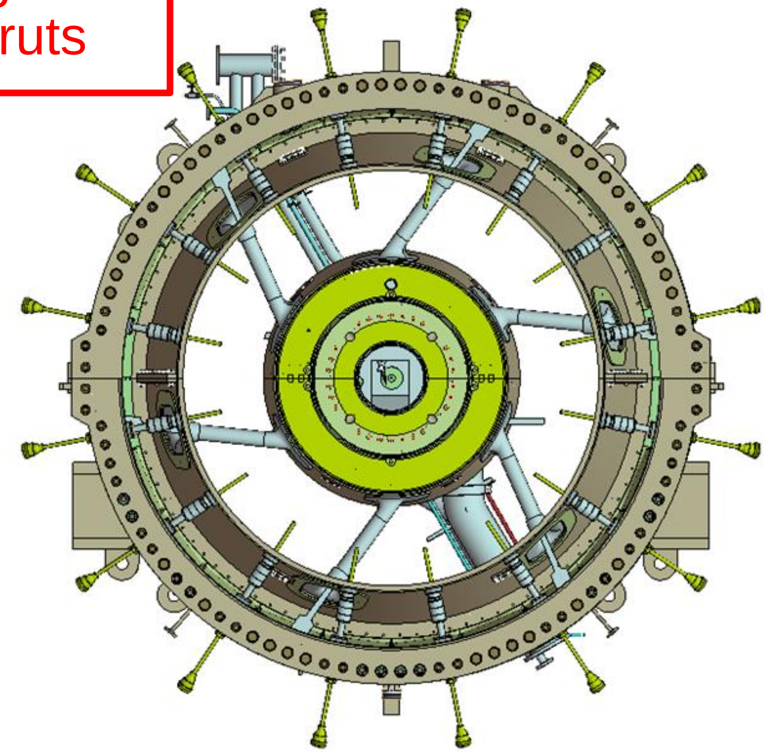
Inlet

Radial Struts

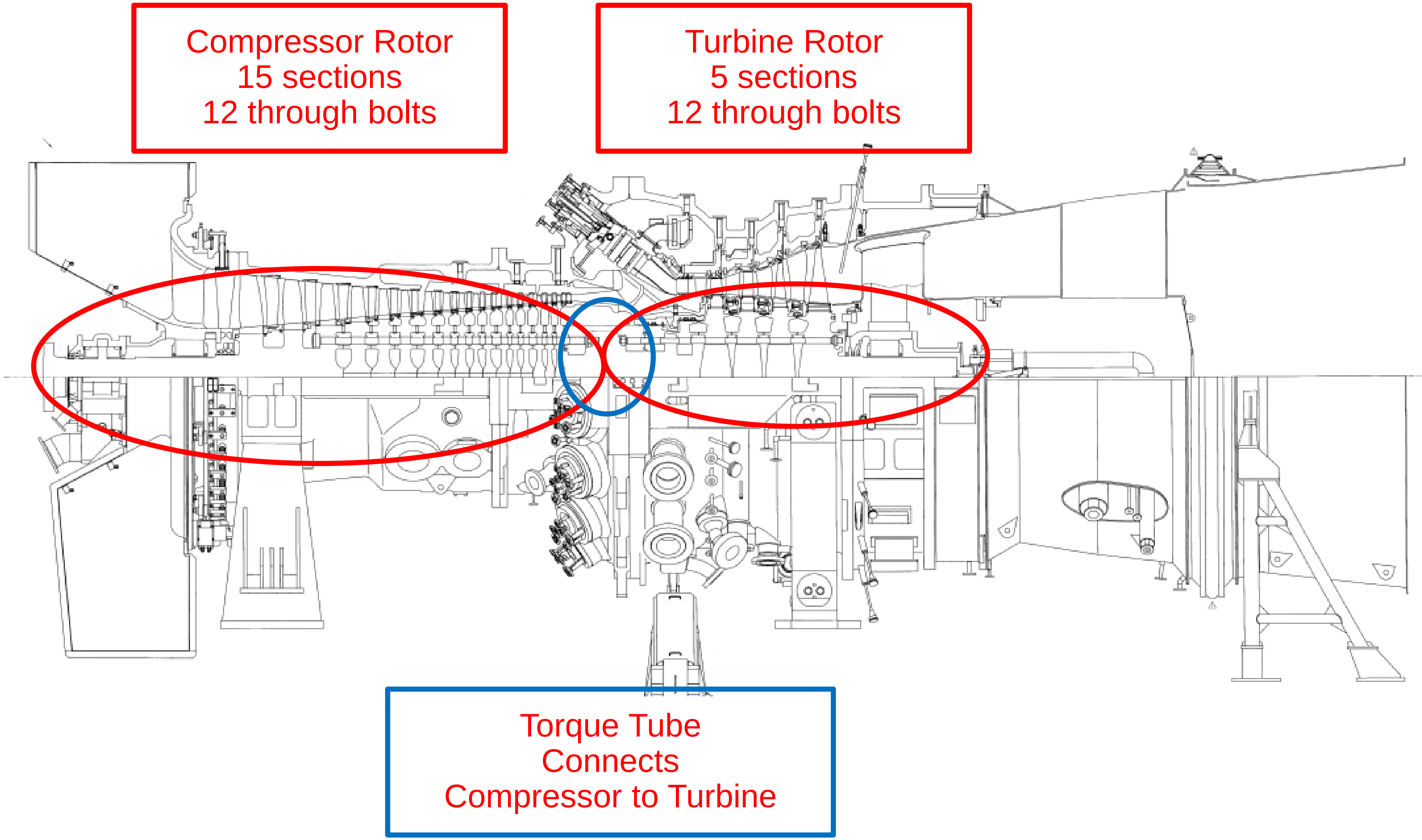


Exhaust

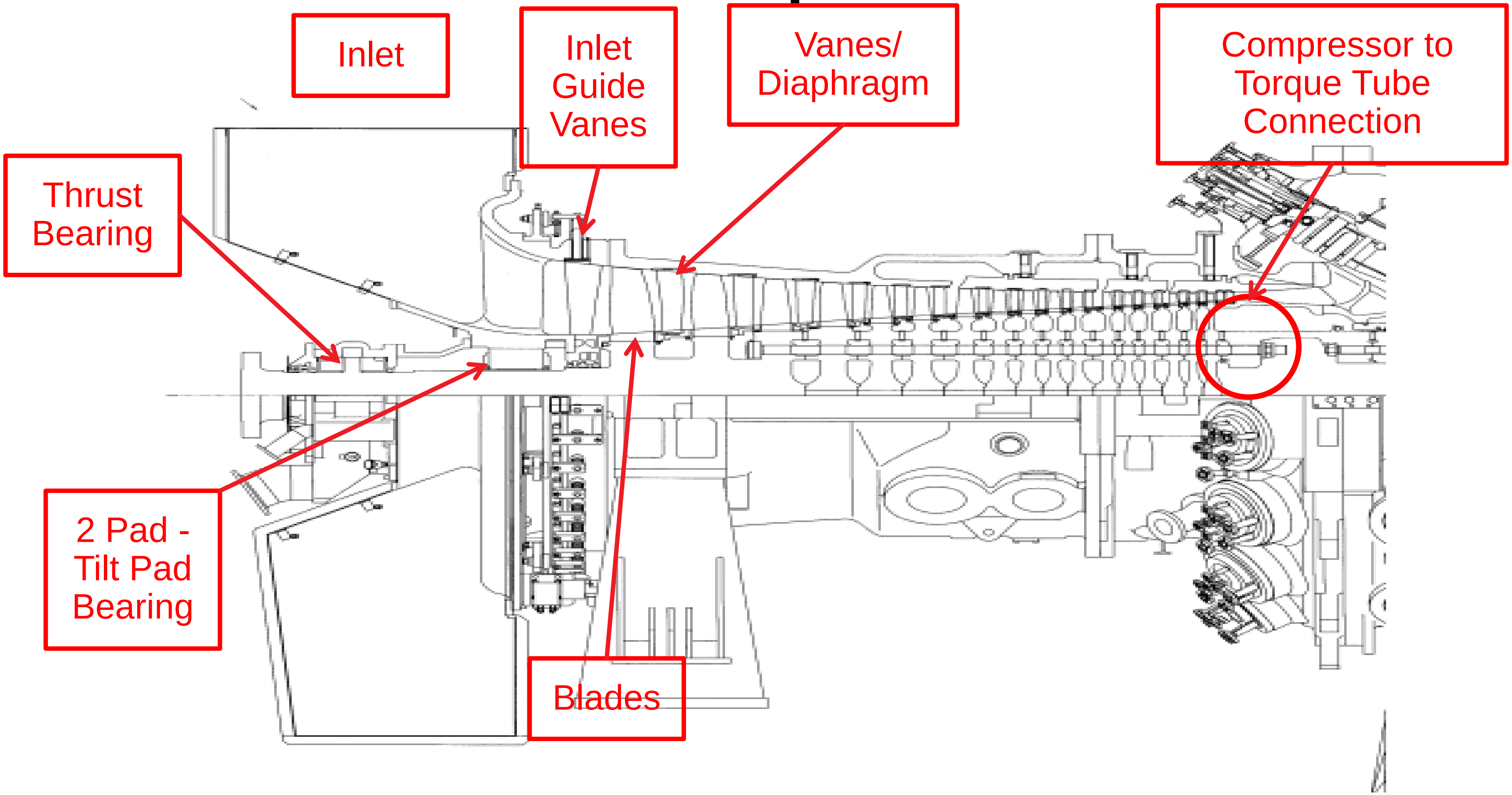
Tangential Struts



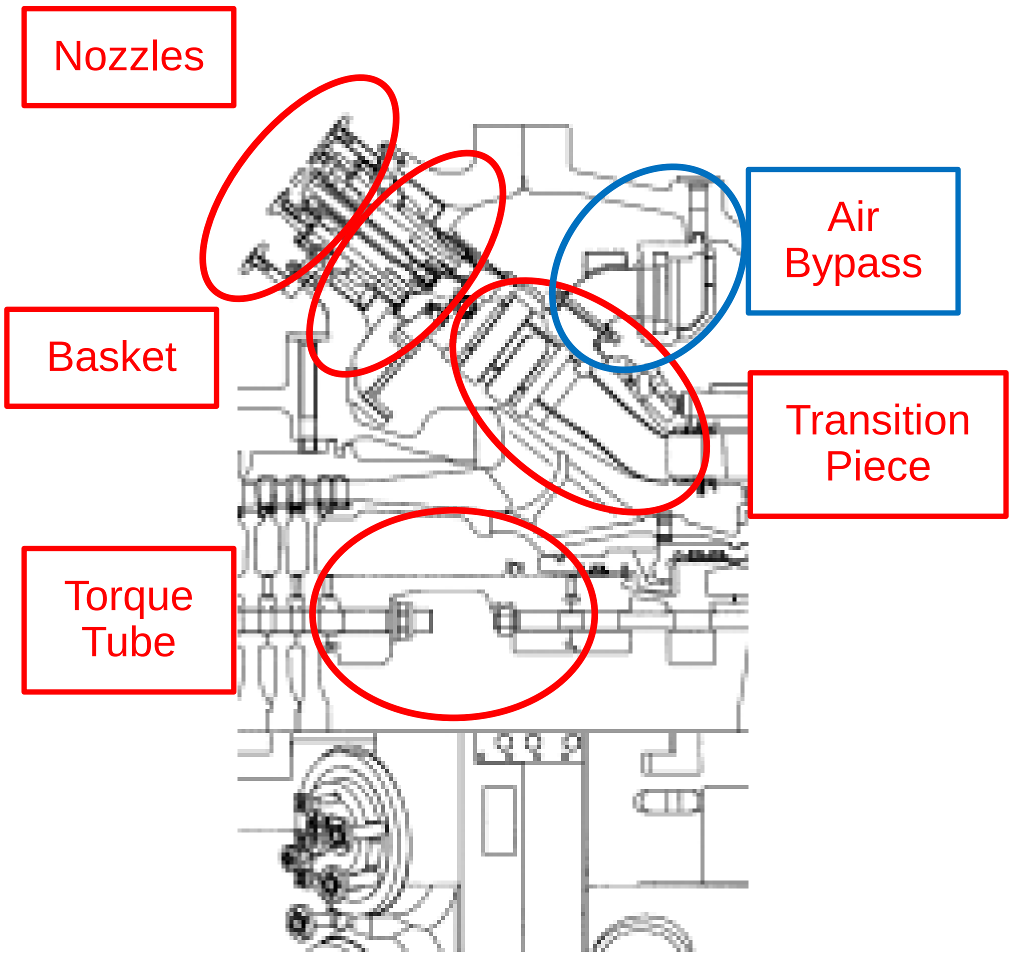
Gas Turbine Basics - Rotor



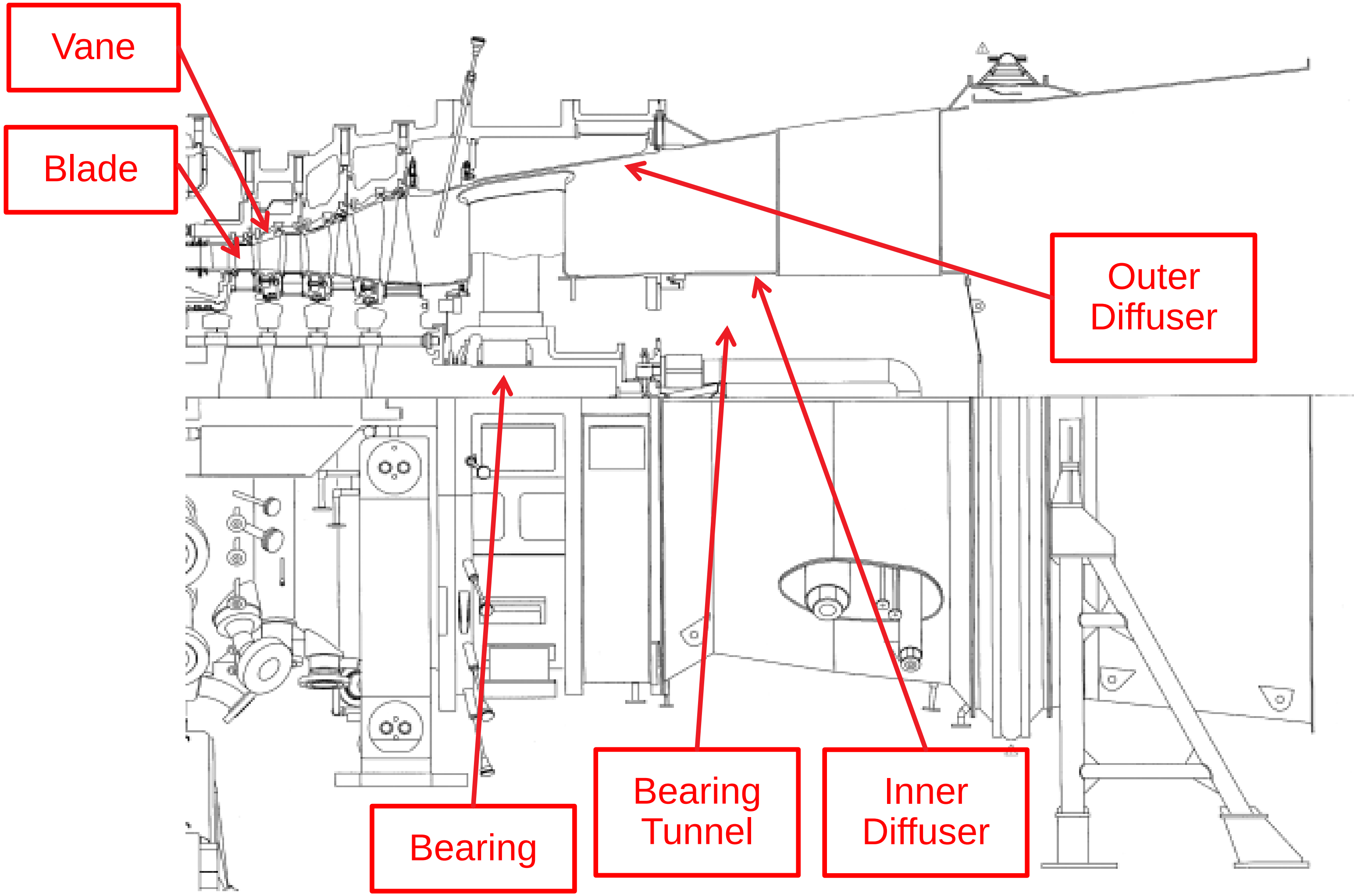
Gas Turbine Basics - Compressor



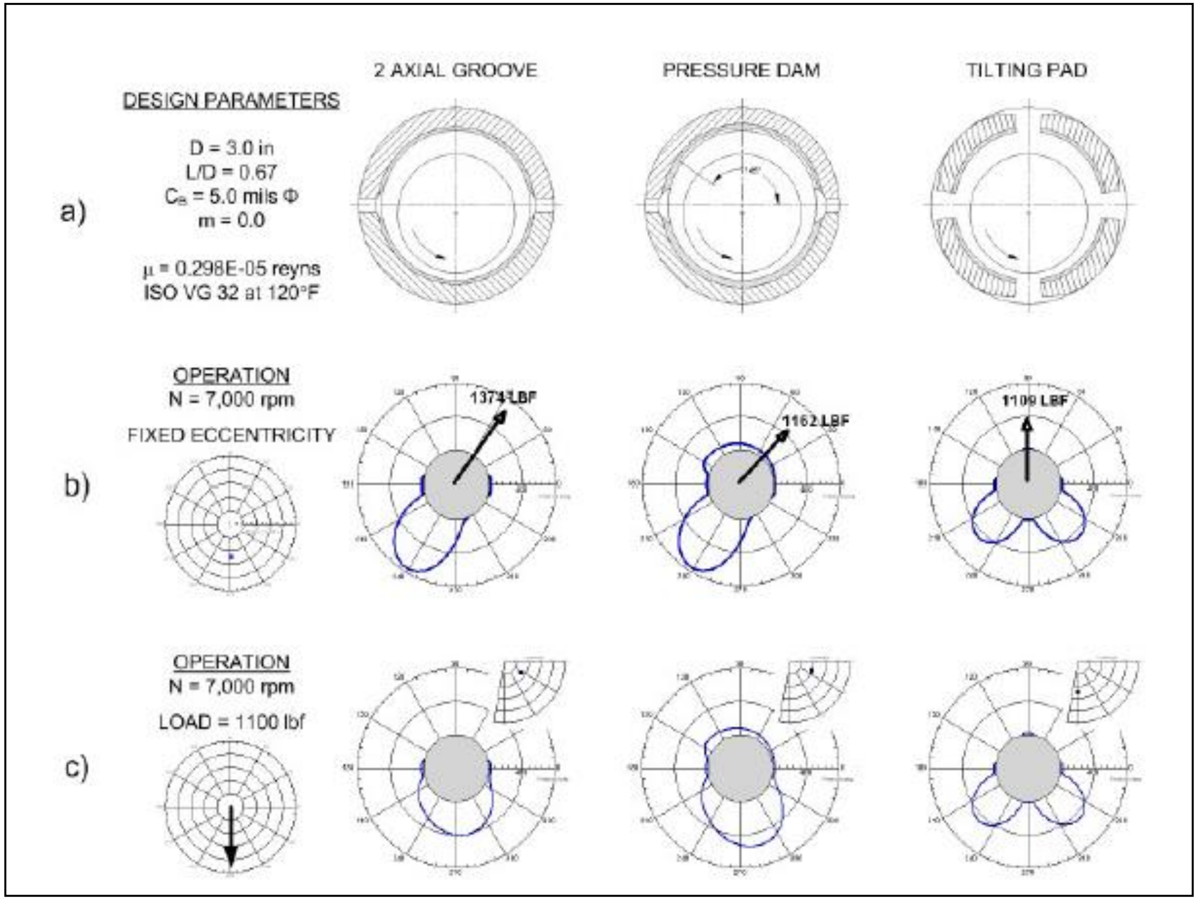
Gas Turbine Basics – Combustor Section



Gas Turbine Basics

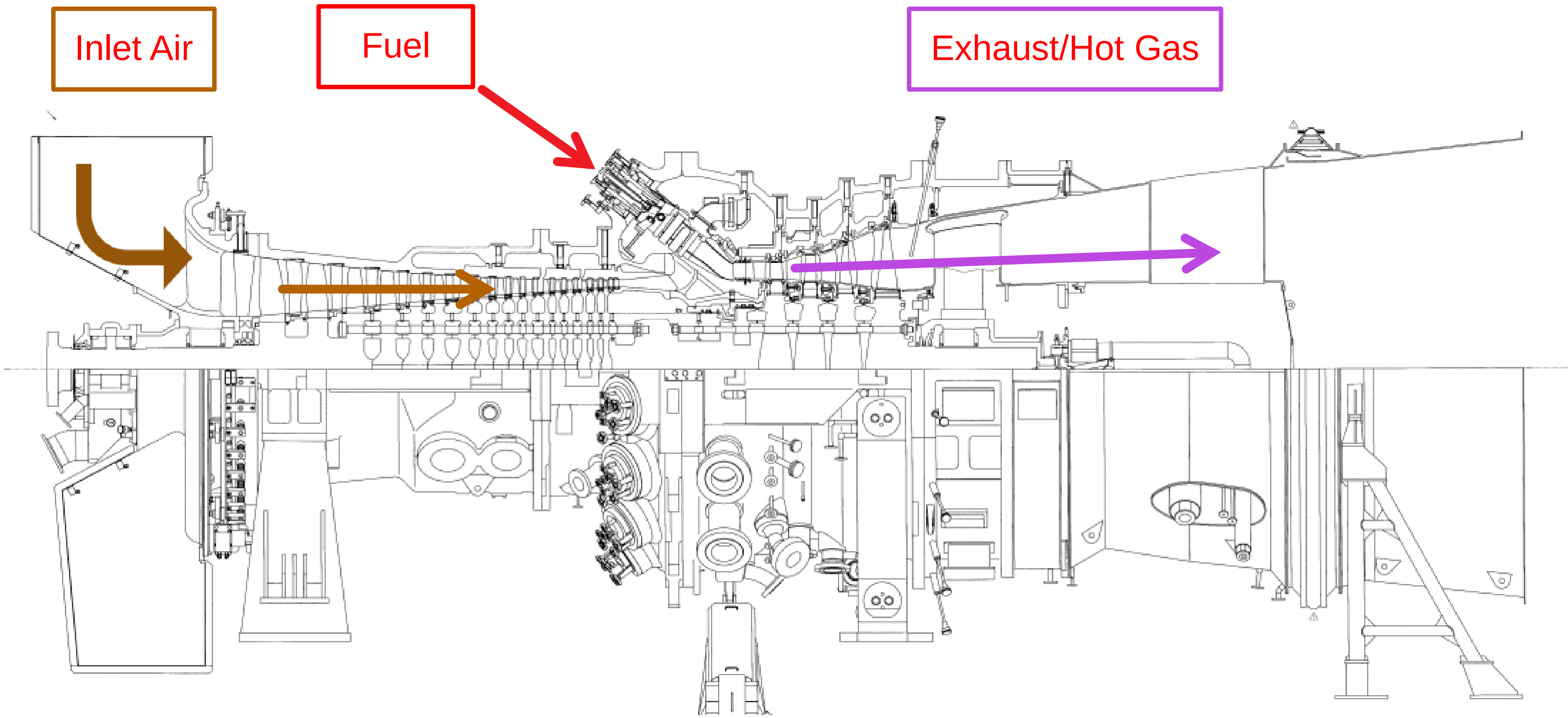


Gas Turbine Basics

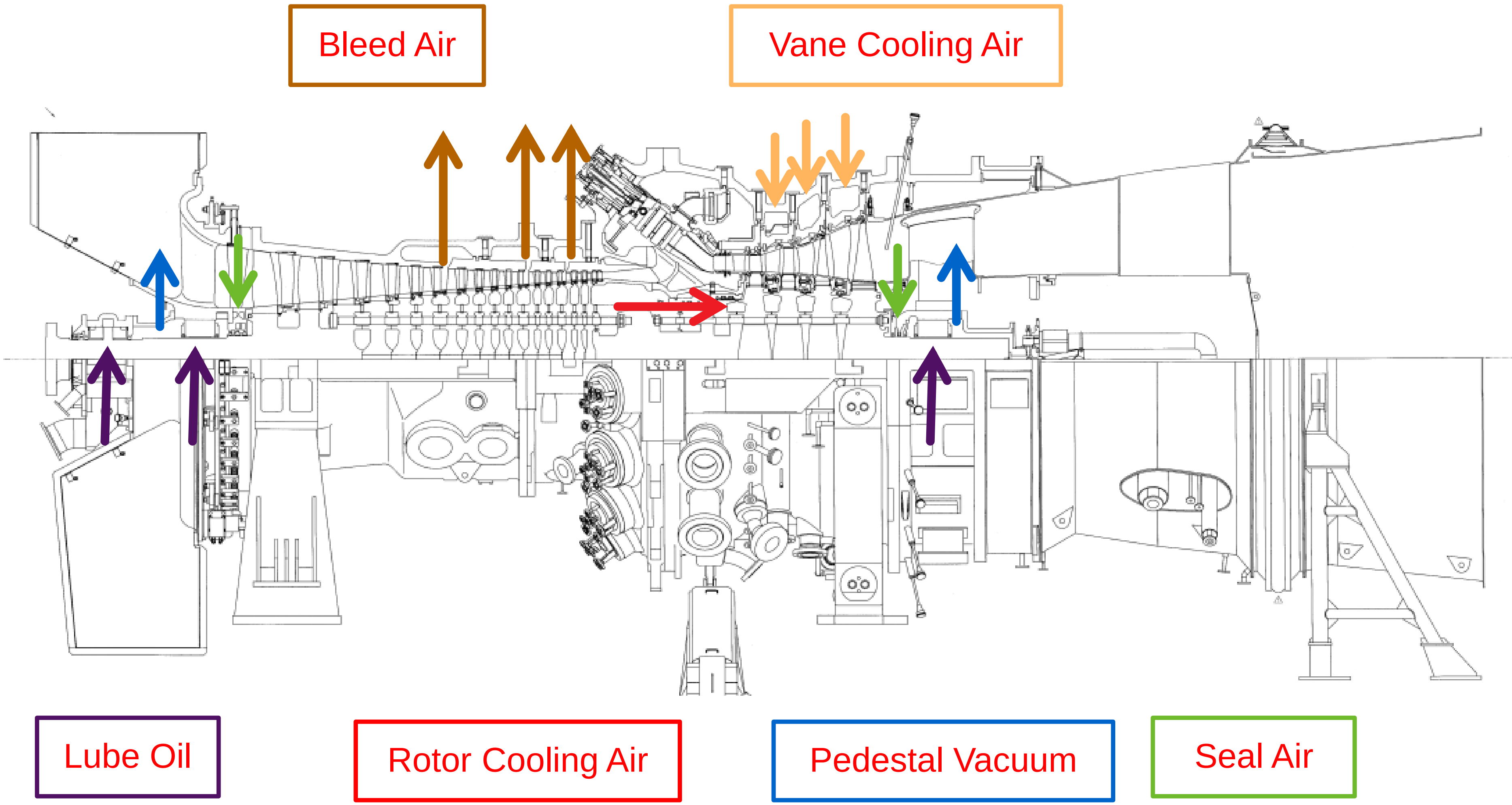


Know your bearings. Different bearings designs produce different operational characteristics.

Gas Turbine Basics – Air and Fuel flows



Gas Turbine Basics – Auxiliary Systems



Gas Turbine Basics

Characteristics of Gas Turbines Rotors

- Rotor Flexibility
- Will typically operate above the 2^{nd} critical
- Bearing supports – The connection from the bearings to the foundation are much more complex than other large turbo-machinery. This affects bearing foundation stiffness and thus rotor and machine operational characteristics
- At 3600 rpm ‘Full Speed No Load’ a gas turbine is still near 2/3 of total power coming from the turbine end to drive the compressor. So even at full speed/no load these machines are not truly idling, and the operational data is meaningful. Although there is still thermal transient to go through during startup conditions that depending on insulation condition, ambient temperatures, etc. will still take many hours to stabilize. Foundations can take a full day or more to stabilize.

Forces on the machine

- Forces that act on a machine
  - Internal influences – interaction with parts of itself
    - Support forces in bearings
    - Forces resulting from shaft deflection
    - Fluid dynamics and subsequent forces
  - External influences – forces that are applied to the rotor system
    - Axial Restraint – Rub
    - Casing distortion – Rub
    - Static radial loads - Rotor to rotor Misalignment
  - Unbalance – typically considered and handled as an external force

Rotor System Parameters

- Rotor System Parameters
  - Mass
  - Stiffness
  - Damping

The equation below describes how displacement, force, and dynamic stiffness are related.

$$\overrightarrow{\text{Displacement}} = \frac{\sum \overrightarrow{\text{Forces}}}{\sum \overrightarrow{\text{Dynamic Stiffness}}}$$

A change in displacement (vibration) is due to a change in the force applied or stiffness of the system. The equation below shows the relationship between frequency, stiffness, and mass.

$$F_n = \frac{1}{2}\Pi \times \sqrt[2]{\frac{k}{M}}$$

Rotor System Parameters

Using the foundation of the previous information the following equation was developed to describe the motion of a shaft:

Rotor Equation of Motion (for fluid film bearings):

$$F_s + F_t + F_d + F_p = M\ddot{r}$$

Spring stiffness + Tangential stiffness + Damping force + Pertubation force = mass x acceleration

$$-Kr + jD\lambda\Omega r - D\dot{r} + m r_u \omega^2 e^{j(\omega t+\delta)} = M\ddot{r}$$

Reference: Fundamentals of Rotating Machinery Diagnostics – Charles T. Hatch & Donald E. Bently

Fault Conditions

- Instrumentation Error
- Unbalance
- Misalignment
  - Rotor to rotor
  - Casing to rotor
    - Radial
    - Axial
- Bearing Damage or excessive clearance
- Rotor Bow
- Looseness
- Fluid Induced Instability
- Shaft Crack
- Resonance

Fault Conditions

- Instrumentation Error
  - Loose connections – spikey signal
  - Failing sensor
  - Drift – change in scale factor
  - Improperly matched components – change in scale factor
  - Incorrect calibration – change in scale factor

- Unbalance
  - Initial/Residual unbalance condition
  - Loss of balance weight
  - Loss of blade mass
  - Increase in blade mass

Fault Conditions

- Misalignment
  - Rotor to rotor
    - Change in relative bearing position
  - Rotor to casing
    - Radial
    - Axial

- Bearing Damage or excessive clearance
  - Babbitt damage
  - Tilt pad – tilting/rocking mechanism wear

- Rotor Bow
  - Assembly issue
  - Thermal distortion (also known as thermal sensitivity)

Fault Conditions

- Looseness
  - Bearing components
  - Bearing to pedestal
  - Pedestal to foundation
  - Rotor Components
- Fluid Induced Instability
  - Bearing Whirl
  - Bearing Whip
  - Tilt pad flutter
- Shaft Crack
  - Shaft stiffness change
- Resonance
  - Is resonance itself a problem?

Data Acquisition for Machinery Diagnostics

Parameters

- Bearing Temperatures
- Operating conditions – Speed, MW, MVars, Blade path temps,
- Lube oil system operating conditions - supply pressure and temperature, drain temperatures
- Seismic vibration probes – velocity, accelerometer, velomitor
- Relative vibration probes – note installation location/orientation
- Transient and Steady State Data – vibration and operational parameters

Defining Terms

Steady State Conditions: The machinery is operating under steady conditions; steady load, speed, etc.

Transient Conditions: The machinery is operating under changing conditions; changing speeds (startup, coast down), changing loads

Static Data is any data that can be represented by a single number or status. Examples include vibration amplitude filtered vibration amplitude, filtered vibration phase lag, transducer gap voltage, etc.

Plot Examples: Tabular List, Trend, Spectrum

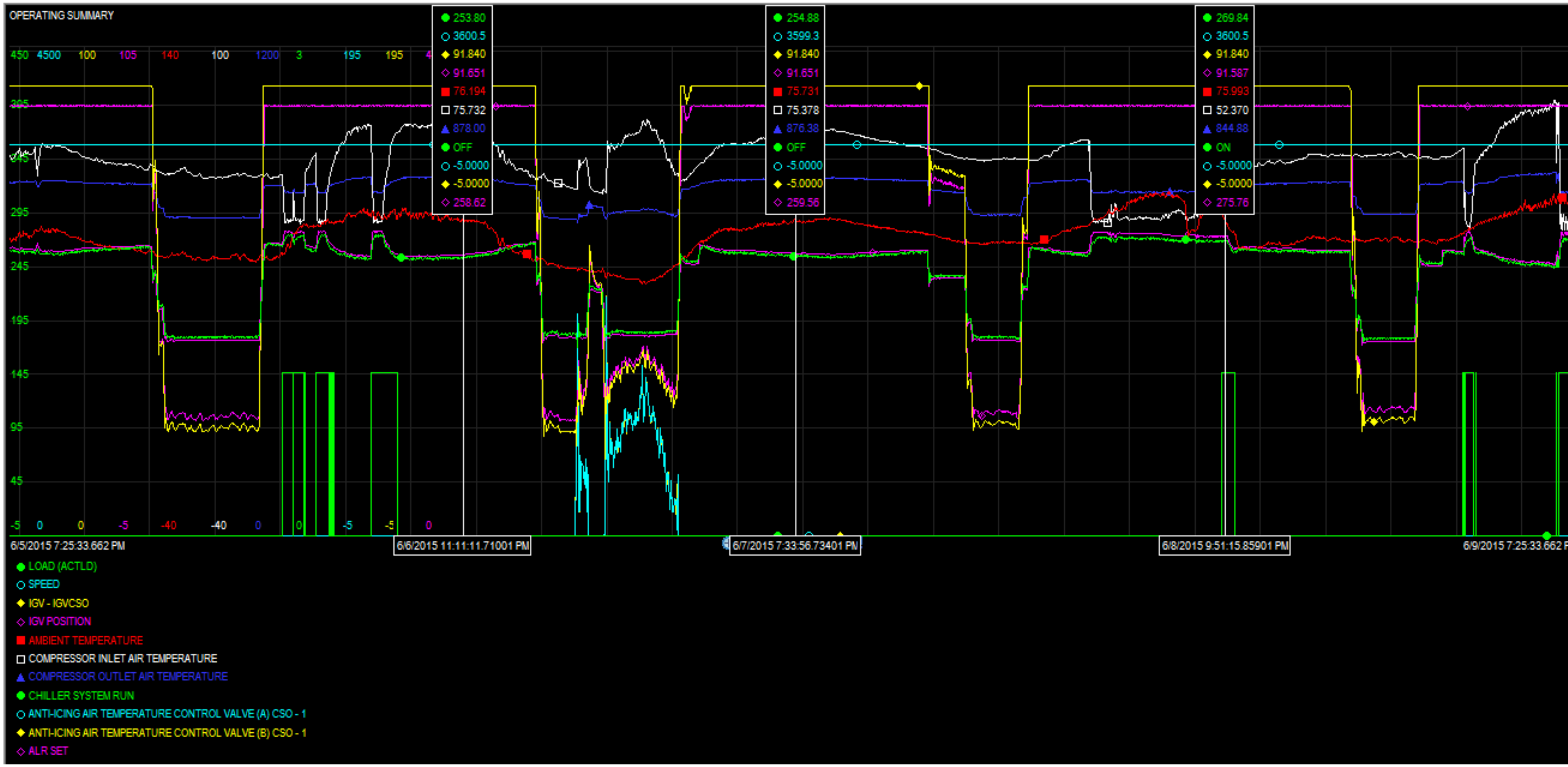
Dynamic Data is the actual vibration waveform. Sampling of the waveform and processing to provide both time domain (Orbit or Timebase plots) and frequency domain (Spectrum plots). Dynamic data cannot be characterized by a single number.

Plot Examples – Bode, Polar, Shaft Centerline, Timebase, Orbits, Cascade, Waterfall

Digital Control System (DCS) Data

Operating Conditions

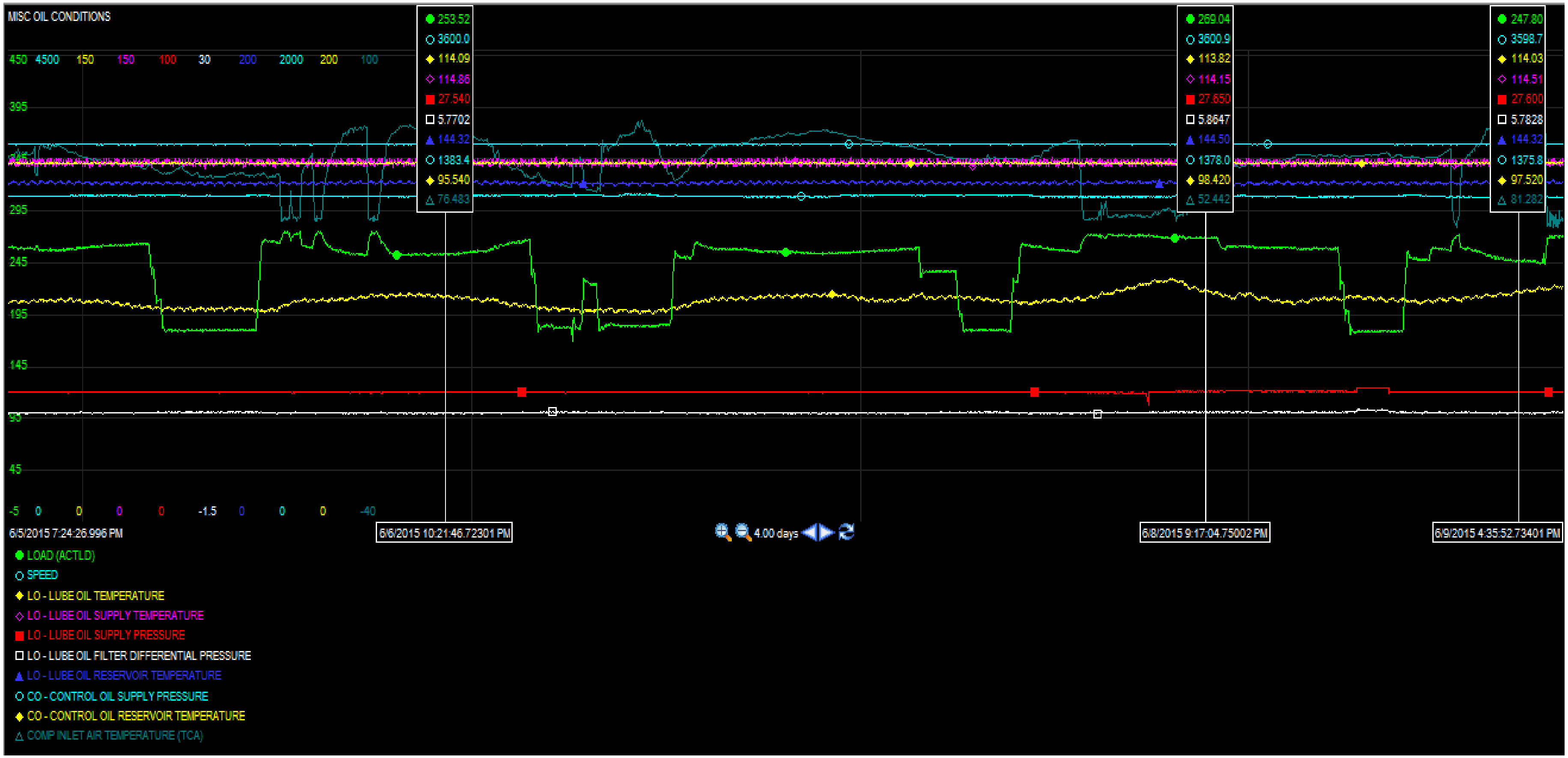
Target Operating Range
Alarm/Trip SetPoints
Historical Operating Information



DCS Data

Lube Oil System Operating Conditions

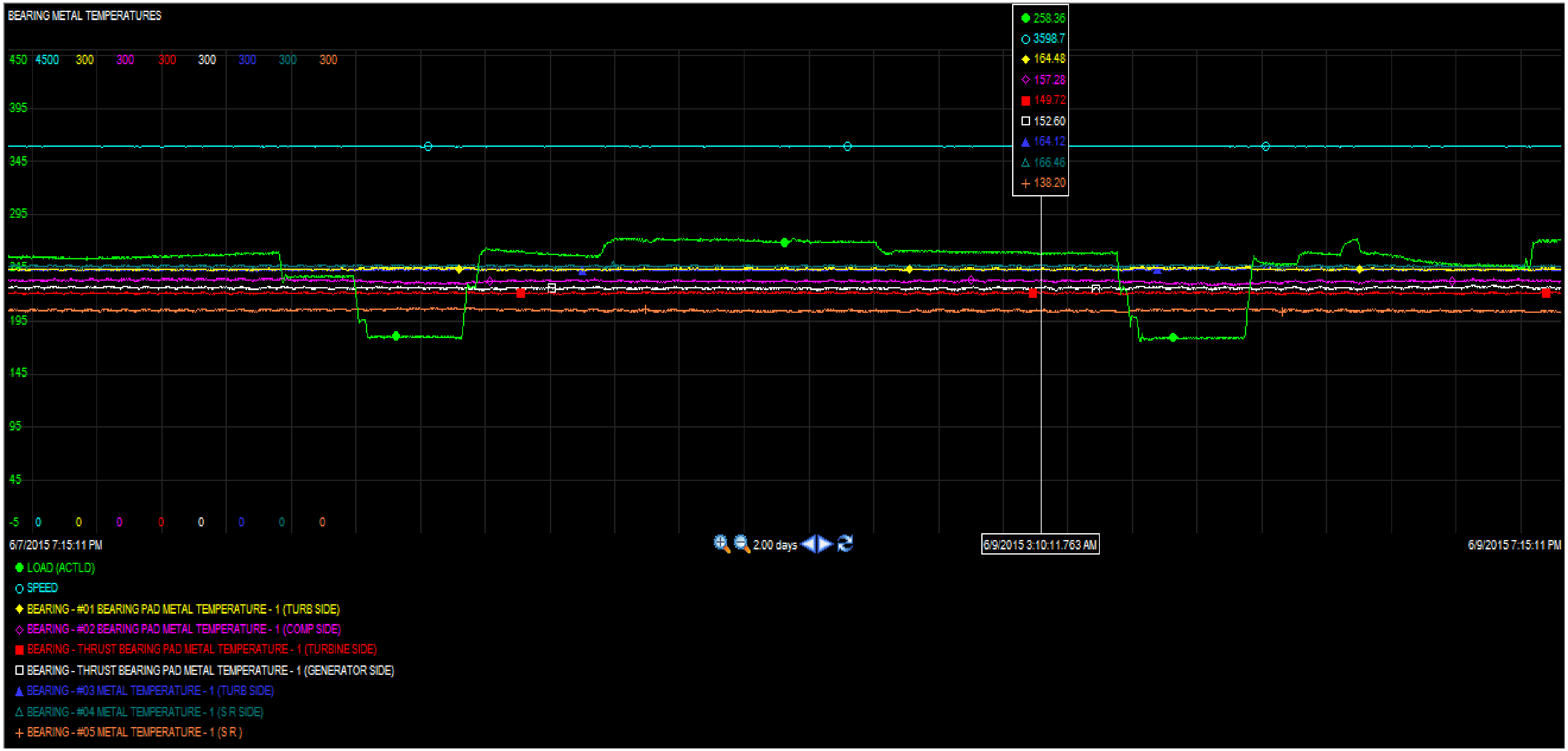
Target Operating Range
Alarm/Trip SetPoints
Historical Operating Information



DCS Data

Bearing Temperatures

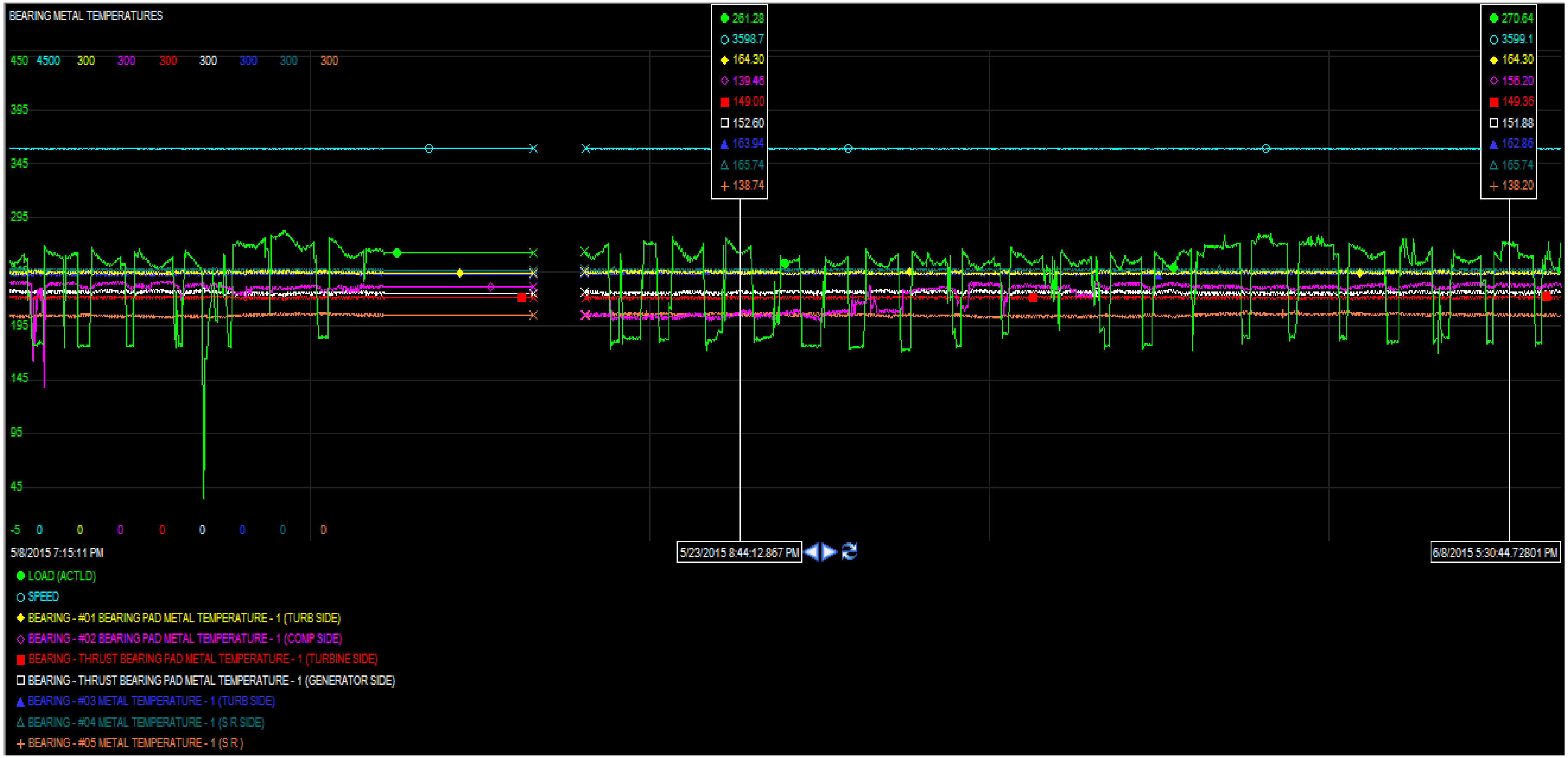
Target Operating Range
Alarm/Trip SetPoints
Historical Operating Information



DCS Data

Bearing Temperatures

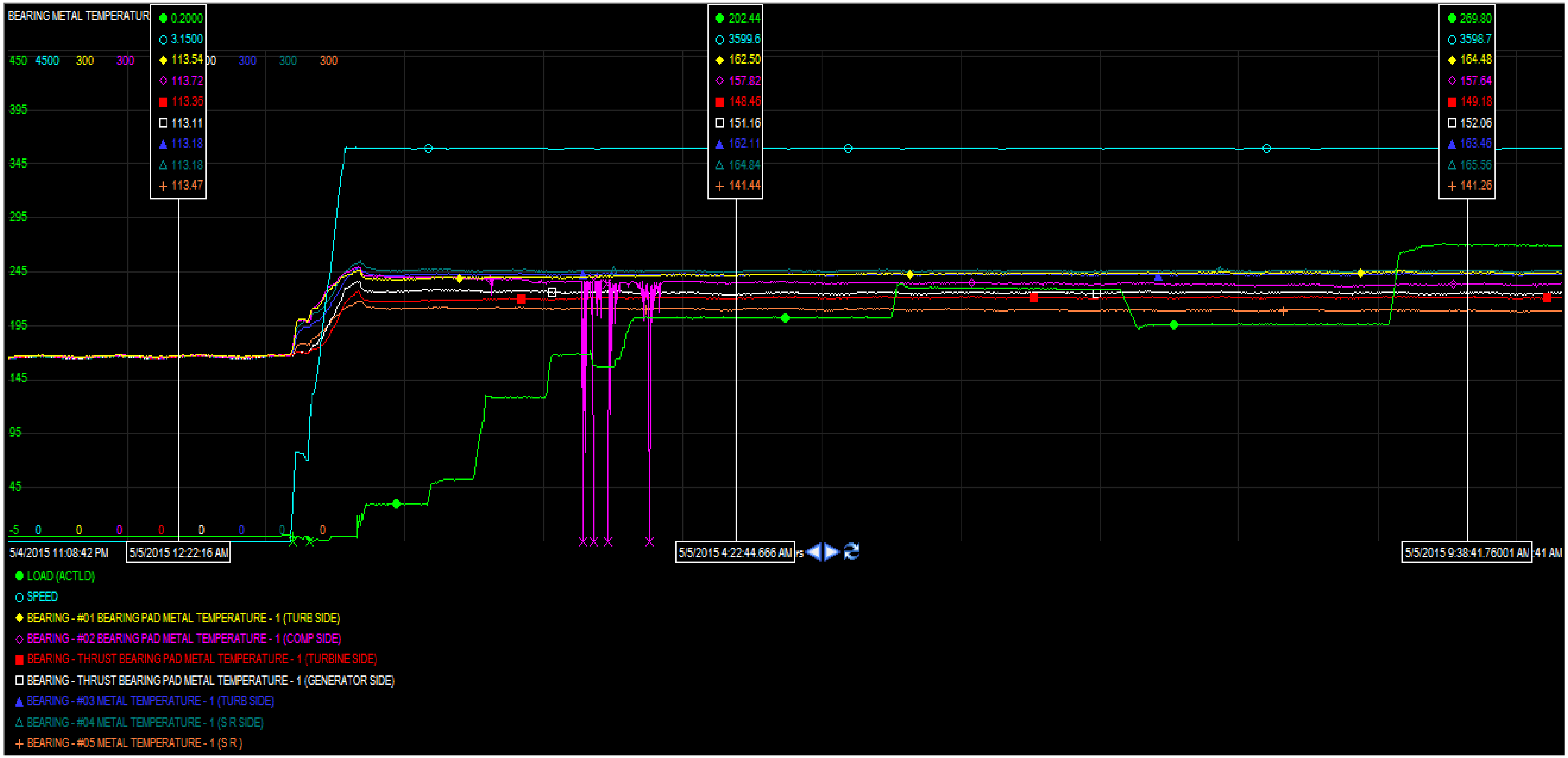
Target Operating Range
Alarm/Trip SetPoints
Historical Operating Information



DCS Data

Bearing Temperatures

Target Operating Range
Alarm/Trip SetPoints
Historical Operating Information



Vibration Data

Tabular List

Note the different items available

CH#	Channel Name	Machine Name	Status	Angle	Direction	Run Type	Date	Speed Units(P)	Amp Unit	Phase Unit
1	1X TVLL	TVLL	OK	45°	Right	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
2	2X TVLC	TVLC	OK	45°	Right	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
3	3X GENLC	GENLC	OK	45°	Right	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
4	3Y GENLC	GENLC	OK	45°	Left	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
5	4X GENLE	GENLE	OK	45°	Right	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
6	4Y GENLE	GENLE	OK	45°	Left	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
7	5X EXC	EXCITADOR	OK	45°	Right	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
8	5Y EXC	EXCITADOR	OK	45°	Left	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	mil pp	deg
9	Kph 1		OK	45°	Right	Start Up	30May2015 17:44:30.000 To 30May2015 18:41:16.800	rpm	V pp	deg

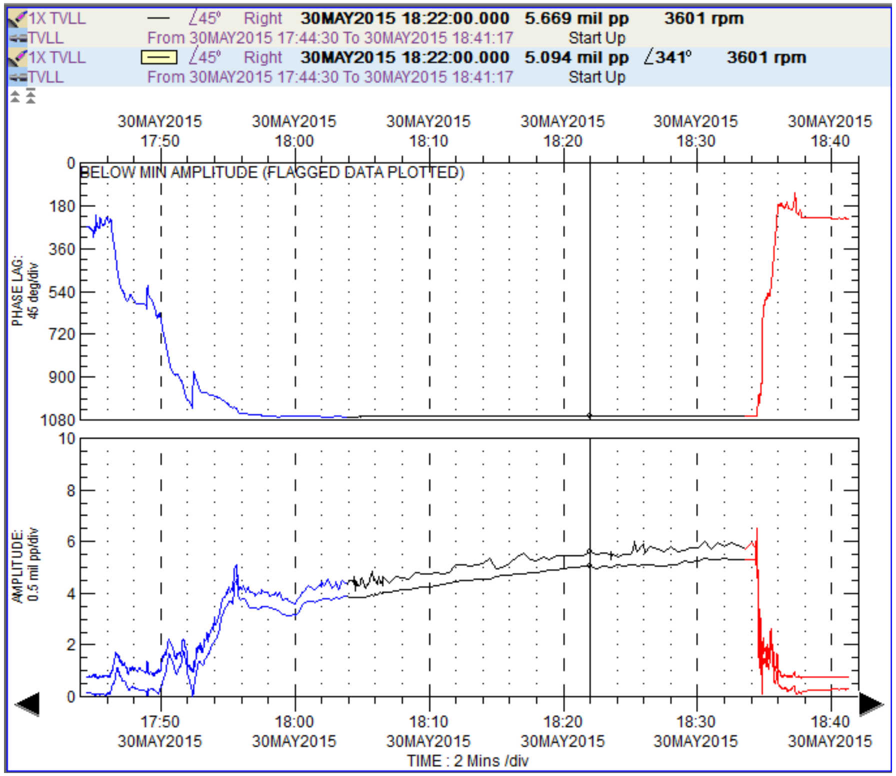
CH#	Chann...	Sample#	Date	Speed(P)	Direct	Avg Gap	1XAmplitude	1X Phase	2XAmplitude	2X Phase	nX-1Amplitude	nX-1 Phase	Speed
1	1X TVLL	460	30May2015 18:23:29.700	3600	5.569	-7.300	5.063	341	0.247	60	0.016	225BMA	
2	2X TVLC	460	30May2015 18:23:29.700	3600	4.965	-7.531	4.806	278	0.087	324	0.062	0BMA	
3	3X GENLC	460	30May2015 18:23:29.700	3600	2.963	-7.336	1.521	333	0.293	295	0.170	205FNX	
4	3Y GENLC	460	30May2015 18:23:29.700	3600	2.277	-8.227	0.843	43	0.221	112	0.031	0BMA	
5	4X GENLE	460	30May2015 18:23:29.700	3600	3.657	-7.397	2.930	330	0.159	310	0.087	201FNX	
6	4Y GENLE	460	30May2015 18:23:29.700	3600	1.938	-8.313	1.059	340	0.072	270...	0.041	194BMA	
7	5X EXC	460	30May2015 18:23:29.700	3600	7.895	-9.094	6.446	56	0.586	195	0.303	24FNX	
8	5Y EXC	460	30May2015 18:23:29.700	3600	4.539	-9.533	3.444	191	0.632	83	0.062	149BMA	
9	Kph 1	460	30May2015 18:23:29.700	3600	5.569INV	-7.300INV							3600

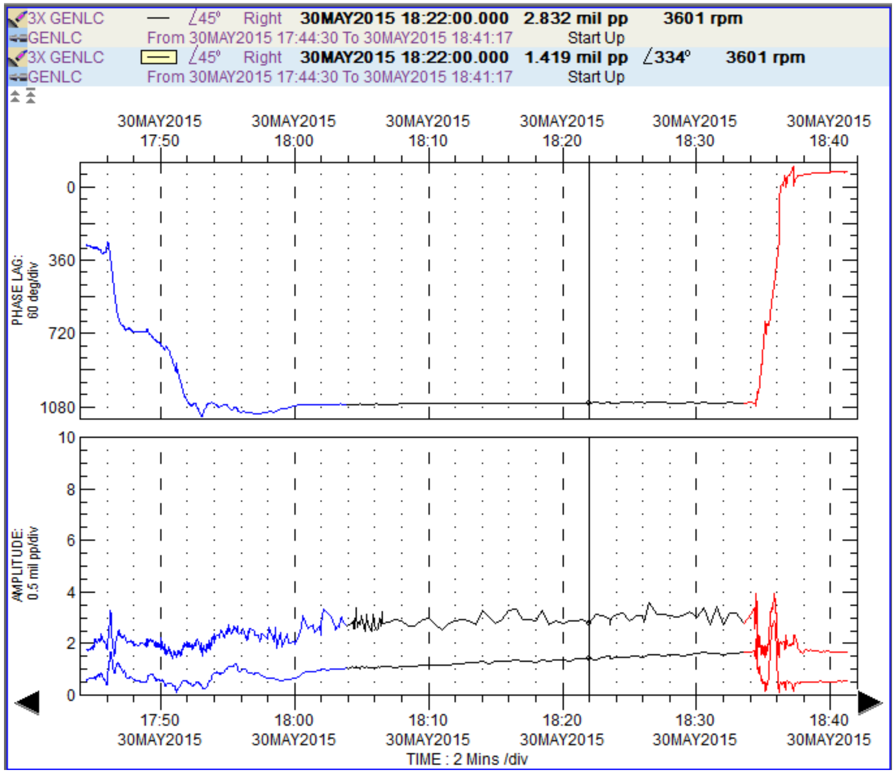
Compare samples
Look for slow roll stability
Compare data of different runs

Vibration Data

Trends

These are more advanced trends that apply not only overall but 1X amplitude and phase for review and analysis



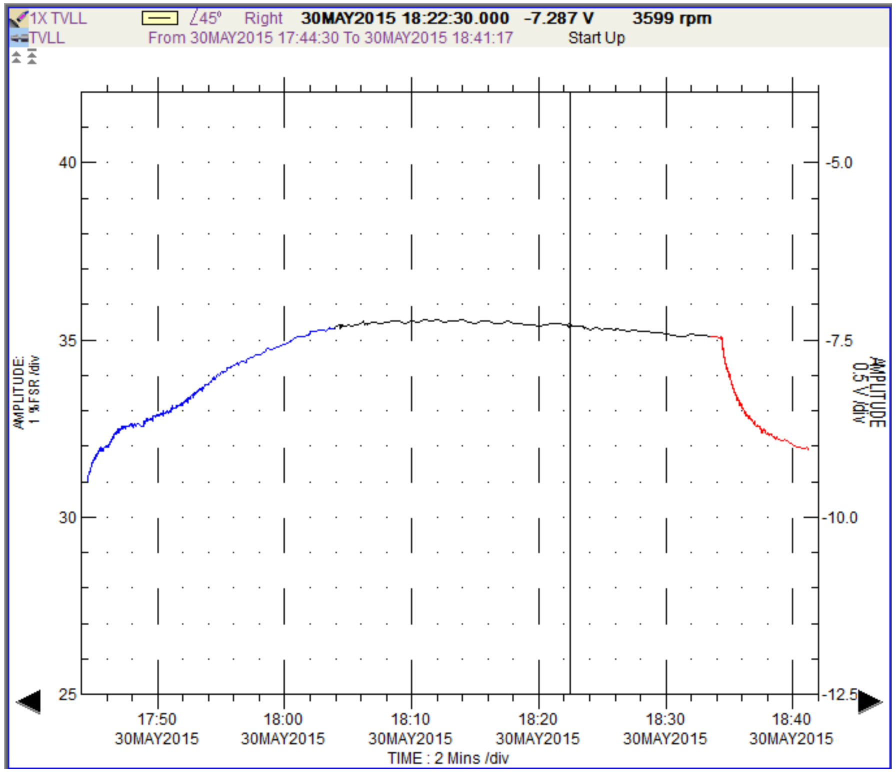


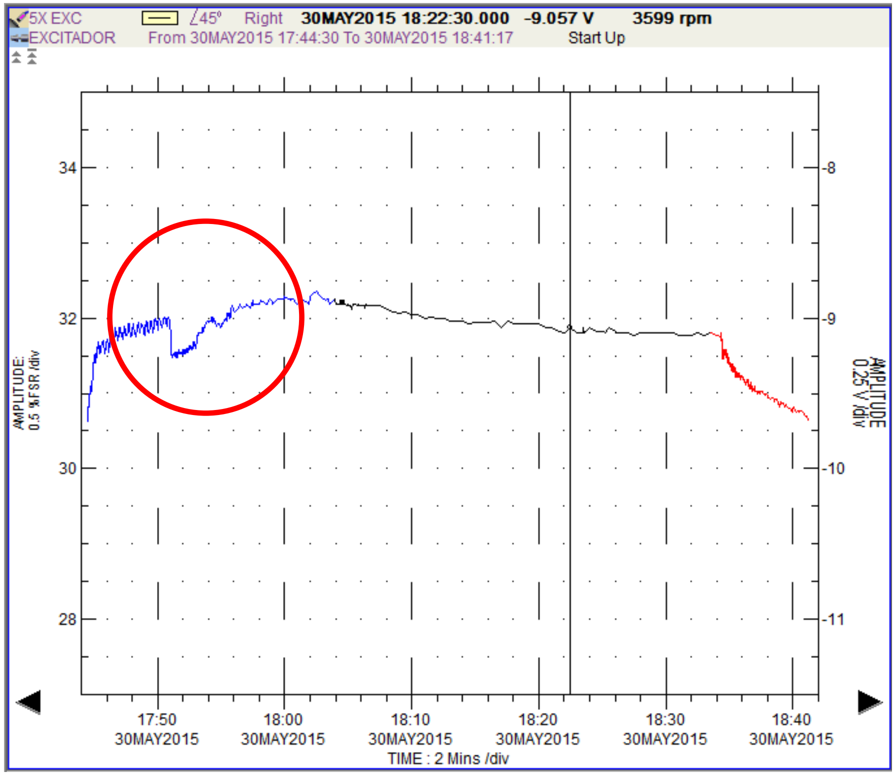
Blue trace – startup; black – loaded/steady state; red – coast down

Vibration Data

Trends – Gap Voltage

These are the raw gap voltages that are used to develop shaft centerlines. Smooth movements are desirable. Anything else could indicate a potential issue



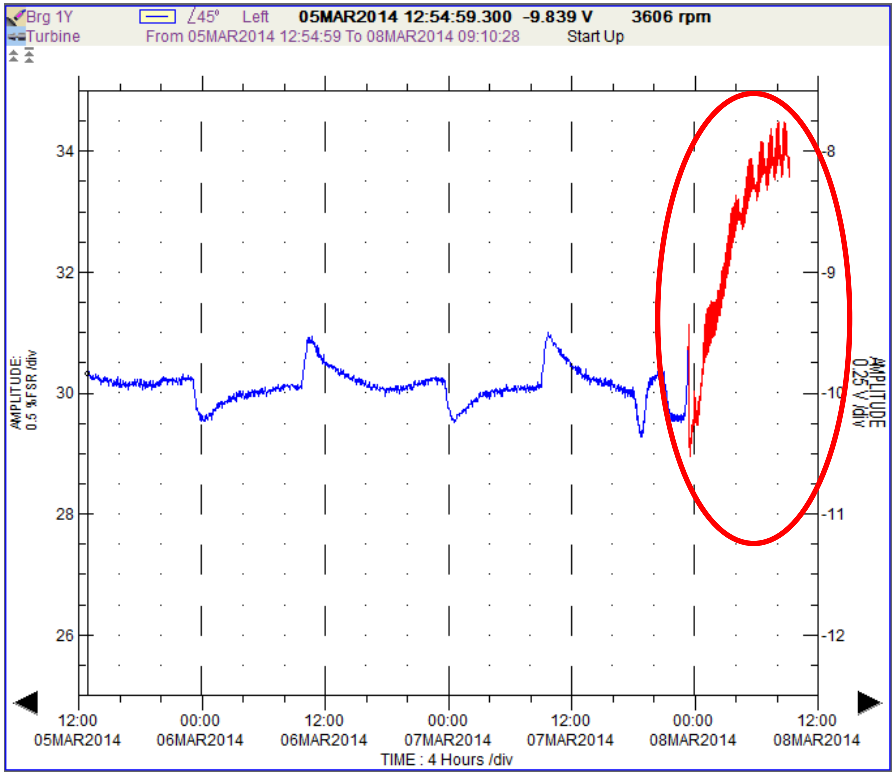


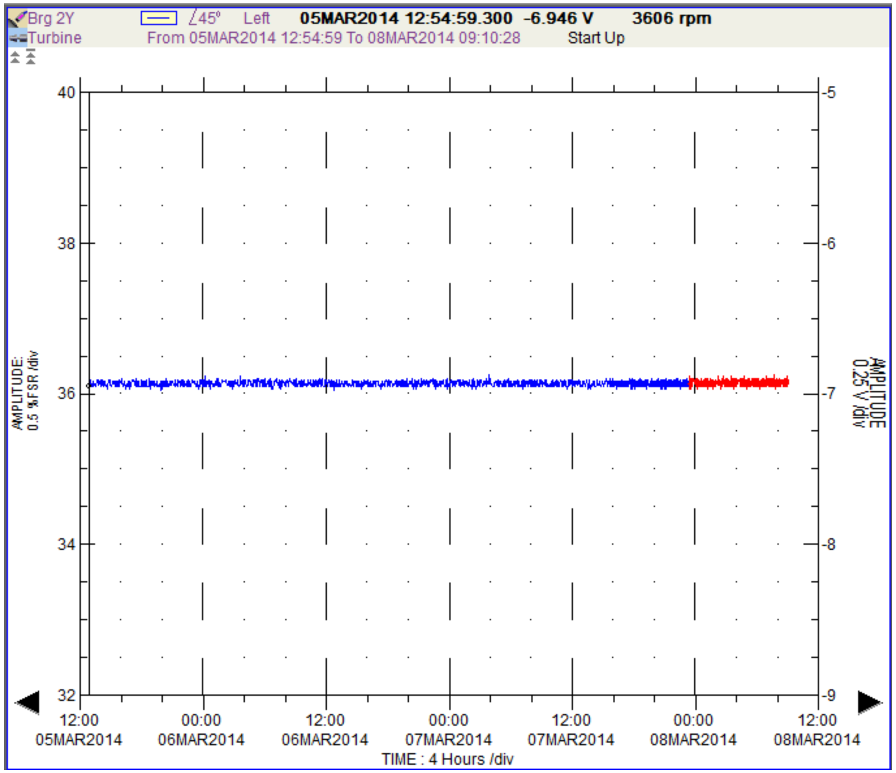
Blue trace – startup; black – loaded/steady state; red – coast down

Vibration Data

Trends

These are the raw gap voltages that are used to develop shaft centerlines. Smooth movements are desirable. Anything else could indicate a potential issue





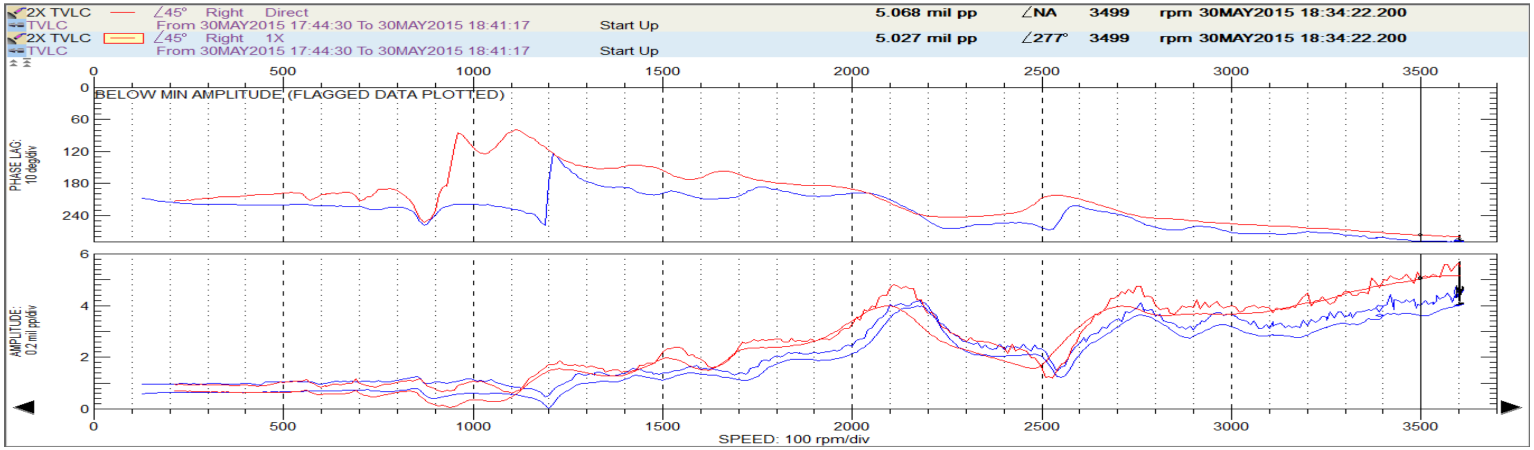
These are abnormal plots

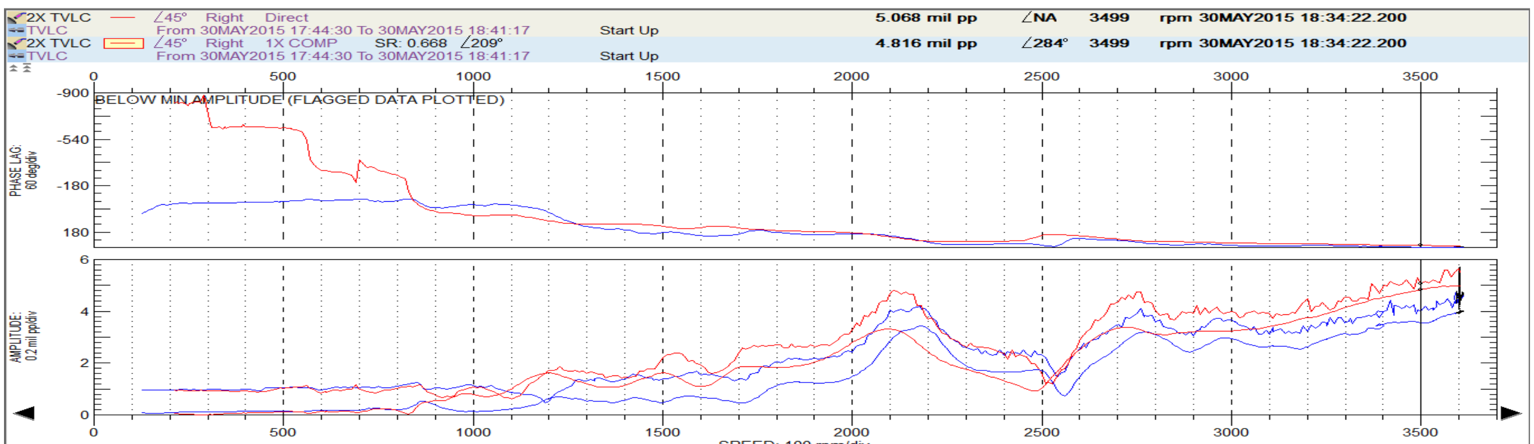
MITSUBISHI HITACHI POWER SYSTEMS
Mitsubishi Hitachi Power Systems Americas, Inc.

Vibration Data

Start-up and coast down comparison
Amplitude shifts; phase shifts
Overall and 1X amplitude and phase

Bode



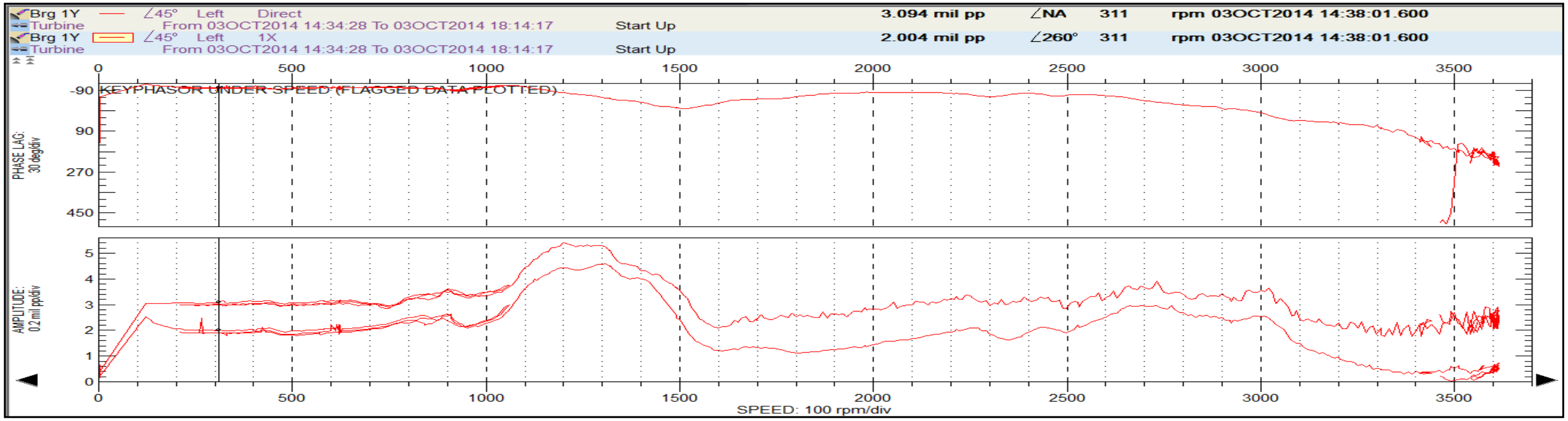


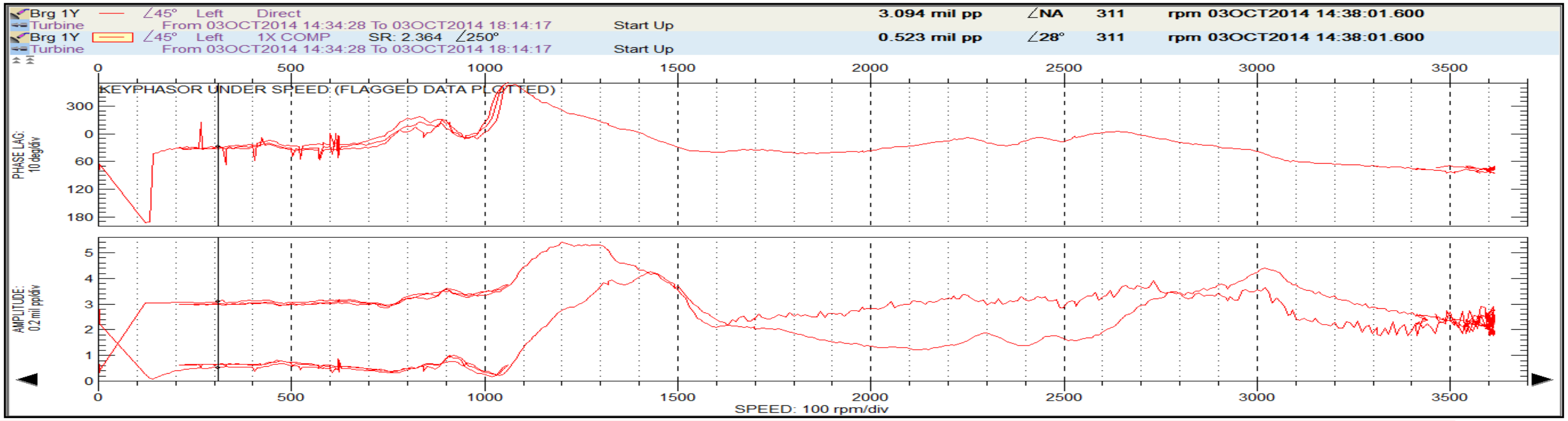
Blue trace – startup; black – loaded/steady state; red – coast down

Vibration Data

Bode

Start-up and coast down comparison
Amplitude shifts; phase shifts
Overall and 1X amplitude and phase
Slow roll change due to a rub



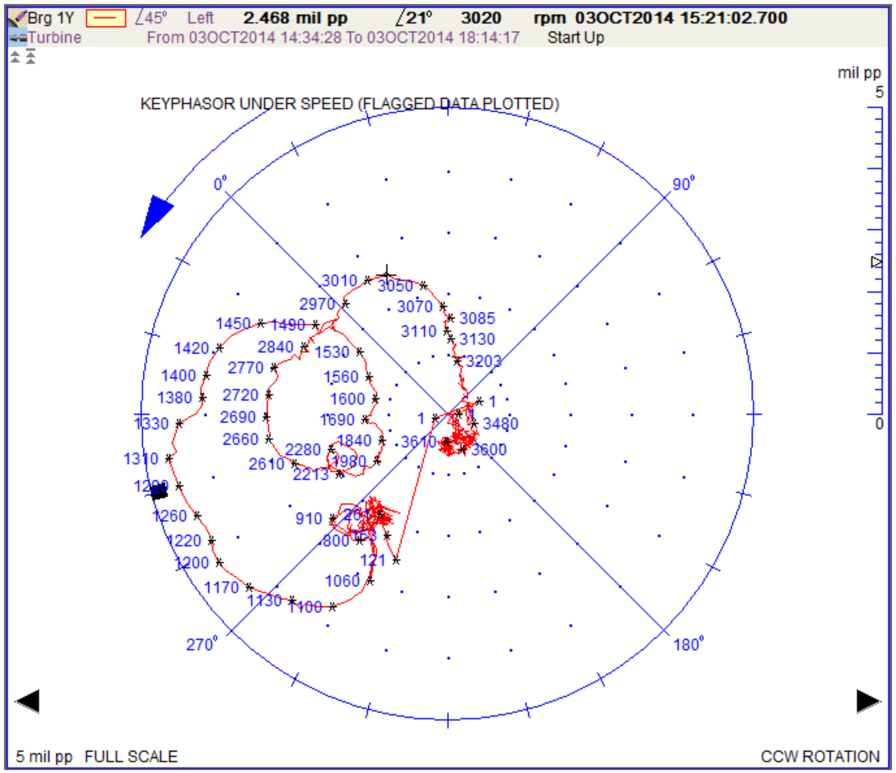


Blue trace – startup; black – loaded/steady state; red – coast down

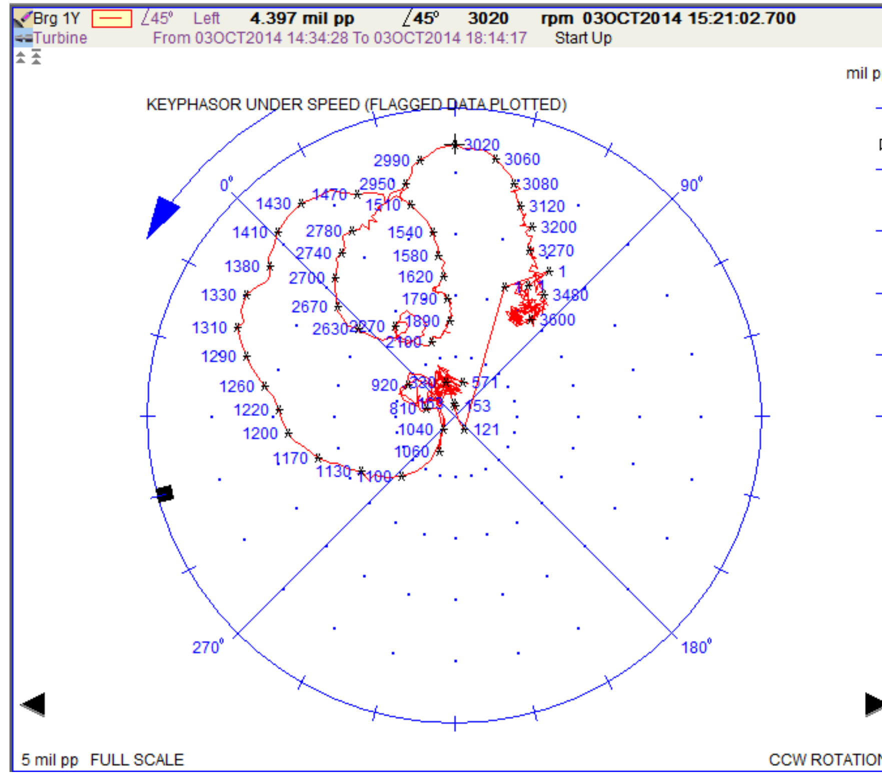
Vibration Data

Polar

Coast down comparison between compensated and uncompensated shows phase and amplitude shifts
And peak critical speed shift



Uncompensated



Compensated

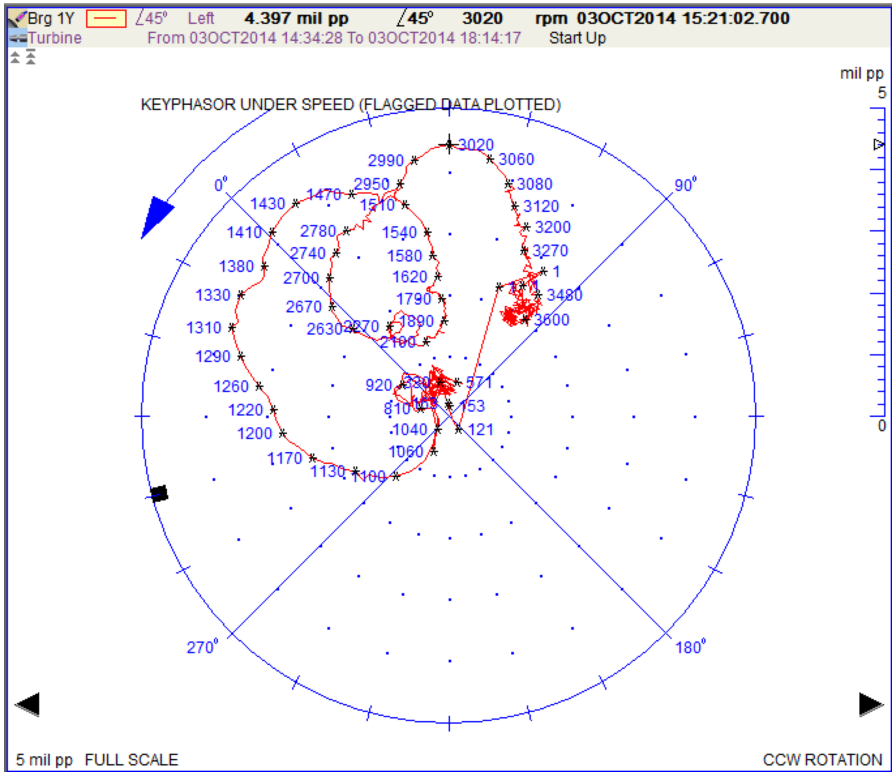
MITSUBISHI HITACHI POWER SYSTEMS

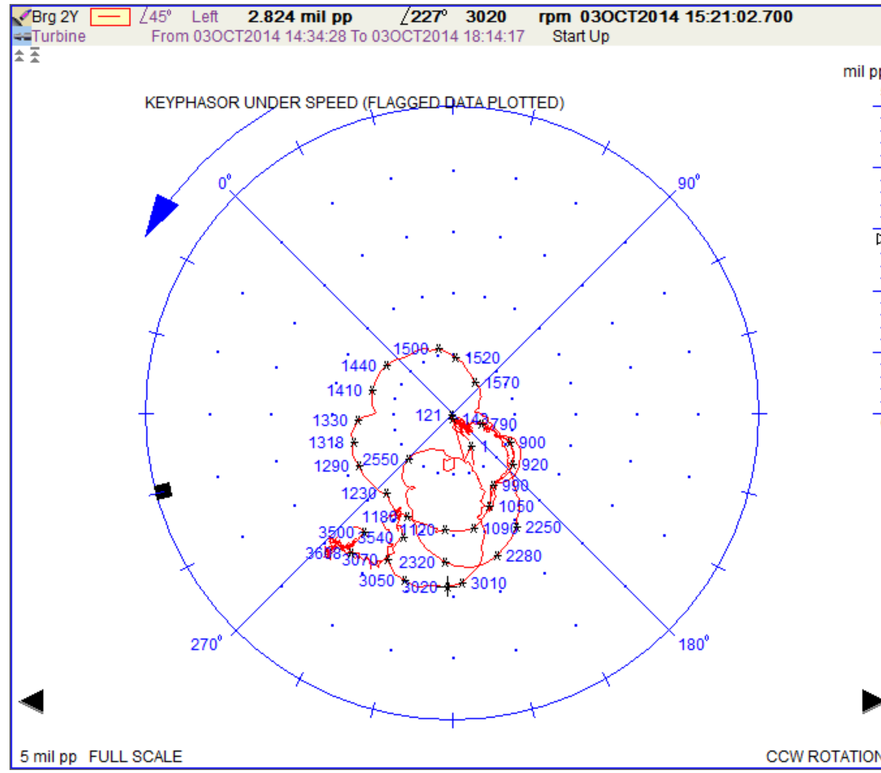
Mitsubishi Hitachi Power Systems Americas, Inc.

Vibration Data

Polar

Compensated data showing vibration signature differences between the two ends of the machine

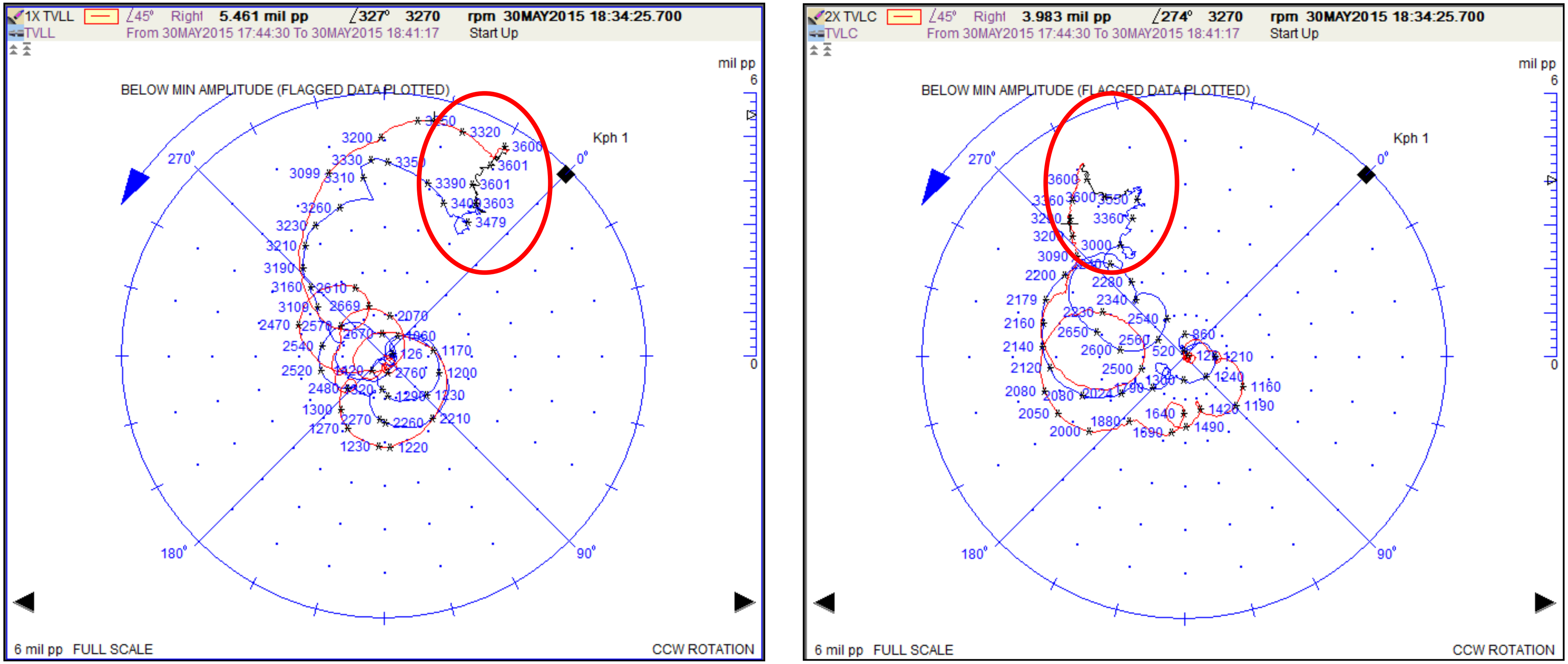




Vibration Data

Polar

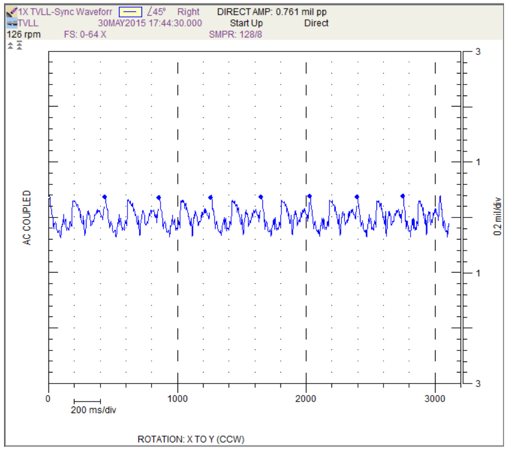
Steady state amplitude and phase shifts due to a rub

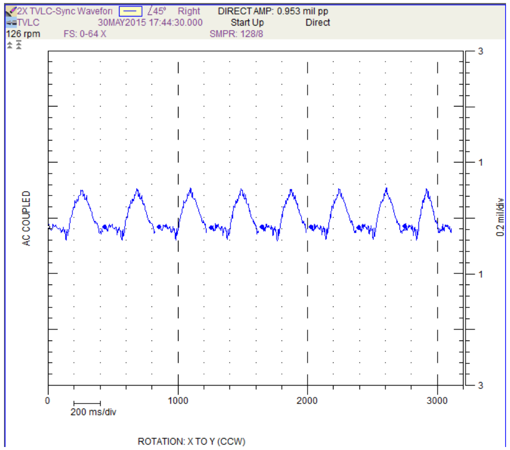


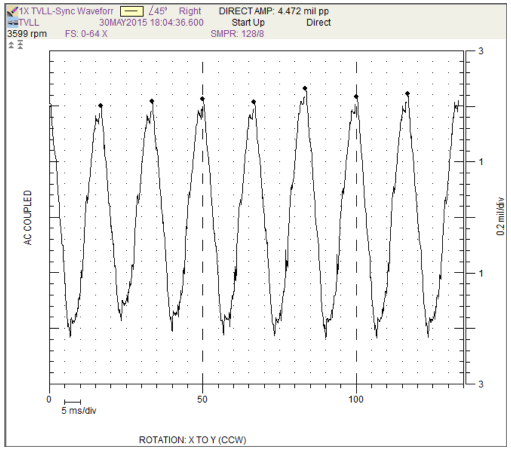
Vibration Data

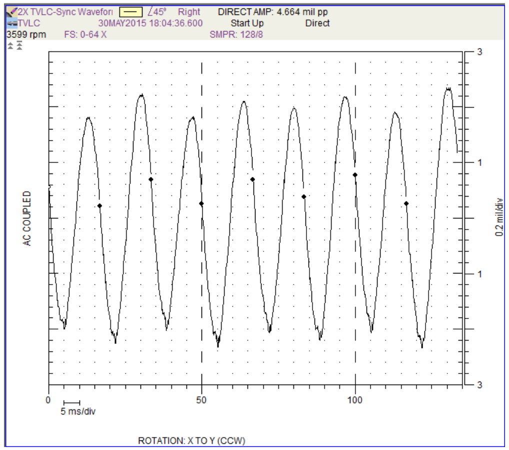
Waveforms

Top two plots are slow roll noise levels for those channels
Bottom two plots are uncompensated 3600 rpm data
Same scales





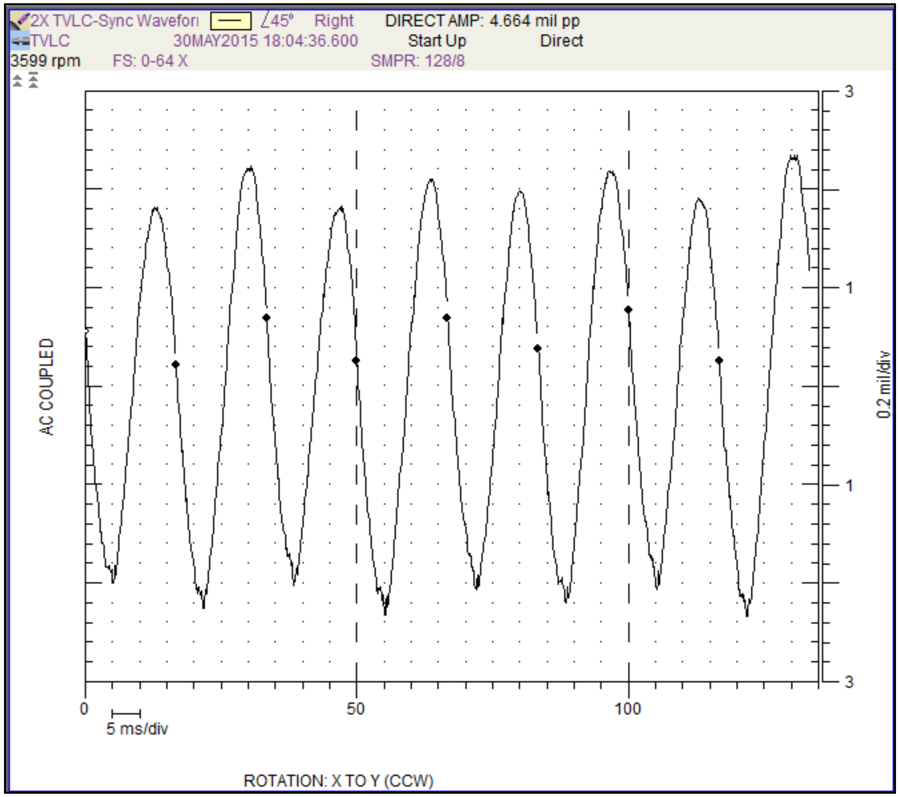


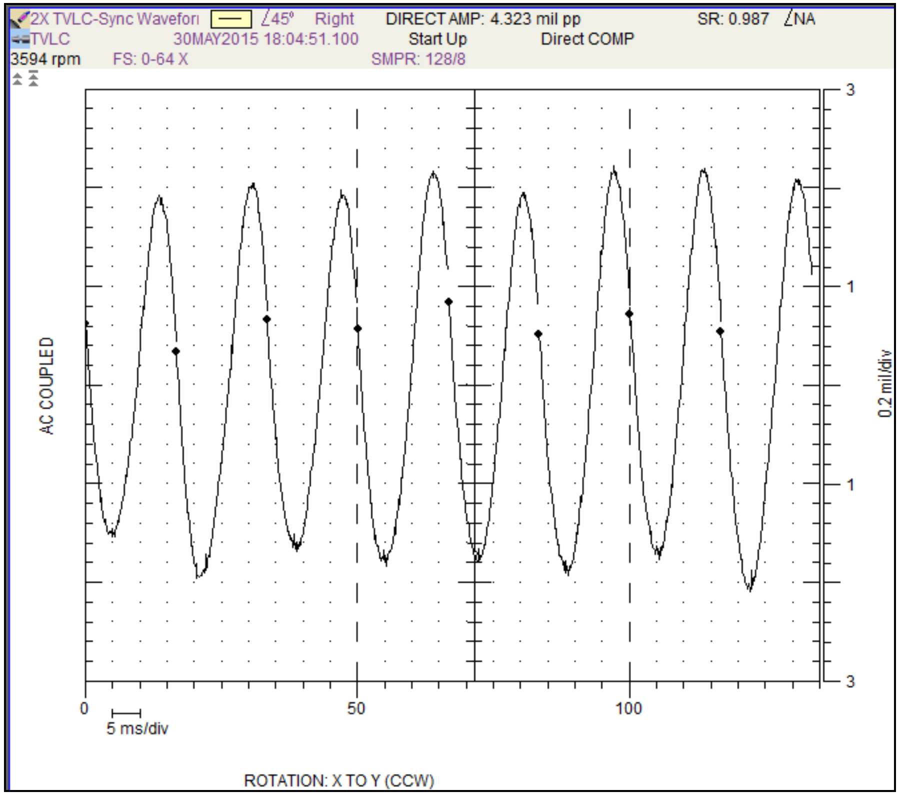


Vibration Data

Waveforms

Compensated plots from previous slide show less than 0.5 mils of change in amplitudes

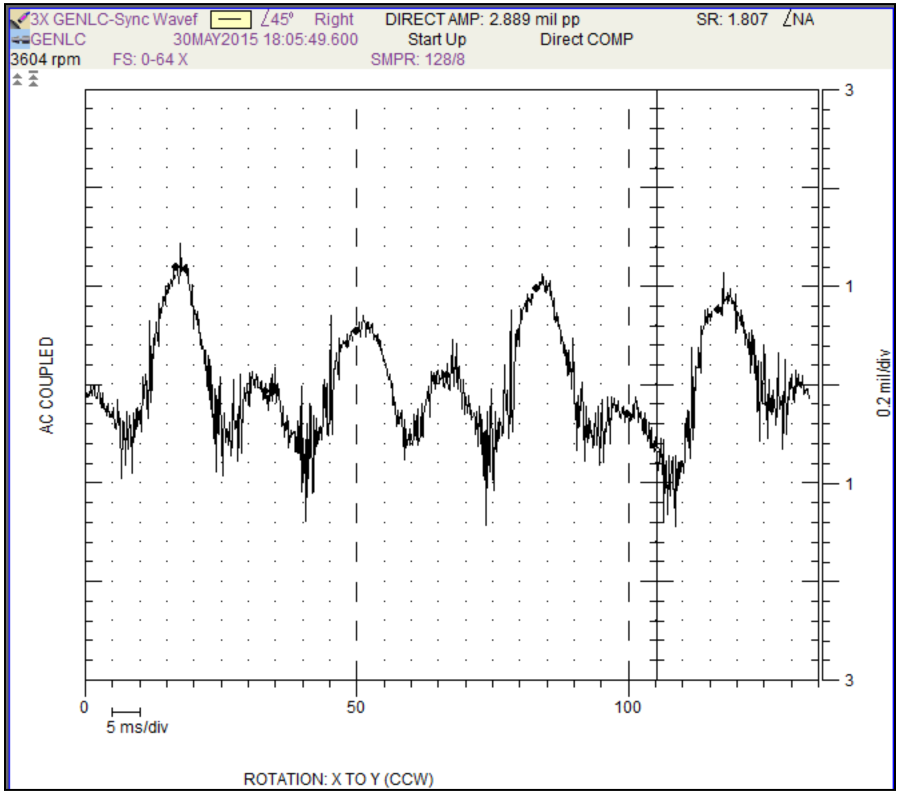


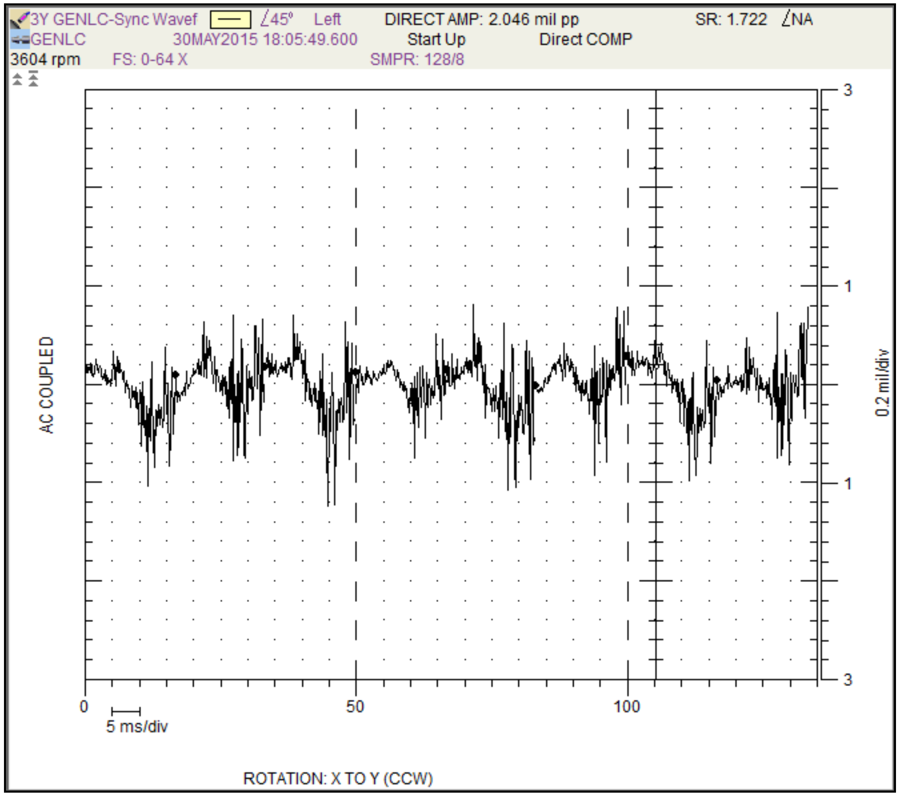


Vibration Data

Waveforms

Example of another machine with higher noise levels. Plots below are 3600 rpm



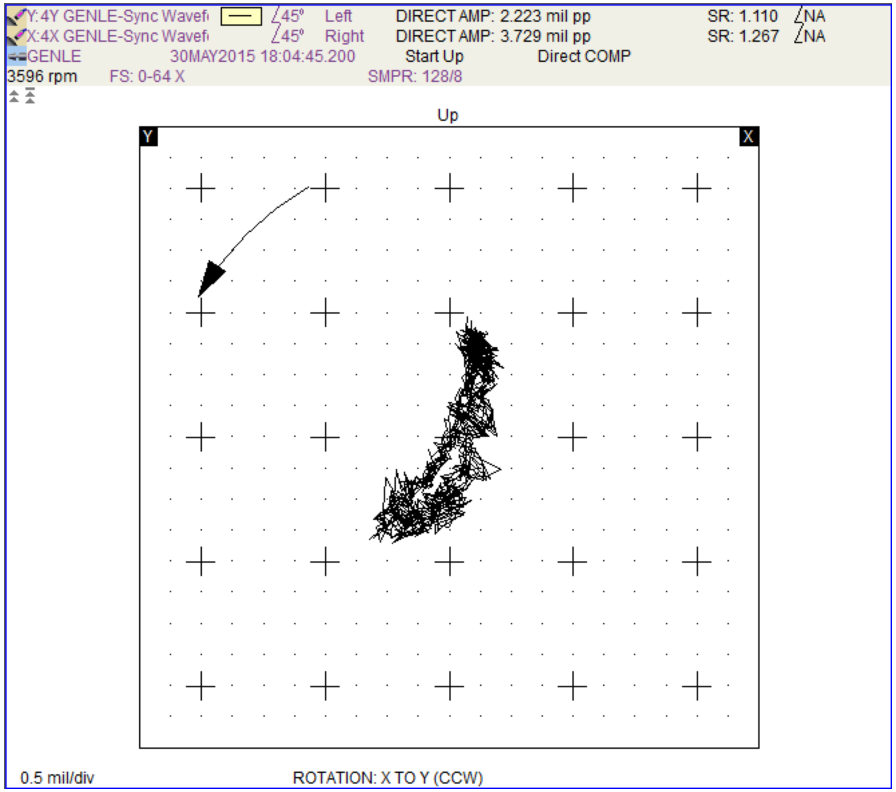


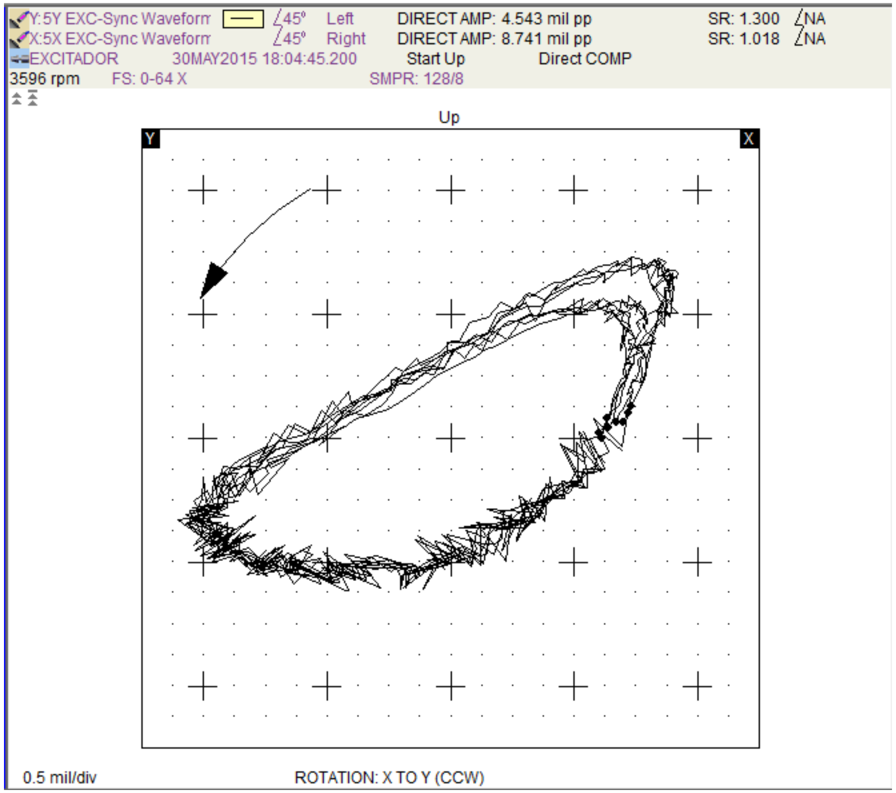
MITSUBISHI HITACHI POWER SYSTEMS
Mitsubishi Hitachi Power Systems Americas, Inc.

Vibration Data

Orbits

Example of a machine with preload on two of it's bearings looking at the Direct Orbits. Left side plot with banana shape; right side plot with 'flattened' side.

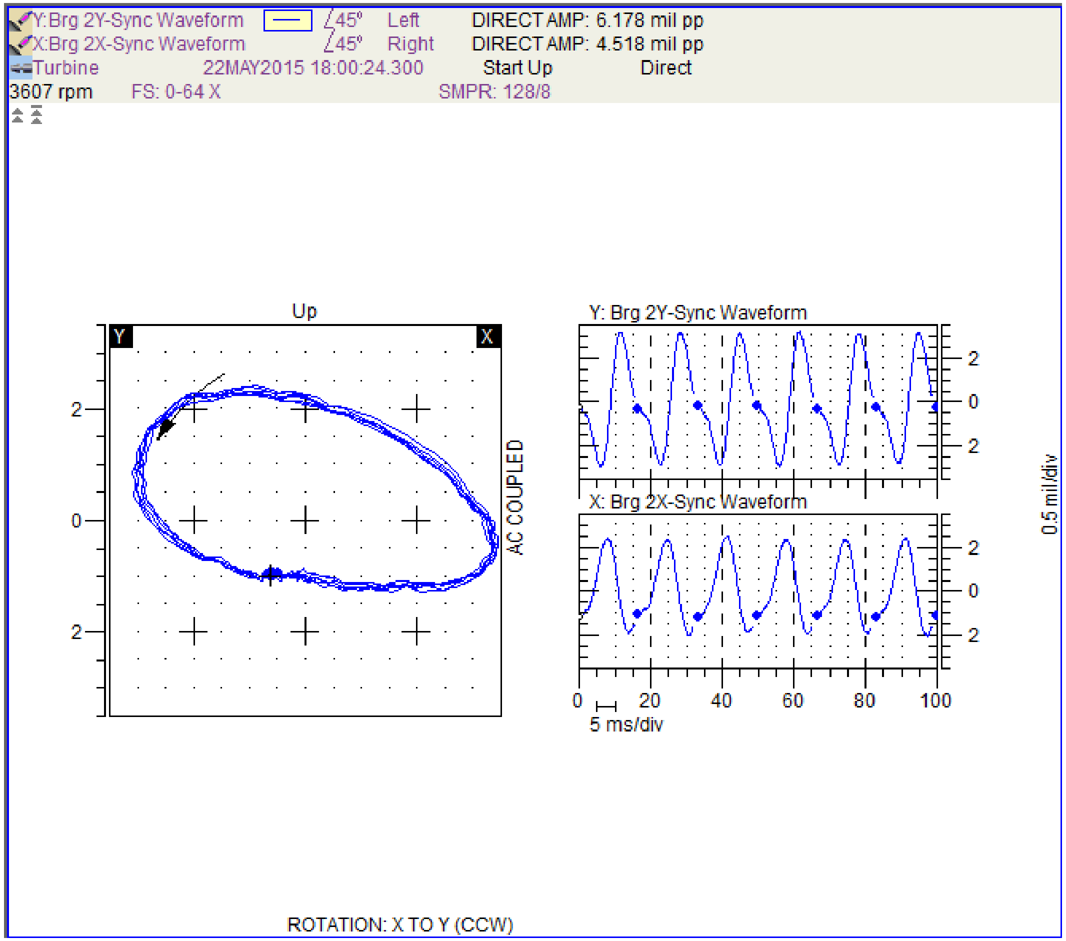




Vibration Data

Orbits

Example of a machine showing the Direct Timebase and Orbit plots. Uneven travel through Timebase resulting in uneven elliptical shape

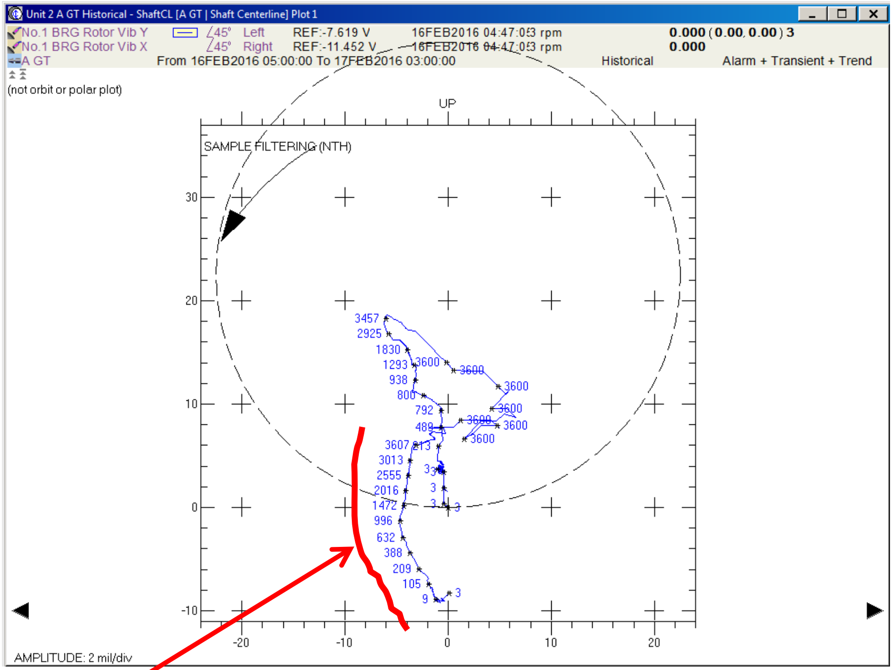


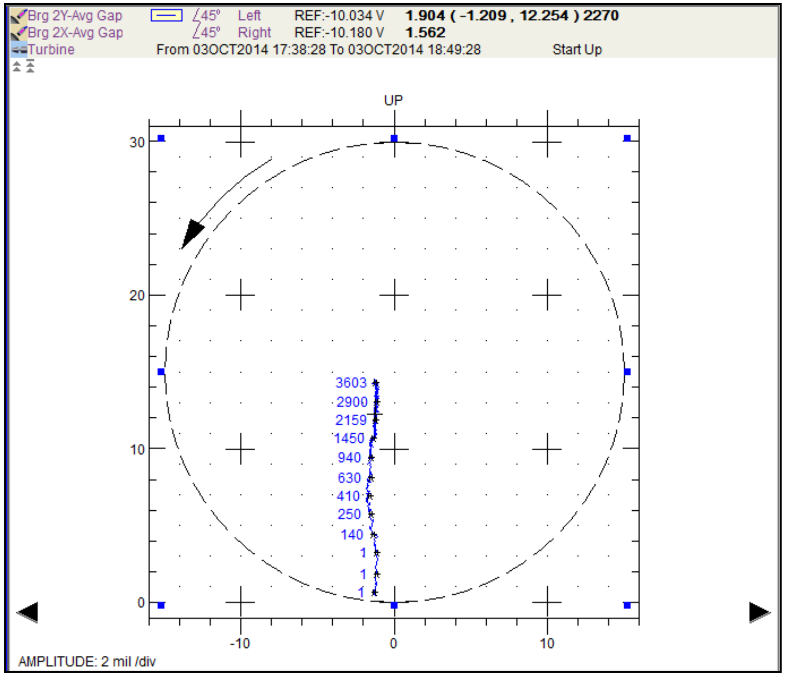
Vibration Data

Shaft Centerlines

Shaft Centerline plots of a startup and coast down on a large frame gas turbine. Left side plot is exhaust or #1 bearing; right side is compressor or #2 bearing.

Abnormal movement of #1 bearing is due to thermal growth of the startup. During coast down, there was a horizontal preload indicated.



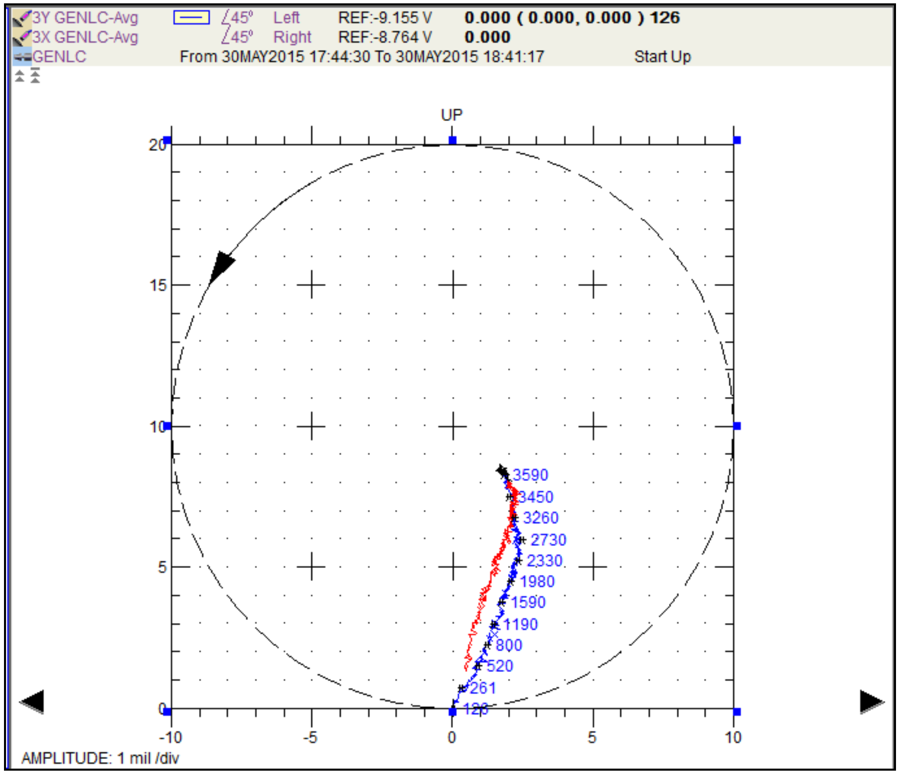


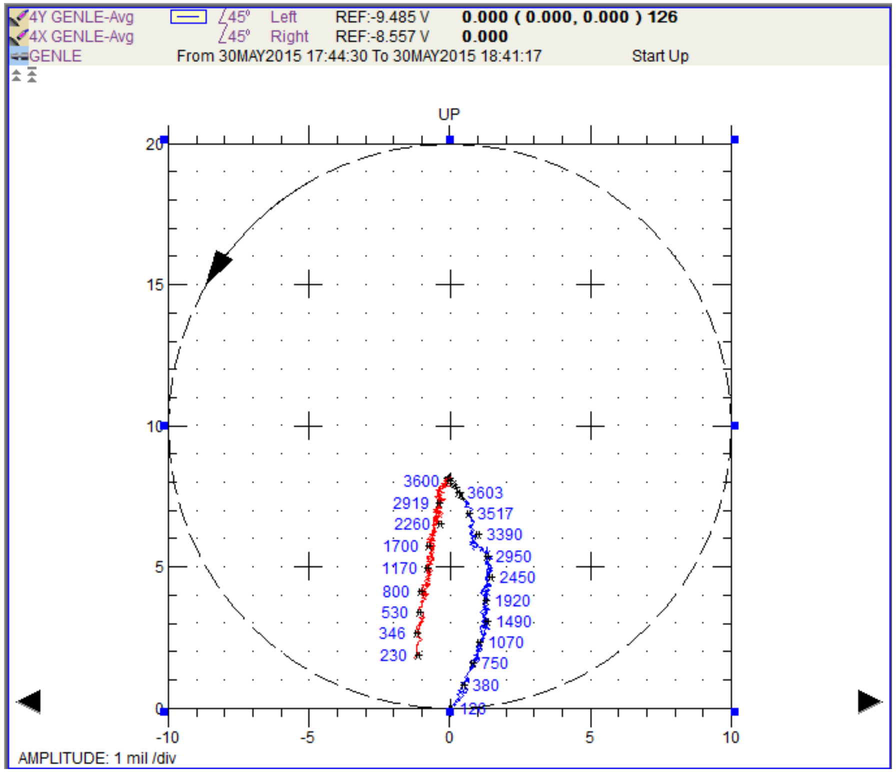
Coast down section of the data

Vibration Data

Shaft Centerlines

Shaft Centerline movements of a gas turbine that are more typical. Some horizontal preload, further evaluation of other data plots would be recommended



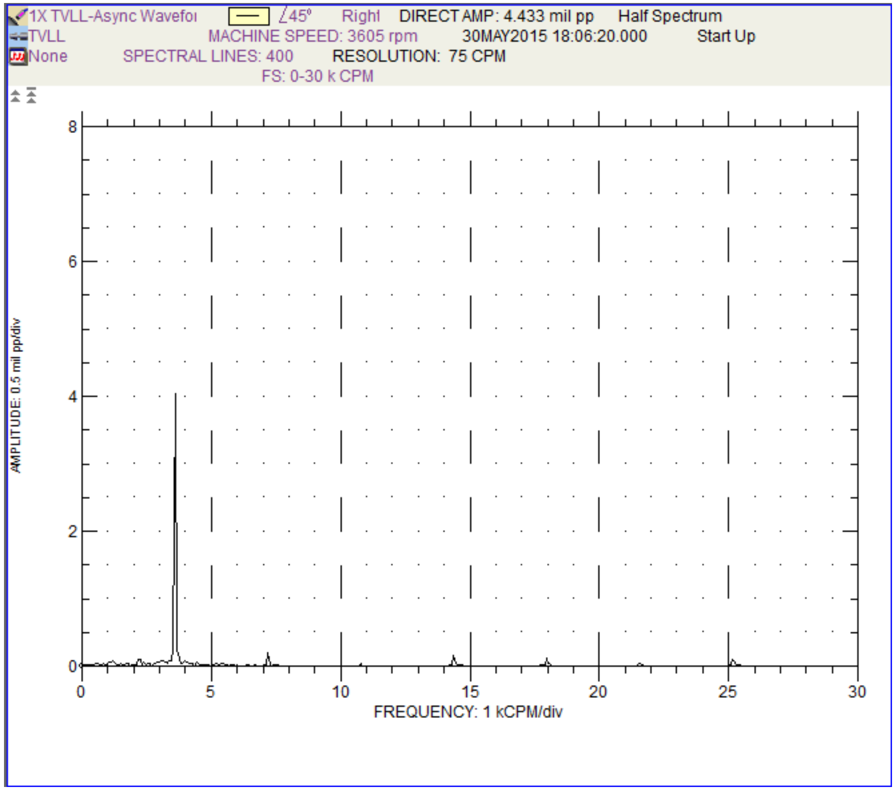


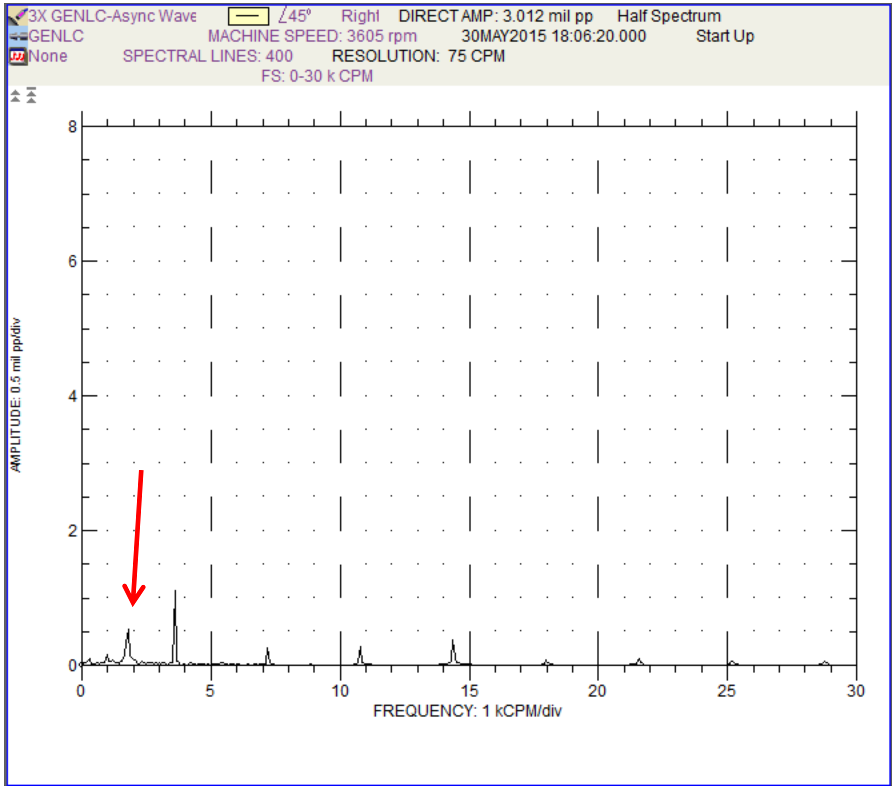
Blue trace – startup; black – loaded/steady state; red – coast down

Vibration Data

Spectrums

Typical Spectral data for a Gas Turbine bearing and a Generator bearing. Generator bearing on right was indicating some sub-synchronous energy.

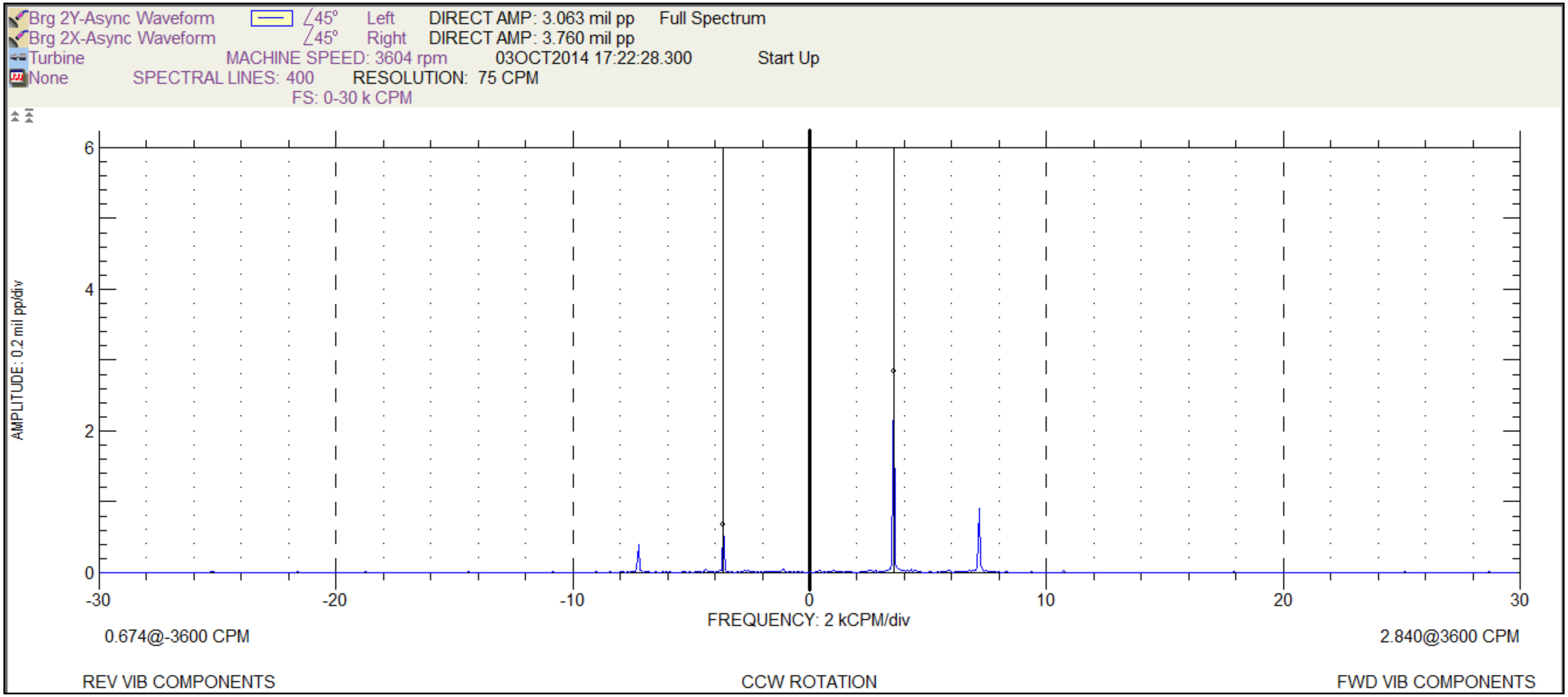




Vibration Data

Full Spectrum

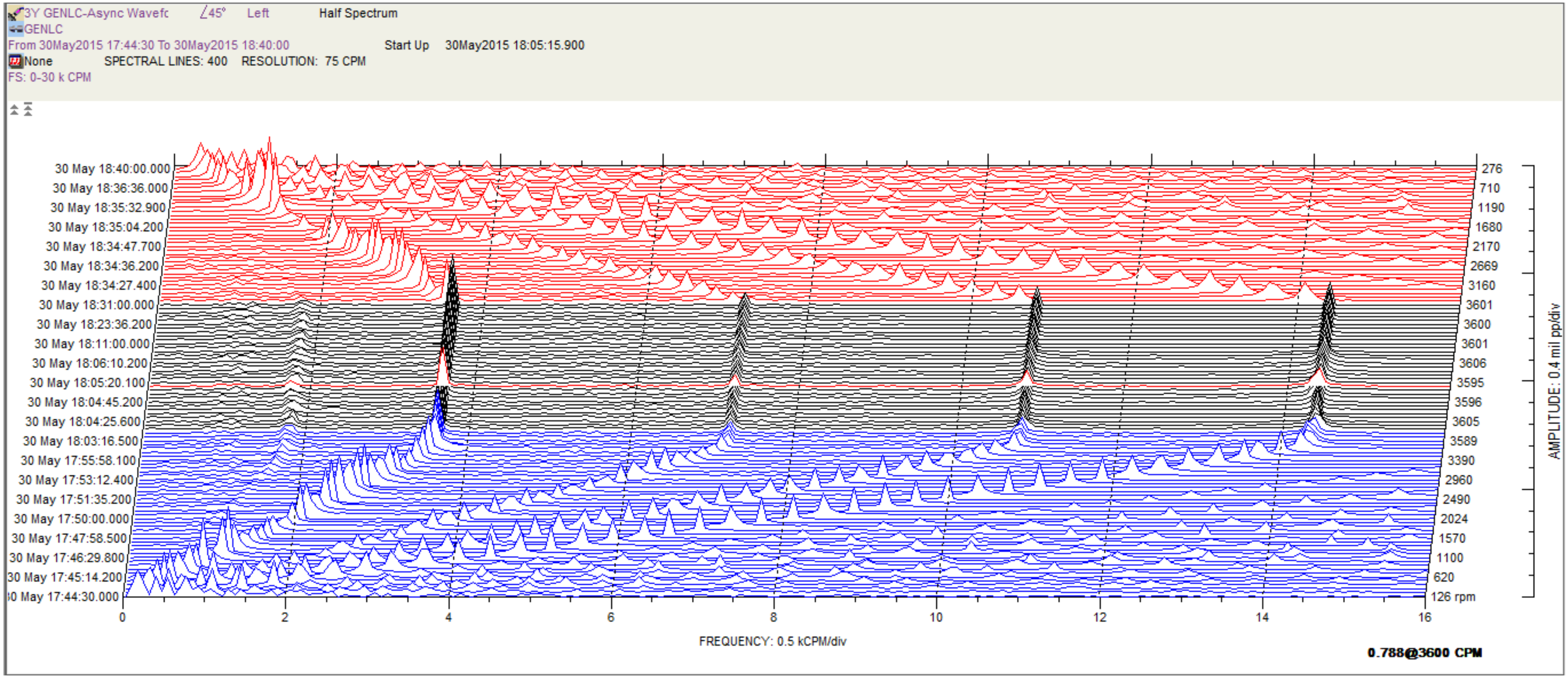
Typical Full Spectrum data for a compressor bearing in a Gas Turbine. Some reverse precession energy indicated. Orbit plot would be elliptical



Vibration Data

Waterfall

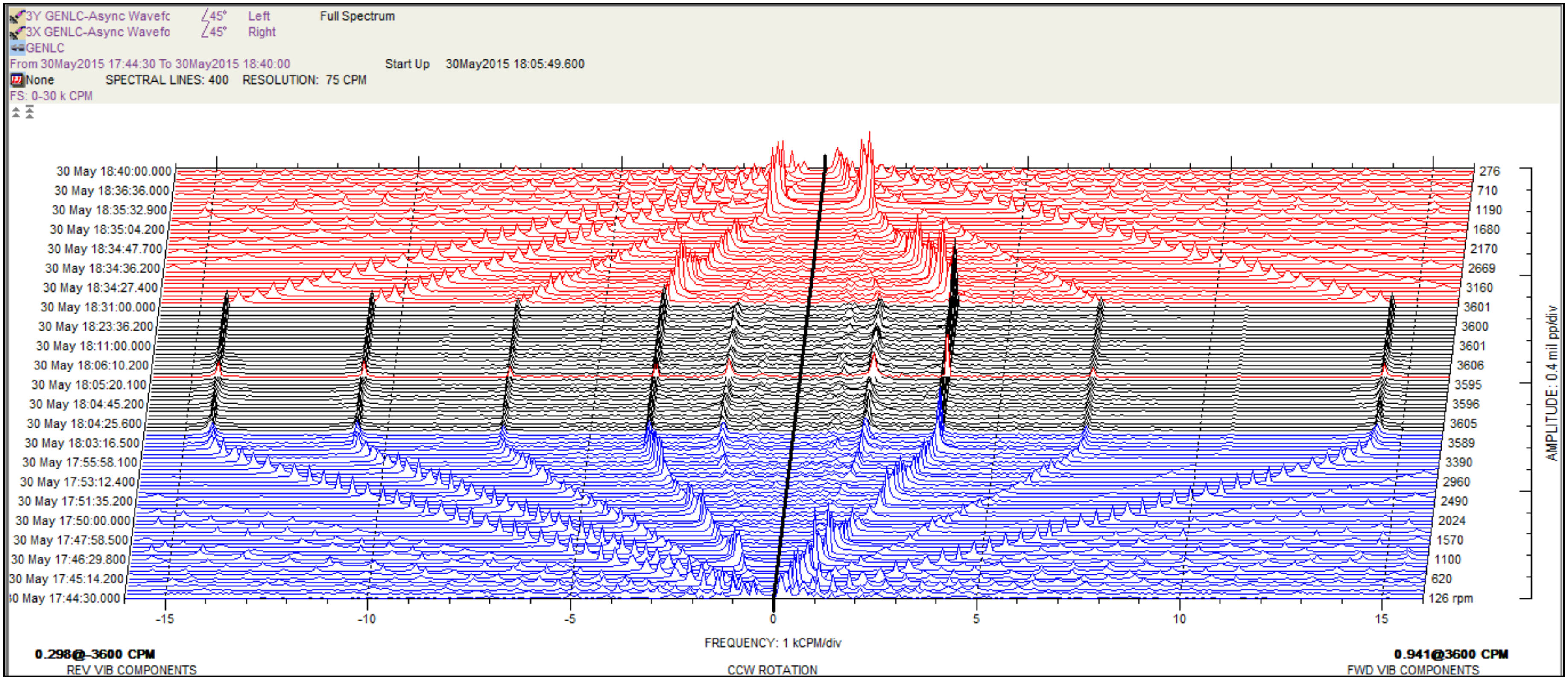
Spectral plot shown during startup, loaded operation, and coast down. Lack of change in synchronous multiples during the speed transients indicated that this is 'glitch' in the signal and not actual vibration energy.



Vibration Data

Full Waterfall

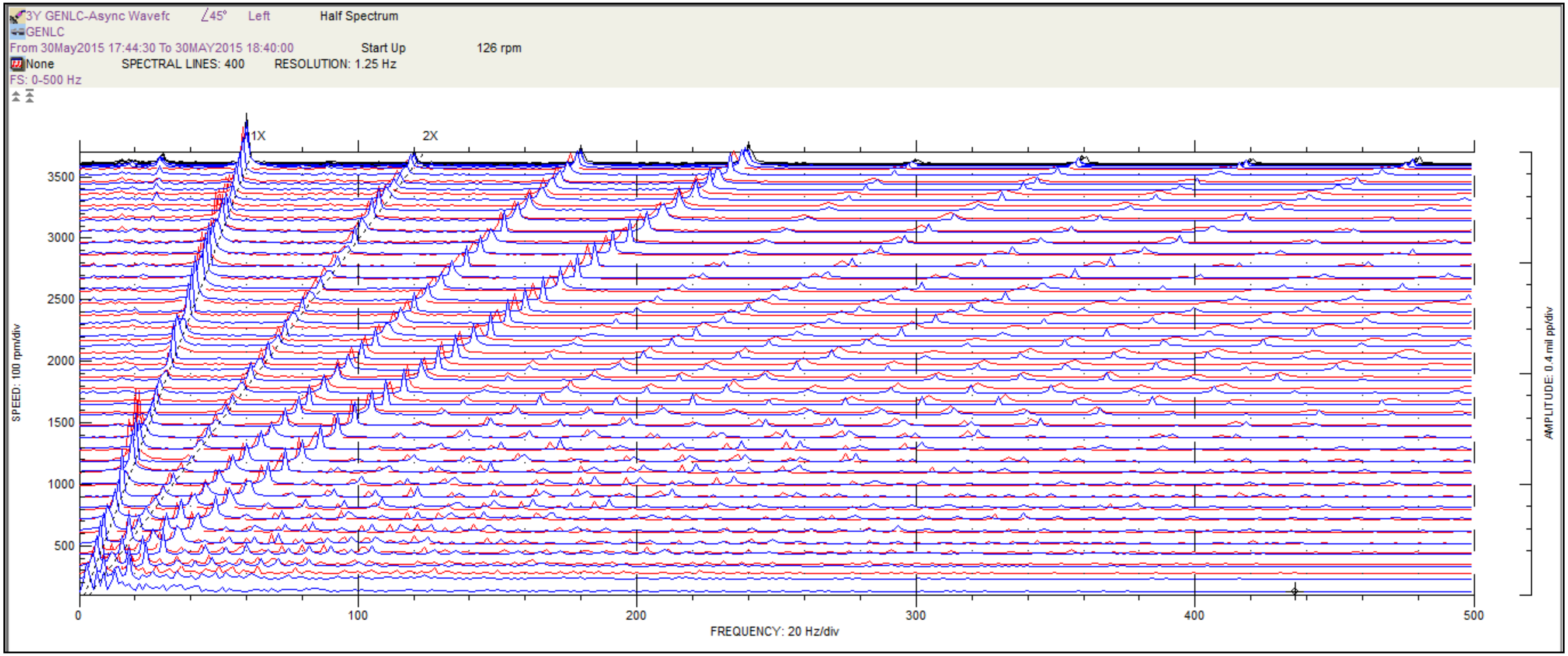
Full Spectrum Waterfall shown (same data as previous slide) during startup, loaded operation, and coast down. Lack of change in synchronous multiples during the speed transients indicated that this is ‘glitch’ in the signal and not actual vibration energy.



Vibration Data

Cascade

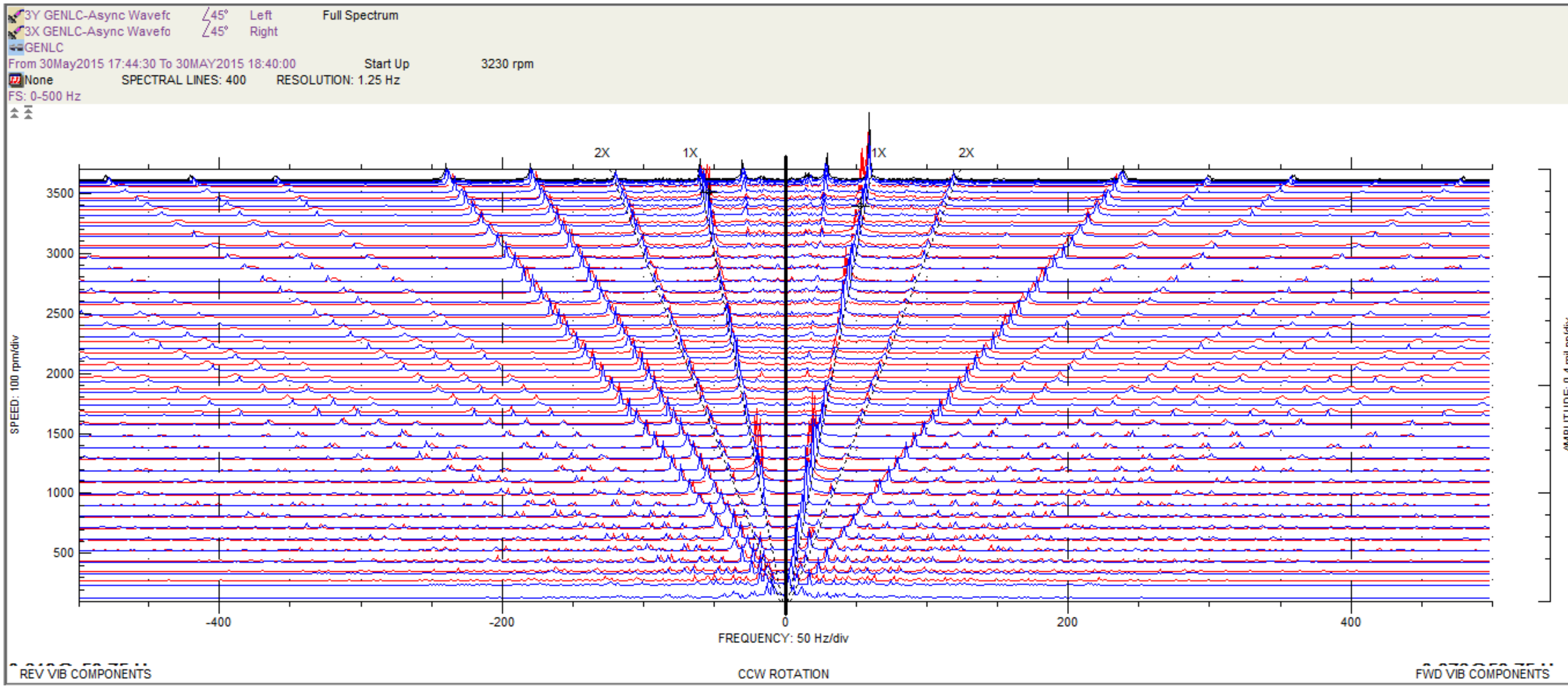
Cascade plot (same data as previous slide) during startup, loaded operation, and coast down. Lack of change in synchronous multiples during the speed transients indicated that this is 'glitch' in the signal and not actual vibration energy.



Vibration Data

Full Cascade

Full Spectrum Cascade shown (same data as previous slide) during startup, loaded operation, and coast down. Lack of change in synchronous multiples during the speed transients indicated that this is 'glitch' in the signal and not actual vibration energy.



Case Studies

Instrumentation Issues

Proximity probe system

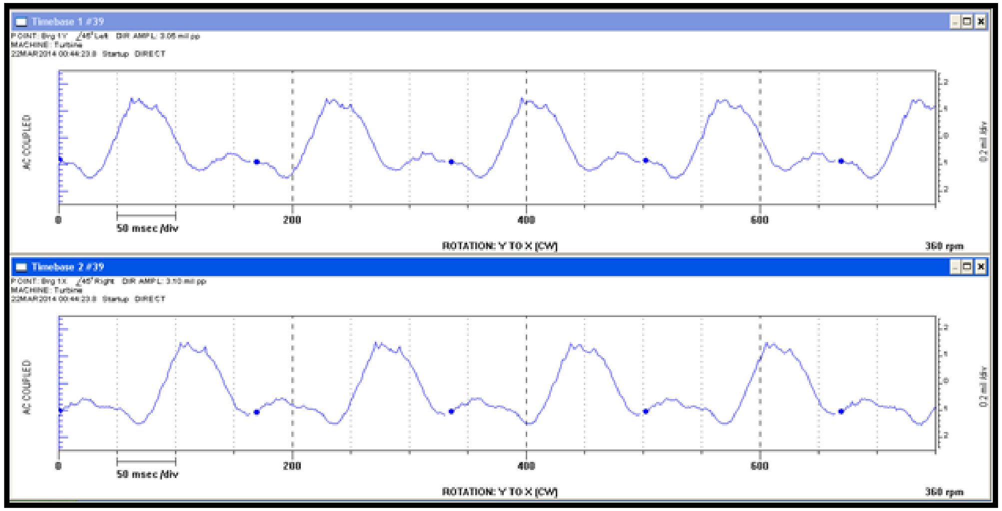
Velocity Coil

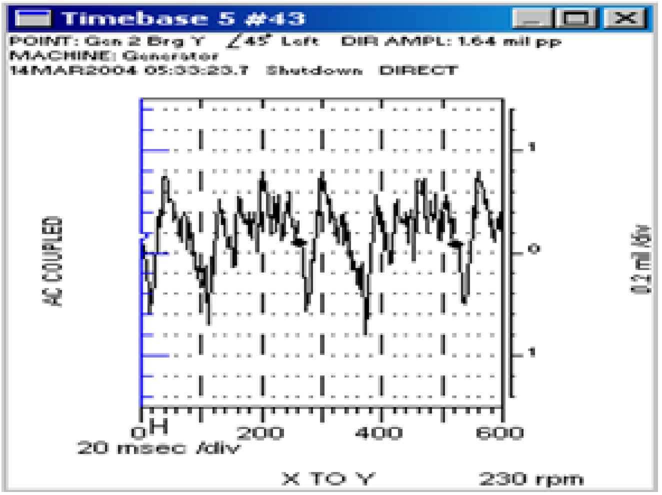
Velomitor

Proximity probe in housing

Case Studies

Instrumentation Issues



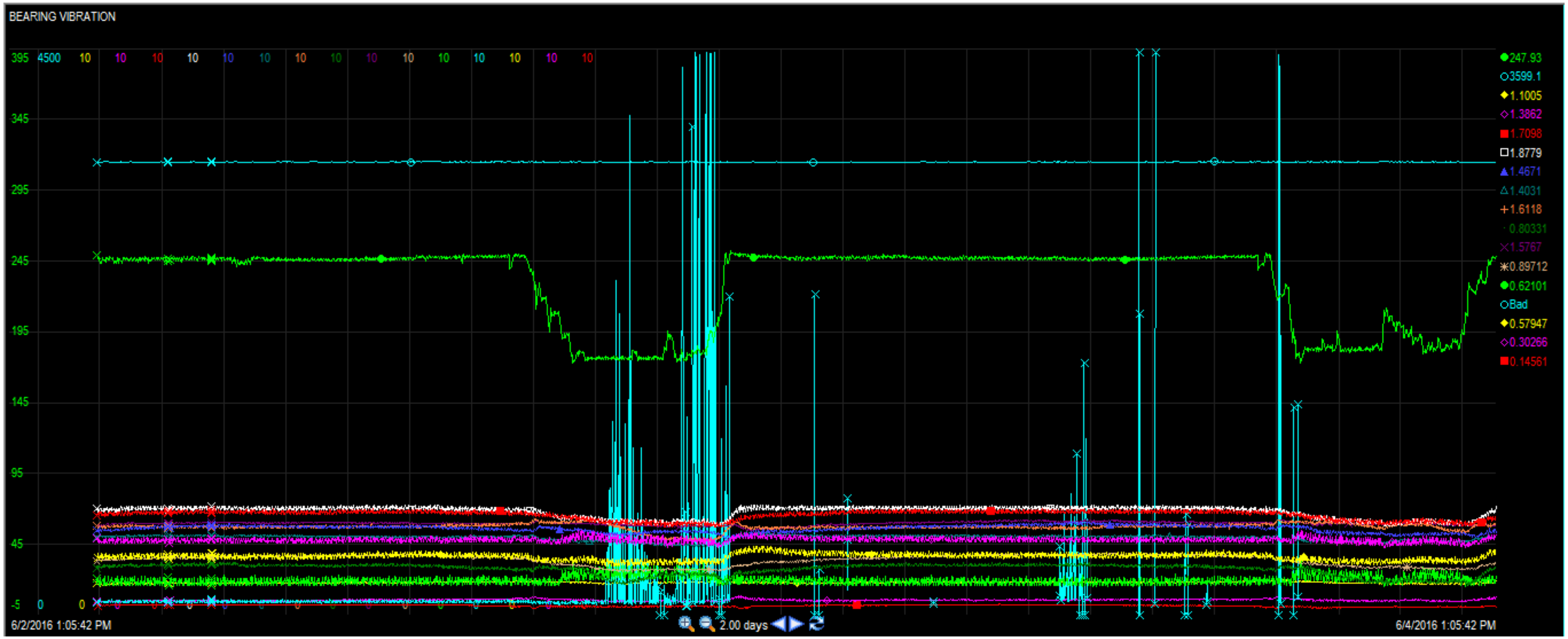


Proximity Probe - Elevated Slow Roll amplitudes

- Mechanical Runout
- Electrical Runout

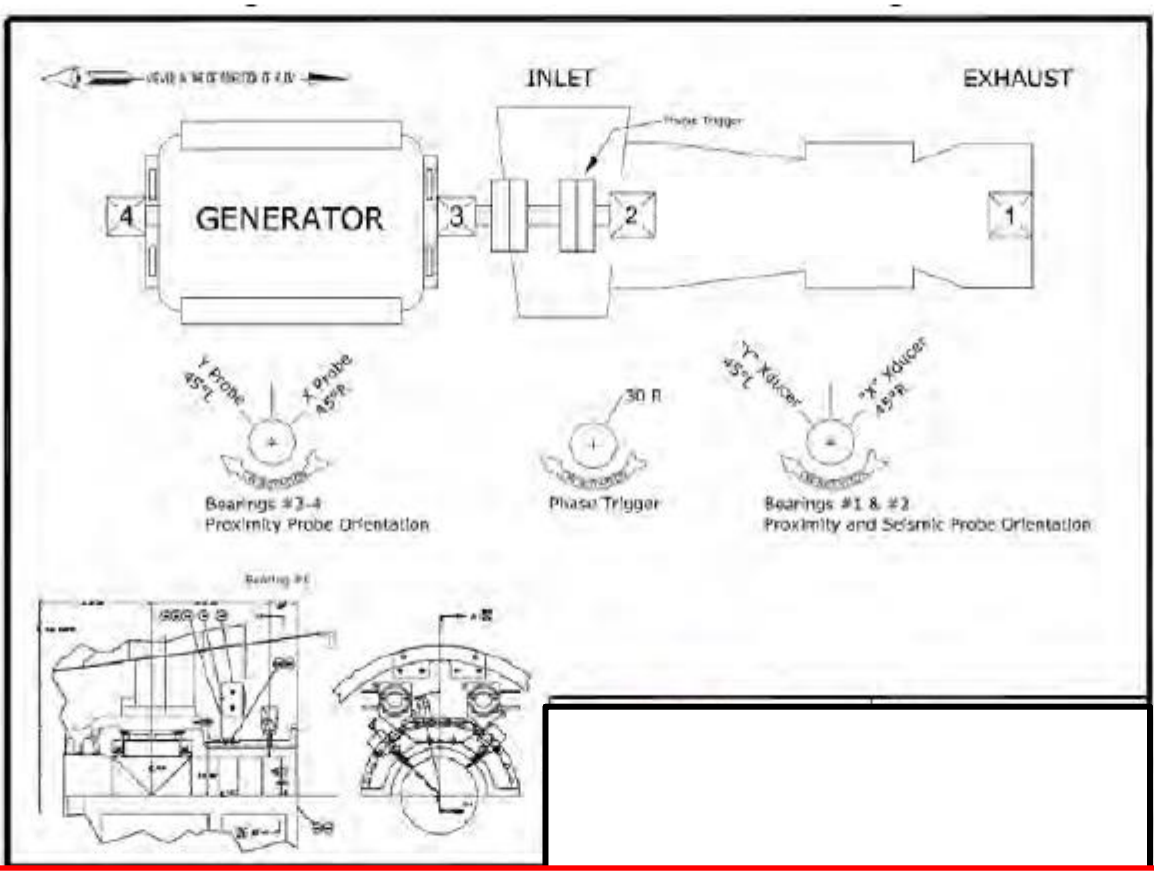
Case Studies

Instrumentation Issues



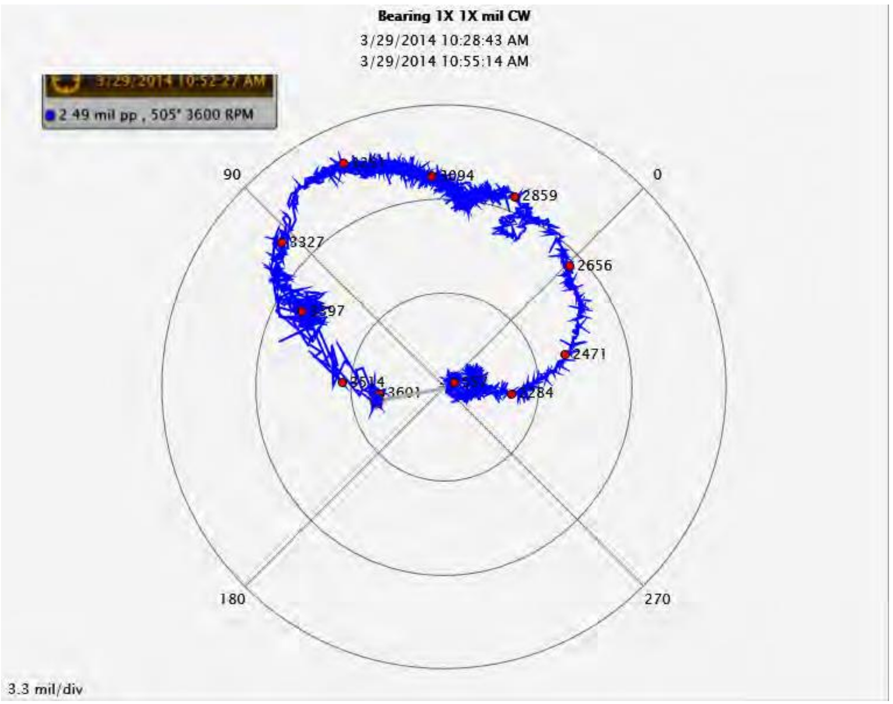
Wiring/Connection Noise

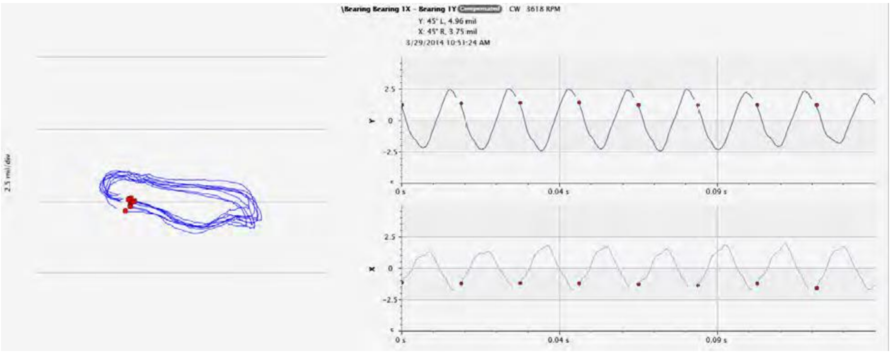
Case Studies



Good documentation layout for machine and instrumentation

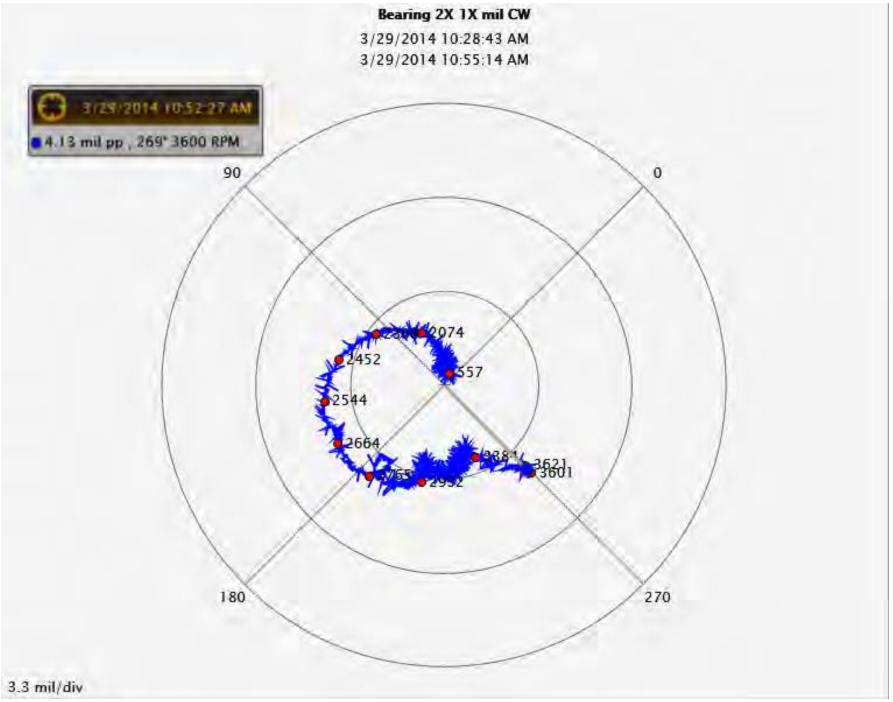
Case Studies

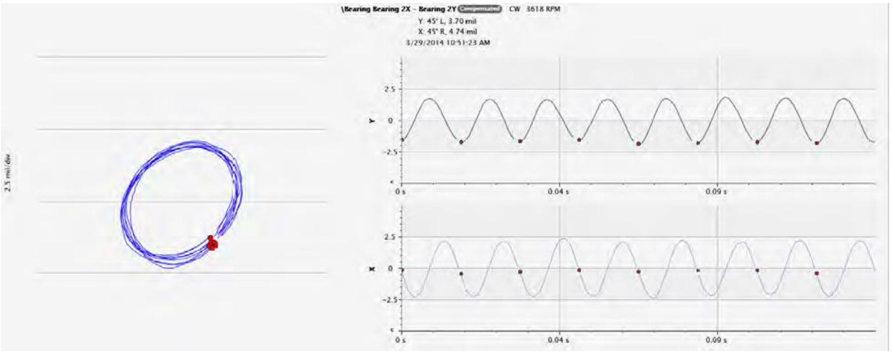




Startup and initial loaded operation; clean 2nd critical; but some vertical preload as it reached full speed; #1 bearing

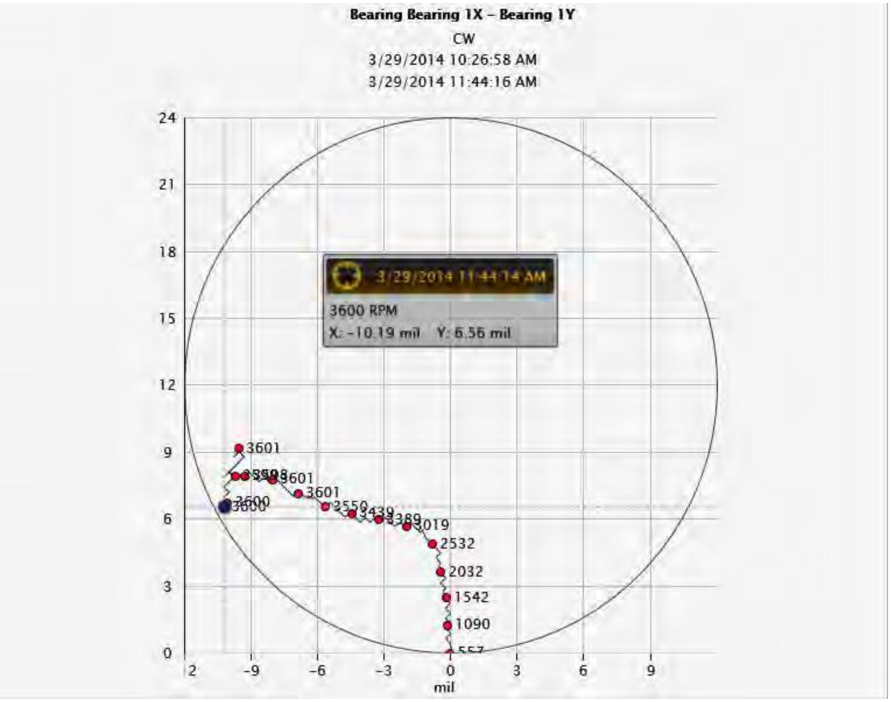
Case Studies

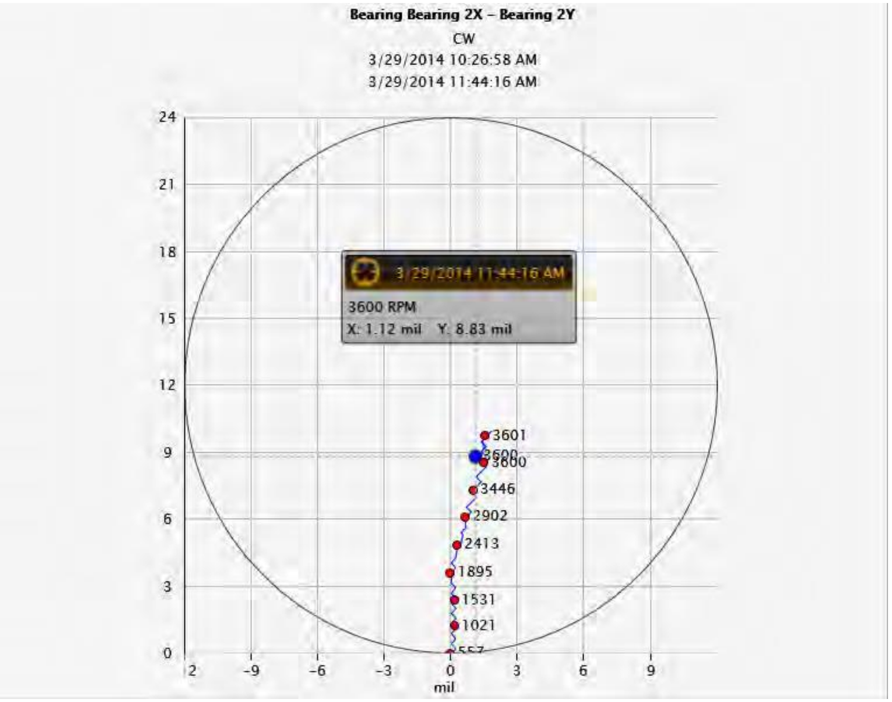




Startup and initial loaded operation; clean 2nd critical; but some vertical preload as it reached full speed - #2 bearing on the same machine.

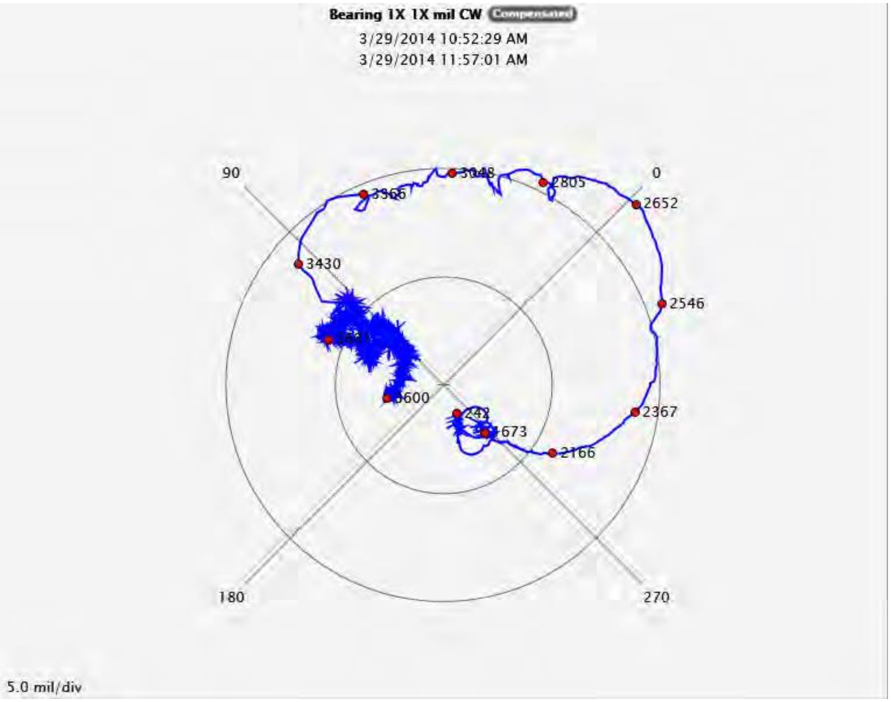
Case Studies

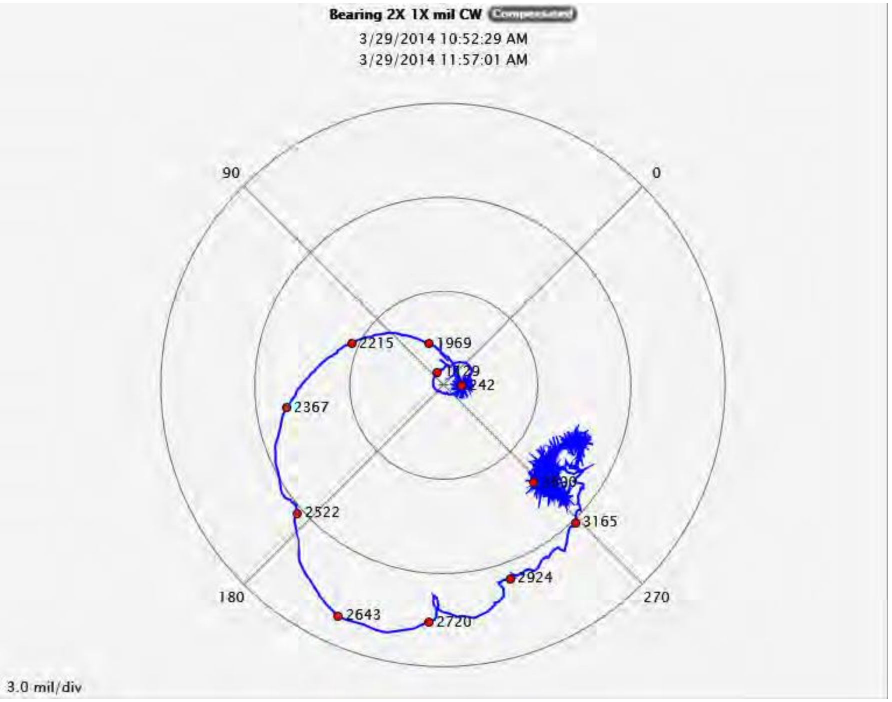




Shaft Centerlines on the same machine during coast down. Rub on the #1 bearing was confirmed with the unusual shaft centerline movement.

Case Studies

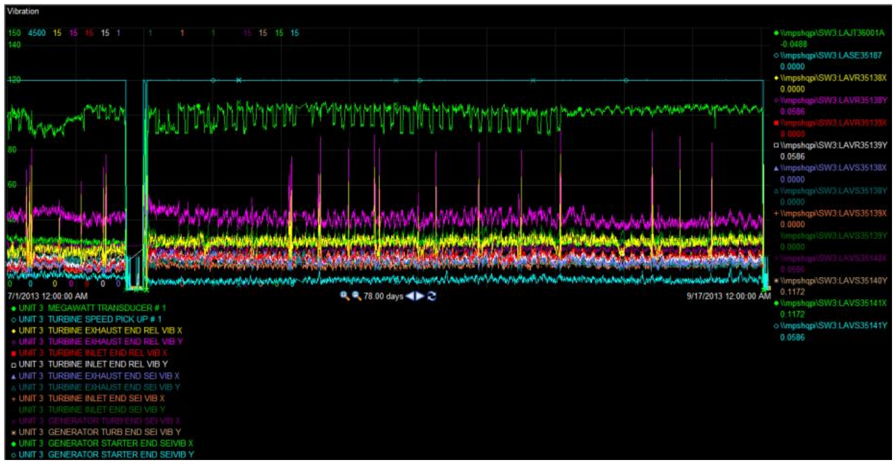




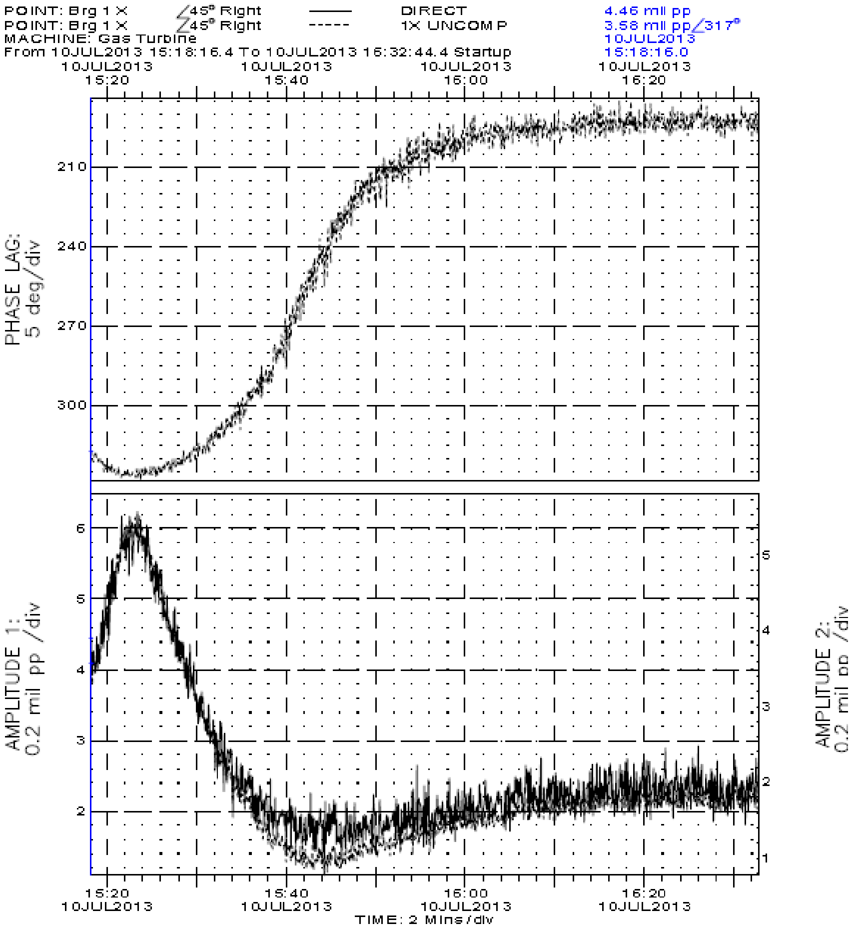
Polar plots – Bearing 1 on the left; bearing 2 on the right during coast down. Shows 180 degree phase shift between ends at the 2nd critical.

Case Studies

Intermittent rub indication from trend data above. Amplitude increases occurred on an infrequent basis.



One amplitude increase was caught on dynamic data collection showing both amplitude swing and phase shifting



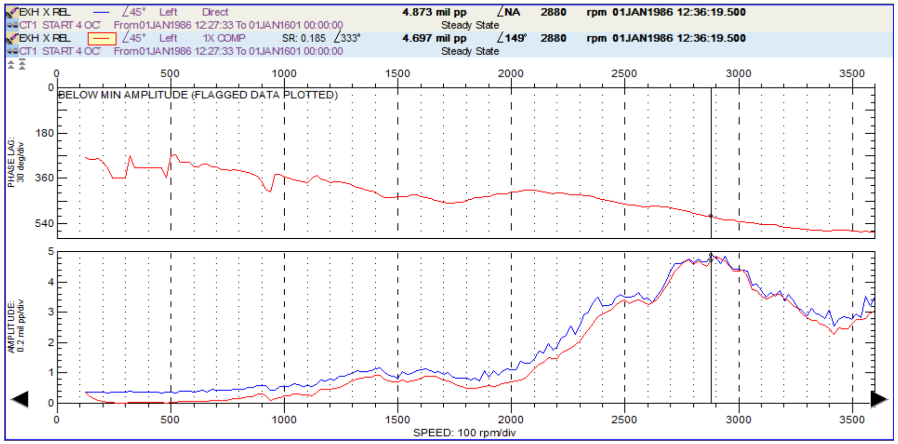
Case Studies

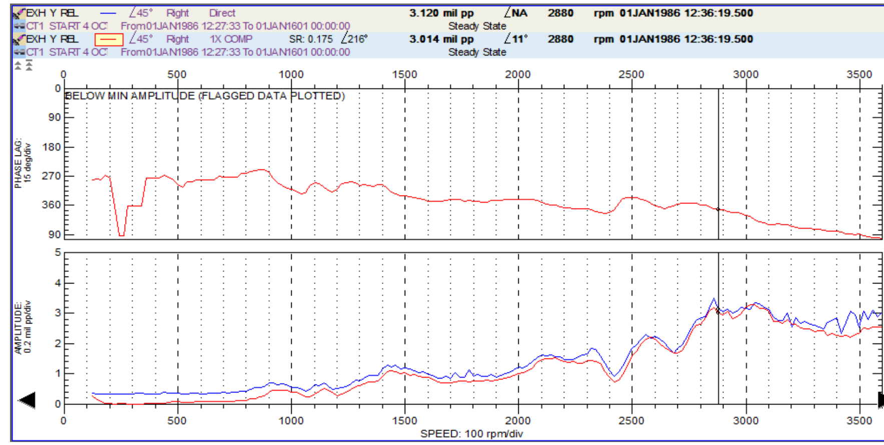
CH#	Channel Name	Machine Name	Status	Angle	Direction	Run Type	Date	Speed Units(P)	Speed Units(S)	Amp Unit	Phase Unit
1	EXH X REL	CT1 START 4 OCT15	OK	45°	Left	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
2	EXH Y REL	CT1 START 4 OCT15	OK	45°	Right	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
3	GEN EXC X	CT1 START 4 OCT15	OK	30°	Left	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
4			OK	90°	Right	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
5	INLET X REL	CT1 START 4 OCT15	OK	45°	Left	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
6	INLET Y REL	CT1 START 4 OCT15	OK	45°	Right	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
7	GEN TURB END X	CT1 START 4 OCT15	OK	30°	Left	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
8	GEN TURB END Y	CT1 START 4 OCT15	OK	60°	Right	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	mil pp	deg
9	Kph 1		OK	0°	None	Steady State	01Jan1986 12:27:33.200 To 01Jan1601 00:00:00.004	rpm	rpm	V pp	deg

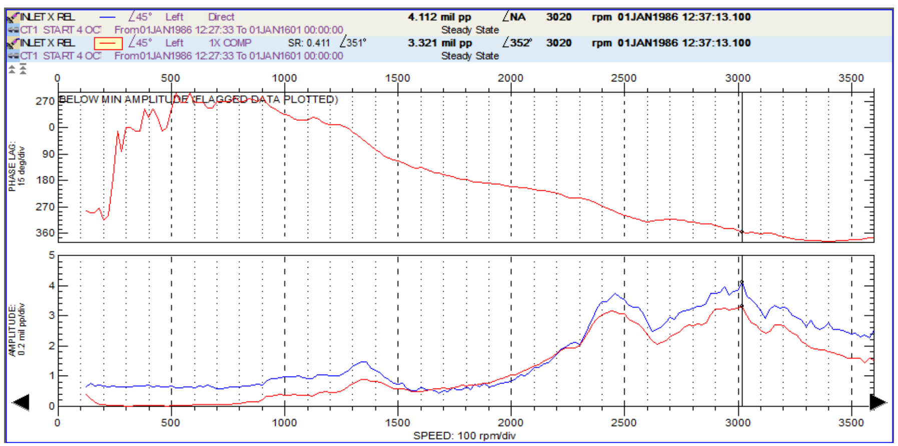
CH#	Channel Name	Sample#	Sample Cause	Date	Speed(P)	Direct	Avg Gap	Inst Gap	1XAmplitude	1X Phase	2XAmplitude	2X Phase
1	EXH X REL	9	DR-T	01Jan1986 12:27:47.000	280	0.360	-10.327	0.000INV	0.185	333BMA	0.000INV	0INV
2	EXH Y REL	9	DR-T	01Jan1986 12:27:47.000	280	0.349	-9.851	0.000INV	0.175	216BMA	0.000INV	0INV
3	GEN EXC X	9	DR-T	01Jan1986 12:27:47.000	280	0.840	-10.168	0.000INV	0.478	6	0.000INV	0INV
4		9	DR-T	01Jan1986 12:27:47.000	280	0.000	0.000	0.000INV	0.000	0BMA	0.000INV	0INV
5	INLET X REL	9	DR-T	01Jan1986 12:27:47.000	280	0.658	-8.337	0.000INV	0.411	354	0.000INV	0INV
6	INLET Y REL	9	DR-T	01Jan1986 12:27:47.000	280	0.637	-8.215	0.000INV	0.411	252	0.000INV	0INV
7	GEN TURB ...	9	DR-T	01Jan1986 12:27:47.000	280	0.576	-9.497	0.000INV	0.524	351	0.000INV	0INV
8	GEN TURB ...	9	DR-T	01Jan1986 12:27:47.000	280	0.586	-9.265	0.000INV	0.462	257	0.000INV	0INV
9	Kph 1	9	DR-T	01Jan1986 12:27:47.000	280	0.360INV	-10.327INV	0.000INV				

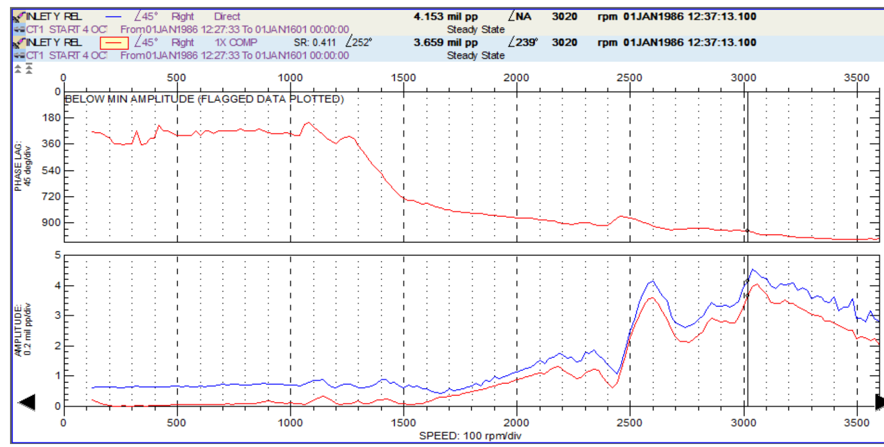
Tabular list used for slow roll data compensation selection and comparison between operational data points. Note all the different information that is available

Case Studies





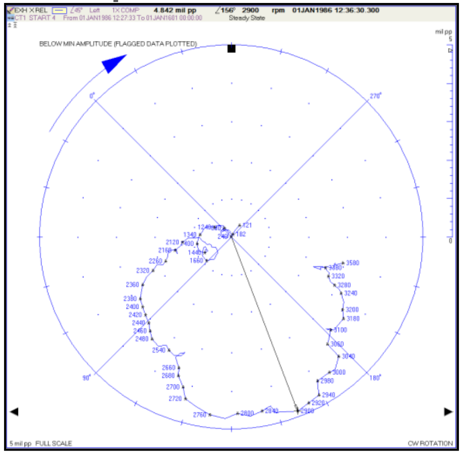


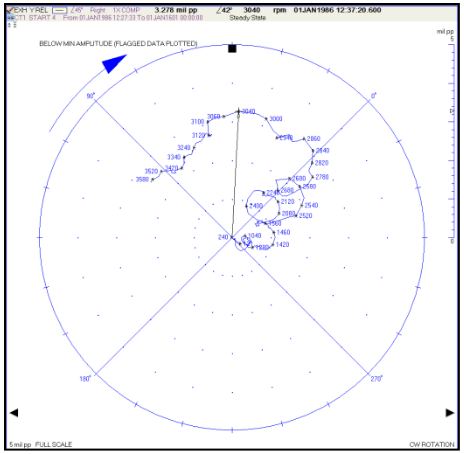


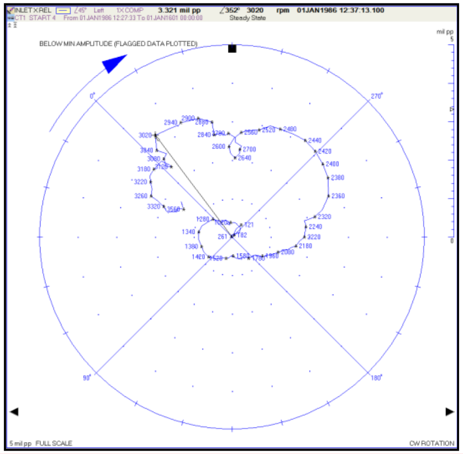
Bode plots showing 1st and 2nd critical responses and increased response after 2nd critical

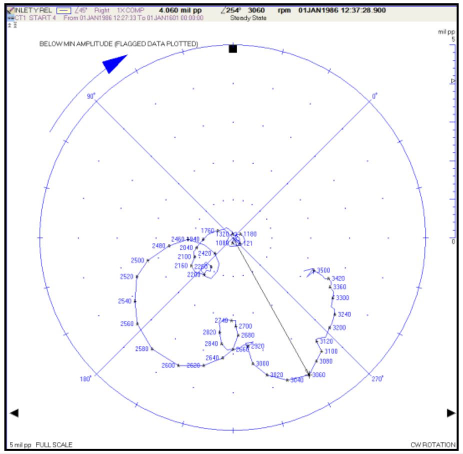
Case Studies

W501F Example 3



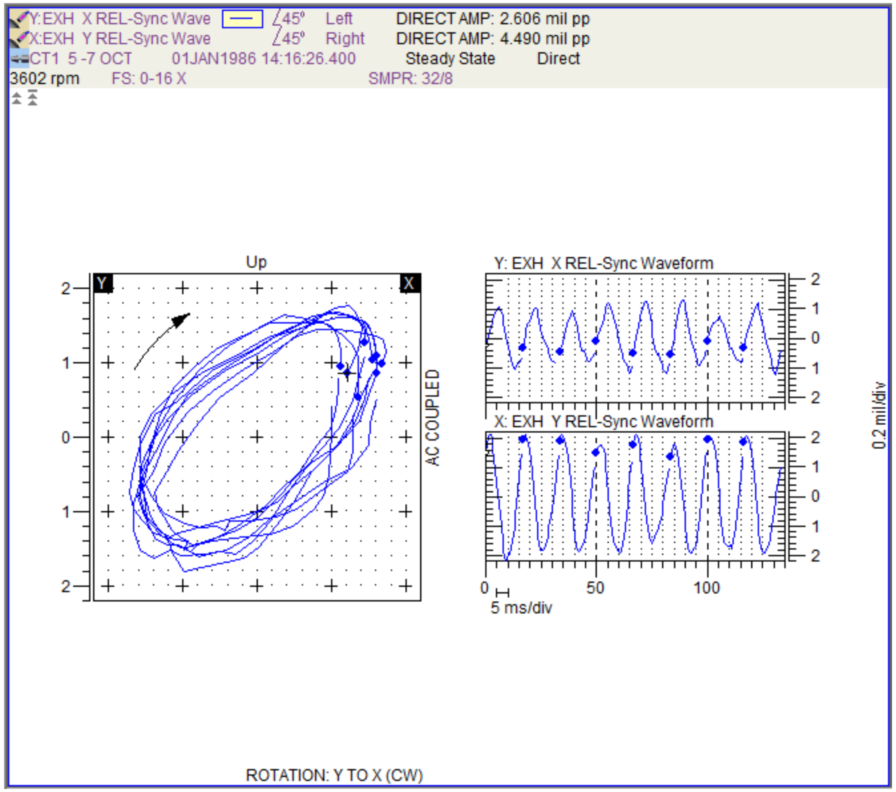


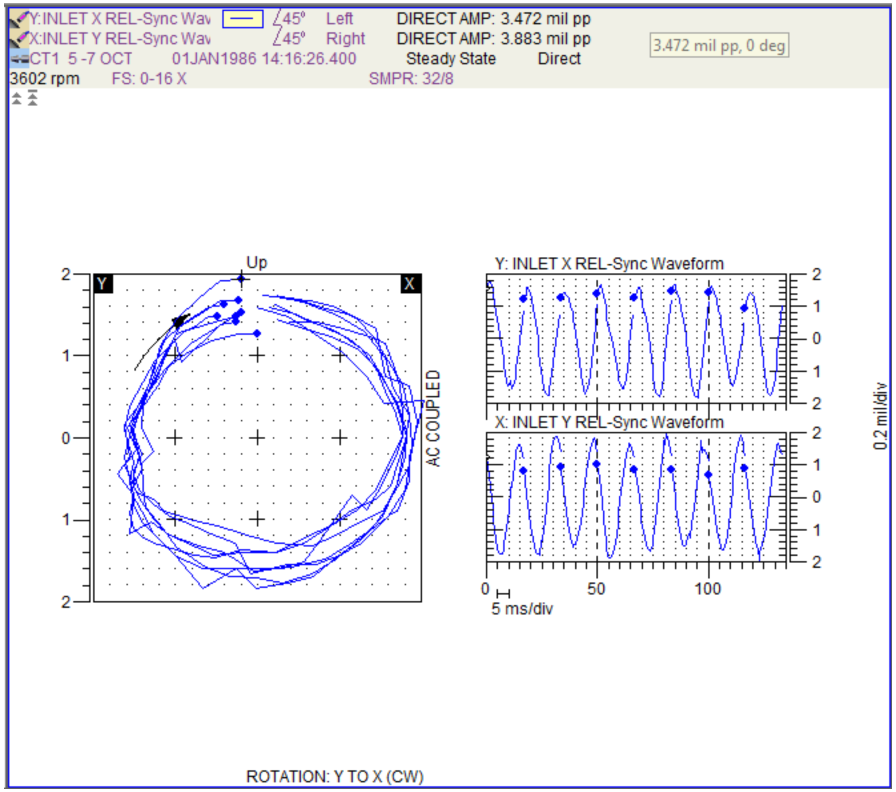




Polar plots showing 1st and 2nd critical responses and increased response after 2nd critical.

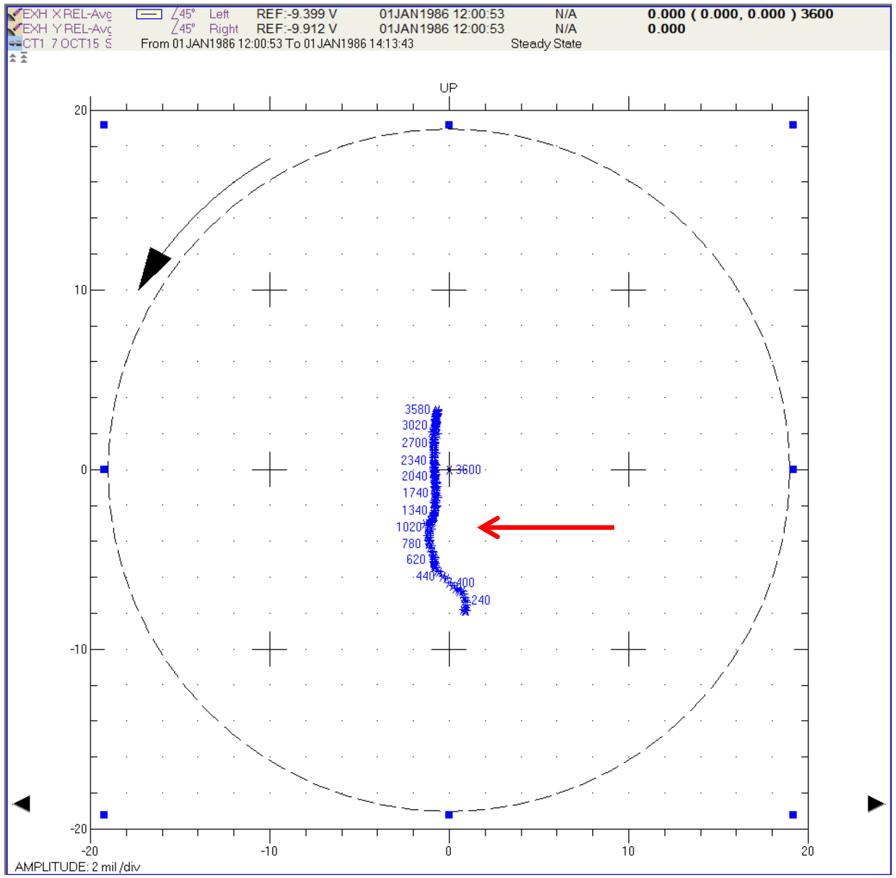
Case Studies

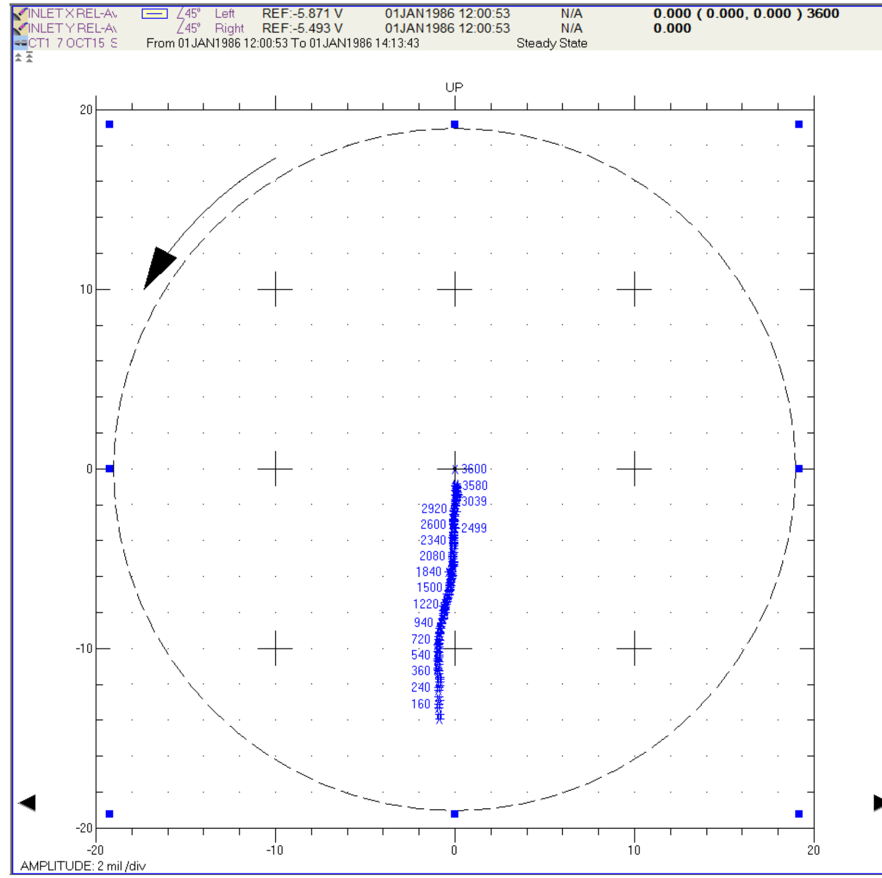




#1 bearing preloaded when compared to #2 bearing. Variation in Orbit shape from one revolution to the next would be good to do further investigation

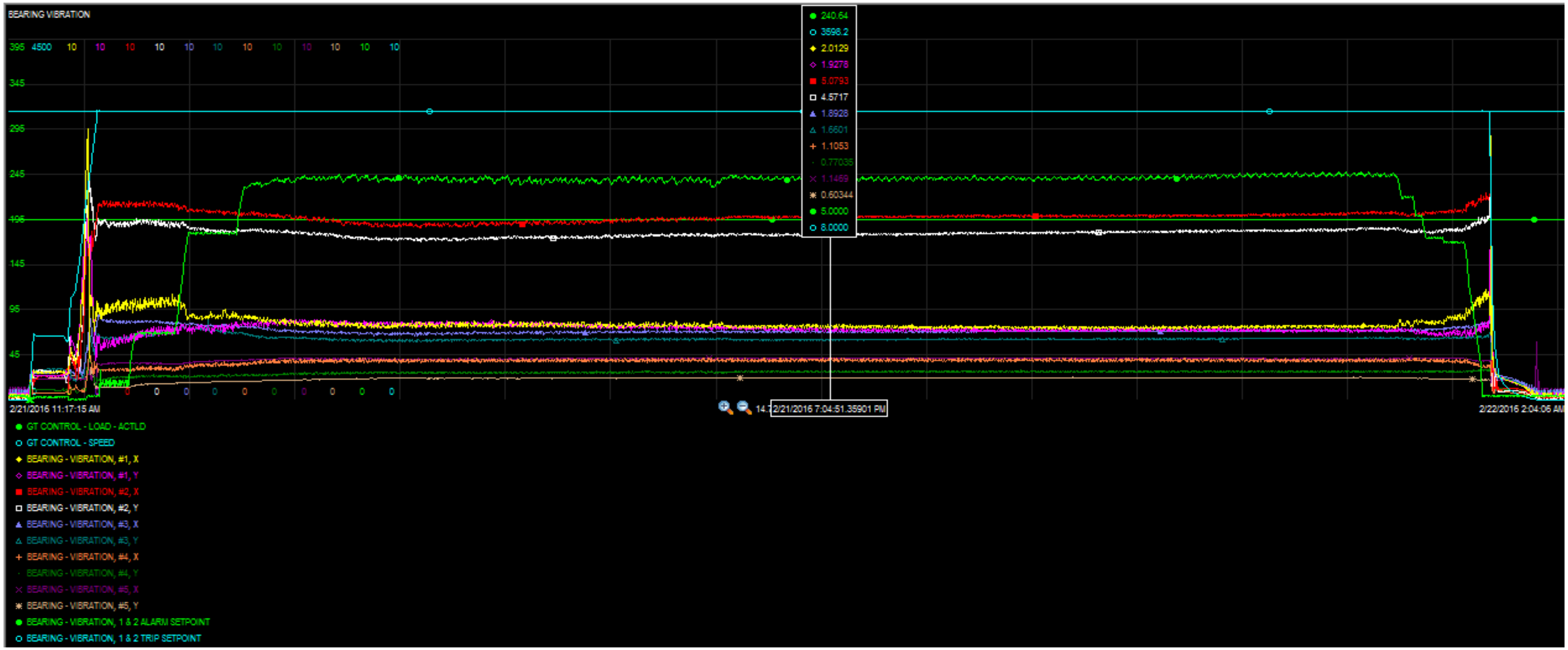
Case Studies





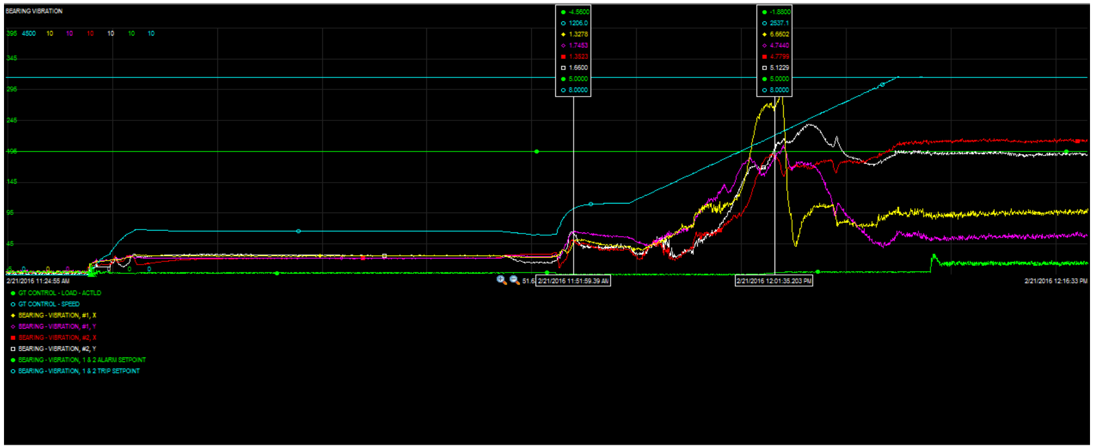
#1 bearing horizontally preloaded when compared to #2 bearing.

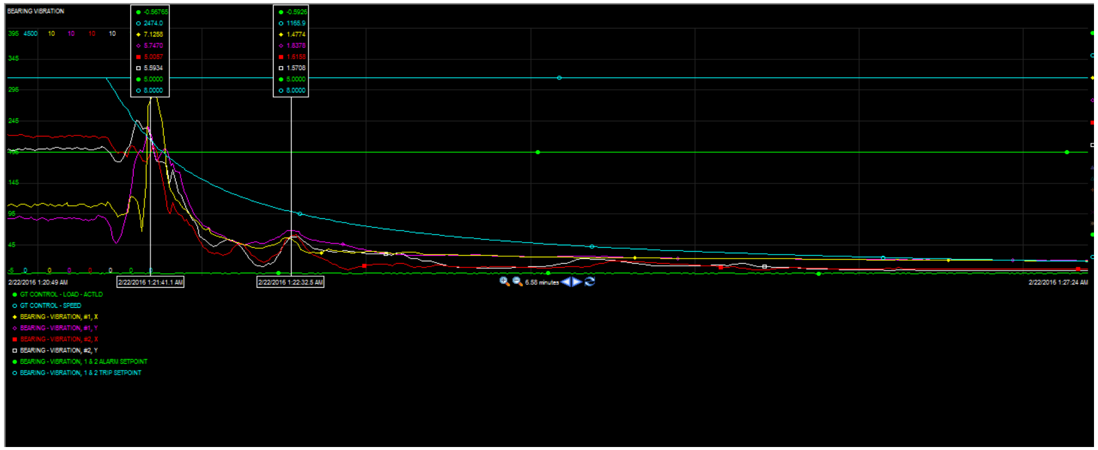
Case Studies



Overall Vibration levels after a row 2 turbine blade replacement. Note blades were changed on turbine end, higher vibration incurred on compressor end.

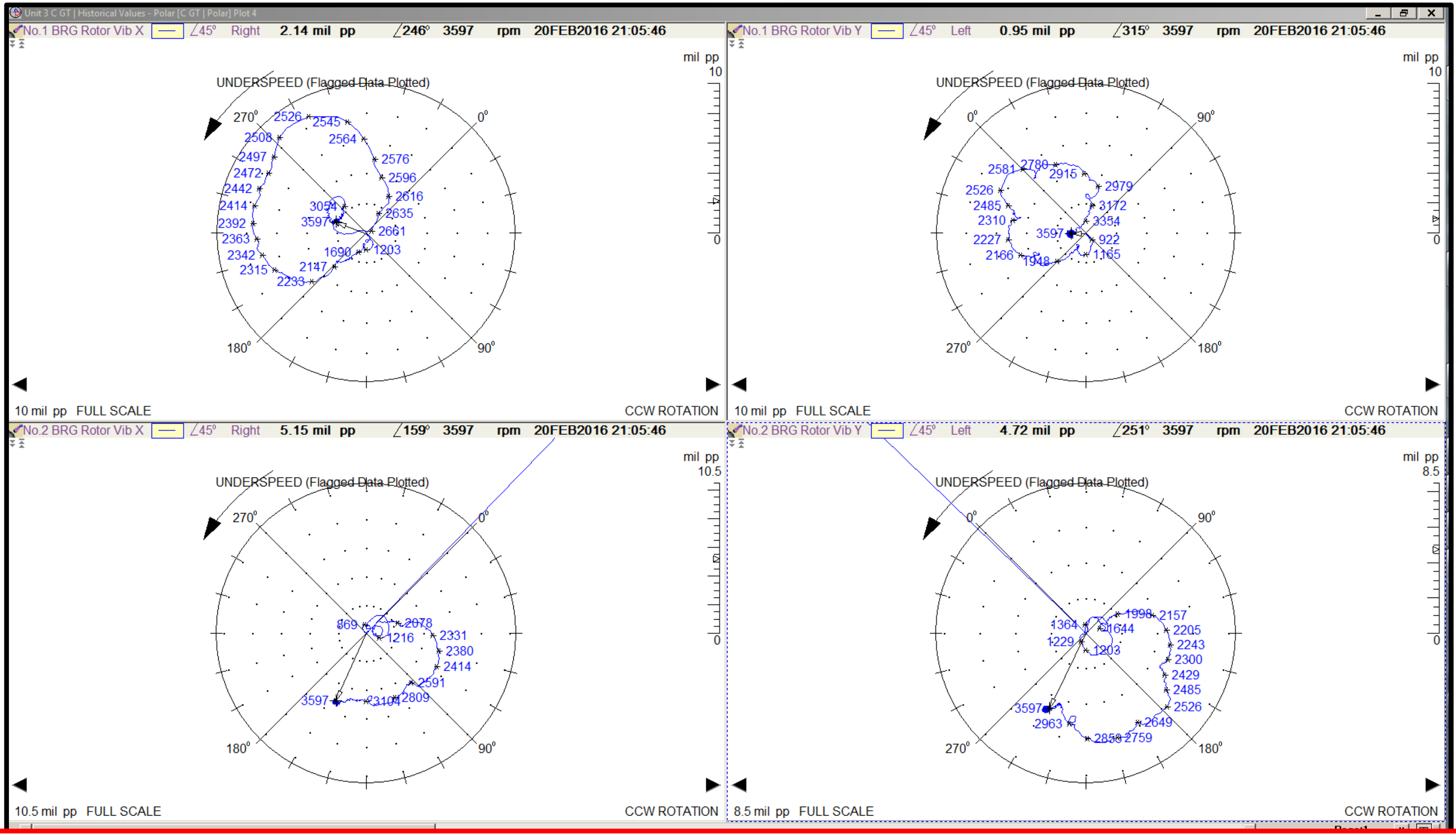
Case Studies





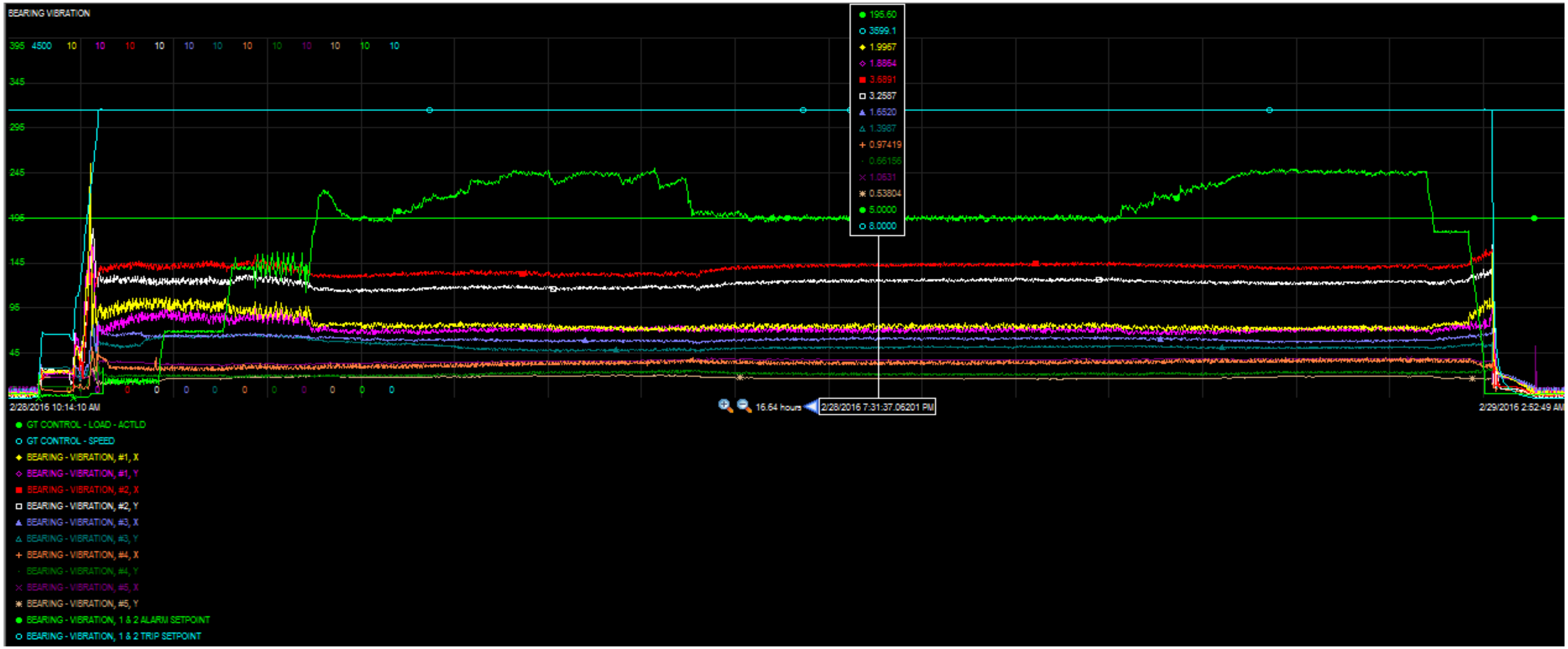
Startup and coast down overall trend behavior after the row 2 turbine blade replacement

Case Studies



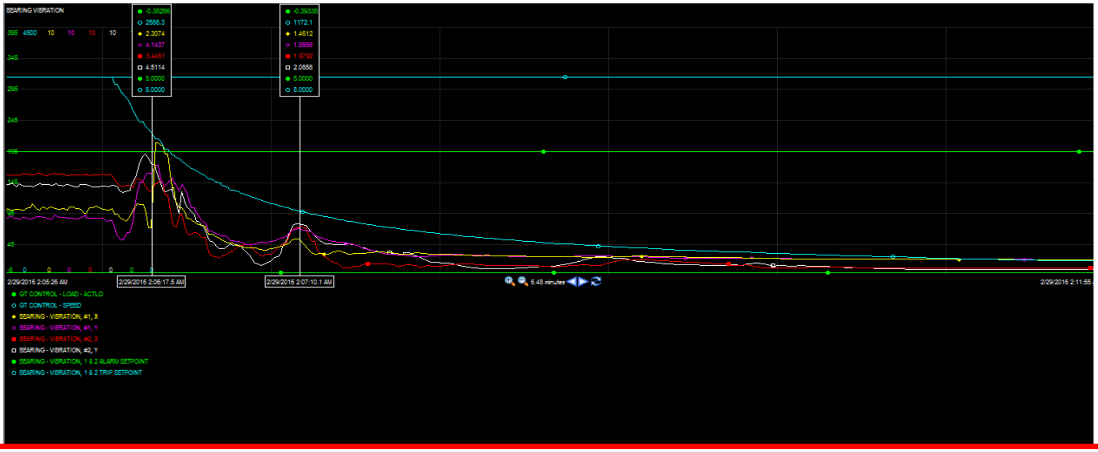
Coast down Polar plot behavior after the row 2 turbine blade replacement

Case Studies



Overall Vibration levels after balancing was performed by installing trim balance weights in the turbine end of the machine.

Case Studies



Startup and coast down overall trend behavior after trim balancing was performed by adding weights in the turbine end of the machine

References & Bibliography

References:

1. Fundamentals of Fluid Film Journal Bearing Operation and Modeling – Minhui He & C. Hunter Cloud & James M. Byrne, Proceedings of the 34^{th} Turbomachinery Symposium 2005, Pages 155-176
2. Fundamentals of Rotating Machinery Diagnostics – Charles T. Hatch & Donald E. Bently, Bently Pressurized Bearing Press

Bibliography:

- Gas Turbine Engineering Handbook – Meherwan P. Boyce, Elsevier Science
- V. Wowk, Machinery Vibration – Measurement and Analysis, McGraw-Hill
- ISO – 10816 – Mechanical Vibration
- ISO – 7919 – Mechanical Vibration
- API – 670 – Machinery Protection systems
- Metrix Machinery Diagnostic Services

End