47TH TURBOMACHINERY & 34TH PUMP SYMPOSIA
HOUSTON, TEXAS | SEPTEMBER 17-20, 2018
GEORGE R. BROWN CONVENTION CENTER

Troubleshooting of Sub-synchronous Torsional Interaction Phenomena on an Electric Motor-Driven Centrifugal Compressor

Natalie R. Smith, Ph.D.

Jason C. Wilkes, Ph.D.

Timothy C. Allison, Ph.D.

J. Jeffrey Moore, Ph.D.

Chris D. Kulhanek

Southwest Research Institute

Authors

***Dr. Natalie Smith** is a Research Engineer in the Rotating Machinery Dynamics Section at Southwest Research Institute in San Antonio, Texas. Her research experience at SwRI includes aerodynamic design, analysis, and testing of turbomachinery for various applications including power generation, oil and gas, and supercritical CO_2. She earned her Ph.D. in Aeronautics and Astronautics from Purdue University.*

***Dr. Jason Wilkes** is a Senior Research Engineer in the Rotating Machinery Dynamics Section at Southwest Research Institute in San Antonio, TX. His experience at SwRI includes design and construction of various test rigs, predicting lateral and torsional rotordynamic analyses, bearings and seals, and auxiliary bearing dynamics following failure of active magnetic bearing-supported turbomachinery. Dr. Wilkes holds a B.S., M.S., and Ph.D. in Mechanical Engineering from Texas A&M University, where he studied at the Turbomachinery Laboratory for 6 years.*

***Dr. Timothy Allison** is the manager of the Rotating Machinery Dynamics Section at Southwest Research Institute in San Antonio, TX. His research at SwRI includes finite element analysis, modal testing, instrumentation, and performance testing for applications including high-pressure turbomachinery, centrifugal compressors, gas turbines, reciprocating compressor valves, and test rigs for rotordynamics, blade dynamics, and aerodynamic performance. He holds a Ph.D. in Mechanical Engineering from Virginia Polytechnic Institute and State University*

***Dr. Jeffrey Moore** is an Institute Engineer in the Machinery Section at Southwest Research Institute in San Antonio, TX. He holds a B.S., M.S., and Ph.D. in Mechanical Engineering from Texas A&M University. His professional experience over the last 25 years includes engineering and management responsibilities related to centrifugal compressors and gas turbines at Solar Turbines Inc., Dresser-Rand, and Southwest Research Institute. His interests include advanced power cycles and compression methods, rotordynamics, seals and bearings, computational fluid dynamics, finite element analysis, machine design, controls and aerodynamics.*

***Chris D. Kulhanek** is a Research Engineer in the Machinery Section at Southwest Research Institute in San Antonio, TX. He holds a B.S. and M.S. in Mechanical Engineering from Texas A&M University. He leads rotordynamic design efforts on many types of rotating equipment. His interests include lateral and torsional rotordynamics, fluid-film bearing analysis and design, structural finite-element analysis (FEA), test rig design, and root cause failure analysis (RCFA).*

Abstract

This case study discusses the identification, troubleshooting, and correction of a torsional instability in an electric motor-driven driveline with variable frequency drive (VFD) for a high-pressure gas compressor test facility permanently installed at SwRI. A torsional instability was identified on the gearbox high-speed shaft at speeds when the VFD output (line) frequency met or exceeded the torsional natural frequency of the train. The issue was resolved by changing to sensorless vector control in the VFD instead of voltage/frequency control. In the literature, this change was not observed to solve similar problems.

Literature on Sub-synchronous Torsional Interaction

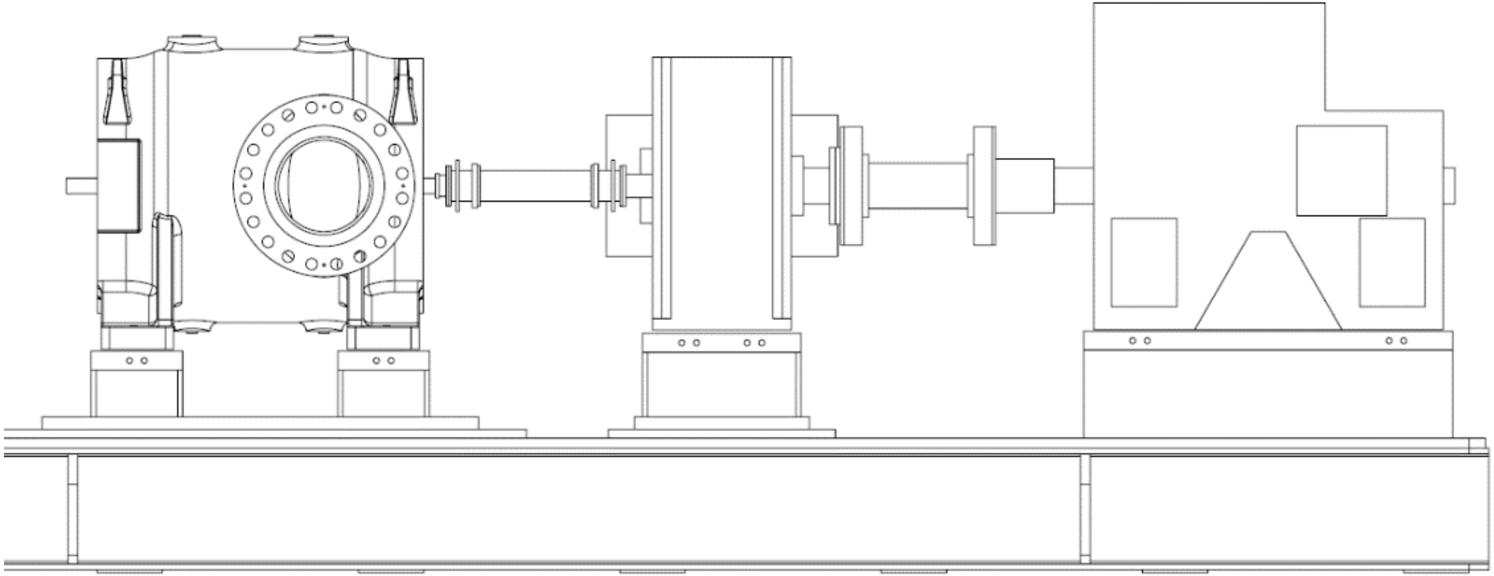
Reference	Summary	Solution
Kerkman et al, 2008. Feese and Maxfield, 2008. Feese, 2017.	ID fan coupling and motor shafts failed due to VFD excitation of TNF at all speeds where 1X EF > TNF. Identified cause: Distortion from PWM, bus voltage feedback, and carrier comparison. Operation in V/F mode was problematic.	Replaced VFD with new one with different parameters for duty cycle update, dead time compensation, bus voltage feedback filtering, and DC link choke to minimize non-characteristic harmonics.
Shimakawa and Kojo, 2007.	Coupling failure due to torsional vibration. Caused by torsional frequency content in speed feedback signal.	Switch to V/F control mode with no speed feedback.
Kocur and Muench, 2012.	Torsional failure of LNG compressor couplings due to combination of typical harmonics and white noise, amplified by feedback of VFD speed signal.	Require limits of white noise produced by VFDs, Speed feedback signals for VFD should be filtered. Consider notch filters around TNF.
Svetti et al., 2015.	Electrical interactions with multiple turbo-generator trains on same electrical grid. Turbo-generator torsional oscillations -> grid voltage oscillations -> VFD current oscillations	Perform interaction studies for island networks with large VFDs and gas turbine generators. Tune VFD control settings.

VFD EMD Compressor Facility used in Case Study

5-stage centrifugal **compressor**, max speed 16,500 rpm

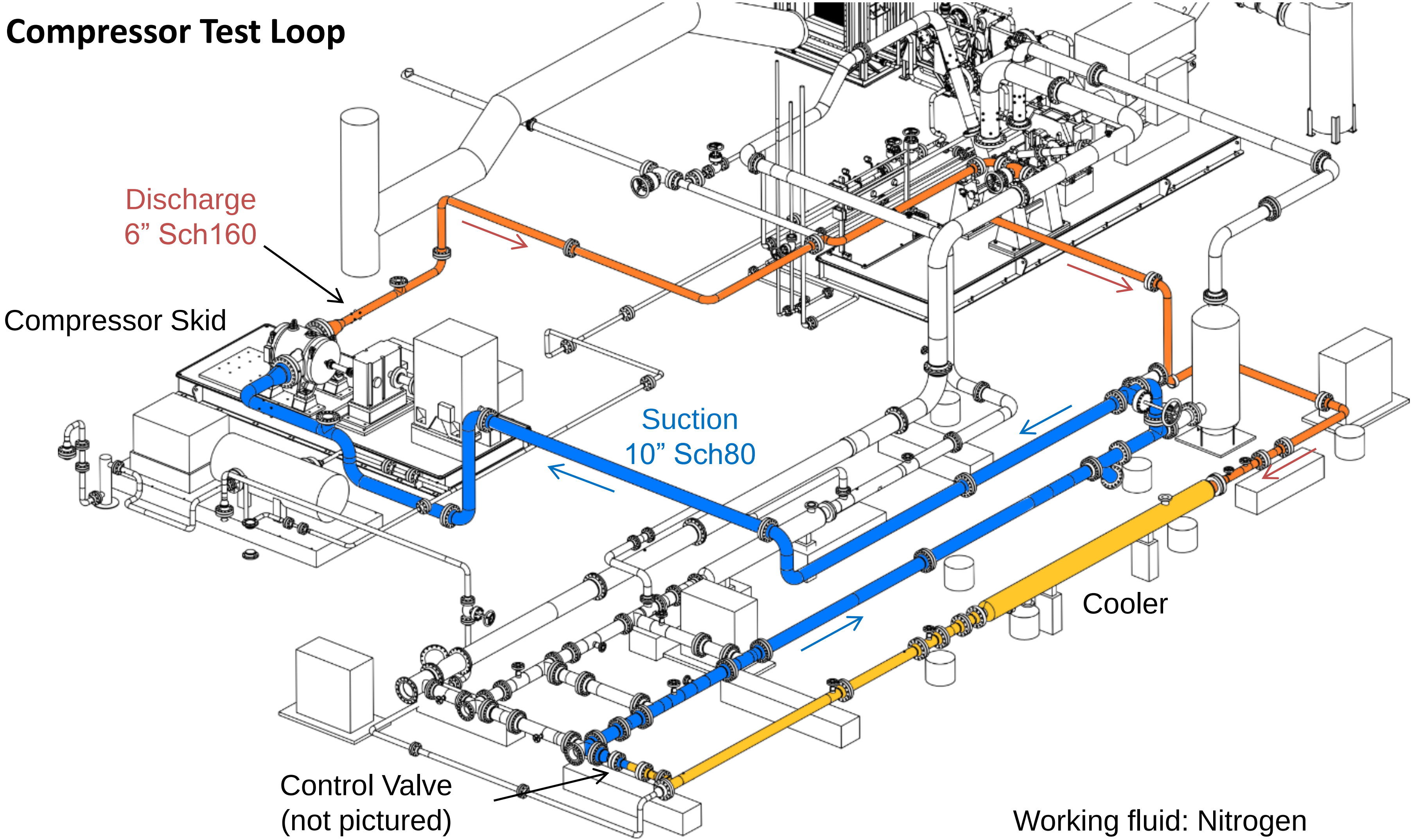
single-stage, single-helical, 7.792 gear ratio, 14,025 rpm output speed **gearbox**

4040 HP, 1800 rpm, 60 Hz induction **motor**



VFD controlled

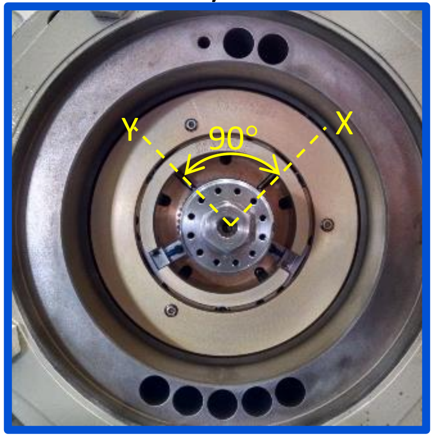
Compressor Test Loop



Working fluid: Nitrogen

Instrumentation

X-Y Proximity Probe Pairs

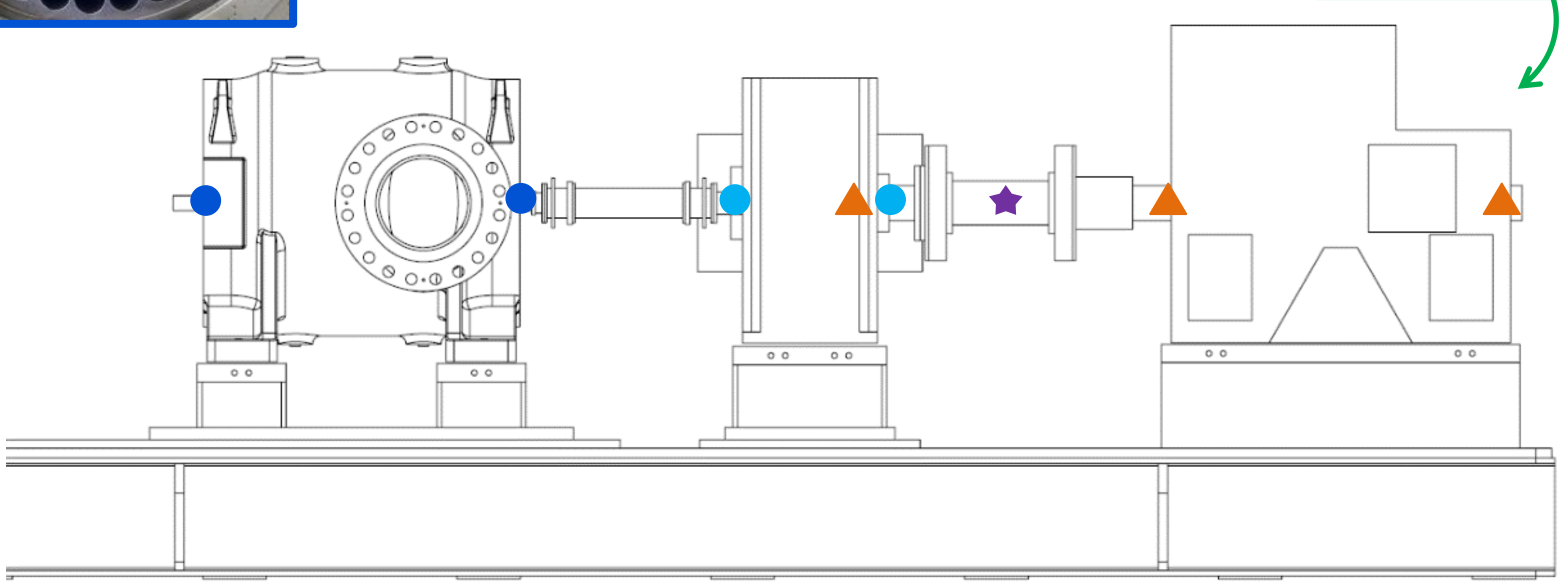


Proximity Probe

Accelerometers

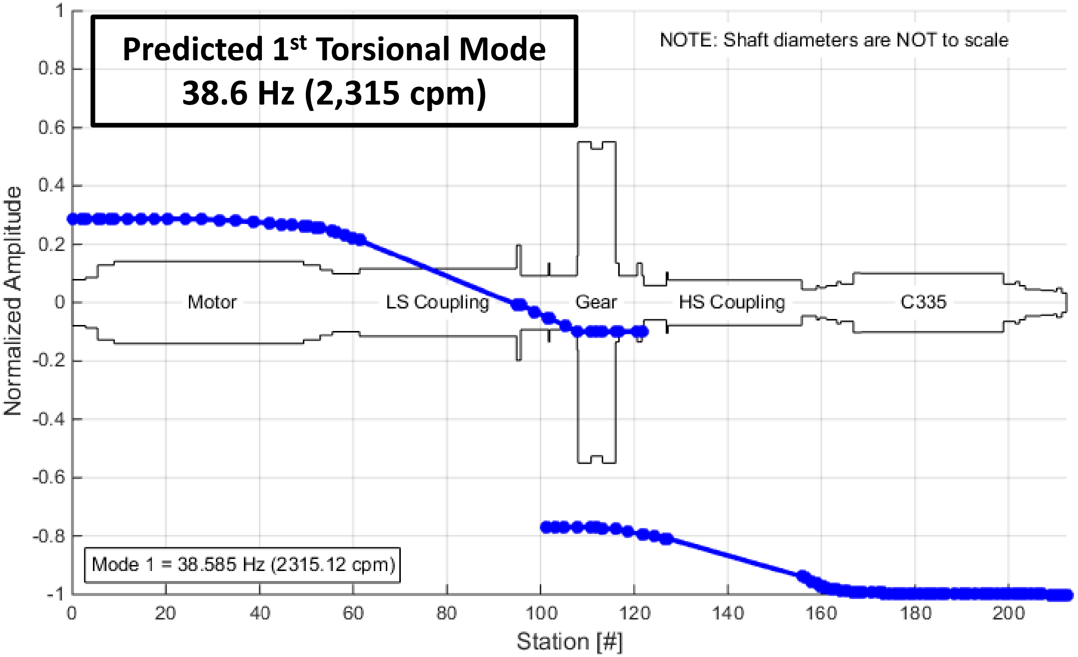
Strain

Voltage & Current

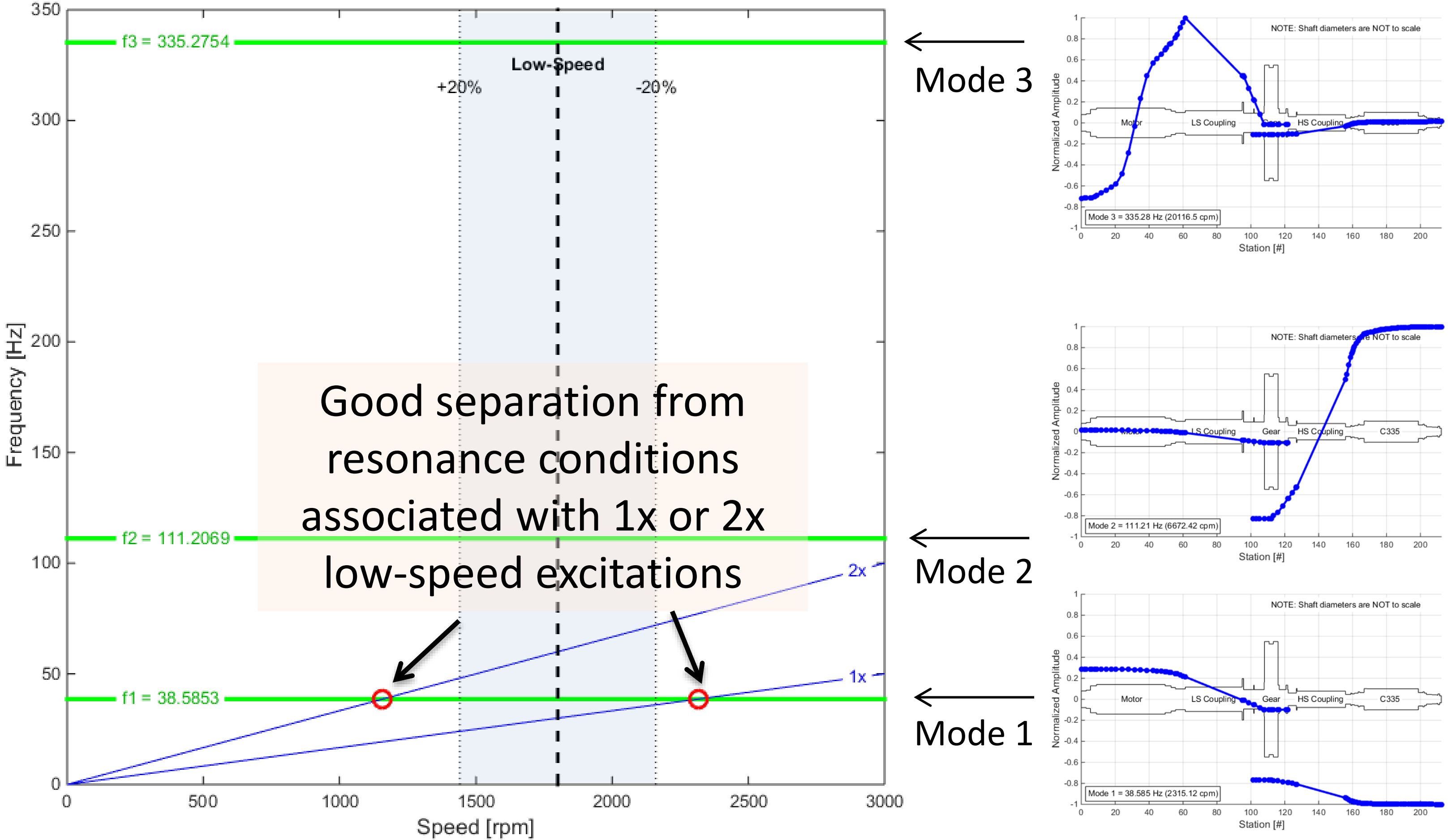


Torsional Rotordynamic Model

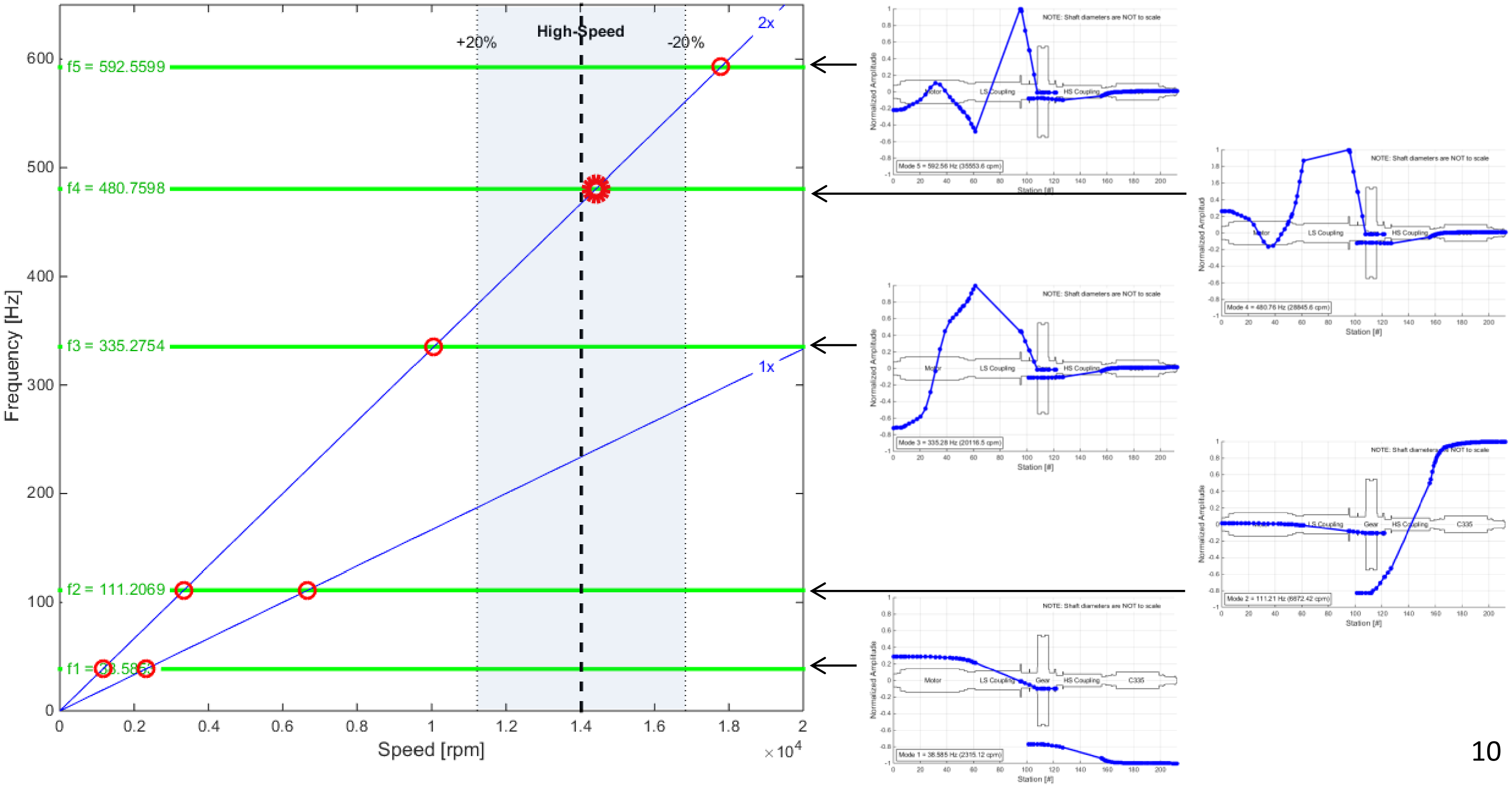
- Campbell diagrams show no interference with 1st mode with mechanical 1x and 2x energy orders (next slides)
- VFD non-integer excitation data not provided by VFD manufacturer



Campbell Diagram: Low-Speed



Campbell Diagram: High-Speed



Drivetrain Commissioning

<u>Mechanical Check-out</u>:
Open Loop / Air
Full speed (14k rpm)

↓

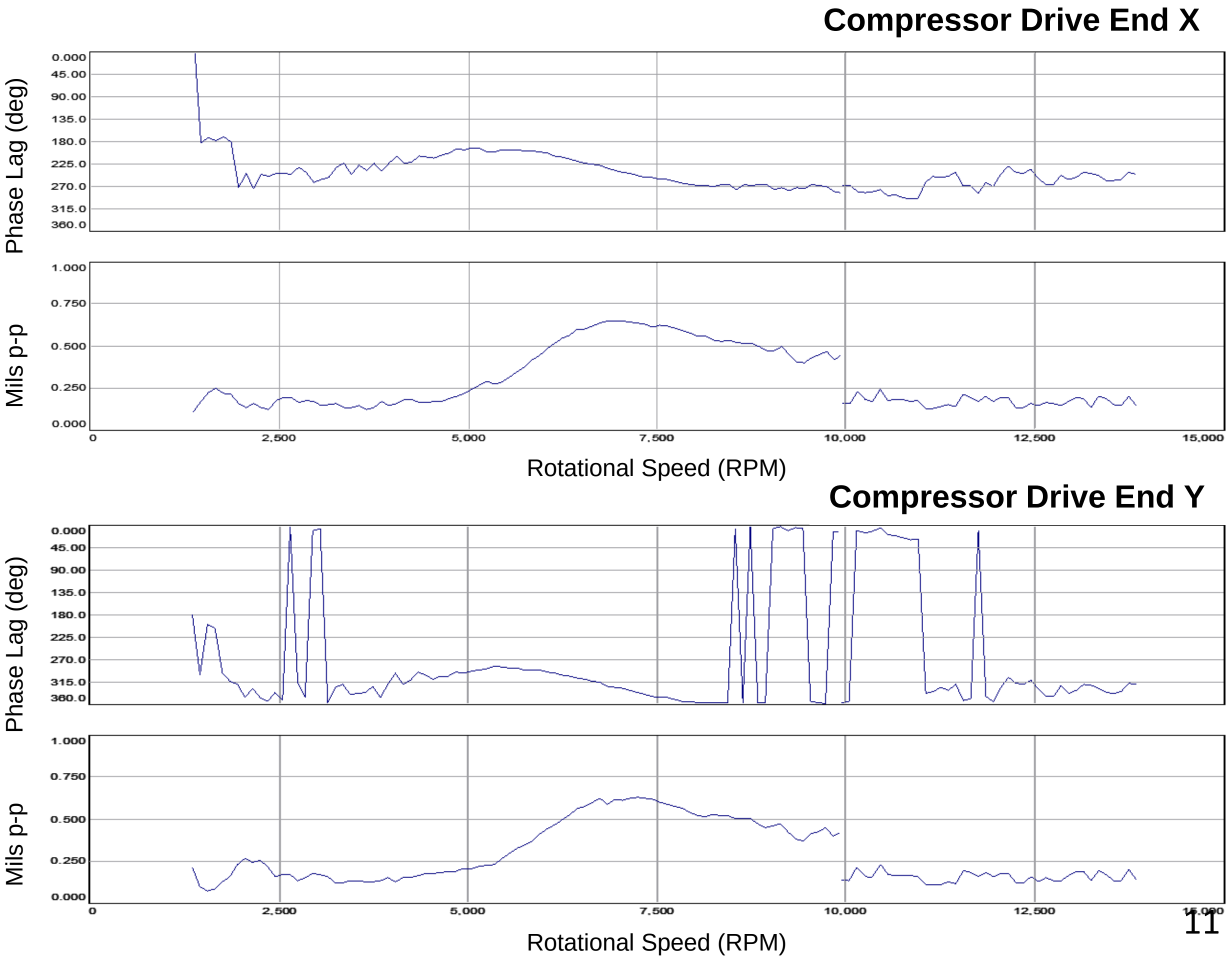
Low pressure (P1 = 30 psia)
Full speed

↓

High pressure (P1 = 600 psia)
Part speed (9.5krpm)

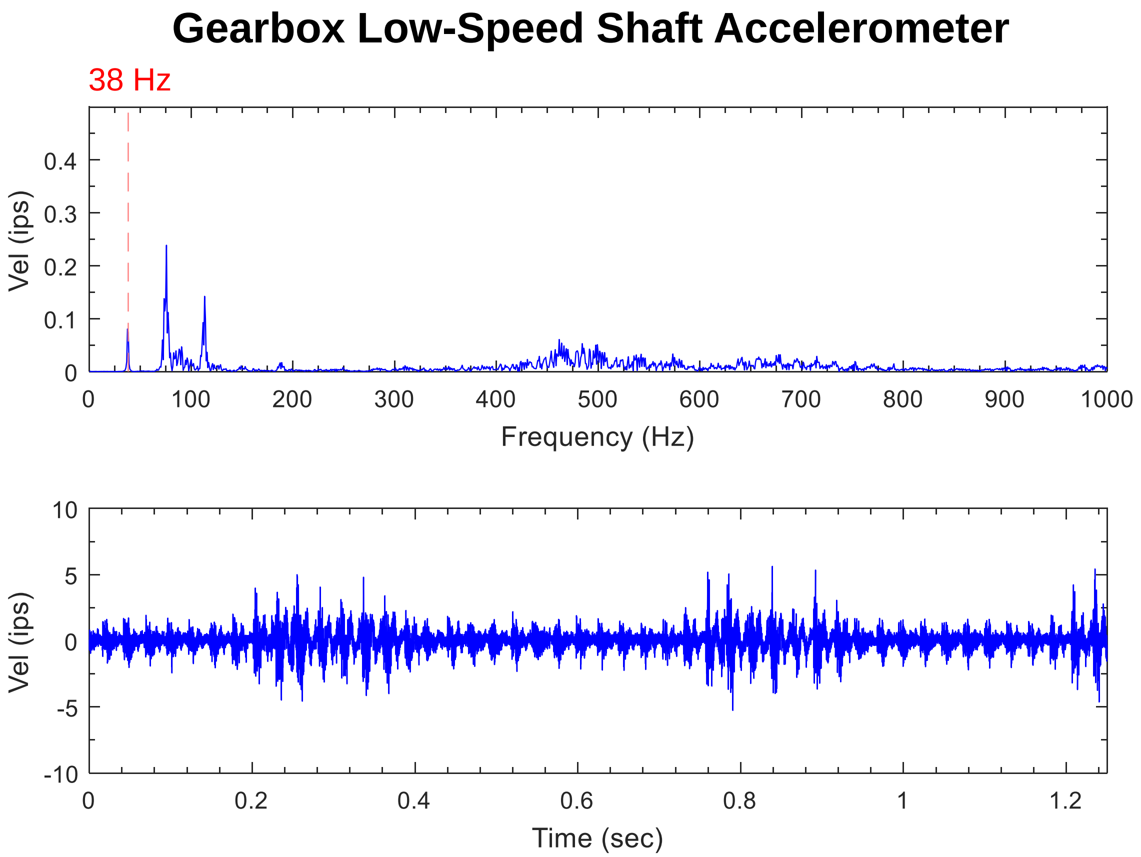
↓

High pressure
Full speed
(OEM present)

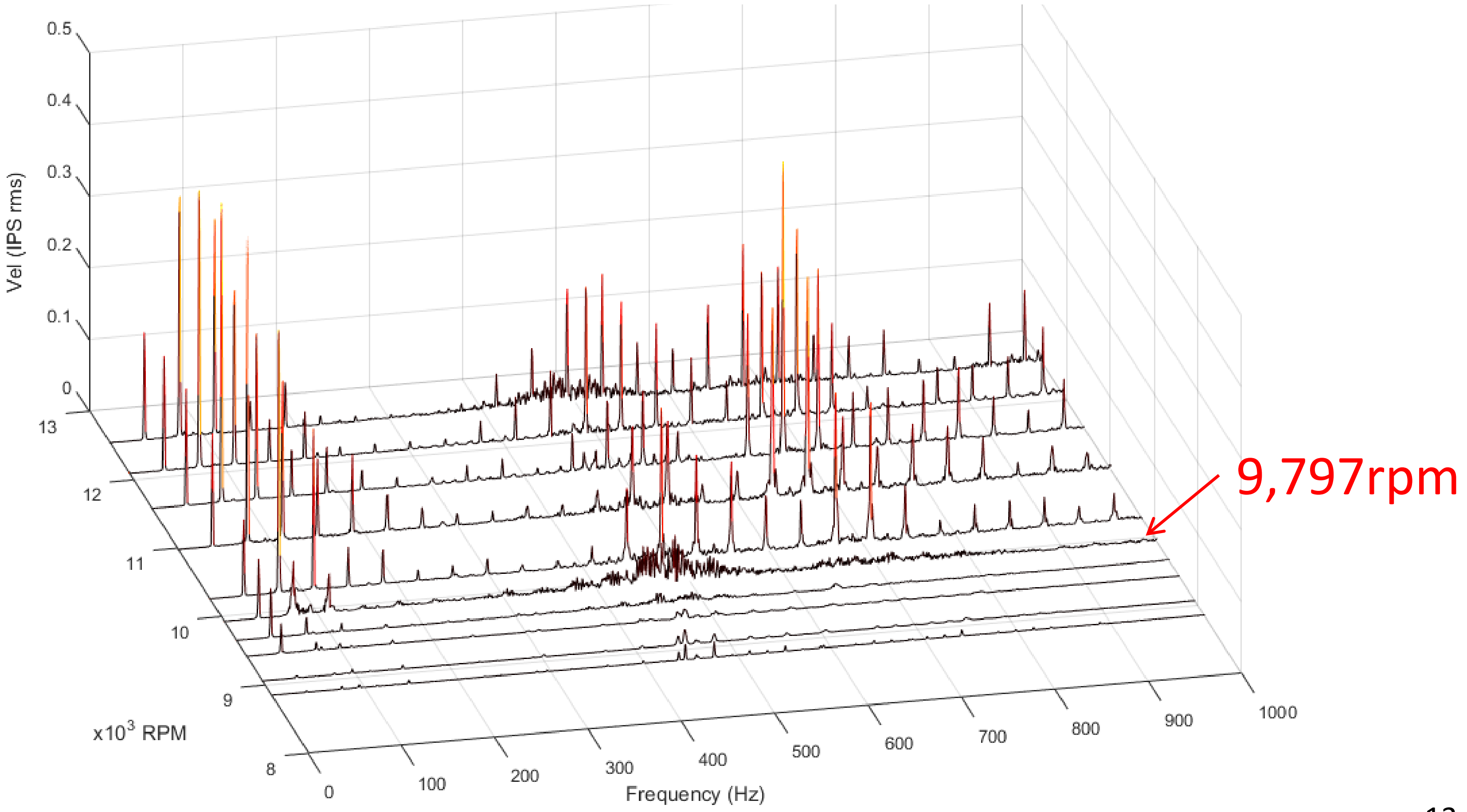


The Issue:

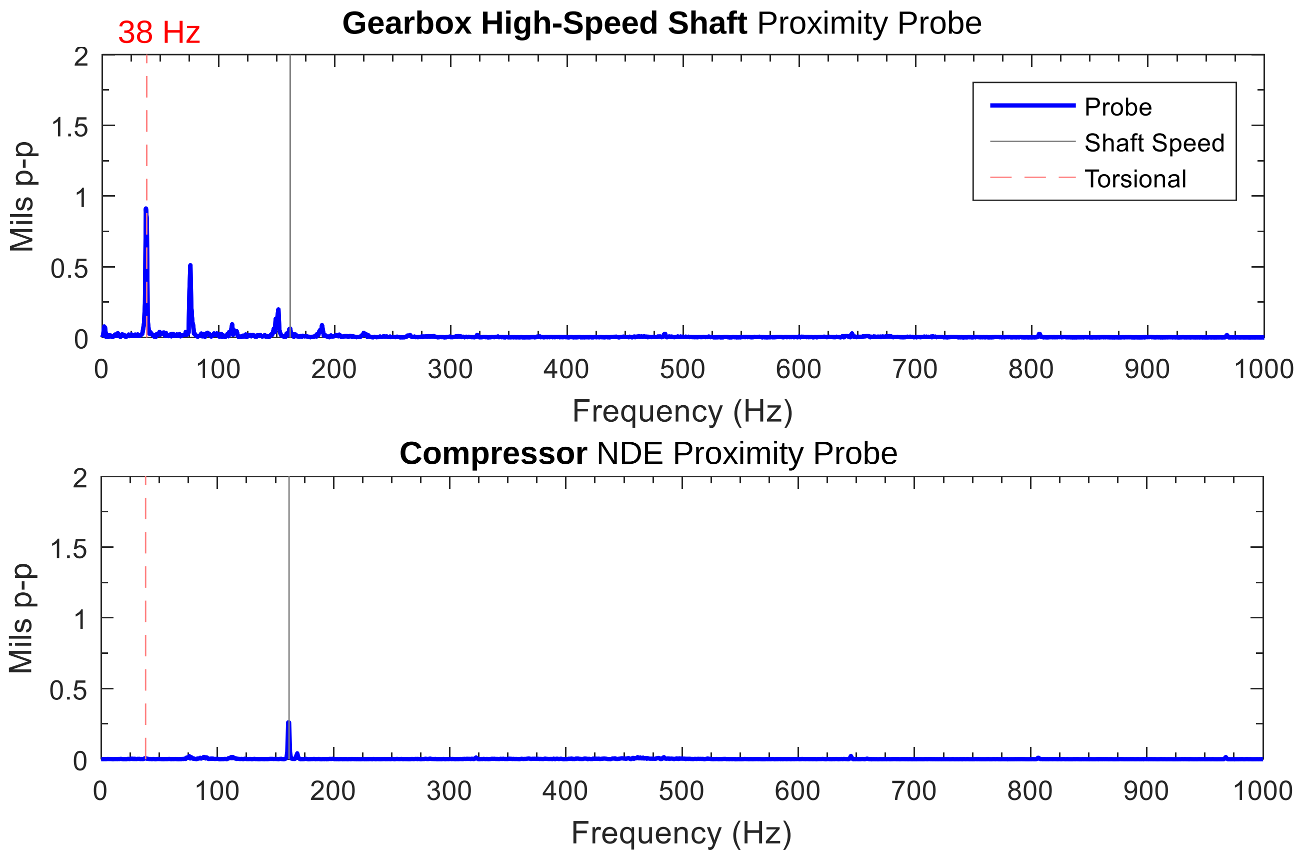
During high-pressure, high-speed testing, high vibrations were observed on the gearbox at the drivetrain's torsional frequency (38 Hz) between the speeds of 9,800 – 11,000 rpm.



Gearbox Low-Speed Shaft Accelerometer



Response observed on the gearbox shafts with proximity probe, but little response observed on the compressor shaft

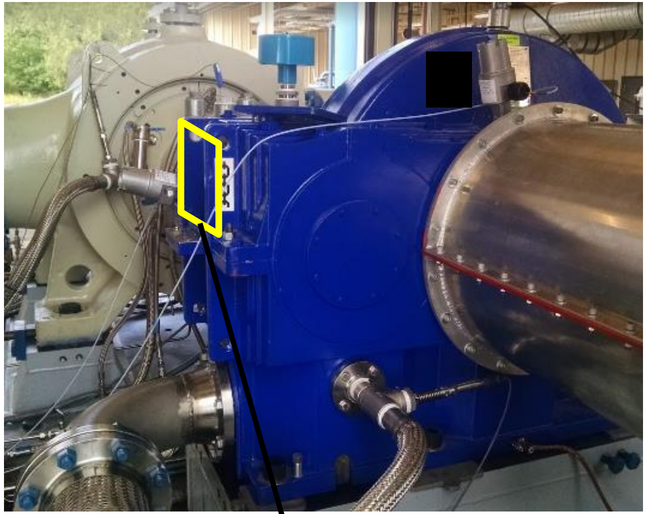


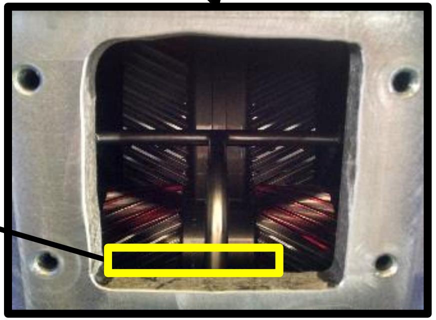
Additional Observations:

1. **Audible noise** during operation (steady state, accelerations, and decelerations) from gearbox

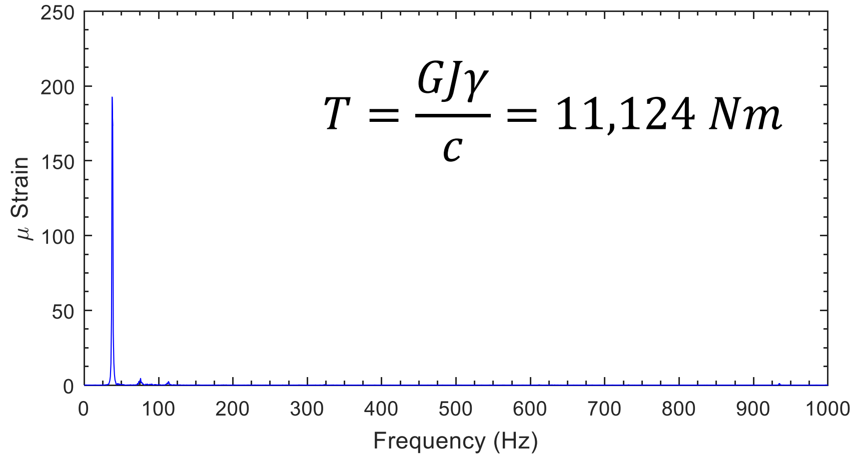
   No noise when deceleration occurred via emergency stop on VFD

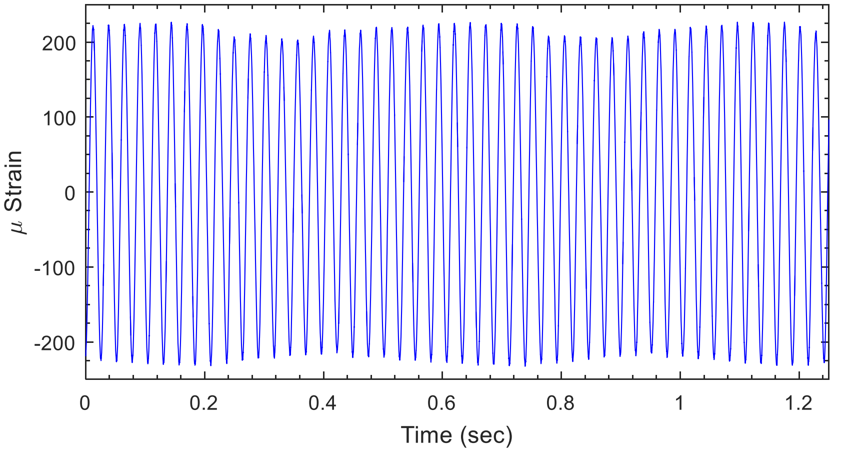
2. **Visual wear** on gearbox teeth in post-test inspection





Dynamic Torque Measurements

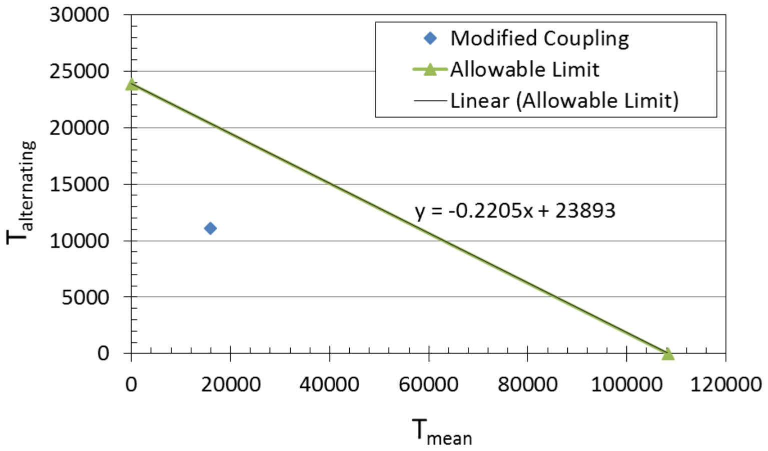




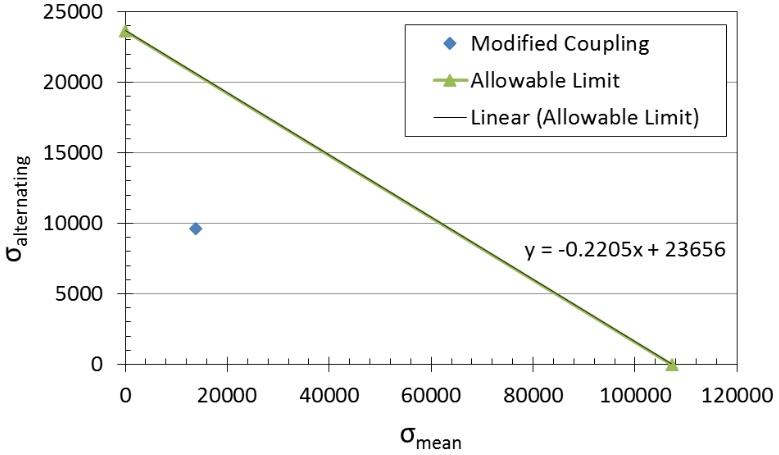
Low Speed Coupling Measurements

- Measured dynamic torque was applied to the torsional model to determine stress at various critical locations in the machine.
- The stress was plotted on a Goodman diagram to determine if low-cycle fatigue had occurred.

Coupling Spacer

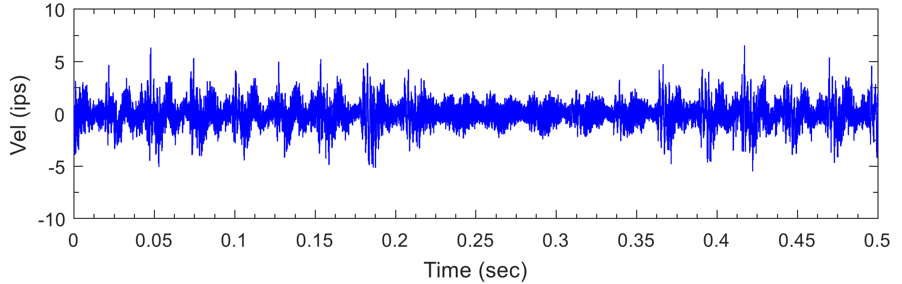


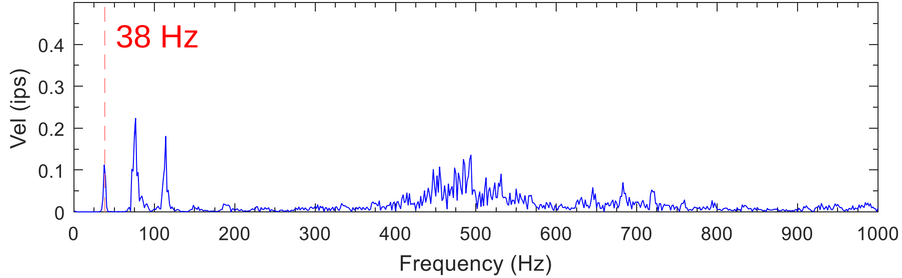
Motor Shaft



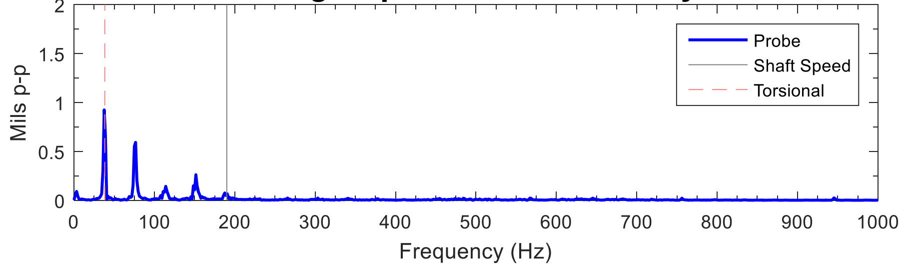
Motor Current Monitoring: 11,400 rpm V/F Mode

Gearbox Low-Speed Shaft Accelerometer



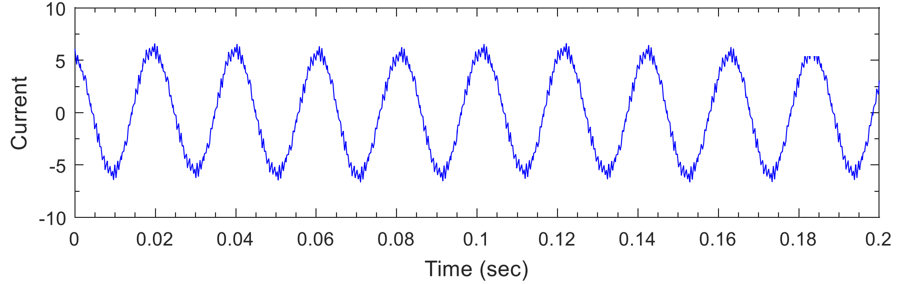


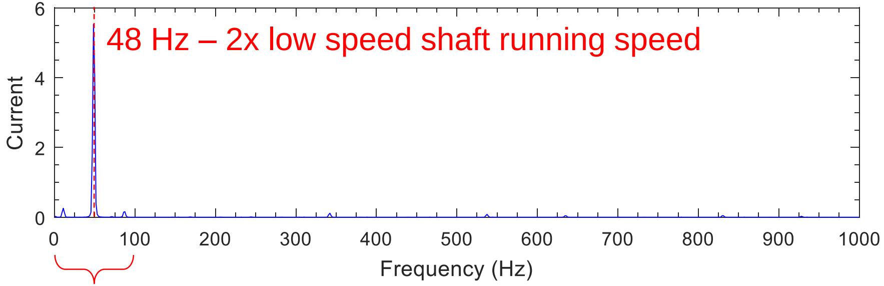
Gearbox High-Speed Shaft Proximity Probe



(All three motor leads gave similar signals)

Motor Current Lead "u"





Sidebands at +/- 38 Hz (torsional frequency)

» **Suggests feedback in speed control**

VFD Operation Mode

Motor OEM was onsite to assist in changing VFD operation mode and related settings and to observe performance.

Major Change:

- Operate VFD in **Sensorless Vector Mode** opposed to **V/F Mode**
- Tuned settings (filter constants and gains) to improve performance (power availability and stability) without inducing response

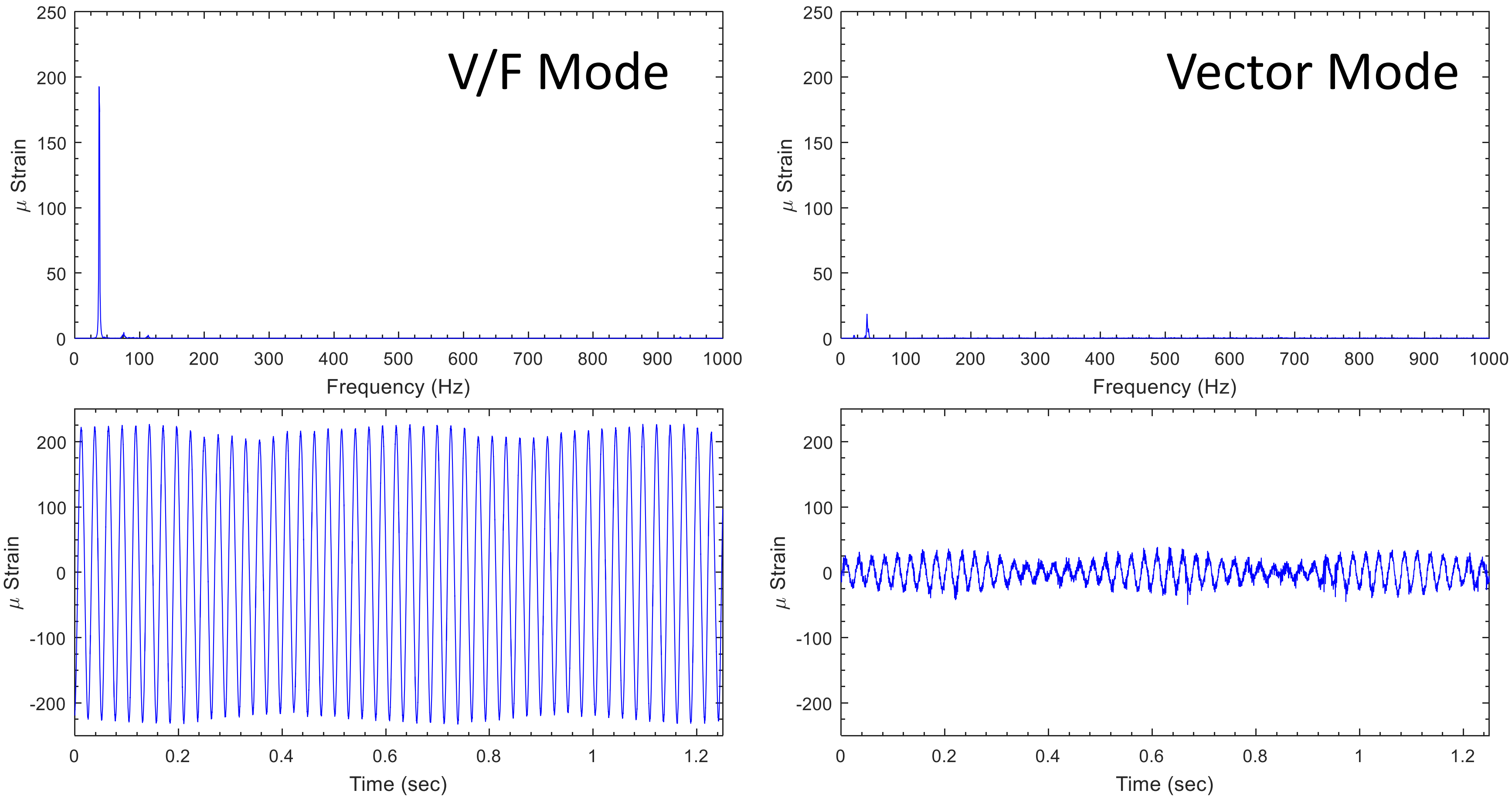
VFD Operational Mode: **V/F**

- V/F Mode is open loop speed control method
- There is a steady state relationship between speed reference and output frequency/voltage determined by parameterization.
- Motor speed is free to seek motor/load-torque equilibrium within a slippage window around synchronous speed.
- Choices of PWM frequency didn’t seem to provide any benefit

VFD Operational Mode: **Sensorless Vector**

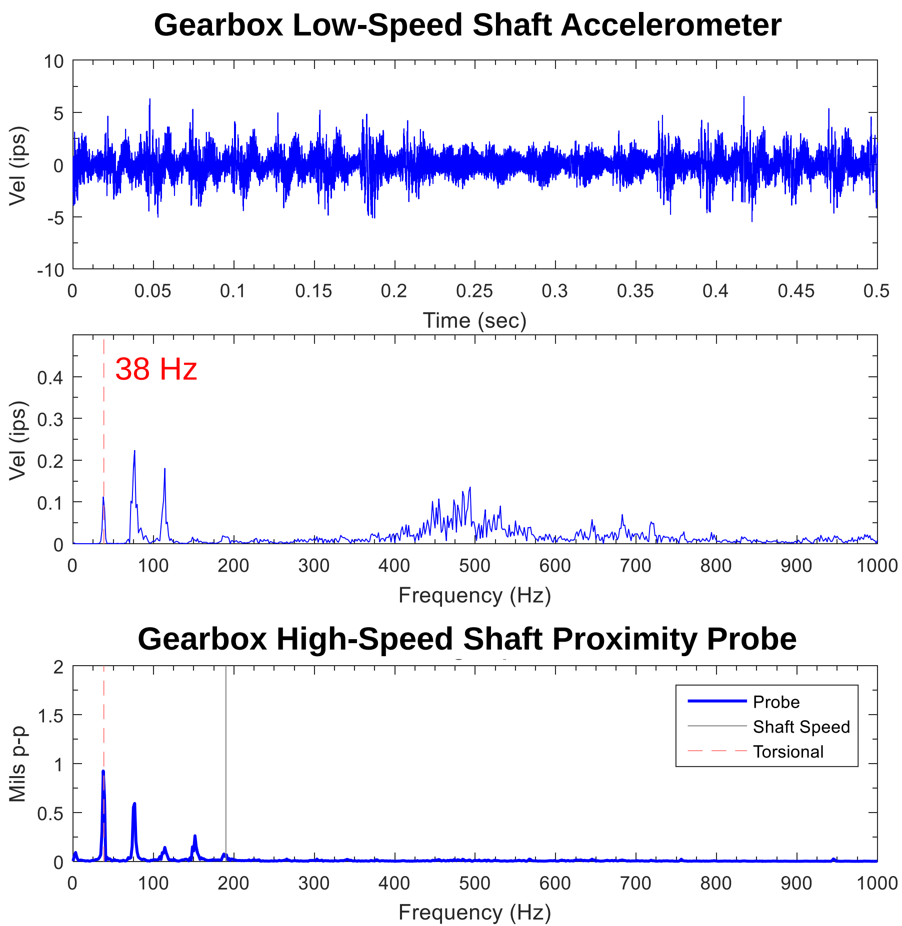
- Sensorless vector mode is closed loop control
- Provides various means of tuning with filter gains and constants
- This operating mode also controls motor excitation precisely, which may be beneficial to the present issue, given the observed effects of adjusting the V/F characteristic.

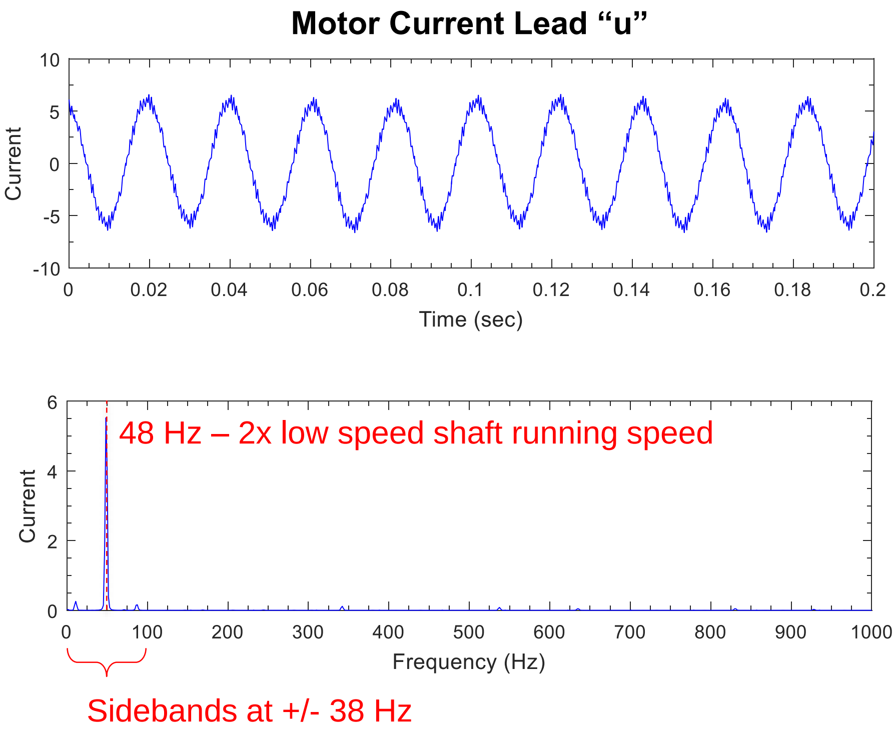
Change in Low-Speed Coupling Strain at 9,800 rpm



As shown earlier…

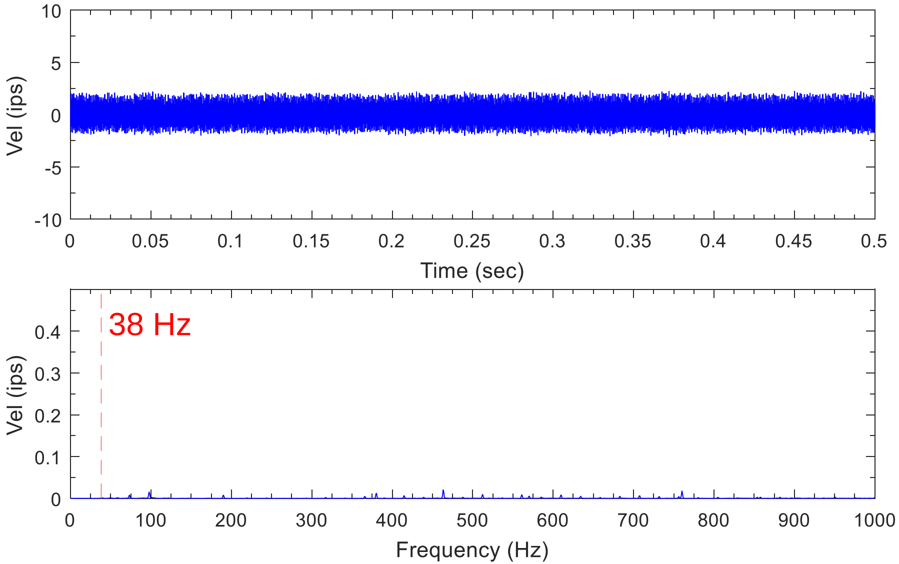
11,400 rpm **V/F** Mode



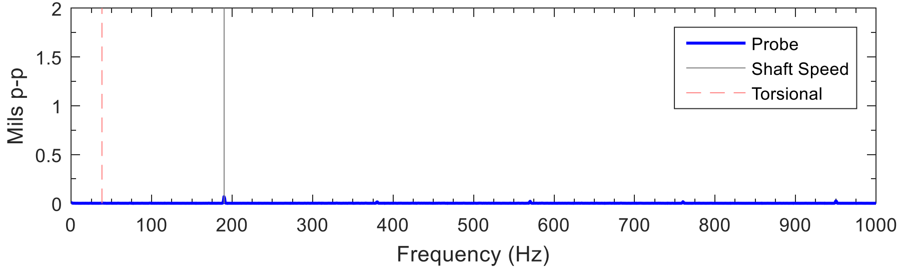


11,400 rpm **Sensorless Vector** Mode

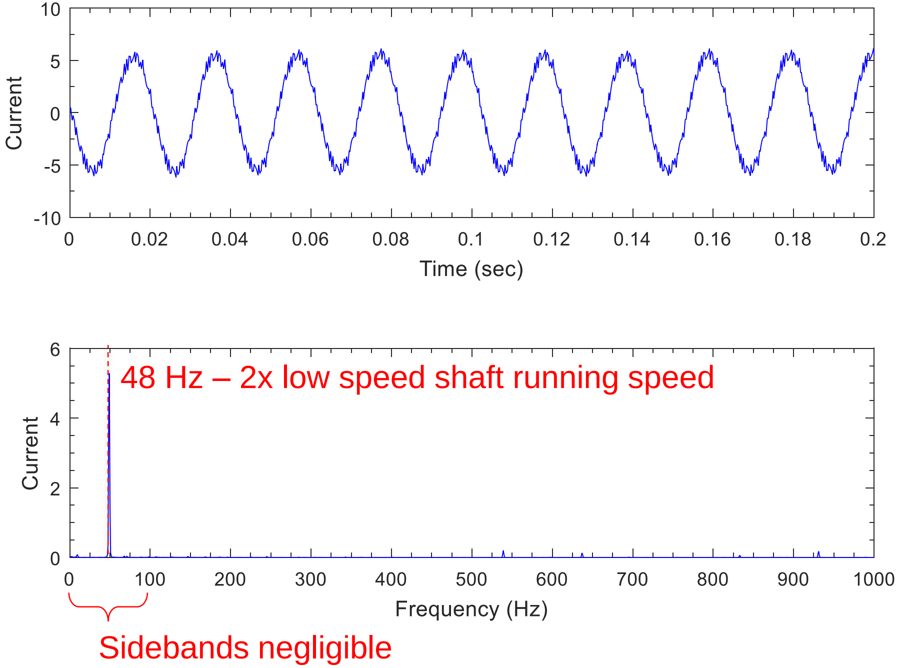
Gearbox Low-Speed Shaft Accelerometer



Gearbox High-Speed Shaft Proximity Probe



Motor Current Lead "u"



Summary & Conclusions

- Torsional excitation and response of the compressor train was unrelated to integer and non-integer VFD harmonics
- Slip associated with speed control in V/F Mode suspected to cause torsional response
- Sensorless Vector Mode did not eliminate response, but significantly reduced the magnitude of the response
- Torsional vibration monitoring recommended to detect problems and avoid unanticipated coupling/shaft failures
- This solution differs from other instances in the literature
- No 'typical' solution for all VFD-excited torsional vibrations; may need to involve VFD manufacturer and utilize coupled mechanical-electrical dynamic model

Thank you & Questions