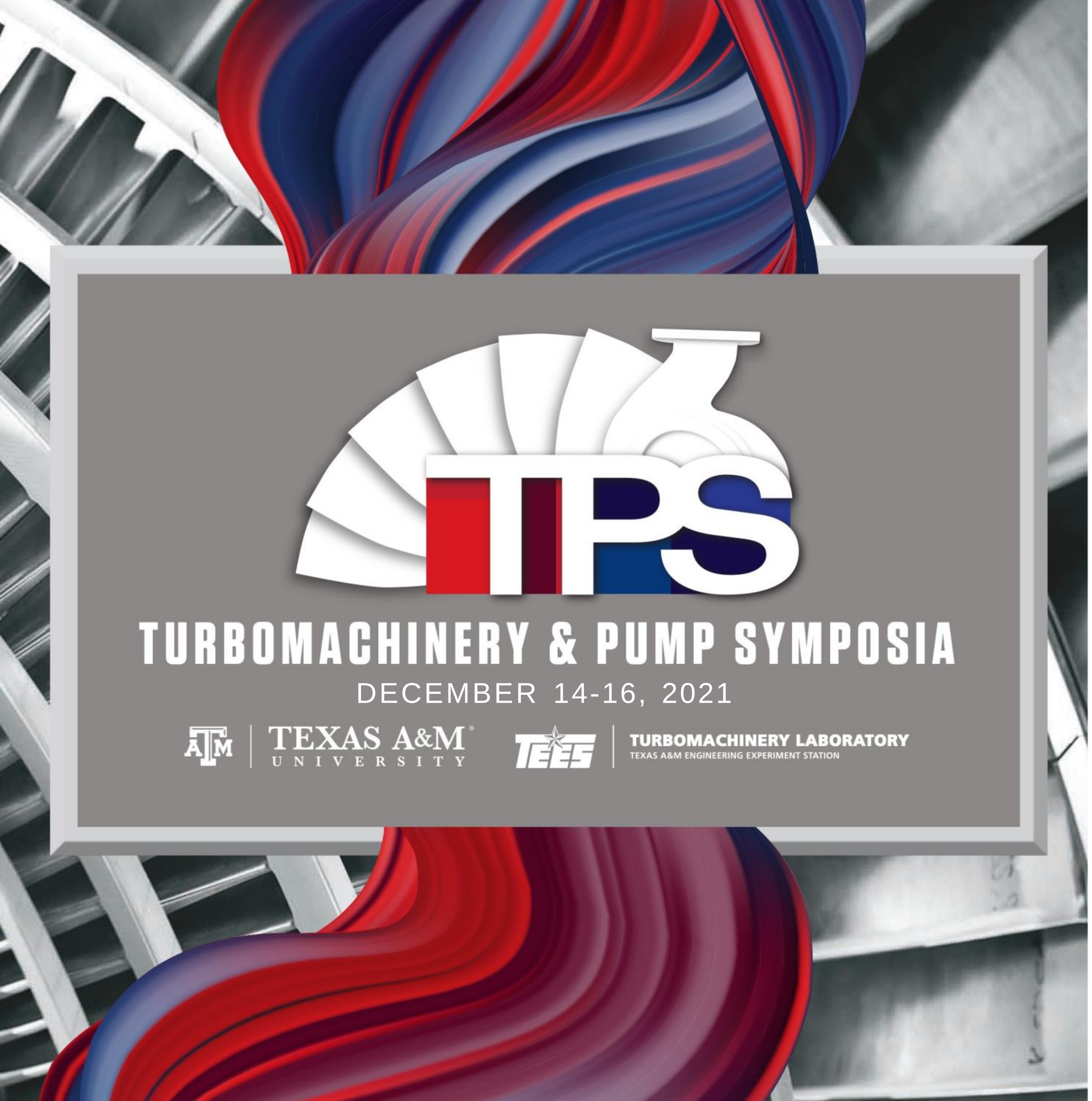

Investigation of a Compressor Coupling Failure by Torsional Excitation

A Problem of a Complex Interaction where a Structural Natural Frequency Excited a Torsional Natural Frequency

Authors

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TURBOMACHINERY & PUMP SYMPOSIA

Abstract

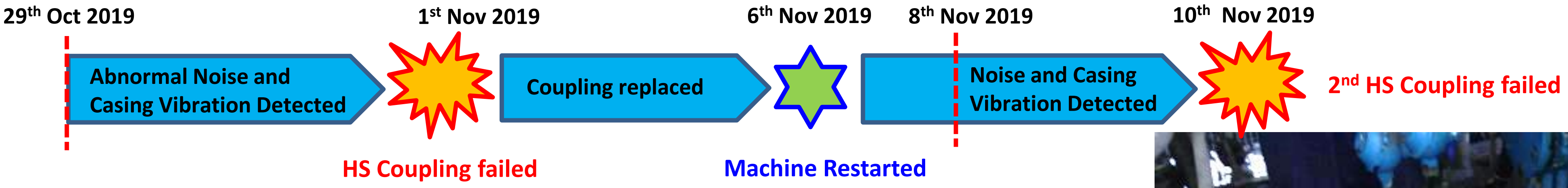
This case study examines a repeat compressor coupling failure that was a result of a complex, dynamic interaction of components that excited the 2nd torsional natural frequency of the train. The mature unit had operated successfully for 17 years until a seemingly insignificant series of compromising events created degradation which triggered the excitation of the natural frequencies.

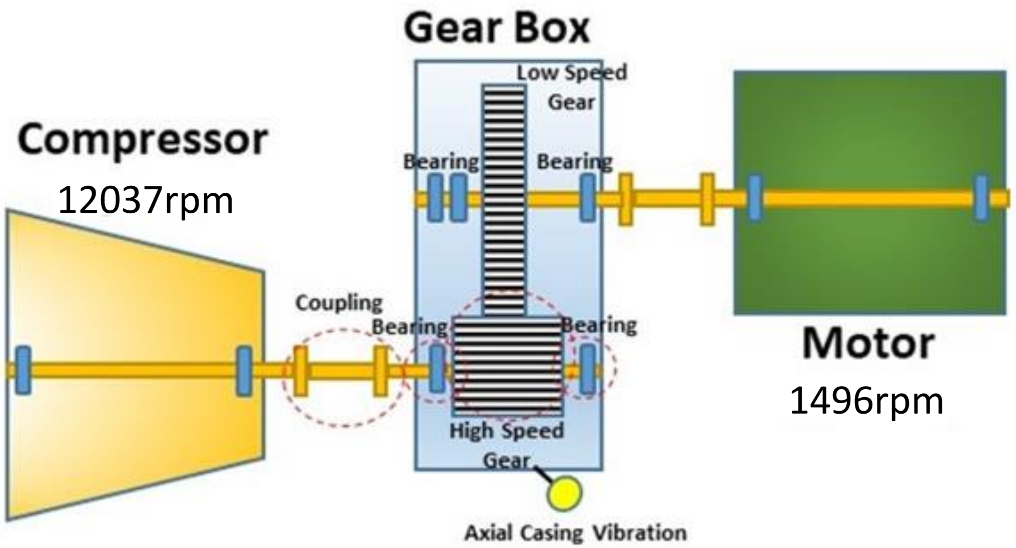
The couplings exhibited evidence of fatigue fractures leading to catastrophic failure due to high alternating torsional stress. A natural frequency modal analysis showed that a mode shape of the compressor train bull gear enabled it to interact within the total system torsional modal response to create an excitation frequency at the 2nd torsional natural frequency.

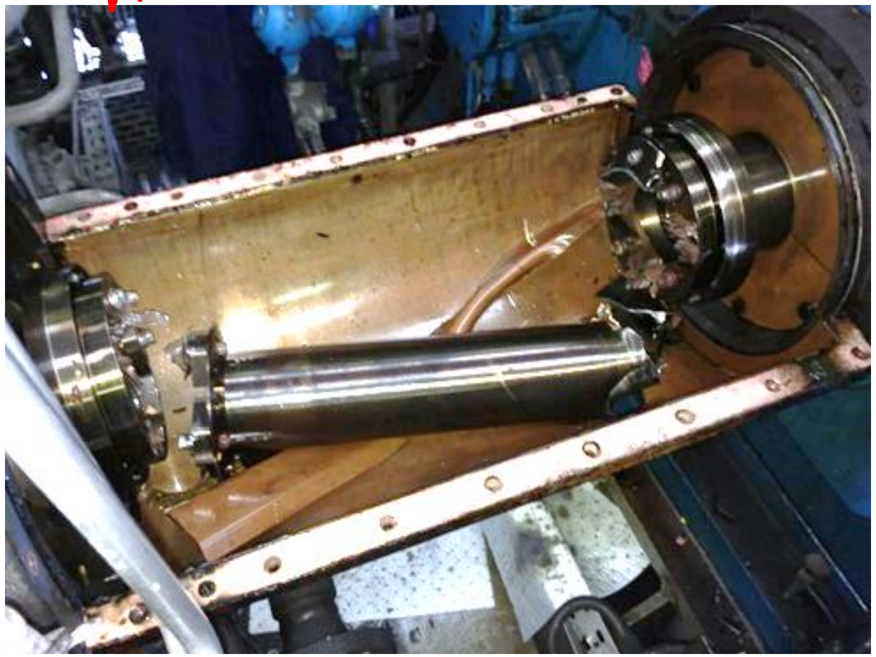
Further, discussion on practical design, operation and equipment monitoring shows limitations in guarding against the vulnerabilities mentioned.

Problem Statement

The motor driven centrifugal compressor had a catastrophic failure on the high-speed coupling. The coupling spacer was sheared while several smaller pieces were ejected through the coupling guard. An emergency repair was carried out on the compressor and the train was restarted. A repeat failure happened 4 days after the restart.







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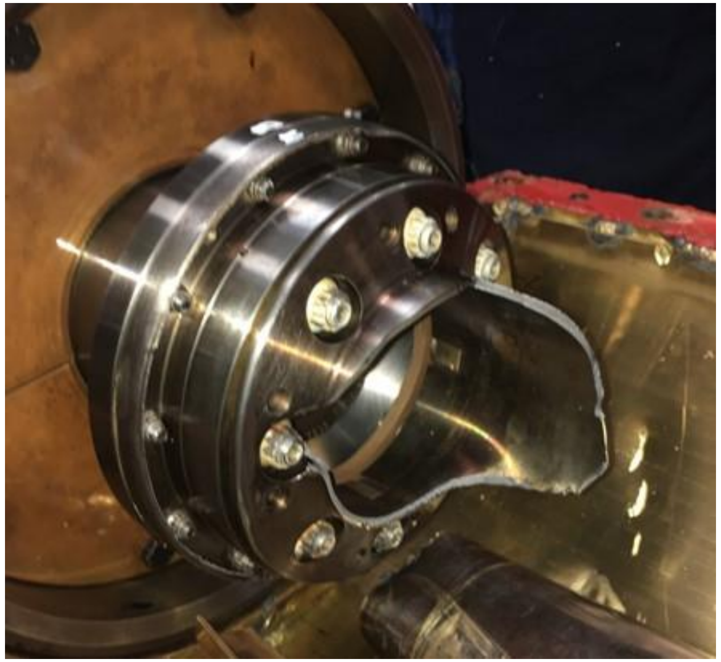
Sequence of Events

- Mature installation with ~17 years run time
- Two lube oil contamination events with seawater over years prior
- Lube oil temperature control valve failed 5 days prior to 1st failure causing oil temperature to rise from 45°C to 58°C
- Intermittent casing vibration alarms on the gearbox casing detected prior to 1st failure
- Gearbox casing vibration reached alarm level and tripped on high shaft vibration when the coupling failed
- Original RCA pointed to axial misalignment and issue was corrected
- After restart, repeat periods intermittent elevated casing vibration (at frequency 9x pinion speed) and noise
- Troubleshooting continued, 2nd coupling failed after 4 days



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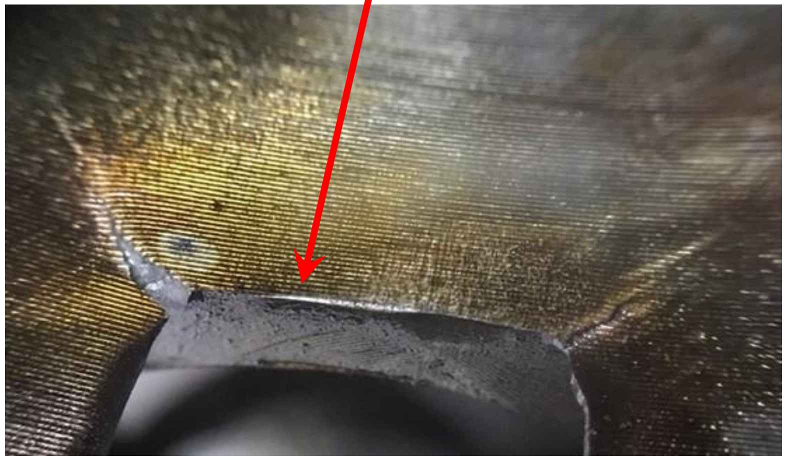
Observations 2nd Failure of Coupling

- Clear indications of torsional fatigue failure
- Multiple crack initiations in both forward and reverse rotation directions
- Gear tooth wear indicating torque reversal
- Crack initiation sites on both gearbox and compressor ends of coupling spacer



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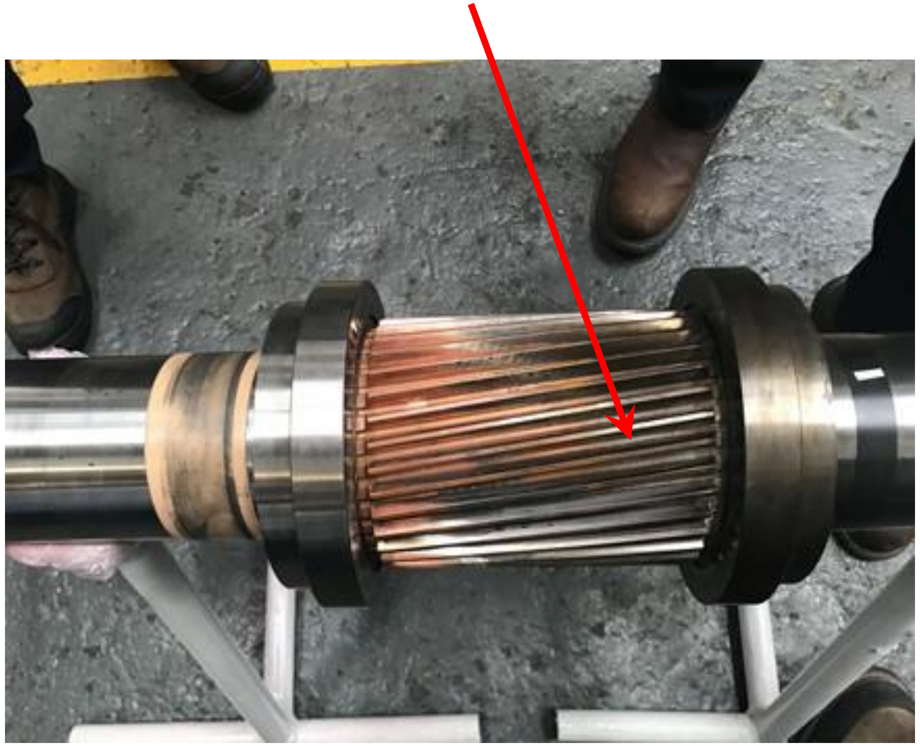
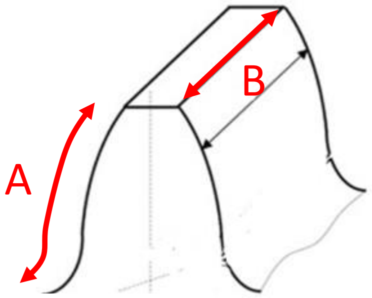
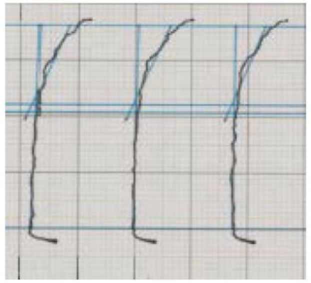
Gear Inspections

- Pinion shaft gear tooth profile showed severe wear compared to original
- Gear tooth wear pattern on both loaded and unloaded flanks

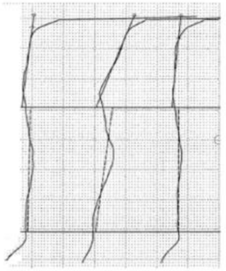




A: Pinion Flank Profile

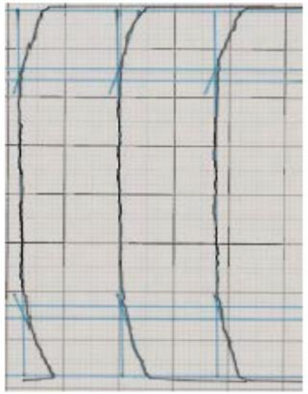


Original delivery 1995 - according to specification

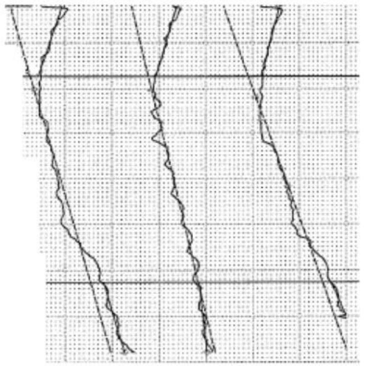


To be repaired pinion shaft - as found

B: Pinion Flank Line Profile



Original delivery 1995 - according to specification



To be repaired pinion shaft – as found

TURBOMACHINERY & PUMP SYMPOSIA

Analyses Completed

- Torsional oscillations and fatigue observations led to commissioning of detailed torsional analyses, focus on high order interferences (9X high speed interference based on observed vibration spectrum)
  - Multiple analyses corroborated no interference at higher orders; likely excitation of 2nd mode based on mode shape (69 Hz - ~3X gear speed)
  - Forced response analysis to understand stresses

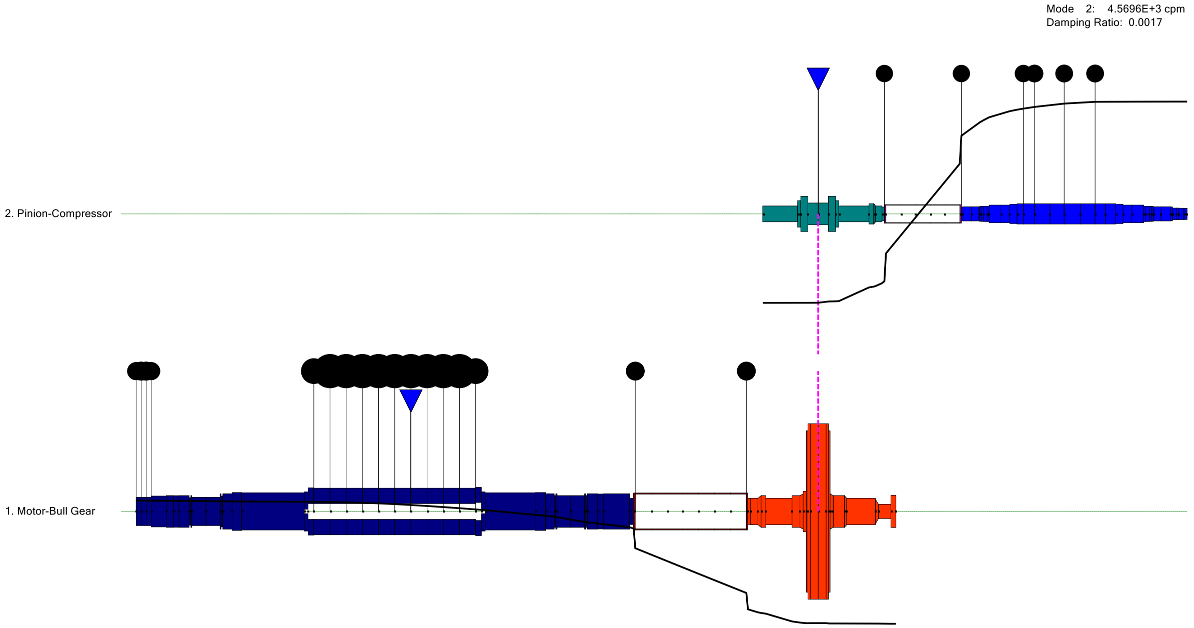
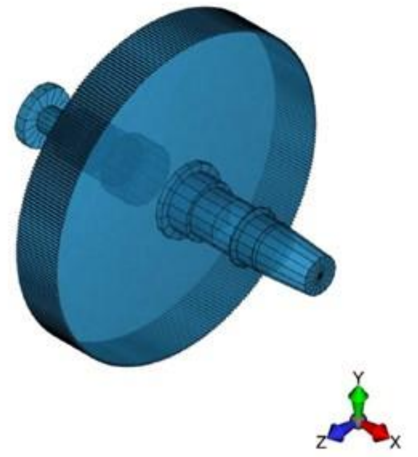
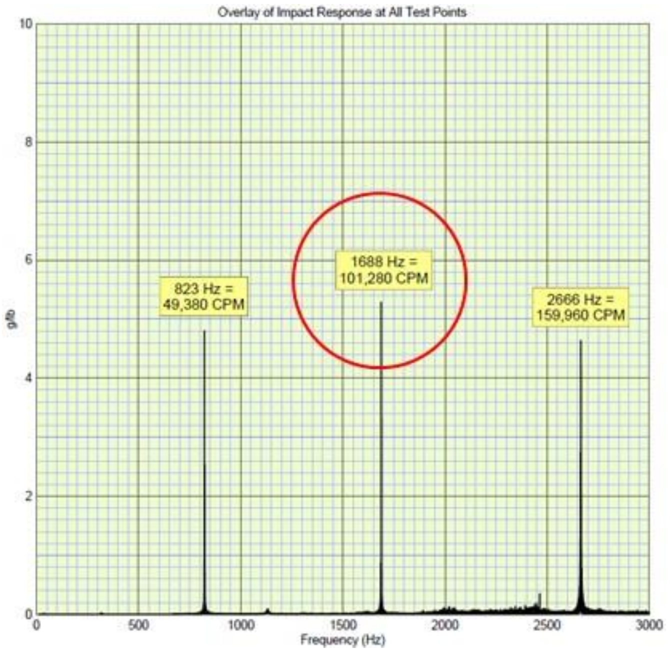


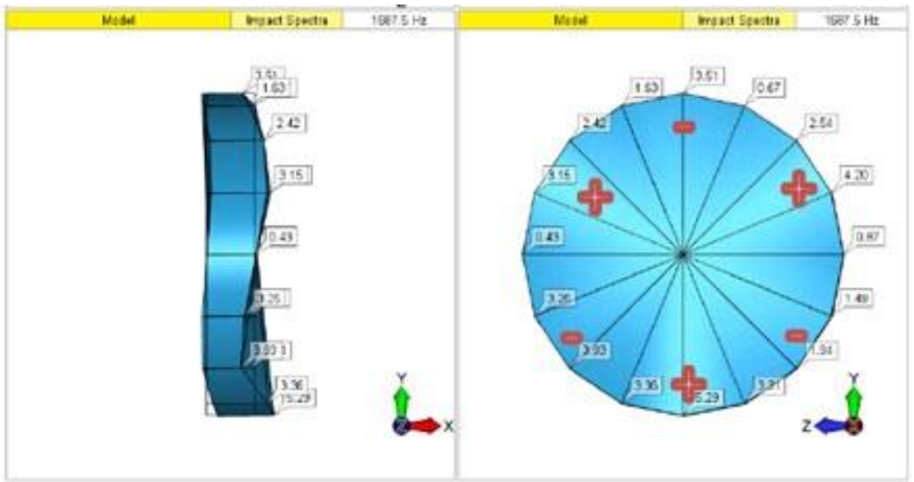
Figure from TNF Analysis

Gear Modal Analysis

- TAMU TPS paper *(Practical Solutions to Complex Gear Problems by John B. Cary)* reference showed pattern of gear teeth wear due to gear resonance
- Modal analysis showing bull gear mode shape
    - Method using multiple accelerometer measurements with calibrated hammer around the bull gear
    - Indicated 9X pinion speed detected on the casing was a gear structural natural frequency
    - Mode shape at 1688 Hz indicated below with 3 lobes







Analyses Completed

- AGMA Gear Lubrication Analysis
  - Analysis indicated marginally adequate design. Analysis indicating high probability of wear post contamination (changes surface roughness) and high oil temperature events.

Reference: AGMA 2101-C95 Appendix Pg. 52
Figure A.12 – Absolute viscosity versus temperature

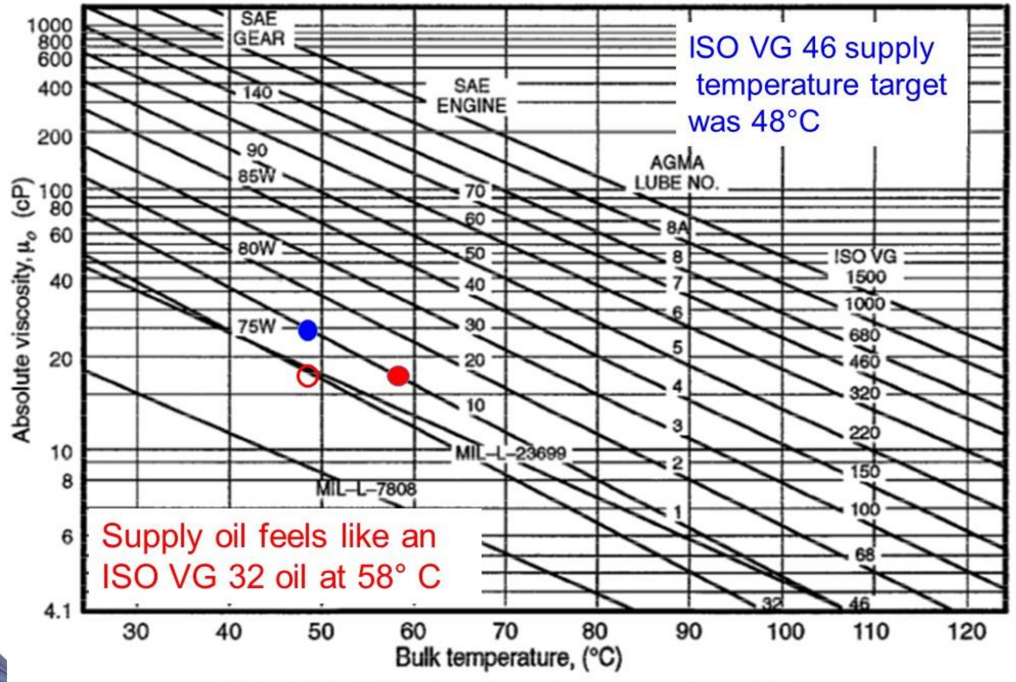
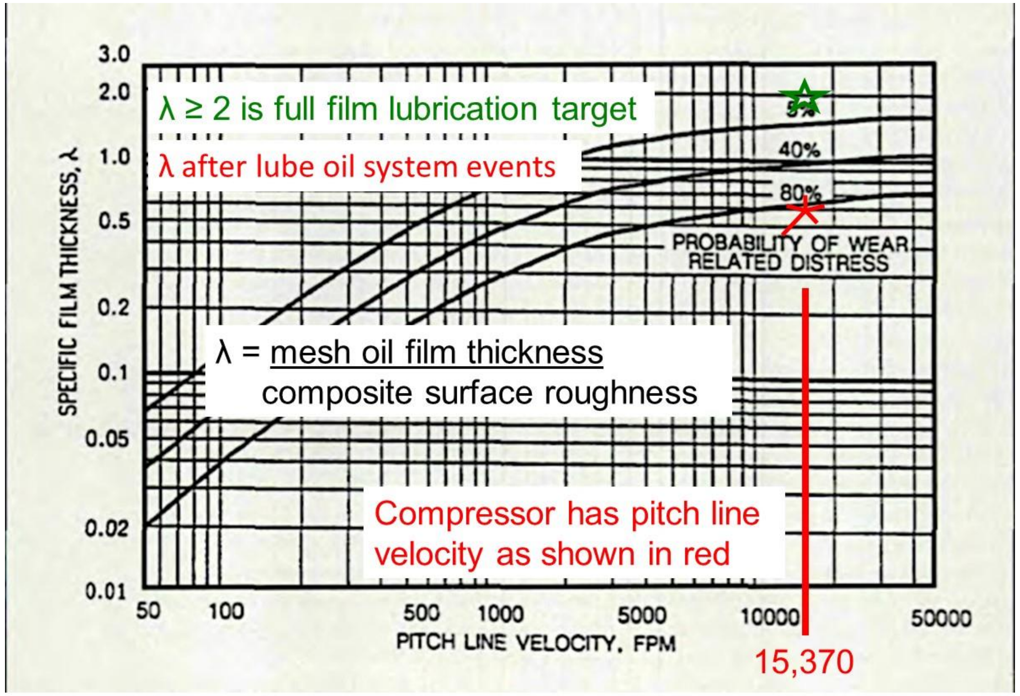


Figure A.12 – Absolute viscosity versus temperature

Reference: AGMA 2101-C95 Appendix Pg. 53
Figure A.13 – Probability of wear distress, percent



Conclusion

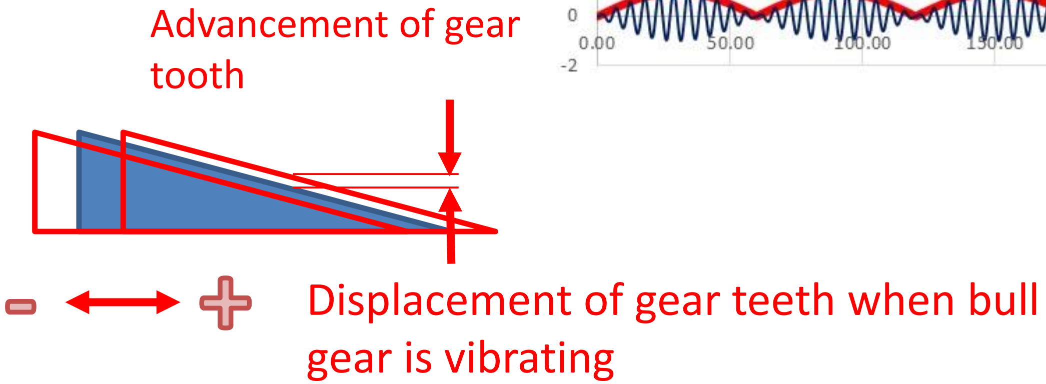
Gear wear resulted in torsional excitation

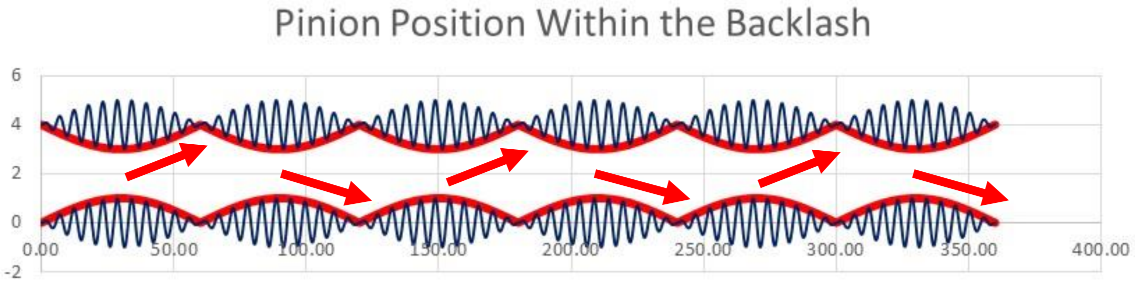
- Significant gear wear resulted in high levels of tooth contact at the gear mesh.
- The tooth impacts generated an energy that excited the gear structural natural frequency
- The bull gear ‘rang’ notably at 1688 Hz on its 3rd modal deflection shape of 3 lobes with 6 nodes.

Marginal Gearbox design for adequate oil film → Corrosion Incident further compromised capability → Rise in oil temperature decreased oil film → Gear tooth wear ruined tooth profile → Increasing excitation energy from impacts of gear mesh → 3rd mode structural vibration fully developed in Bull Gear

Conclusion

- The displacement of the single helical gear teeth due to modal oscillation resulted in a relative tooth advancement at the lobes.
- With the relative tooth advancement of the bull gear and axial inertia of the pinion gear, there were intermittent contacts of the gear teeth to create an effective torsional excitation at 3x of the low-speed shaft (74 Hz), which was close enough to intermittently excite the 2nd TNF of 69 Hz.
- Once the 2nd torsional natural frequency was excited, the train experienced torque reversal as evidenced by unloaded flank tooth wear, gear vibration increase and audible noise..

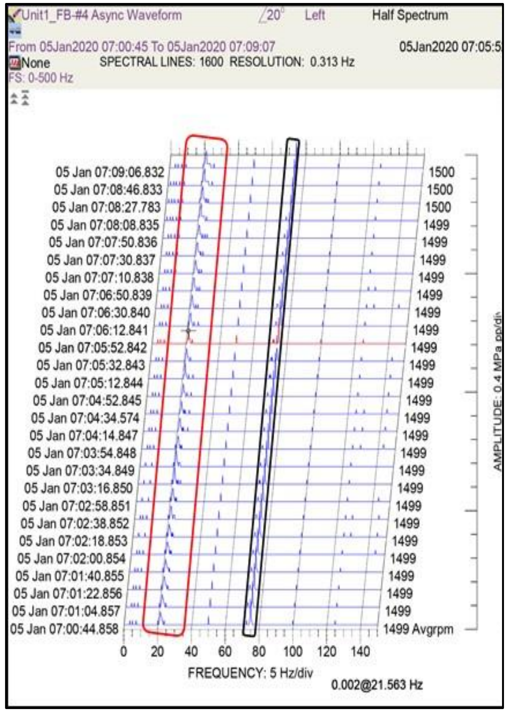


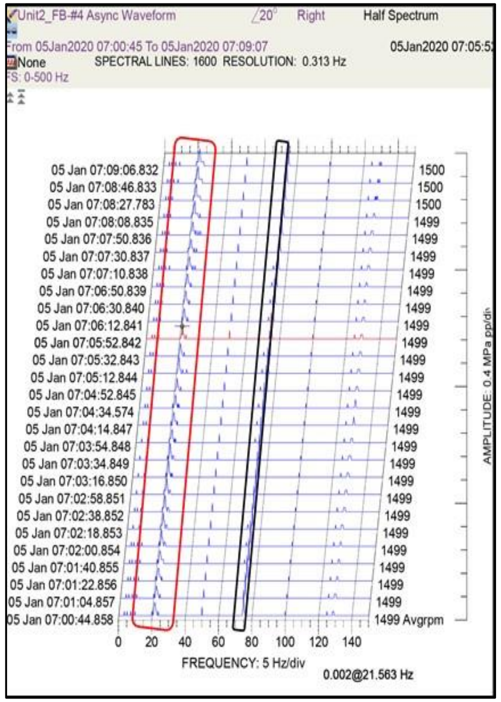


Mitigations

- Short term:
  - Replace bull gear and resurface pinion gear
  - Change oil system TCV to fail-close type
  - Field measurement of torsional vibration
    - Magnetostrictive measurement on both coupling spacers (First 2 modes close to model prediction)
    - Confirmation that torsional resonance no longer exist
    - Demonstration of practical application of novel method ("*Motor/Generator Set Non-contacting Torsional Vibration Measurements", TPS 2019*)

Torsional Vibration Sensors
Installed at LS Coupling (HS Similar)





- Long term:
  - Evaluate purchase of new double helical gear set that has different natural frequencies.

Lessons Learned

- Incrementally chipped away at the narrow design margins
- Caution to avoid assigning a root cause to the initiating event, the last straw that is put on the camel
- 9x frequency that was so apparent was an early focus and somewhat of a red herring that in the end was the tie in point
- Typical radial or axial proximity type instrumentation does not detect torsional vibration
- Coupling guards are not designed to contain failed coupling components
- Key mitigation to prevent torsional excitement is design

References

- TAMU TPS paper “Practical Solutions to Complex Gear Problems by John B. Cary”
- TAMU TPS paper 2019 “Motor/Generator Set Non-contacting Torsional Vibration Measurements”
- AGAM 2101 – C95 “Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth”
- Notable contribution: Dick Gill, ExxonMobil Annuitant
- Notable contribution: John Kocur, ExxonMobil Annuitant
- Dudley’s “Handbook of Practical Gear Design and Manufacture”