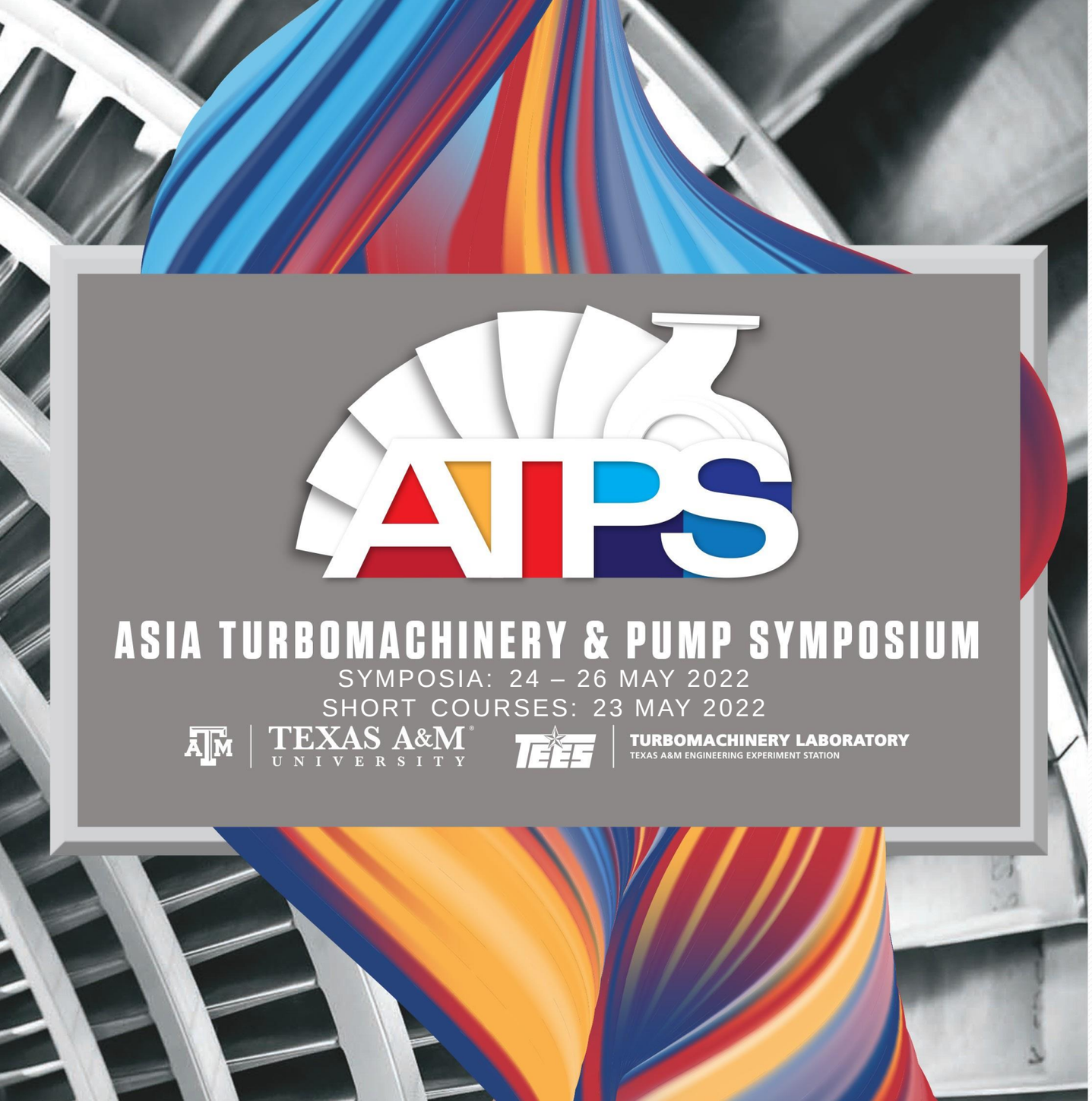

High Speed Coupling Failure related to Torsional Vibration

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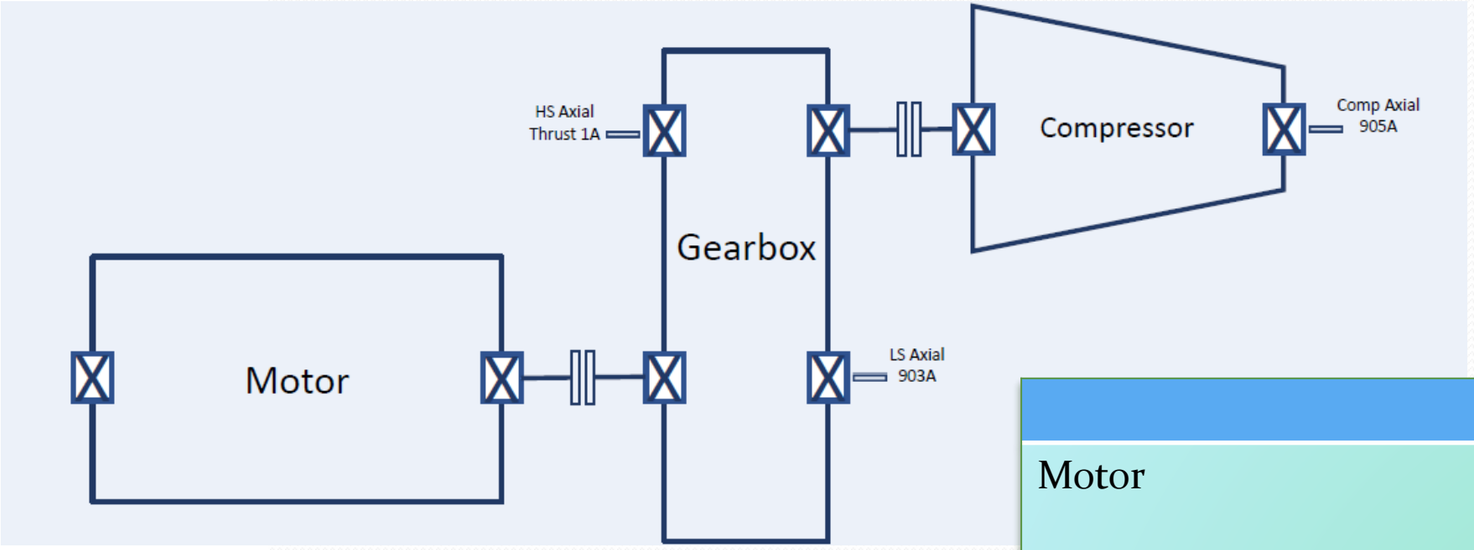
Abstract

- This case study presents compressor high speed coupling failure where torsional natural frequency is excited.
- The case study examines a repeat high speed coupling failure that excited 2nd torsional natural frequency of the compressor train.
- The mature unit had operated successfully for more than 15 years with no changes that would affect fundamental natural frequencies within compressor train until a series of compromising events created gears degradation which triggered natural frequencies excitation.
- Results are presented herein of the evidence of the failure mode of the couplings which show fatigue fractures leading to catastrophic failure due to high alternating torsional stress.
- An examination of bull gear modal analysis showed the possibility of excitation frequency
- Limitation of existing equipment monitoring (radial vibration measurement) cannot detect torsional vibration
- Root cause failure analysis to be discussed

Agenda:

1. Machine Detail
2. Problem Statement
3. Sequence of Events
4. Observations
5. Analysis (Torsional Analysis)
6. Solution (Torsional Natural Frequency Verification, Bull Gear Modal Analysis)
7. Lessons Learnt

Machine Details



Detail	
Motor	Rated: 2,800kW Speed: 1,494 rpm
Low Speed Coupling	Disc Coupling Service Factor: 3.6
Gearbox	Single Helical Gearbox Ratio: 8.057 : 1 (282 gear teeth, 35 pinion teeth)
High Speed Coupling	Disc Coupling Service Factor: 3.8
Compressor	Suction Pressure = 12barG Discharge Pressure = 17 barG 3-stage centrifugal – Hydrogen service – 17 vanes impellers Speed: 12,037 rpm

Problem Statement:

- Compressor High Speed Coupling (between Gearbox and Compressor) failed after operating more than 15 years.

- Repeat failure within 2 weeks.

Sequences of Event:

1st Failure

4 years before 1st failure

Lube oil Cooler leak. Cooling Water (Seawater) leak into Lube oil system

3 months before 1st failure

Lube Oil Cooler Leak. Cooling water (Seawater) leak into Lube Oil System

2 weeks before 1st failure

Lube Oil Temperature Control Valve failed. Actual temperature is higher than 50 degC (58 degC)

4 days before 1st failure

Gearbox Casing Vibration spiked intermittently. Vibration data collected at field. Abnormal vibration observed but below alarm limit.

1st HS Coupling Failure

Compressor tripped due to high vibration. Gearbox HS coupling failed

2nd Failure

6 – 9 days before 2nd failure

Repair Scope:

Damaged GB HS coupling, HS coupling hub and HS pinion bearings were replaced

5 days before 2nd failure

Compressor restarted

3 days before 2nd failure

Gearbox casing vibration spike when Unit oil-in. Compressor load increase

1 – 2 days before 2nd failure

Gearbox casing vibration activated intermittently.

Constant monitoring, abnormal radial vibration observed but well below alarm limit. 9x vibration observed

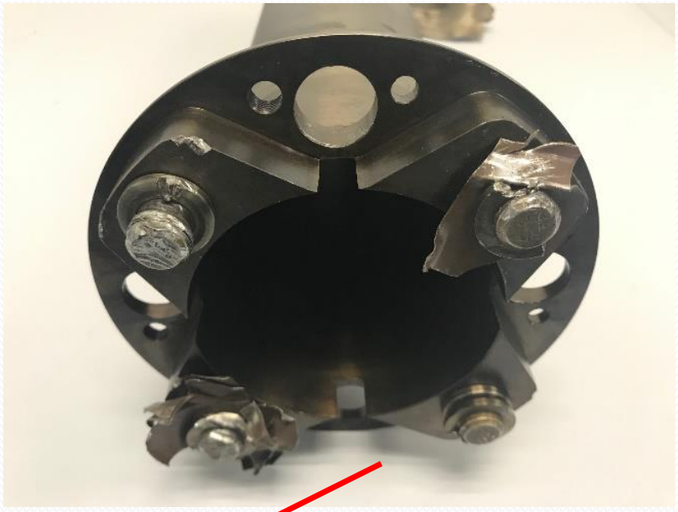
2nd HS Coupling Failure

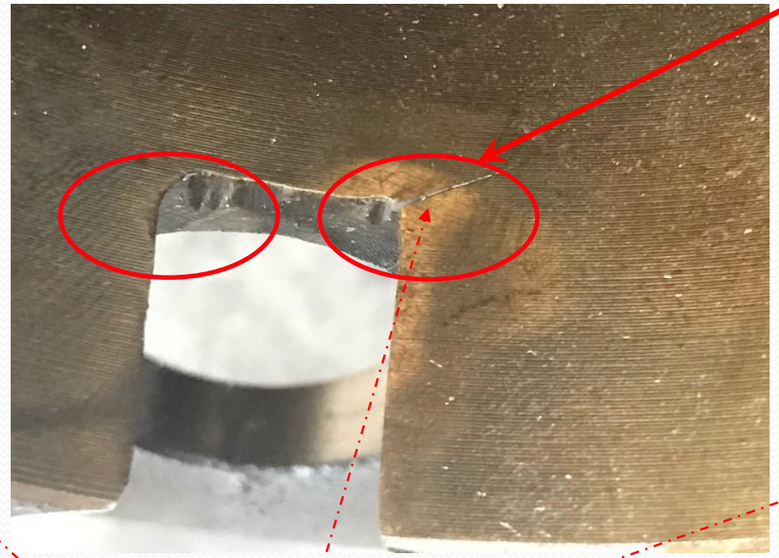
Compressor tripped due to high vibration. Gearbox HS coupling failed

Observations

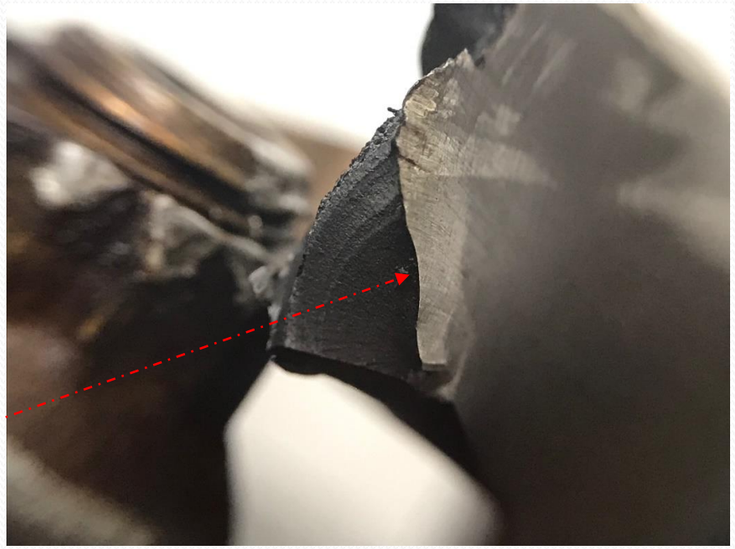
First Failure:

Coupling Spacer





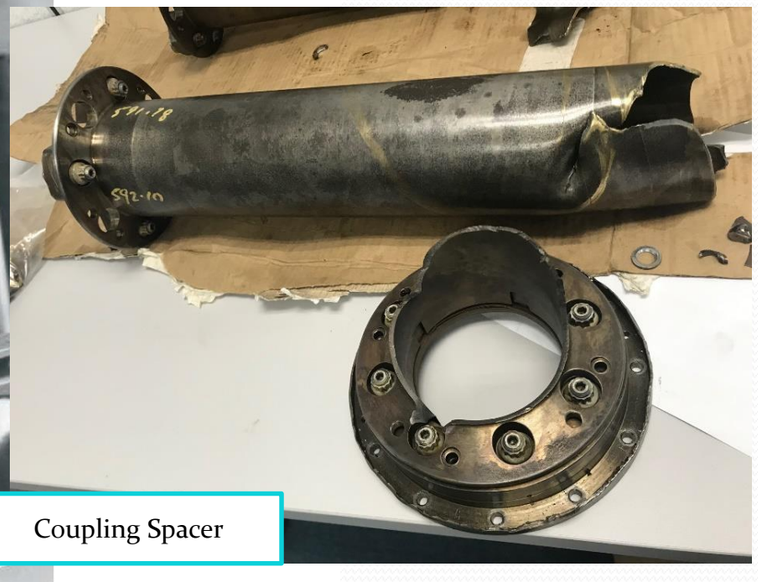
Crack propagated



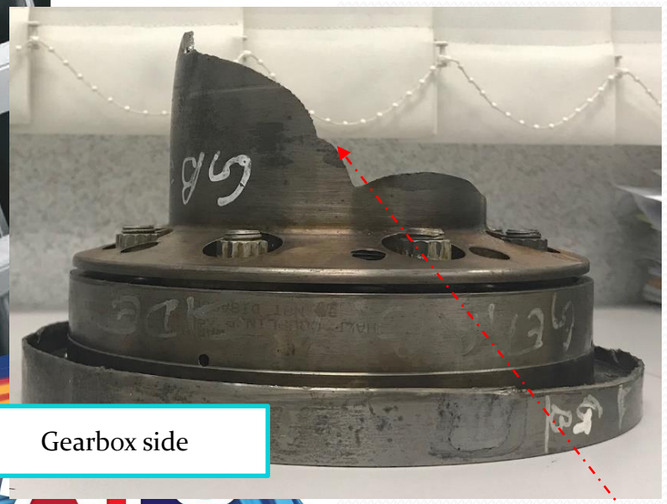
Findings are similar for First failure and Second failure

Observations

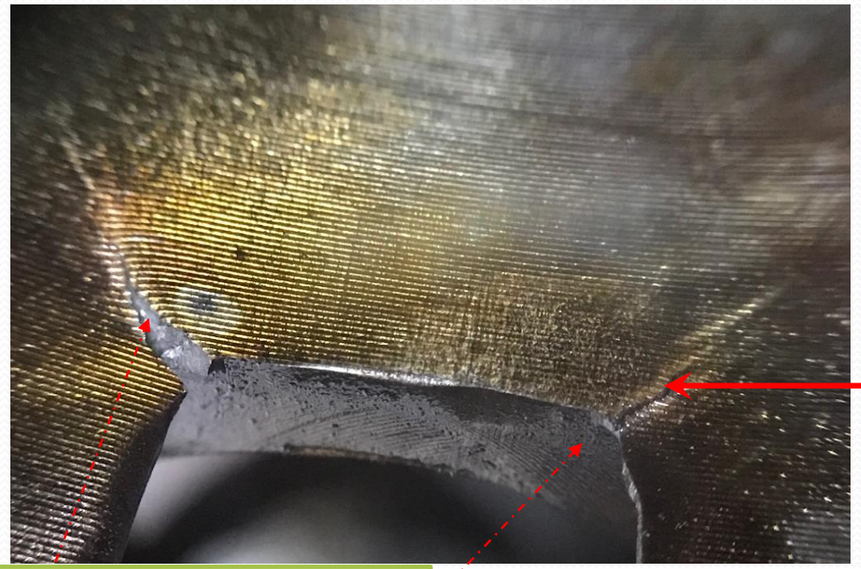
Second Failure:



Coupling Spacer



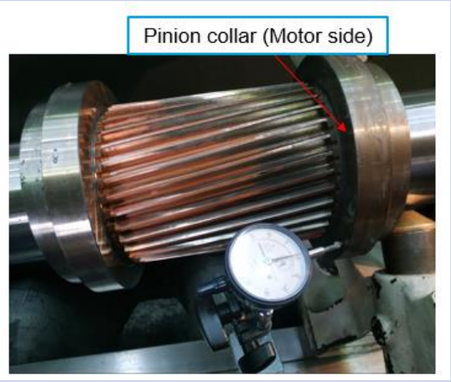
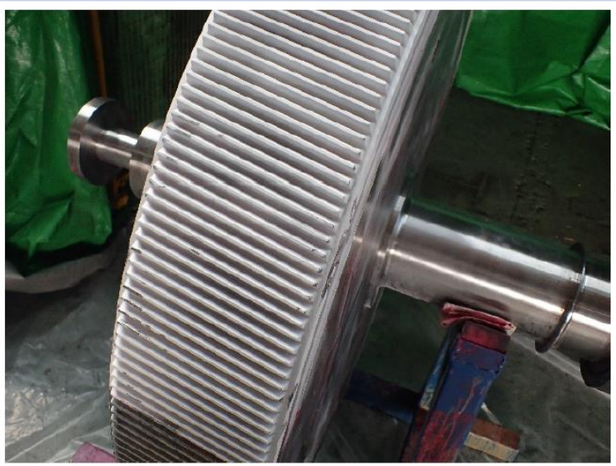
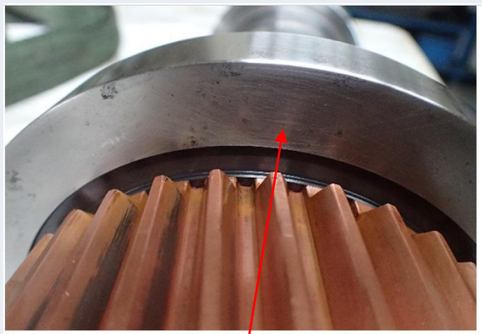
Gearbox side



Crack propagated

Findings are similar for First failure and Second failure

As Found Condition: Pinion and Bull Gear Inspection & Repair

	Pinion Gear	Bull Gear
As found condition	  Pinion collar axial run-out : 0.05 mm (comp side), 0.09 mm (motor side); Allowable:0.01 mm	
Thrust Collar	 DE trust collar (after polishing): The corrosion spots have left deep scars  NDE trust collar (after polishing): The corrosion spots have left deep scars	 DE trust collar (after polishing): The corrosion spots have left deep scars  NDE trust collar (after polishing): The corrosion spots have left deep scars

As Found: Pinion and Bull Gear Inspection & Repair

	Pinion Gear		Bull Gear	
Load & Non-load flank	 Load flank after polishing, the corrosion spots have left deep scars	 Load flank after polishing, the corrosion spots have left slight scars	 Load flank after polishing, the corrosion spots have left deep scars	 Load flank after polishing, the corrosion spots have left deep scars

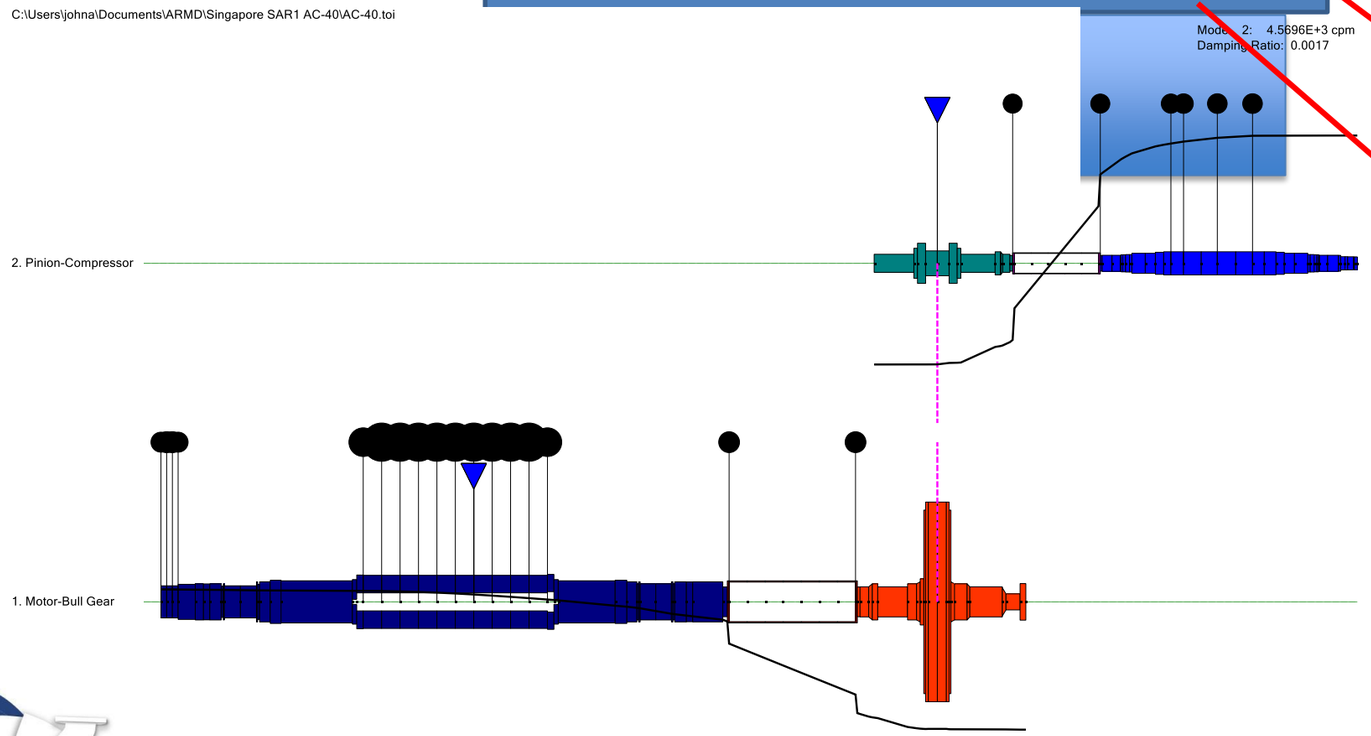
- Corrosion spot and deep scars marks were evident in bull gear & pinion gear.
- Pinion gear and bull gear were sent back to Gearbox OEM for repair / refurbishment

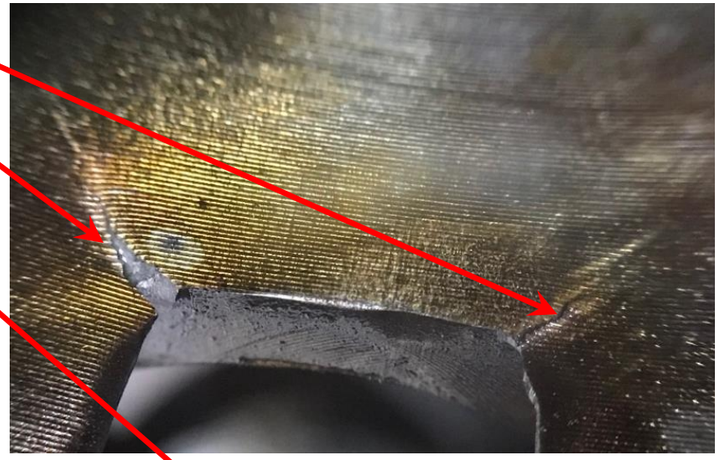
Torsional Analysis

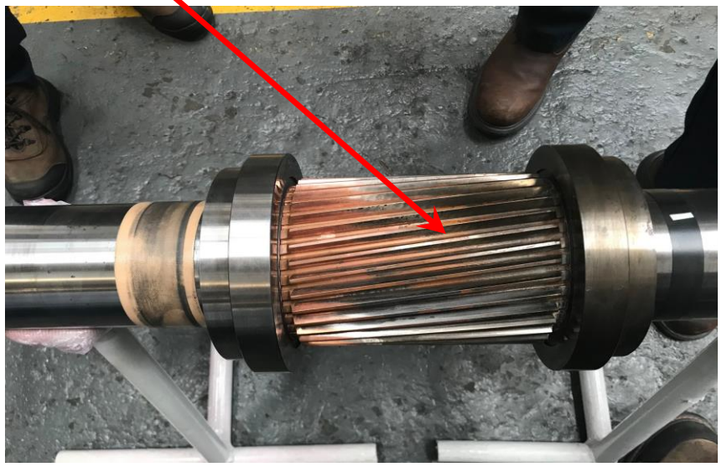
- Experienced coupling failures – observed 9x pinion speed vibration on the pinion shaft
- Torsional analysis was performed to identify modes close to 9x pinion speed
- Likely excitation of 2nd TNF

Torsional Natural Frequency (cpm)	OEM	EM
1st	1342	1341
2nd	4566	4570

- Fatigue crack initiation in two principle directions
- Gear tooth wear pattern on both sides







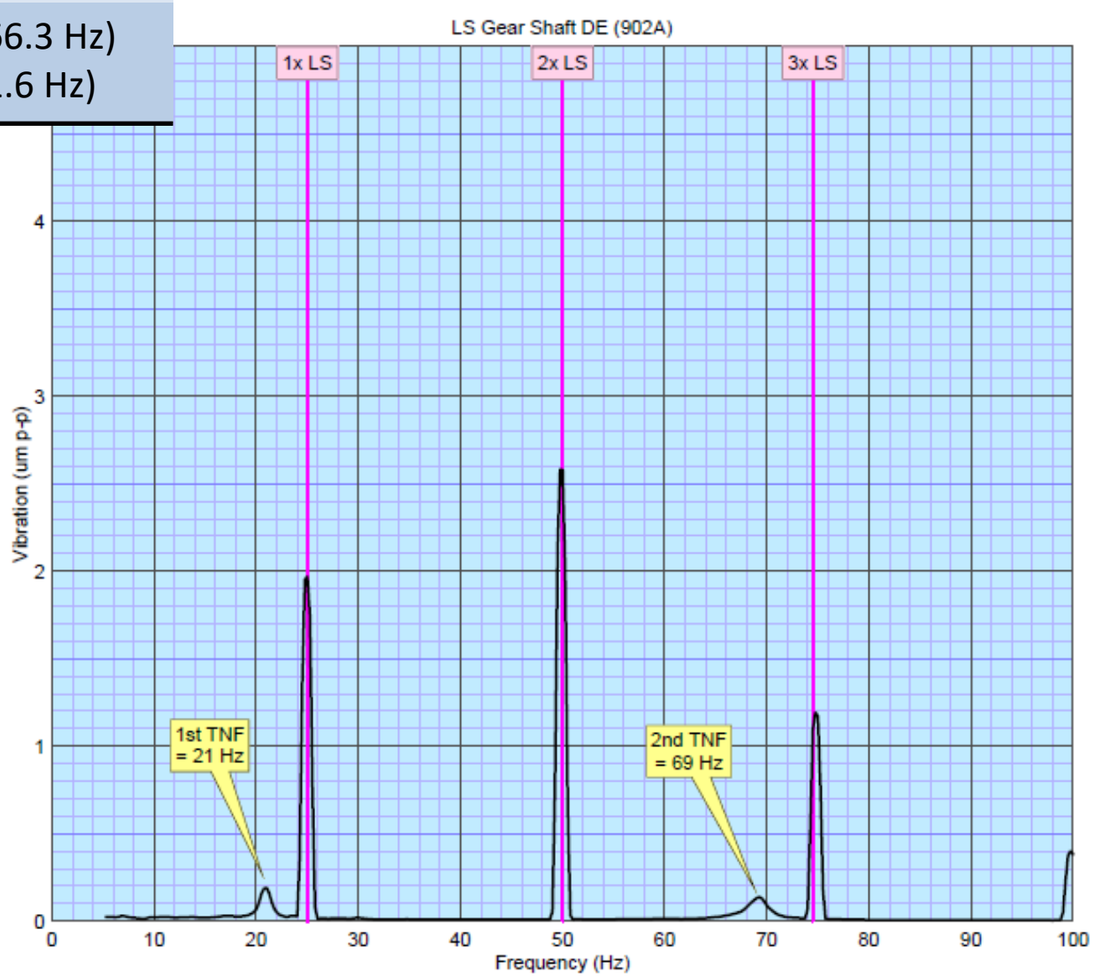
From John Kocur's Torsional Natural Frequency (TNF) Analysis

Torsional Natural Frequencies (TNF) Verification

Torsional Natural Frequency	OEM	EM	Vendor A	Vendor B
1st	1342 cpm (22.4 Hz)	1341 cpm (22.4Hz)	1260 cpm (21 Hz)	1296 cpm (21.6 Hz)
2nd	4566 cpm (76.1 Hz)	4570 cpm (76.1 Hz)	4140 cpm (69 Hz)	3978 cpm (66.3 Hz) - 4296 (71.6 Hz)

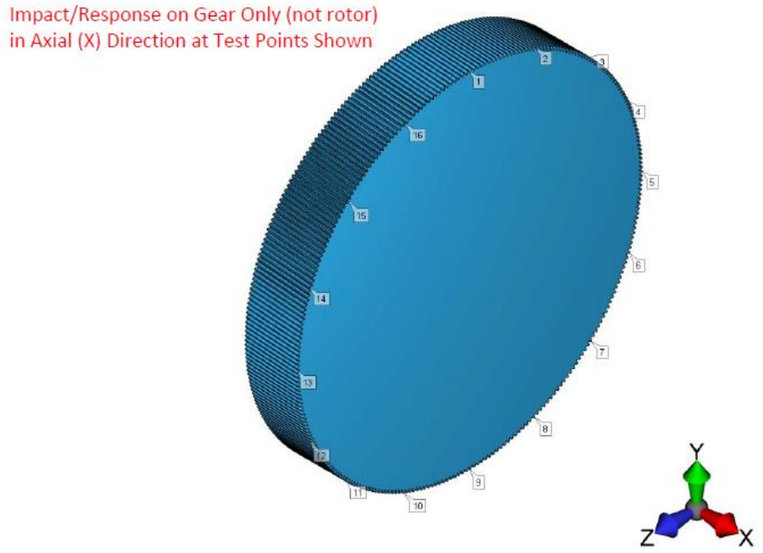
During Unit Start-up, various instruments were setup to measure TNF

- 1st TNF is found ~ 1260 cpm (21Hz)
- 2nd TNF is found ~ 4140 cpm (69Hz)



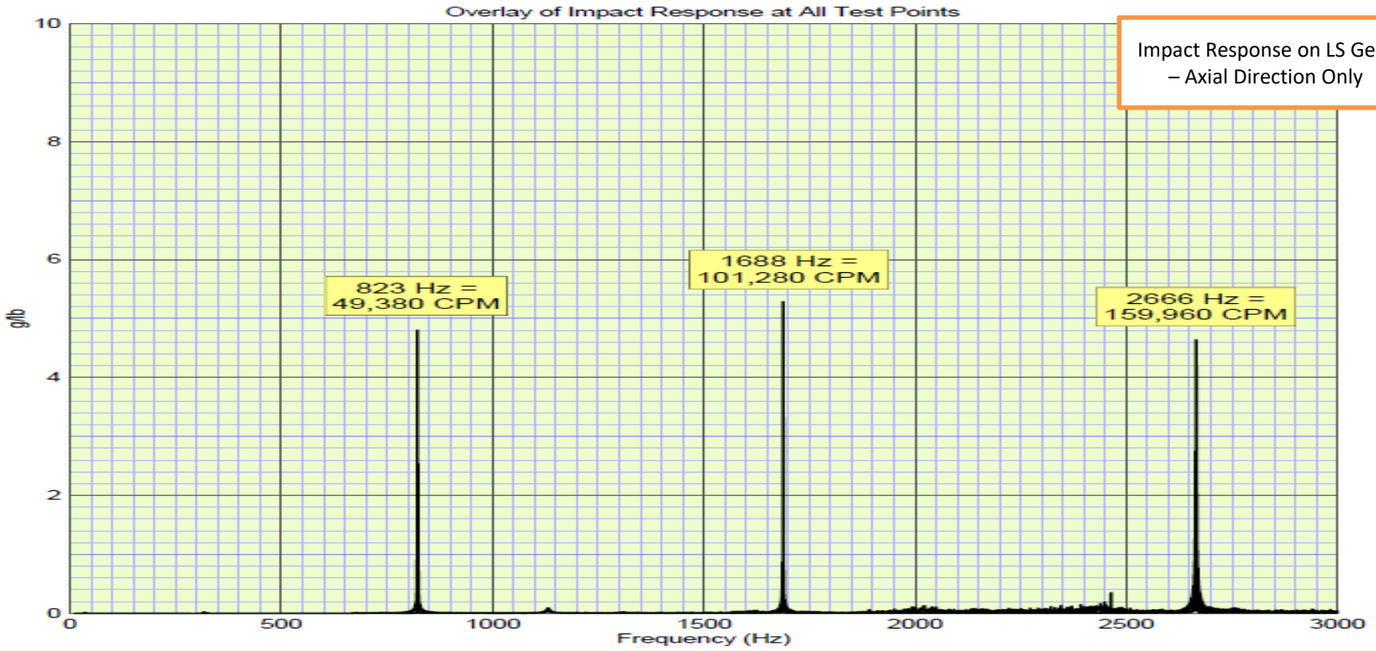
Bull Gear – Modal Analysis

- Impact mode shape (IMS) was performed on Bull Gear.
- The purpose is to identify axial mechanical natural frequencies and mode shapes of the bull gear itself
- Response at 1,688Hz (101,280cpm) corresponds to 8.4x pinion speed.



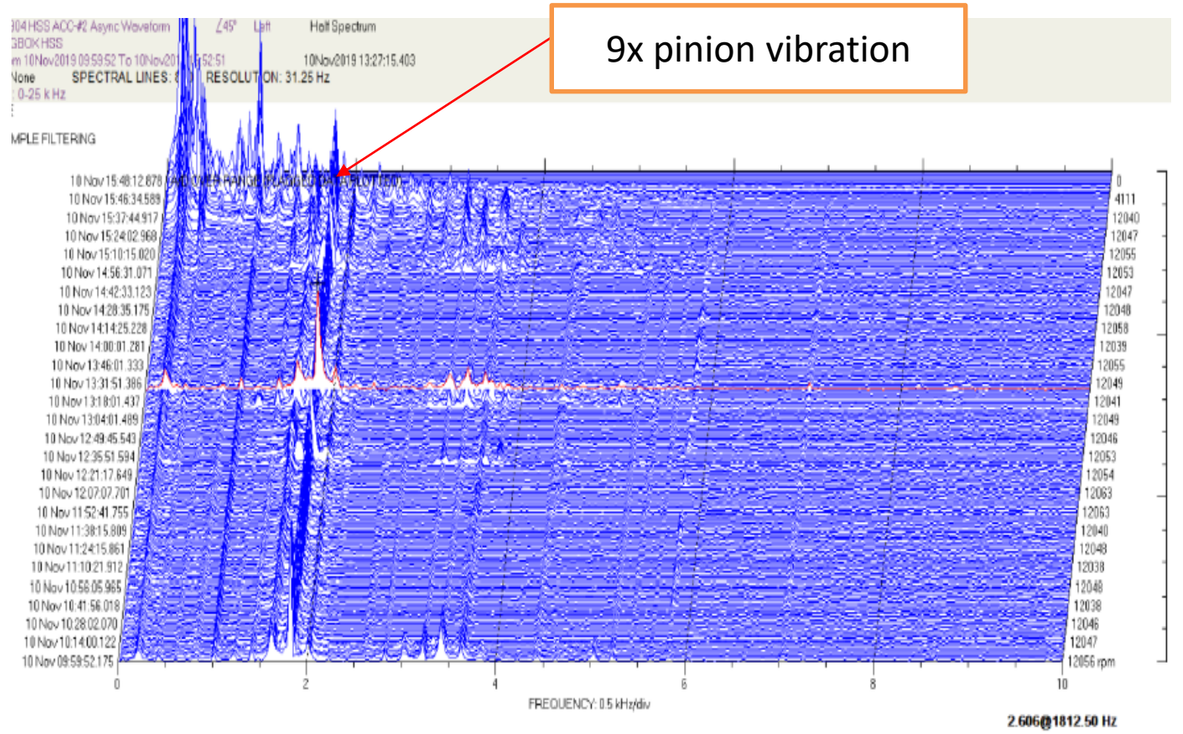
Impact Response Frequency

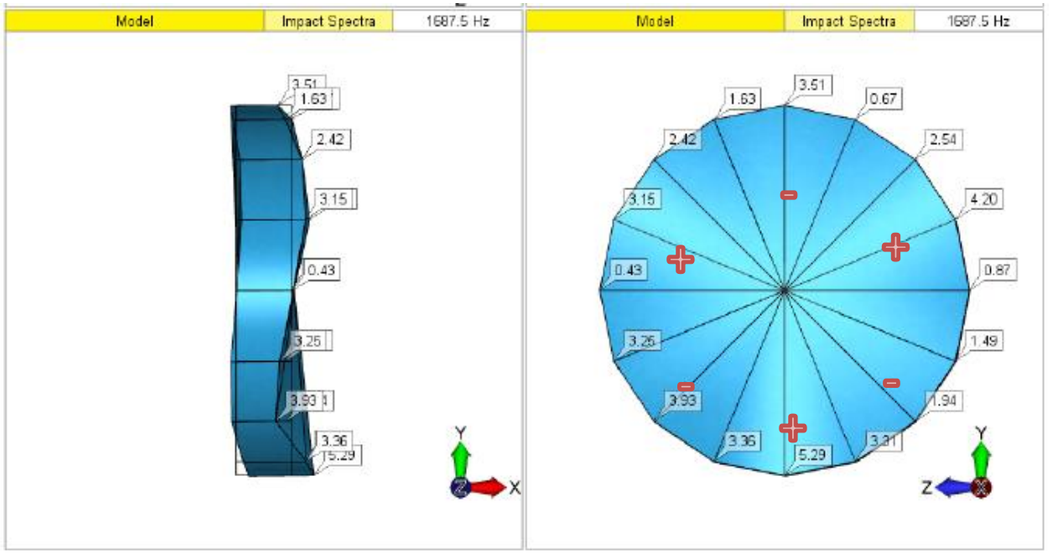
	Response Frequency		Comments
	Hz	CPM	
1	823	49,380	33x bull gear (motor) speed 4.1x pinion speed
2	1,688	101,280	67.8x bull gear speed 8.4x pinion speed
3	2,666	159,960	107x bull gear speed 13.3x pinion speed

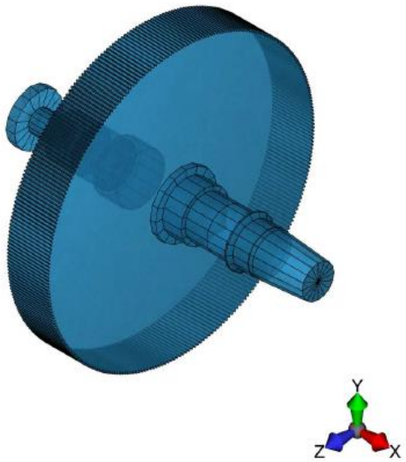


Lessons Learnt : Torsional Natural Frequency Excitement

- Oil contamination from cooler leaks
- Significant gear wear results in imperfect teeth contact at the gear mesh.
- Extra friction with scuffing tooth contact, especially during lower viscosity oil period results ring the bull gear like a bell
- Increased ‘play’ between mating gear teeth possibly leading to excitation of Bull Gear natural frequency at 9x pinion speed
- Measured 9x pinion speed vibration, probably caused by excitation of Bull Gear natural frequency
- Mitigations of bull gear and pinion replacement/repair have been implemented and the failure has not reoccurred







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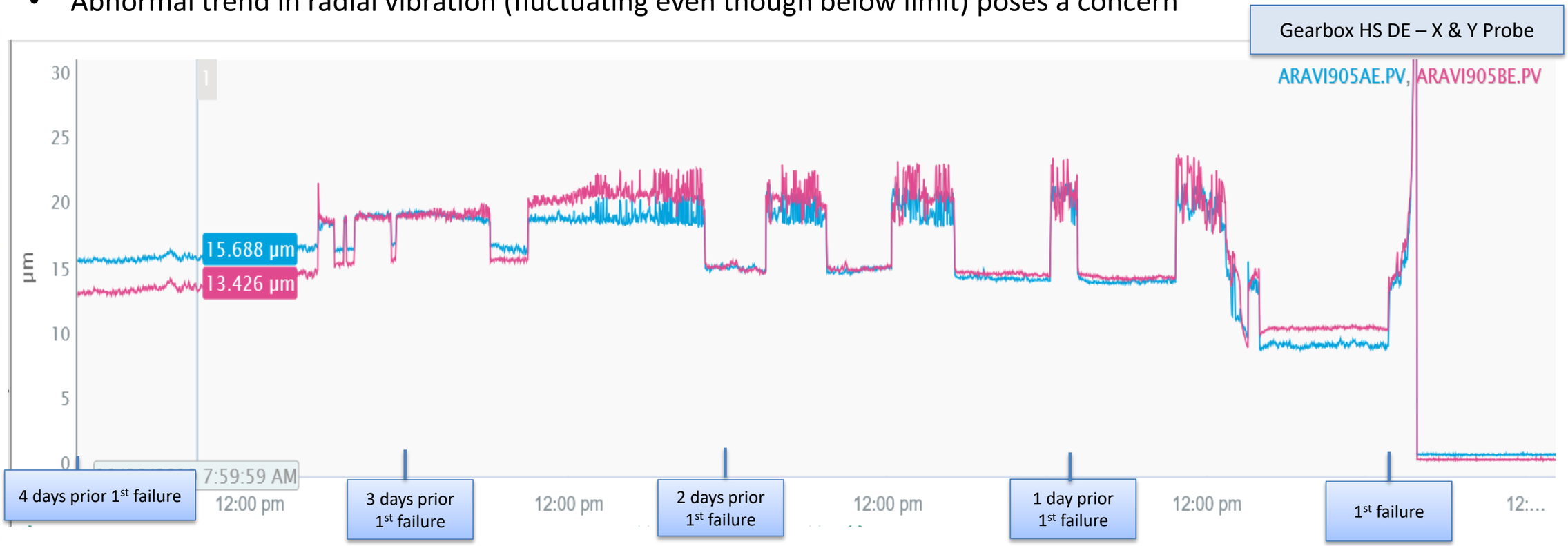
Lessons Learnt:

- Torsional vibration is typically a silent killer, meaning traditional vibration measurements (such as accelerometer) cannot detect its presence.
- Increase in 9x pinion speed vibration prior each failure indicate the failure is related to 9x
- Abnormal trend in radial vibration (fluctuating even though below limit) poses a concern



- End of Presentation
- Thank You !
- Any questions please