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Field Techniques for Torsional Vibration Measurement

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wood.

Wednesday October 25, 2023
DOW Centennial Centre - Fort Saskatchewan

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His more than 25 years of design and field experience include turbomachinery design, acoustical (pulsation) analysis, finite element analysis, machinery diagnostics, rotordynamics and field troubleshooting. Wally has presented at multiple industry conferences including the Gas Machinery Conference (GMC), Vibration Institute Annual Training Conference (VIATC), Calgary Pump Symposium (CPS) and RATS Maintenance Reliability Operation (MRO) conference. He has served on API Standards 618 and 688 committees and is a member of the GMRC Gas Machinery Conference Planning Committee.

Field Techniques for Torsional Vibration Measurements

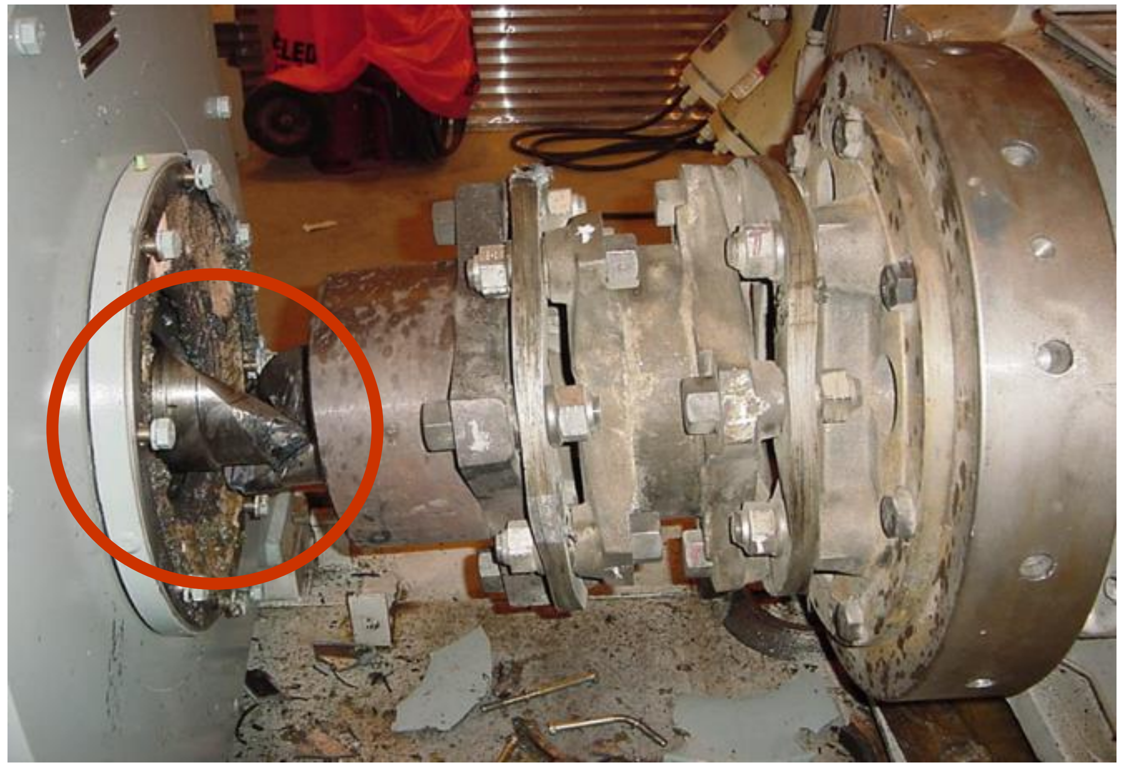
Abstract:

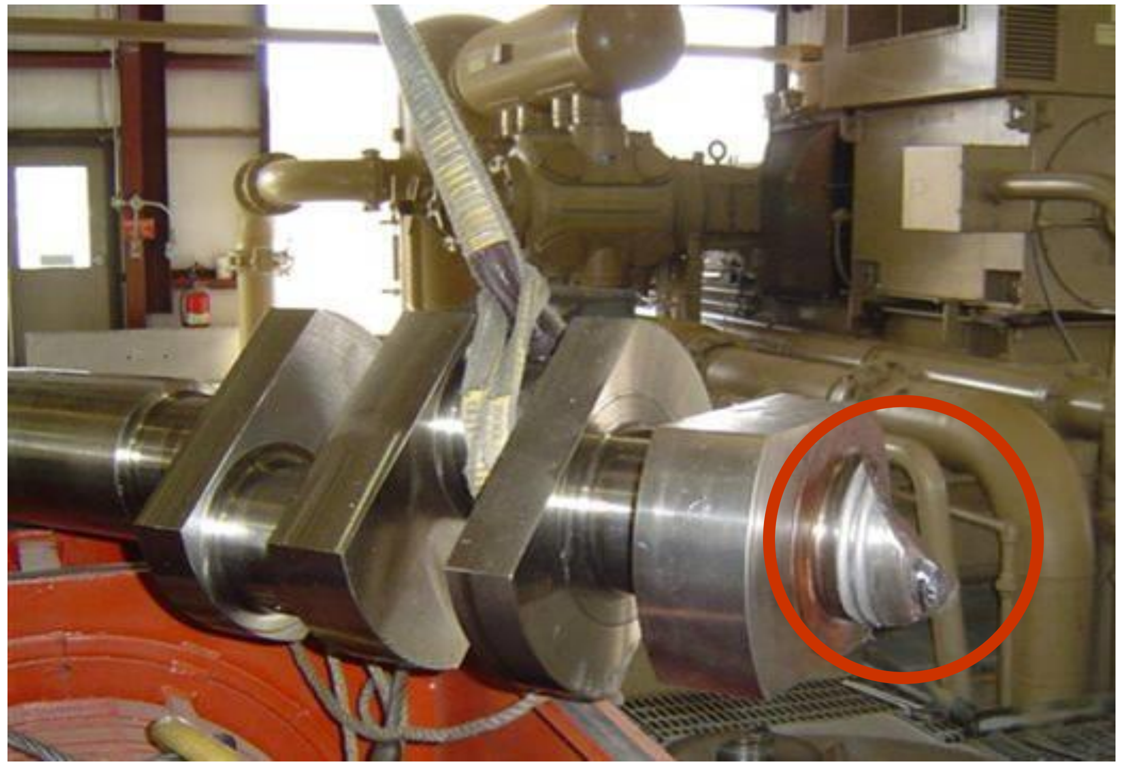
Torsional vibration design analysis (TVA) is essential to ensure the reliability of rotating machinery, particularly when the driver or driven machine is a reciprocating engine or compressor. Since reciprocating machinery torque curves (torque effort) are never flat due to the conversion of the reciprocating motion to rotation and vice-versa, a specialized analysis is required to provide the predicted (calculated) torque curves. As a matter of fact, the alternating component of torque is quite often as much as two to three times greater than the mean, or constant torque during normal operation. Each component in the drive train must be designed to withstand these alternating "rough" torque requirements. Dynamic response due to torsional resonance can amplify these torque levels beyond the fatigue (failure) limits of the individual components.

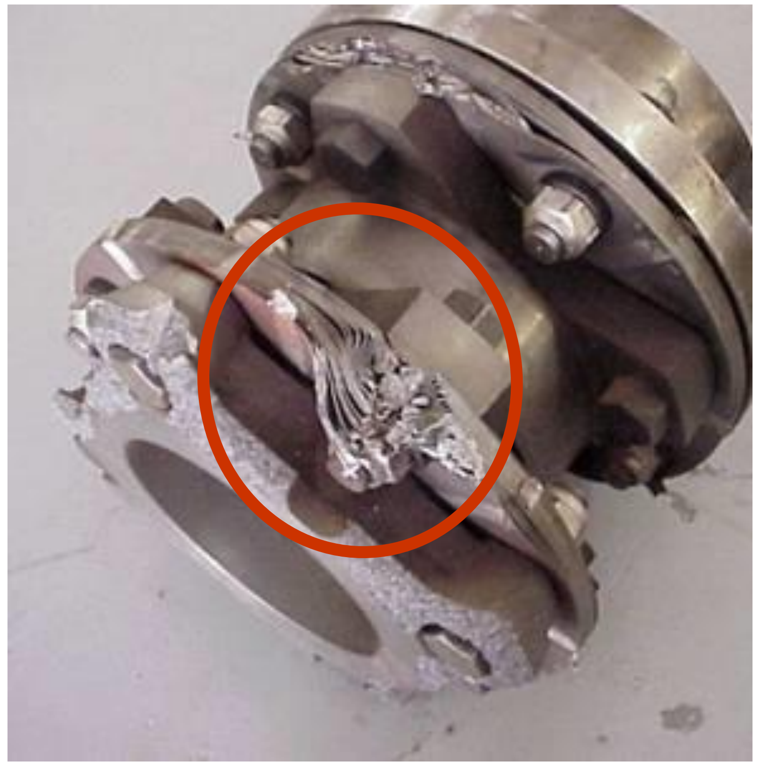
Even with a successful design analysis, torsional failures may occur due to differences in construction, errors in the TVA modeling information, or changes in machinery loading. The differences between the design (predicted) and real-world (field) operation can and occasionally do lead to major failures and lost production. Since torsional vibration problems often go unnoticed during startup, the failures are usually sudden and occur without prior signs. When a torsional failure does occur, the consequences are significant given the costs and time to replace a motor shaft or engine or compressor crankshaft. Unlike lateral vibration that can be detected using typical vibration instrumentation such as accelerometers or proximity probes, measurement of torsional vibration requires specialized instrumentation and approaches.

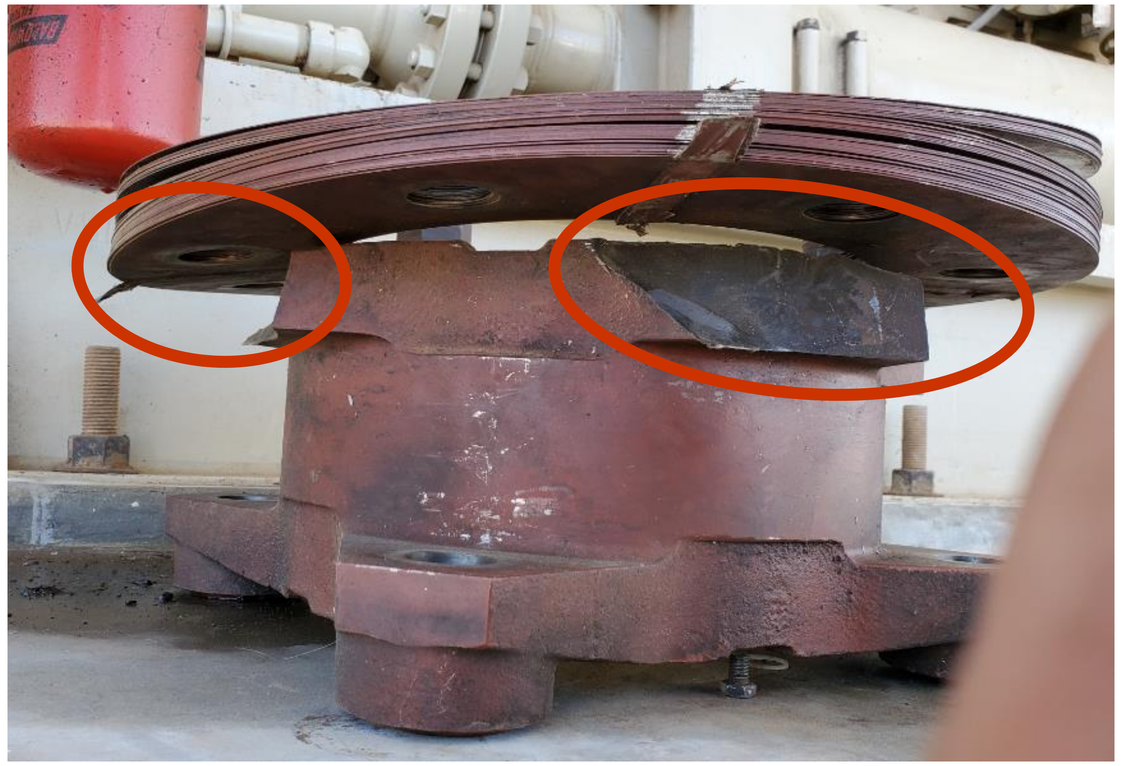
This presentation is intended for rotating equipment engineers, operators, and millwrights who are responsible for rotating equipment. The goal is to provide guidance to decide when field torsional measurements are appropriate, and to describe techniques for measuring torsional vibration. Methods for torsional vibration measurement using strain gage telemetry, shaft encoders, magnetic pick-ups, laser vibrometers, and optical pick-ups will be described. Relevant statements from industry guidelines will also be presented, including those from API 618 and the GMRC Guideline and Recommended Practice for Control of Torsional Vibrations in Direct-Driven Separable Reciprocating Compressors. Case studies will be provided to demonstrate approaches for identifying and solving torsional vibration problems before failures occur.

Why do we care about Torsional Vibrations?



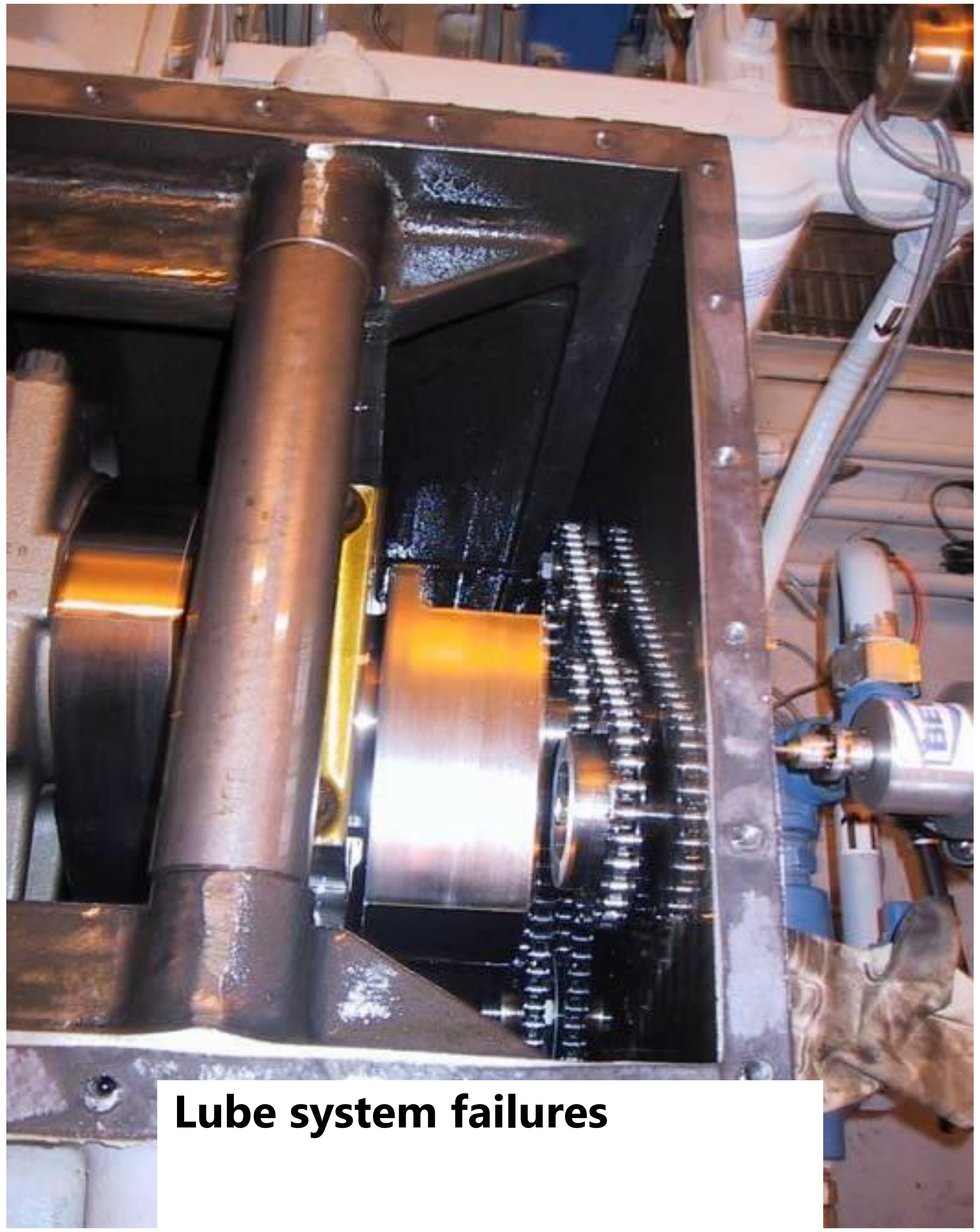






Other Torsional Problems

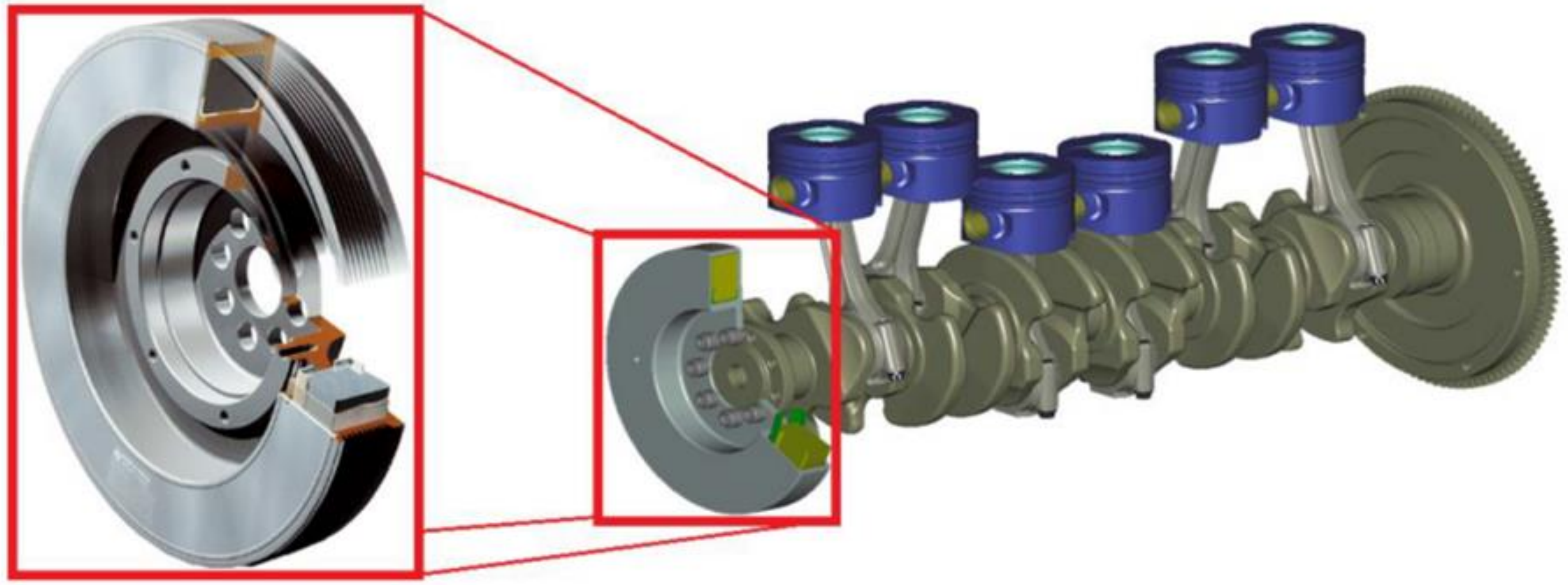
- Compressor auxiliary drive (most common issue)
- Gear backlash
- Motor fan failures
- Current pulsation
- Premature damper wear
- Failure of other auxiliary driven equipment
- Lateral vibration of bottles, cylinders, and compressor frame



Lube system failures

Viscous Torsional Dampers

- Consist of closed annular space with a freely moving inertia ring immersed in silicone oil
- After long intervals, the silicone inside the damper slowly undergoes a hardening process, and its ability to reduce vibration is diminished.
- Viscous damper ineffectiveness and uncontrolled torsional vibration has resulted in torsional fatigue failure on many packages.
- Periodic torsional measurements would ensure that the viscous damper is effective



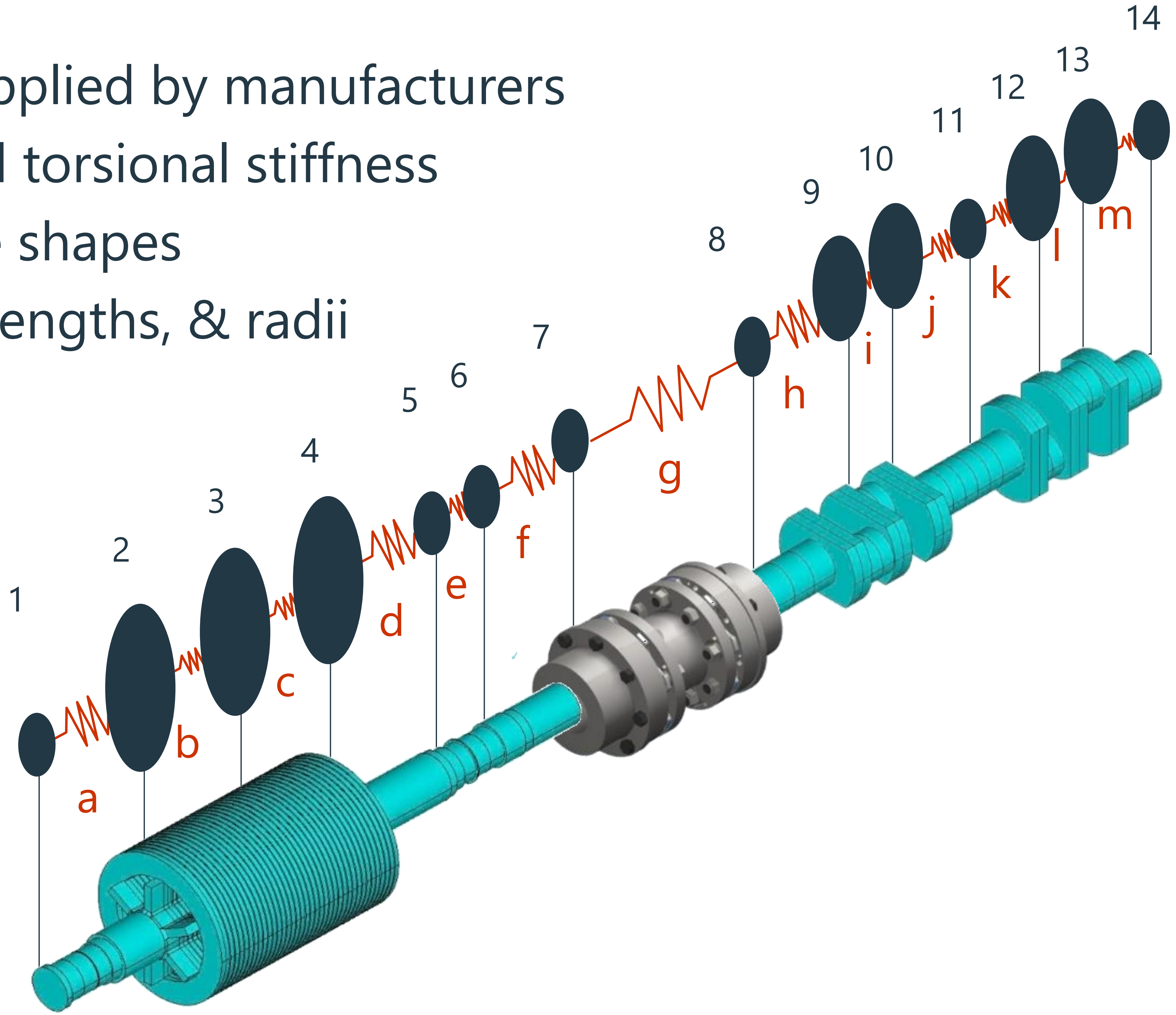
Torsional Vibration Analysis (TVA) Overview

Mass Elastic Model

- MED (Mass Elastic Data) often supplied by manufacturers
- A simplified model of inertias and torsional stiffness
- Used to calculate TNFs and mode shapes
- Motors: include shaft diameters, lengths, & radii
  (avoid 1 spring mass model)

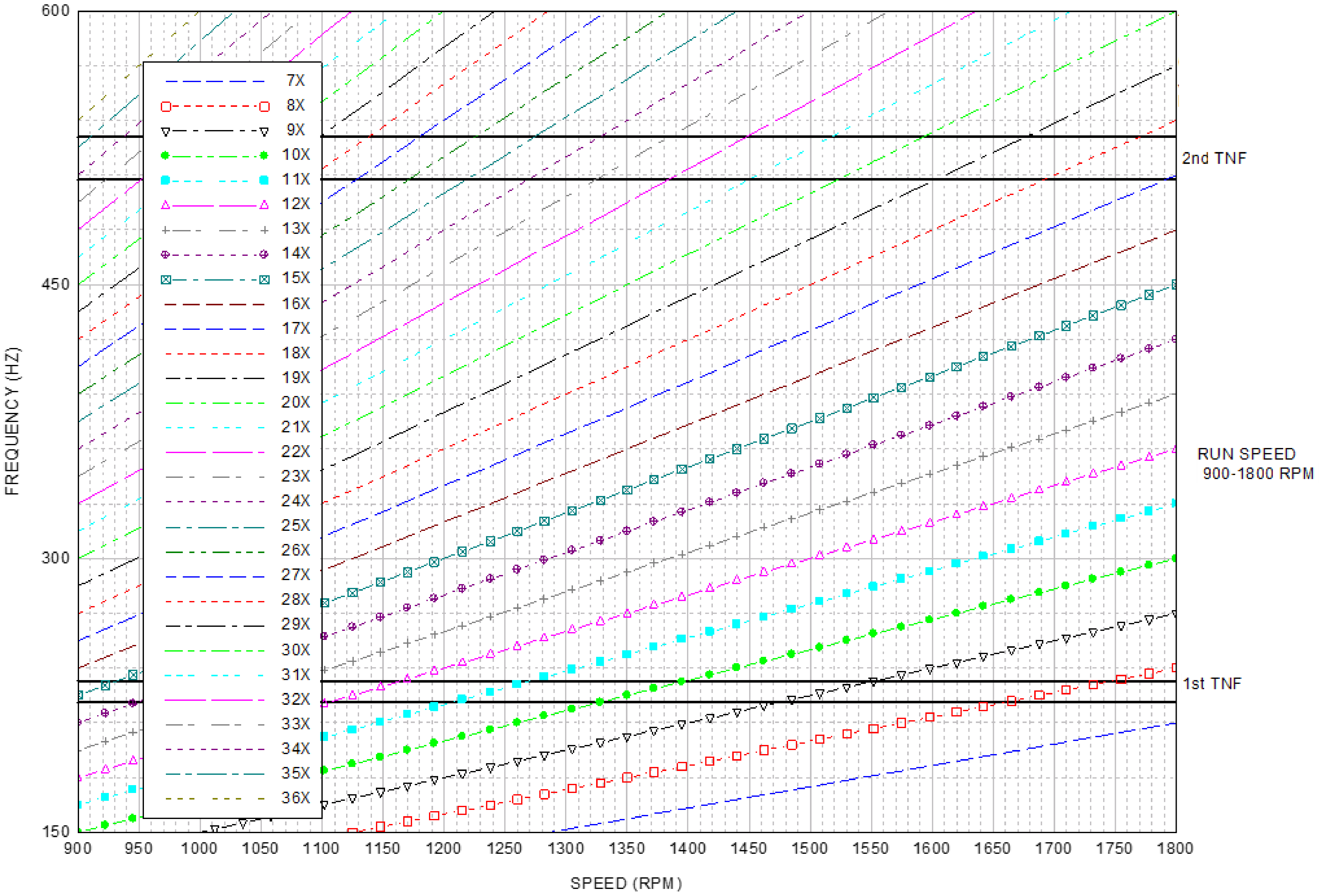
J = Mass Inertia (lb_m-in^2, lb_f-in-s^2)

K = Torsional stiffness (lb_f-in/rad)

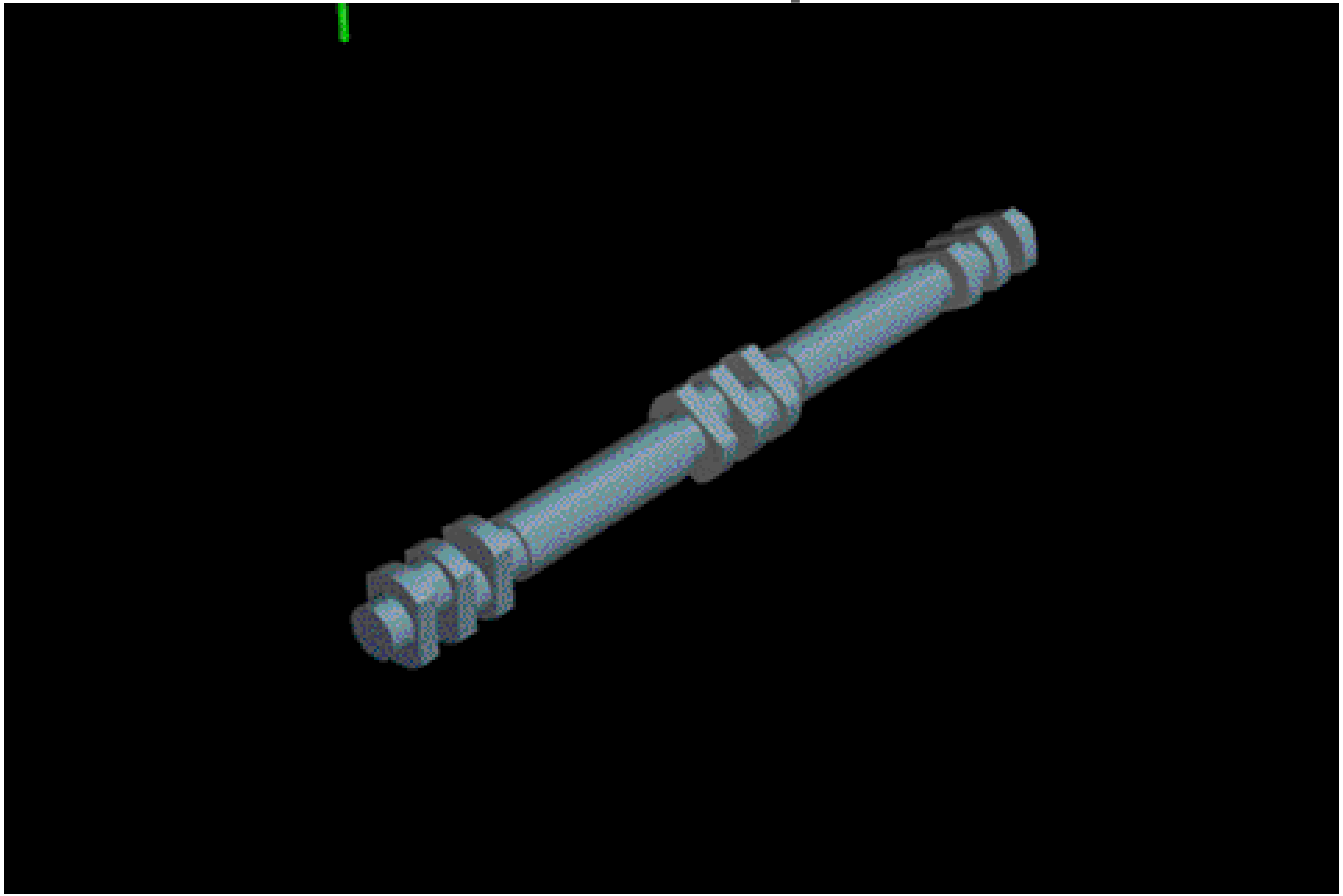


Campbell Diagram

- Common presentation of torsional natural frequencies
- Provide graphical display of TNFs and harmonics of potential excitation

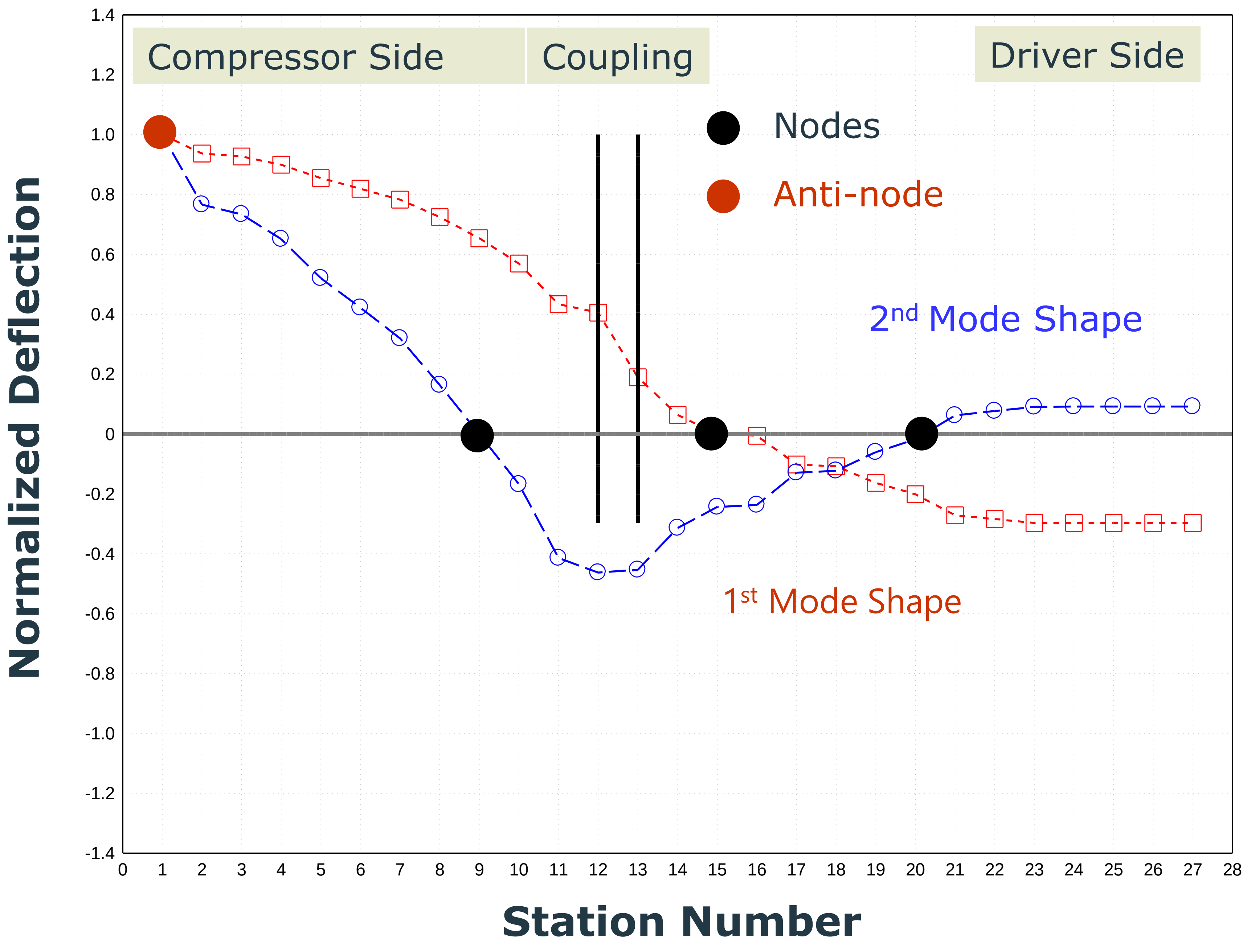


Torsional Response



Mode Shape Plot

- Every TNF has a corresponding mode shape
- Nodes: Location of LOW sensitivity to changes in inertia
- Anti-Nodes: Location of HIGH sensitivity to changes in inertia

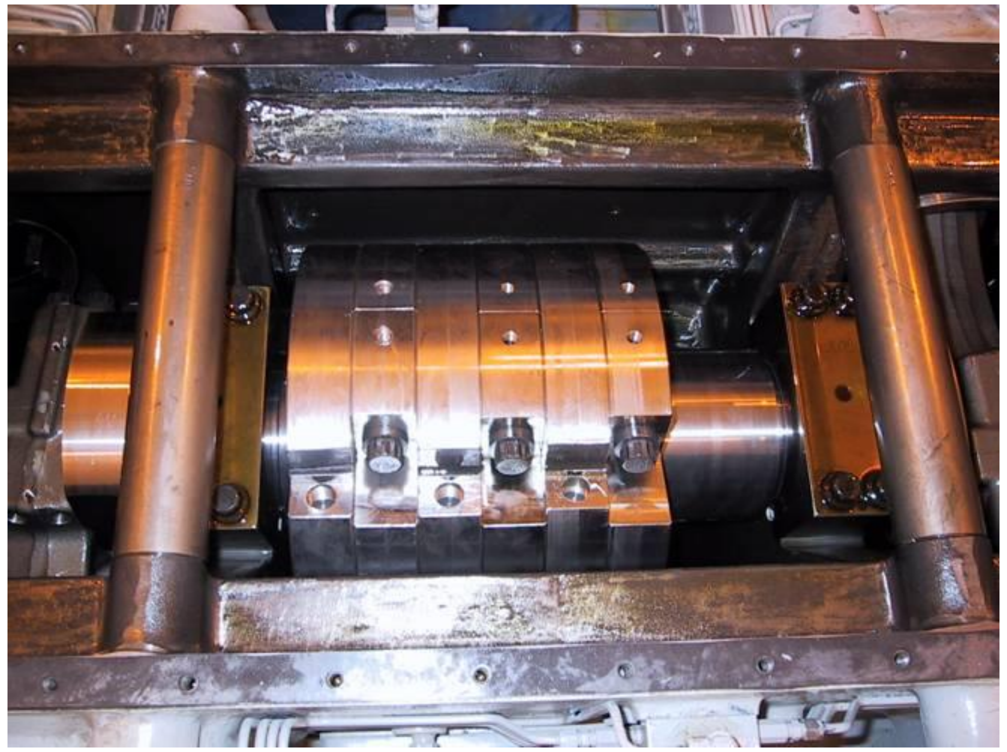


Methods to Change TNFs (and Avoid Resonance)

1. Coupling size (Slight change in TNF ±)
   - Larger couplings can accommodate more torque and lower TNF
   - Smaller couplings can increase the TNF

2. Flywheel (lowers TNF)
   - Attenuate torsional energy
   - larger flywheel, more change

3. Crankshaft Detuners
   - Fine tuning TNF
   - Helps protect lubrication system
   - But can’t install on a 2 throw → need a spreader (4 or 6 throw)



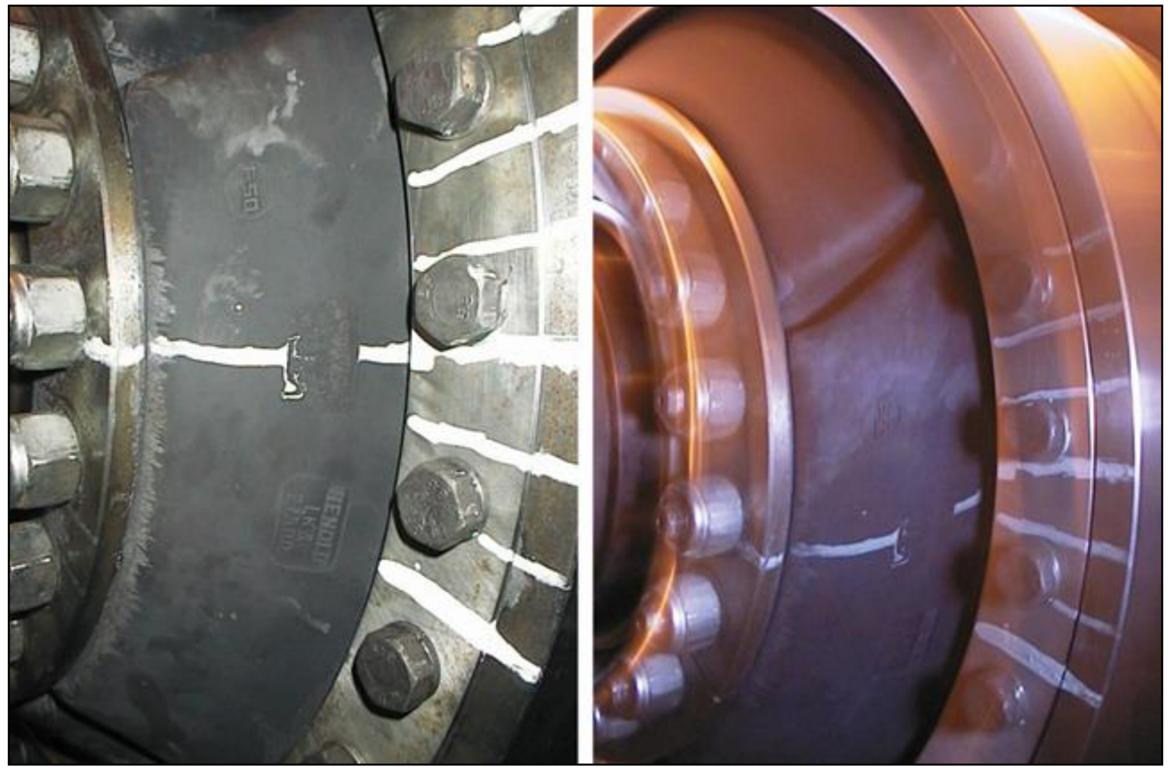
Methods to Change TNFs (2)

4. Shaft changes
   - Bigger or stronger shafting
   - Lower stress concentrations

5. Soft coupling
   - Big change in TNF
   - Lots of torque absorbed
   - Very expensive and regular maintenance required!

6. Change equipment
   - Different compressor – more throws, bigger frame
   - Larger driver

7. Change operating conditions (may not change TNF)
   - Change cylinder arrangement (can change TNF)
   - Add clearance instead of single acting
   - Recycle instead of single acting
   - Block speeds



GMRC Guideline

- When TVA is needed
- Technical Approach for TVA
- Chapter 4 Torsional Vibration Testing

  Compressor systems may require torsional vibration testing in addition to (or, in some cases, in lieu of) the torsional vibration analysis (TVA).

  Is best practice to conduct torsional vibration testing as soon as possible on new design.


GUIDELINE AND RECOMMENDED PRACTICE
FOR
CONTROL OF TORSIONAL VIBRATIONS
IN DIRECT-DRIVEN SEPARABLE
RECIPROCATING COMPRESSORS

Draft Release - Rev. 5
March 25, 2015

Gas Machinery Research Council
ACI Services Inc.

GMRC
Gas Machinery Research Council est 1952

ACI Services, Inc.

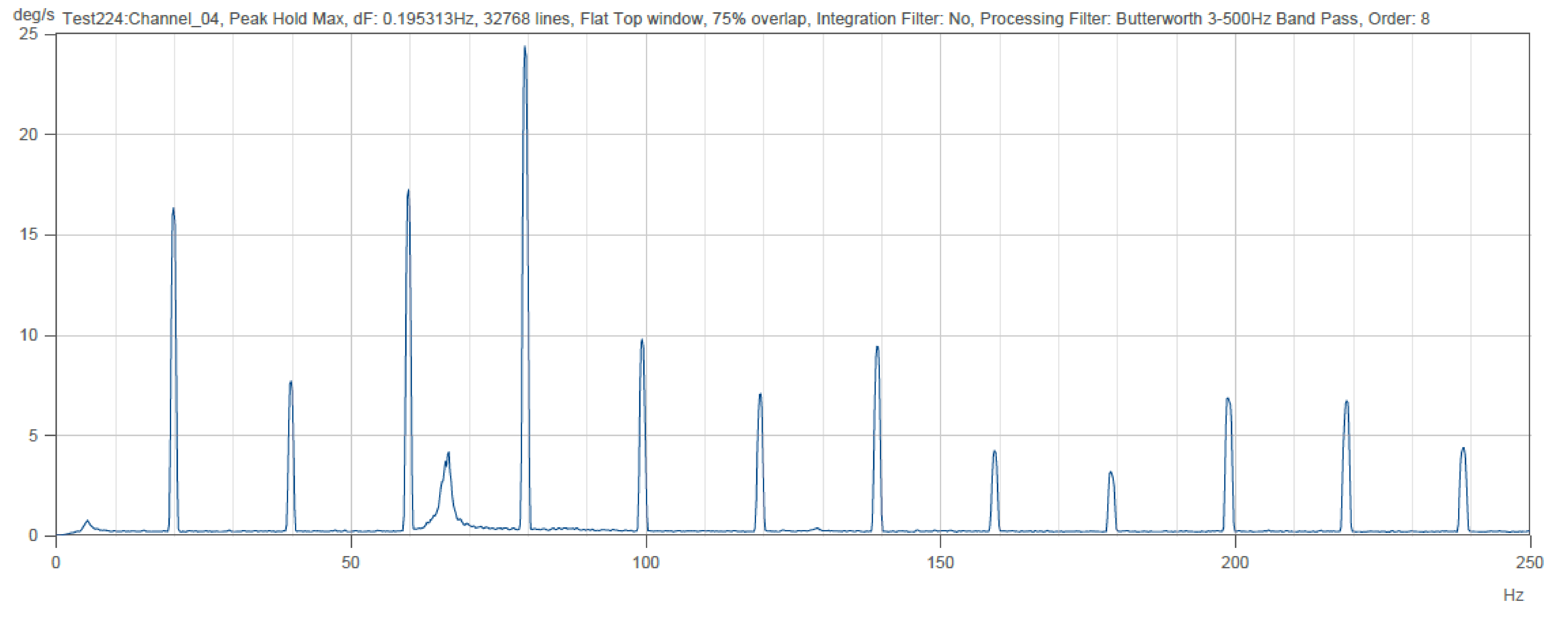
http://reliabilityweb.com/index.php/articles/torsional_vibration_problem_with_vfd_motor/

GMRC Guideline

Other situations where it may be necessary to obtain torsional vibration measurements:

- Failure of Existing System
- Modified or Restaged Equipment
- New Application or Addition of Infinite Step Unloaders
- Critical Applications
- Prototypes
- Specified Testing

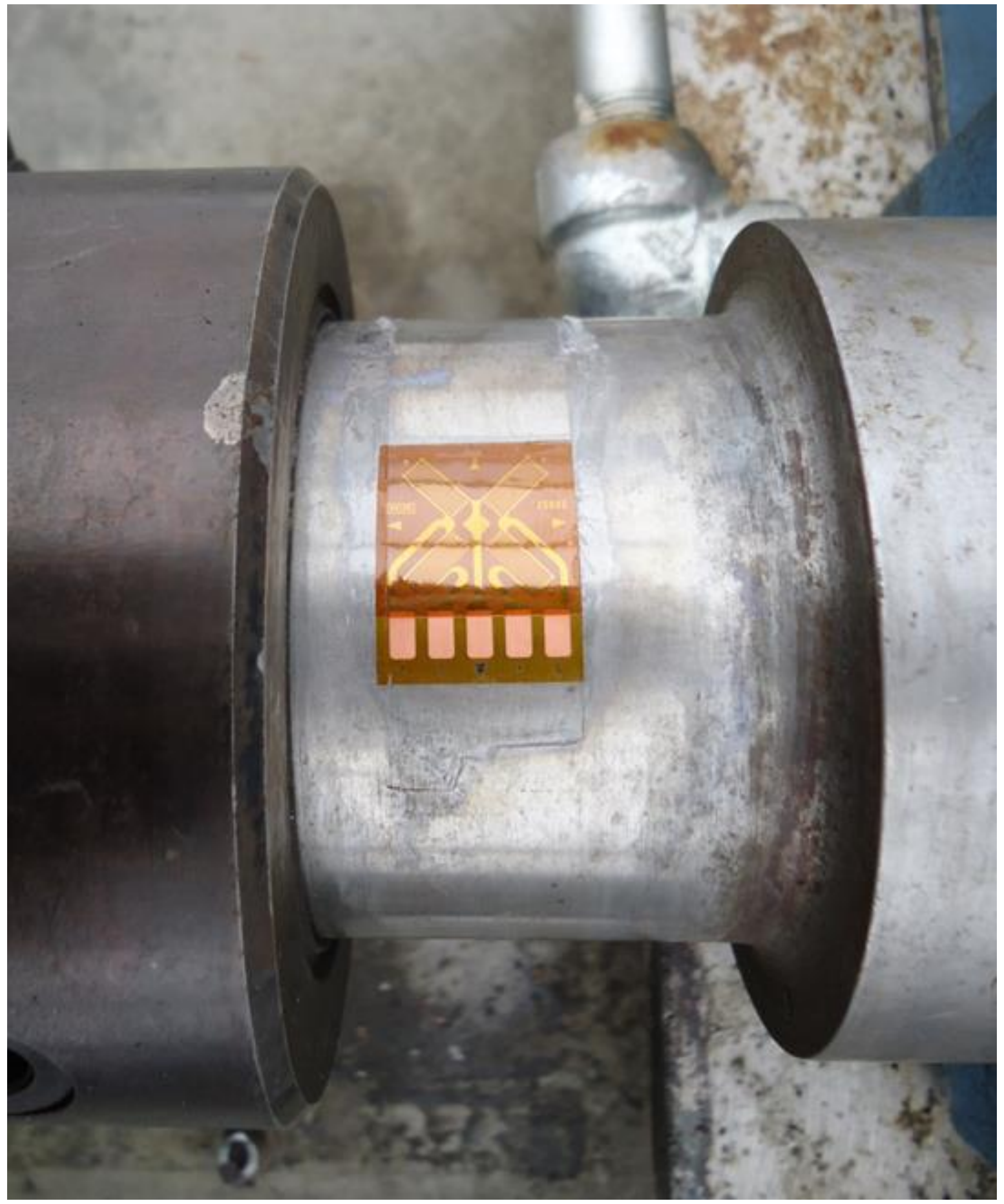
Torsional Vibration Measurement Techniques



Torsional Vibration Measurement Methods

Unlike lateral vibration that can be detected using typical vibration instrumentation such as accelerometers or proximity probes, measurement of torsional vibration requires specialized techniques:

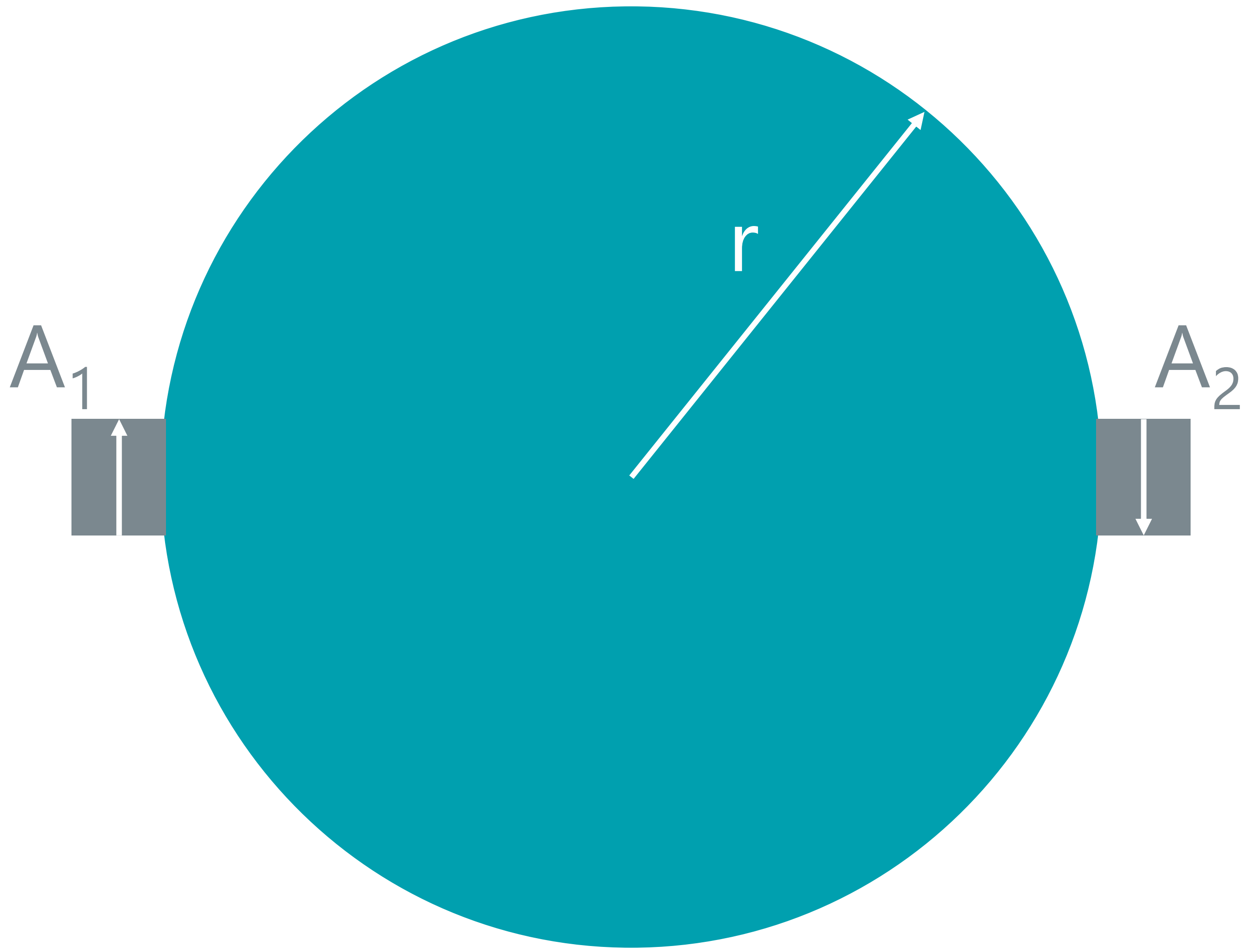
- Two accelerometers
- Shaft encoder attached to machine shaft
- Encoder (zebra) tape installed on a rotating part of the machine
- Magnetic pickup installation at any toothed or geared location (commonly engine ring gear)
- Strain gauge installation on the machine shaft
- Laser vibrometer pointing at retroreflective tape installed on the shaft



These are most common methods, there are others…

2 Accelerometer Setup

- Accelerometers oriented to measure tangential acceleration
- Translational acceleration is canceled
- Requires telemetry system
- Centrifugal force may be too large for higher RPM machinery

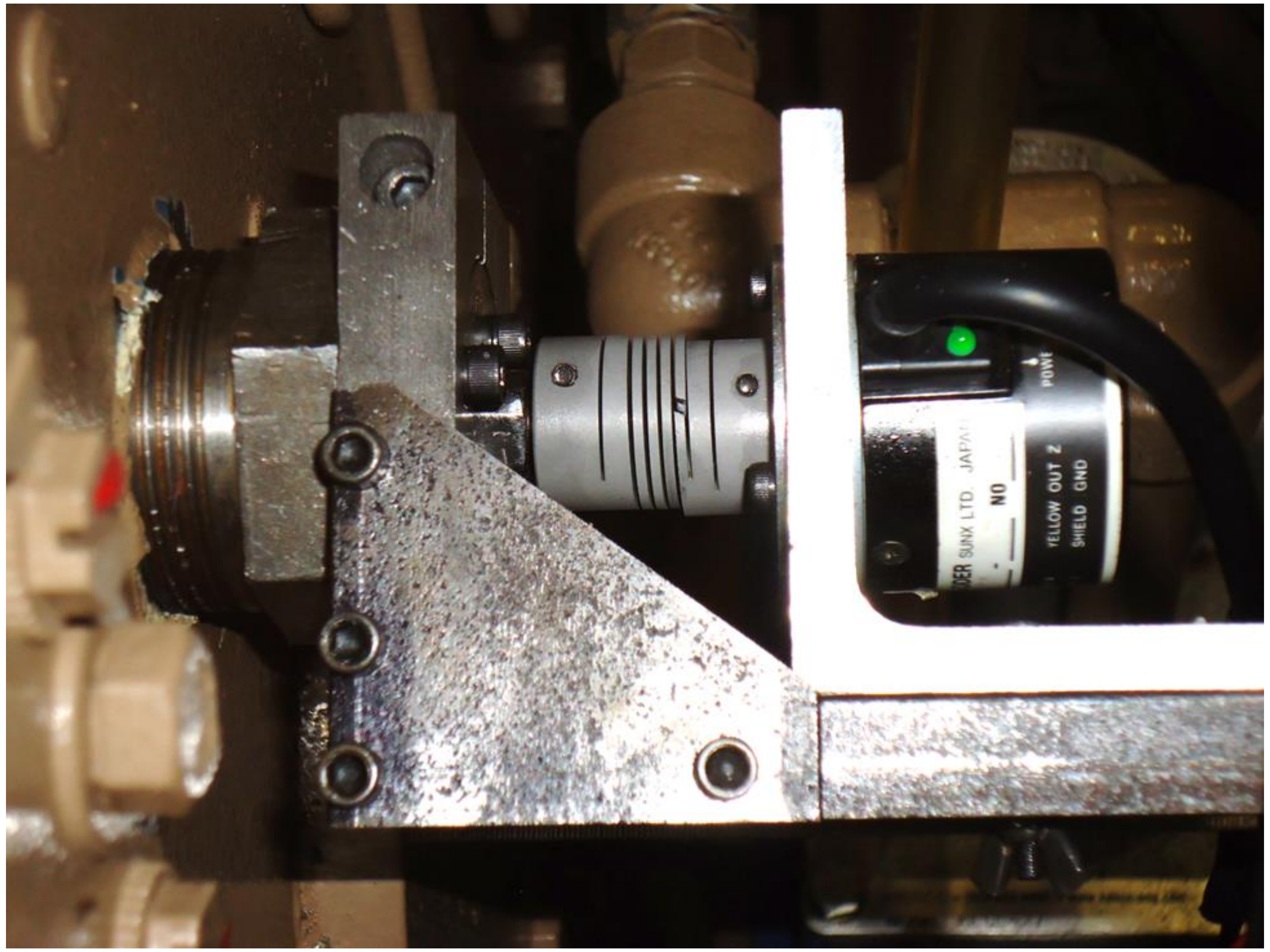


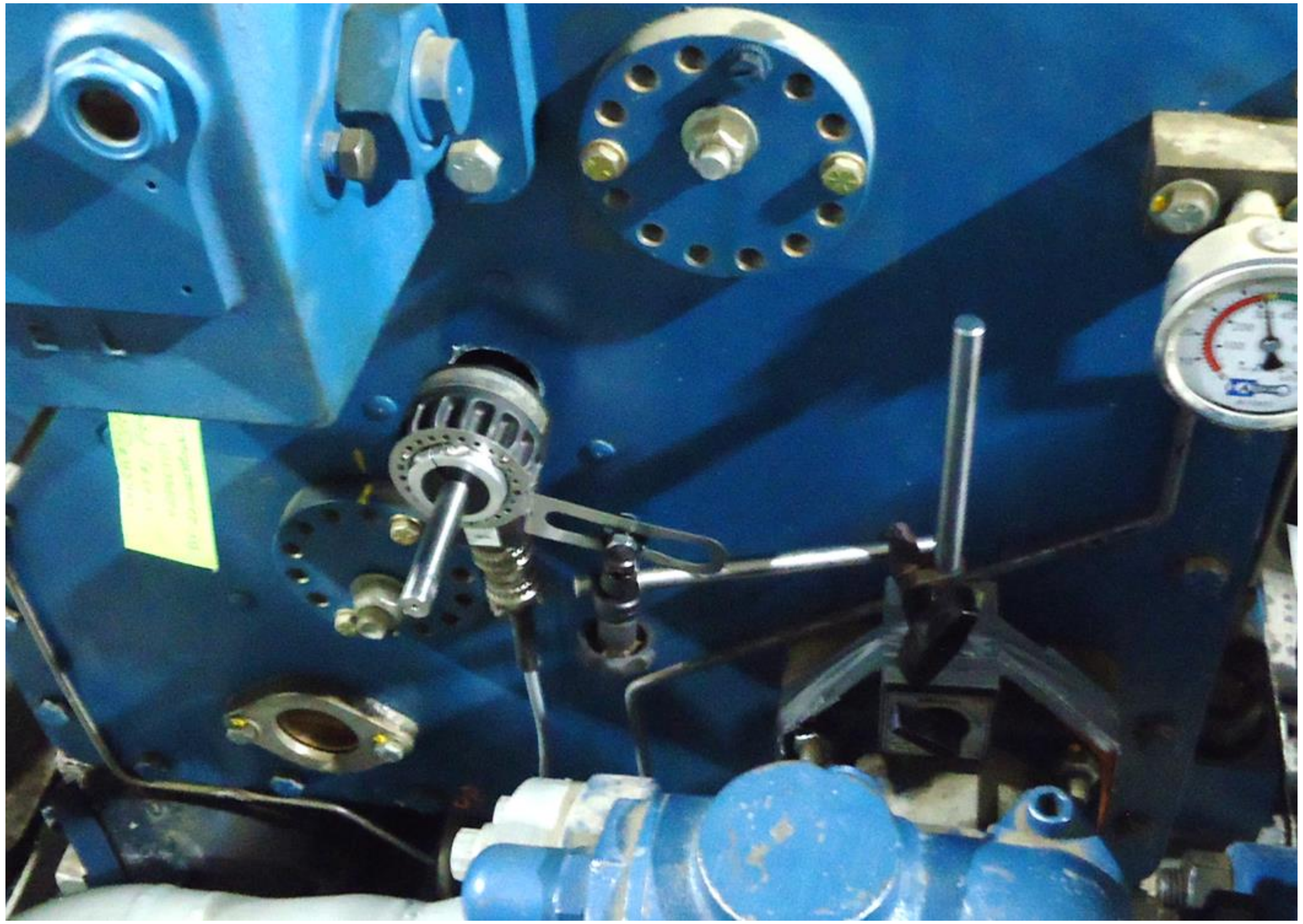
Angular Acceleration $= (A_1 + A_2)/2r$

Shaft Encoder Setup

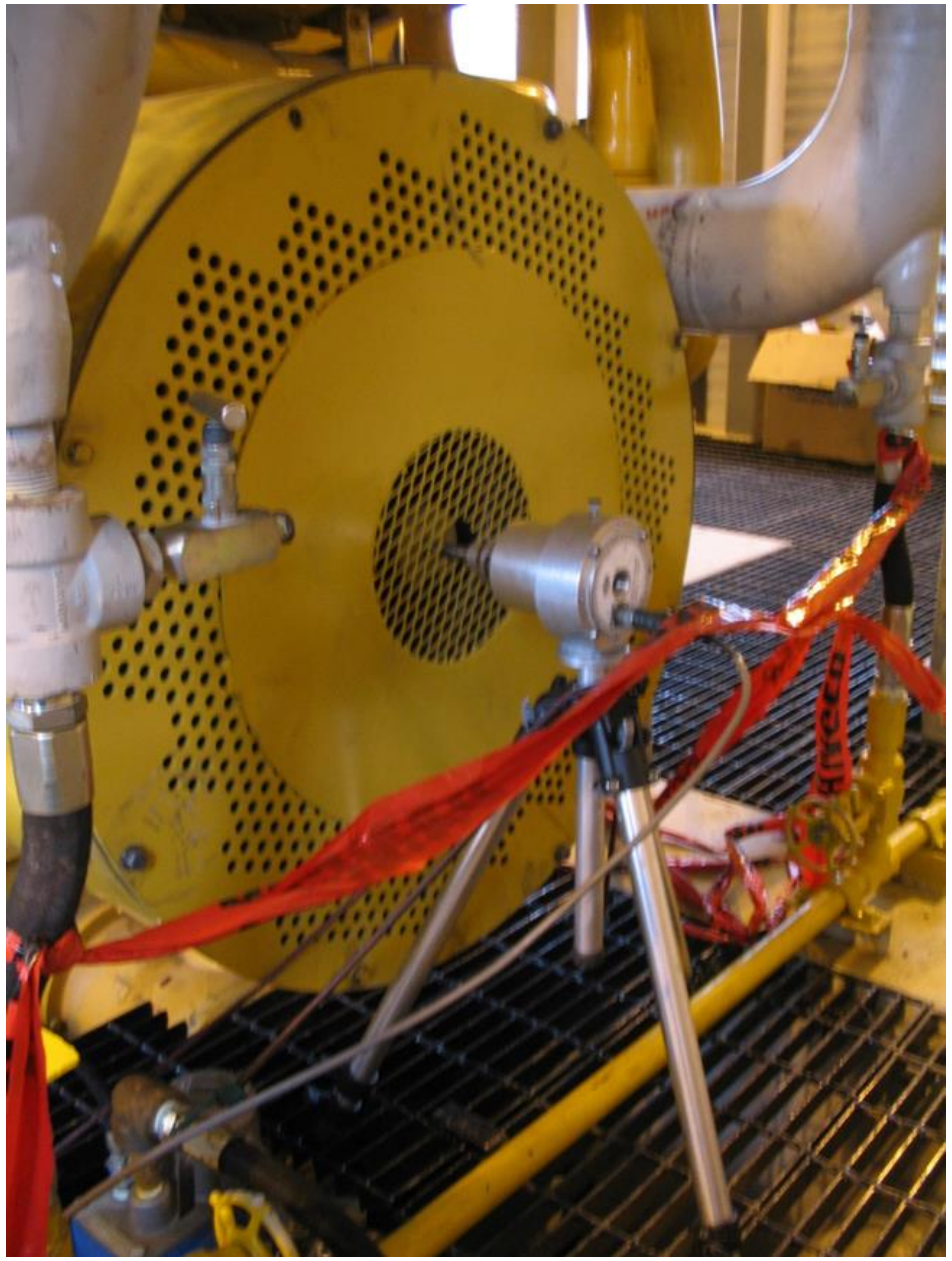
- Usually requires an access to the shaft
  - Stub (oil pump) shaft
  - Drilled and tapped crankshaft or motor shaft
- Encoder is used to obtain the instantaneous shaft speed
- Encoders are commercially available from many manufacturers.
- Often used in robotics applications for accurate measurement of shaft position.
- Based on optical technology
- Useful for torsional vibration measurements

Shaft Encoder Examples



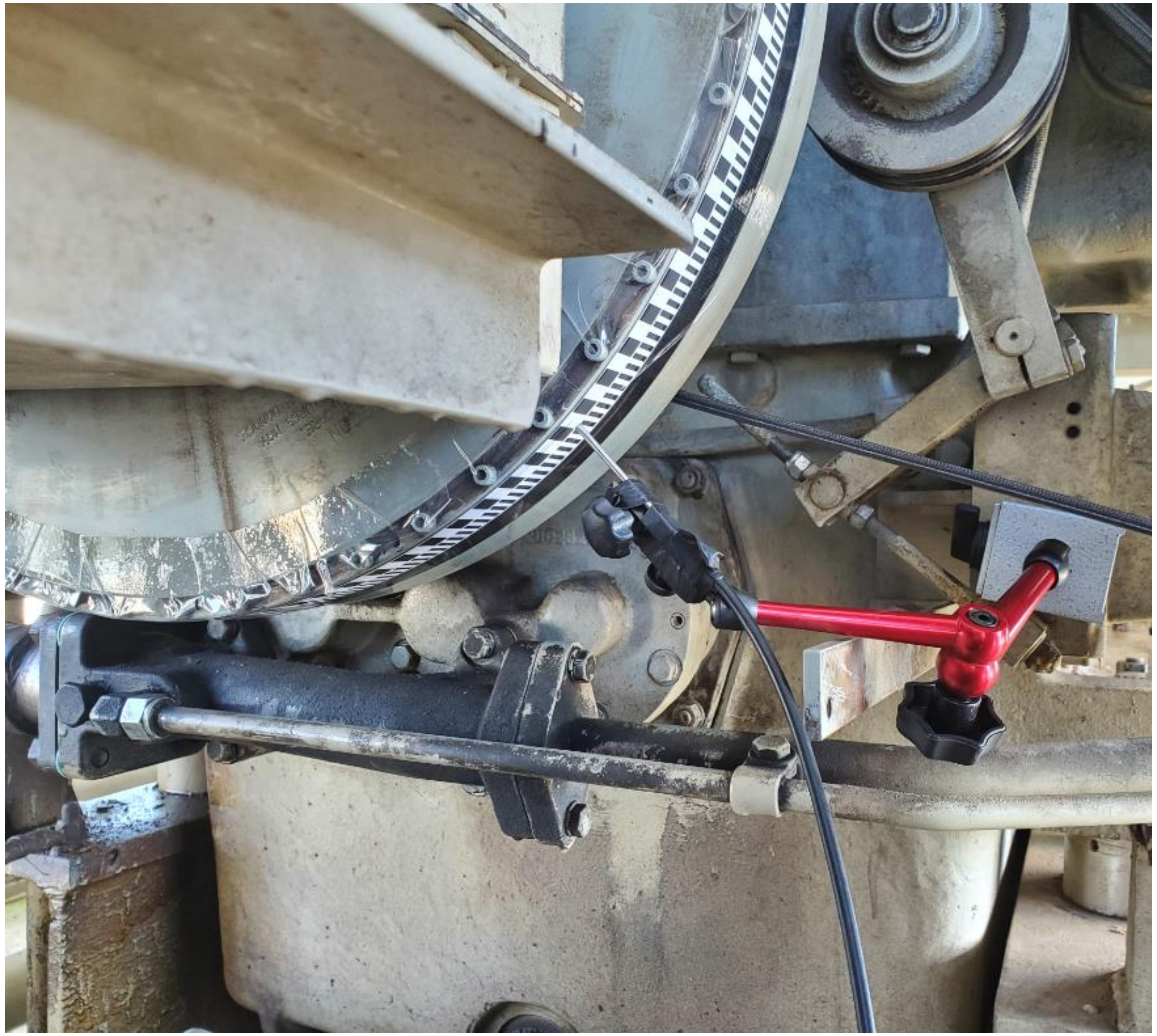


Shaft Encoder Examples

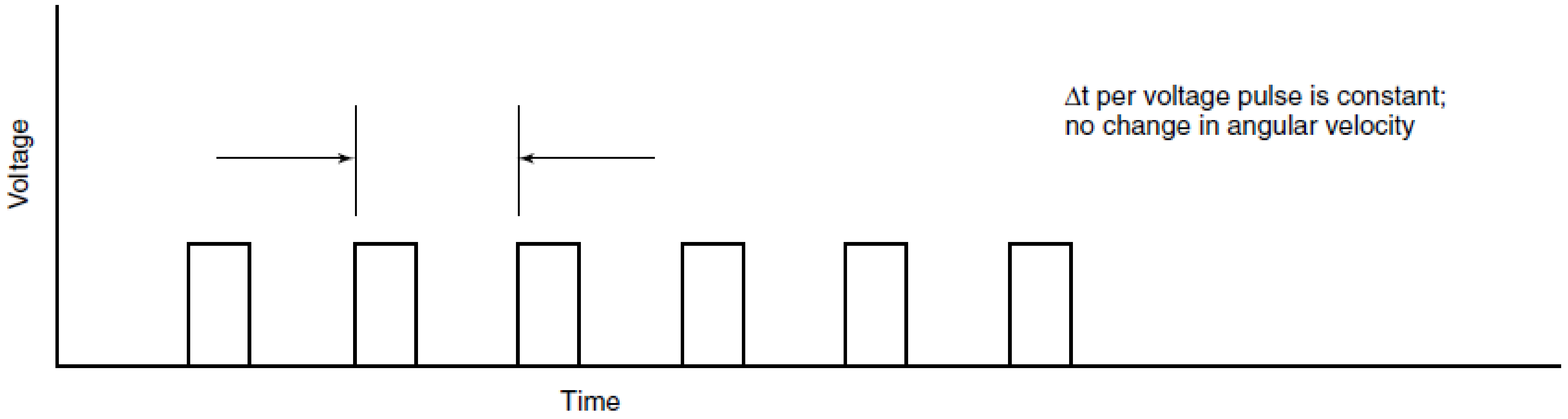


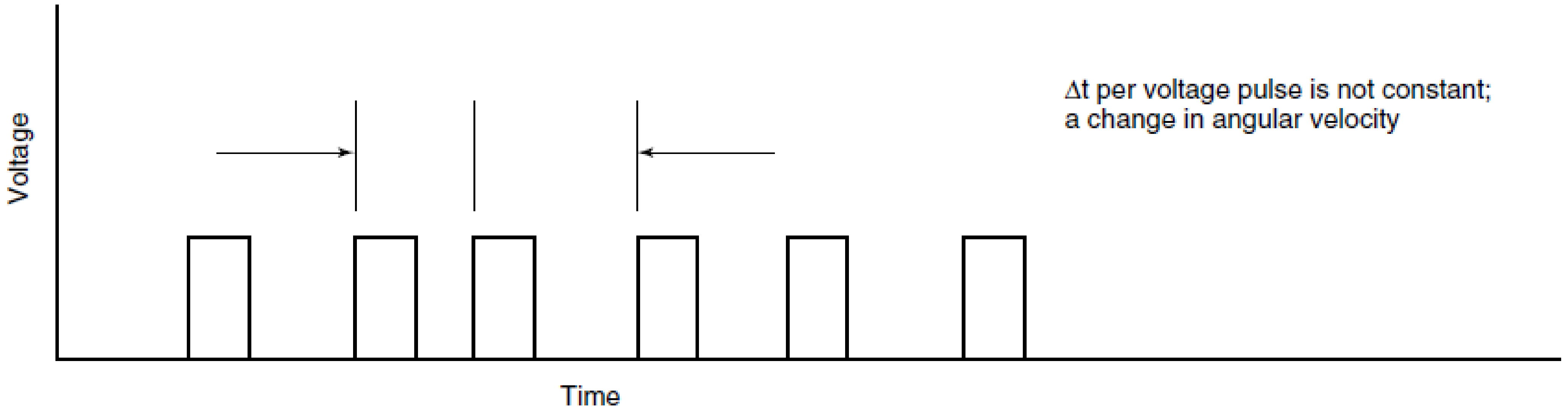
Encoder Tape Setup

- Zebra tape is wrapped around the rotating rotor
- Used with laser/optical sensors
  - the optical device used to trigger the pulses must be able to react quickly enough.
- The time between the passing of each stripe is used to measure RPM very precisely.



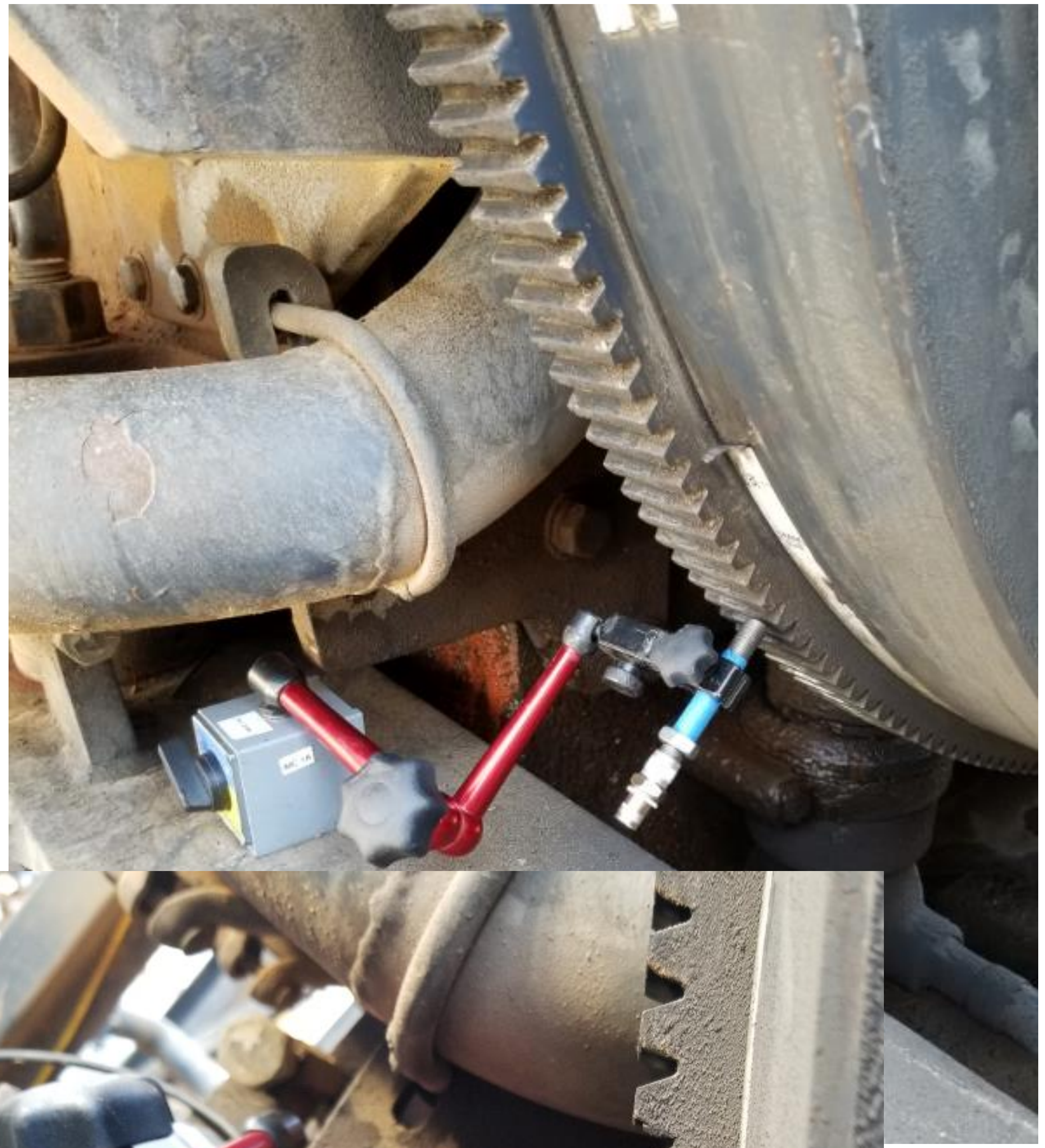
Encoder Tape Setup

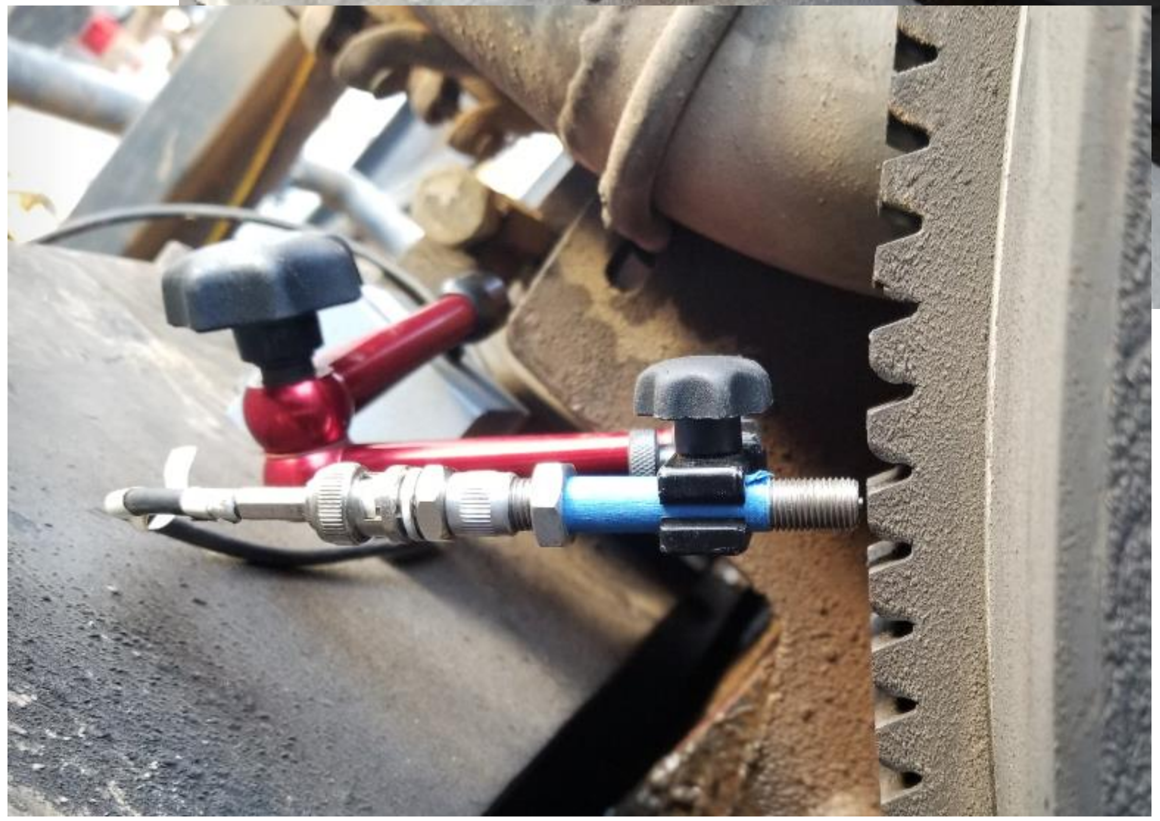




Magnetic Pickup Setup

- Can utilize existing magnetic (speed) pickup
- Can be installed on engine flywheel or accessory ring gear
- Efficient due to existing ring gear and easy setup
- No special setup may be needed (if using existing magnetic pickup)
- Runout creates 1x error (2 probes mounted 180 degrees apart can correct for 1x error)
- Gear tooth-tooth variations can create elevated noise
- Can also use proximity probe

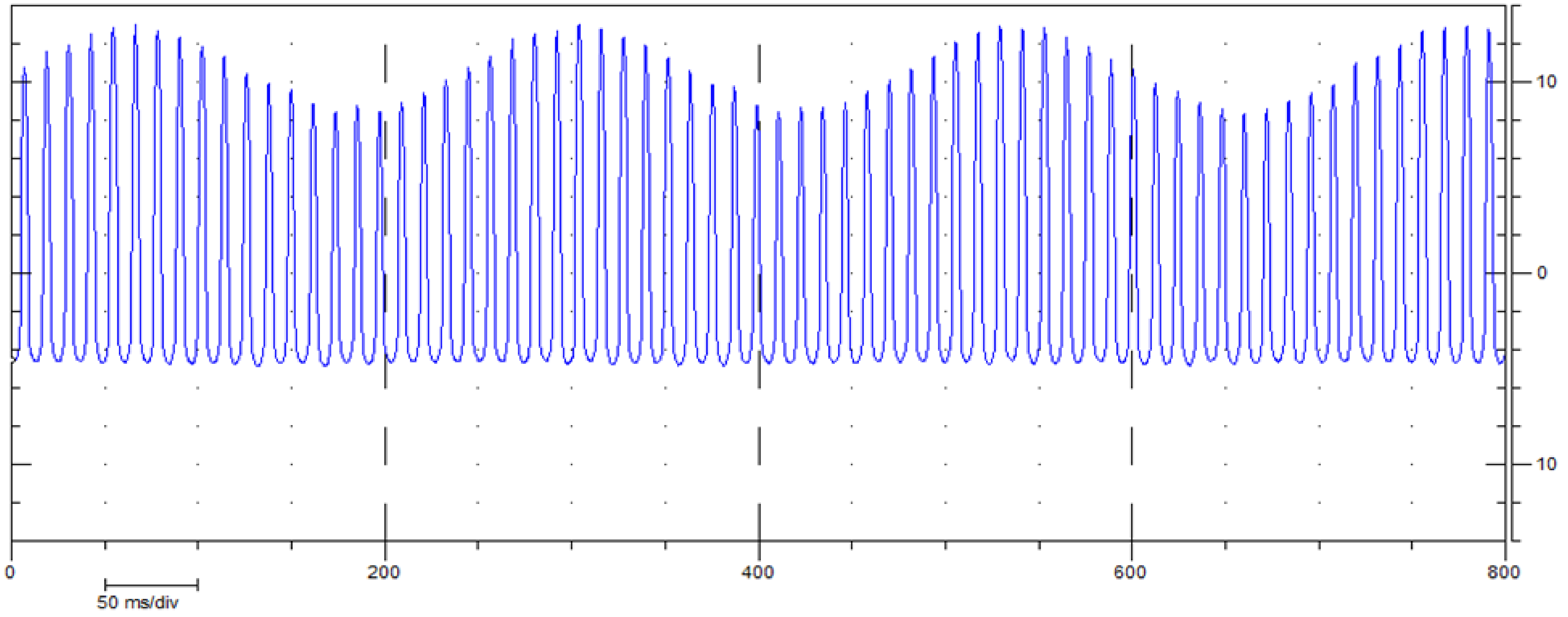




Demodulation of Coder Based Signals

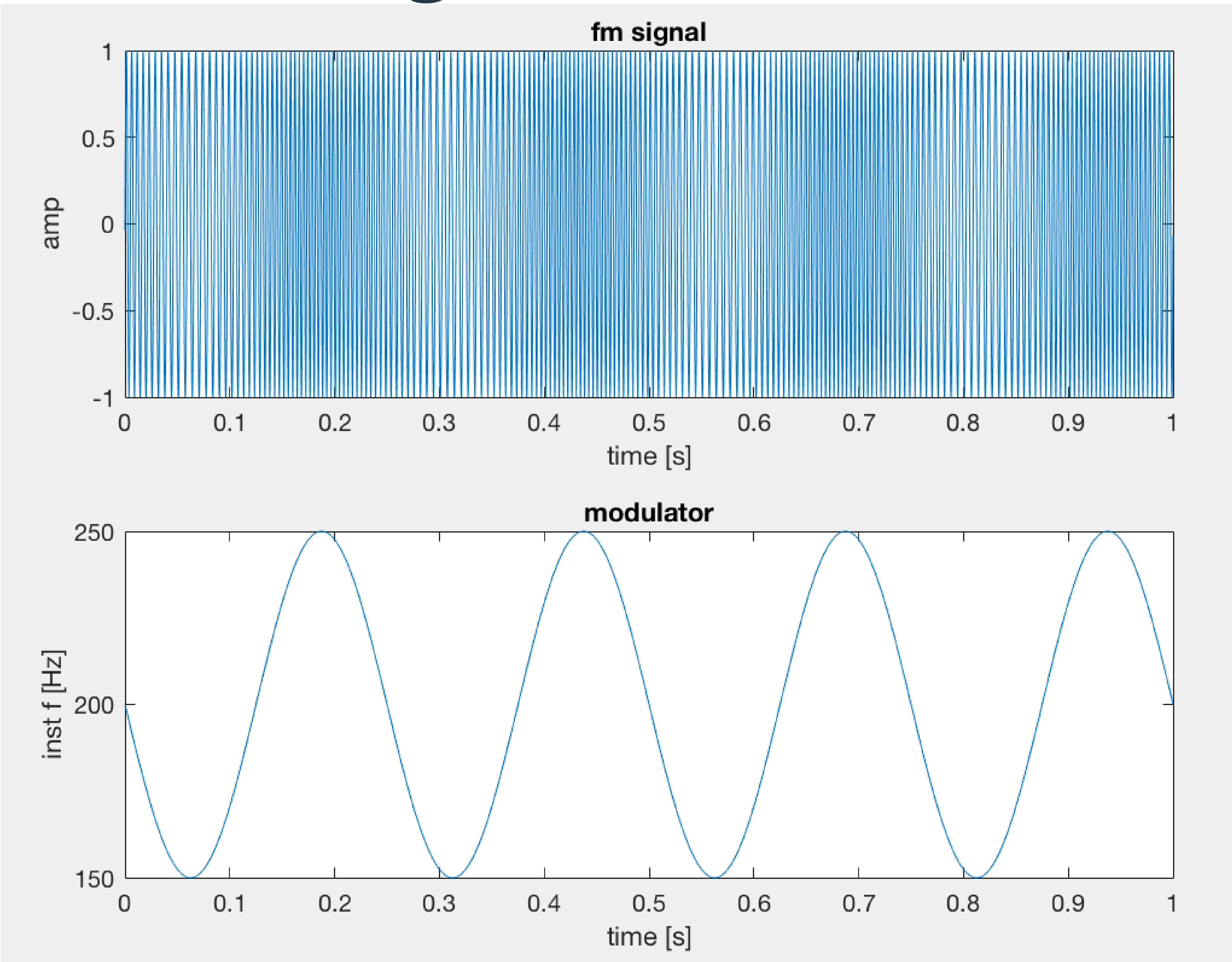
- Mag pick-ups, optical sensors, and encoders all output periodic signals to be processed into angular velocity
- Torsional vibration will cause **frequency modulation** of coder signal

Question: What can explain the amplitude modulation in this signal?



Demodulation of Coder Based Signals

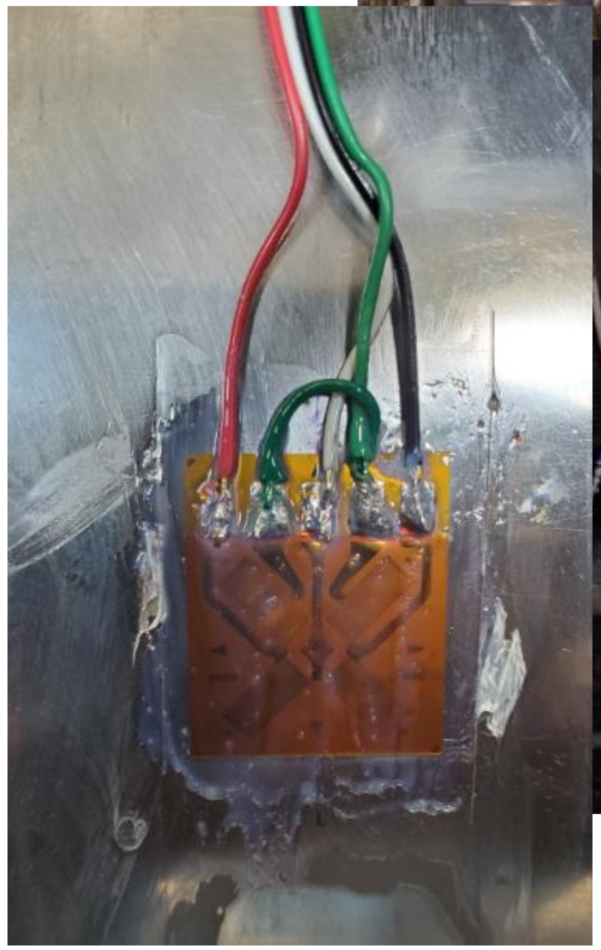
- Hardware/Electronic methods
- Hilbert Transform analytical method



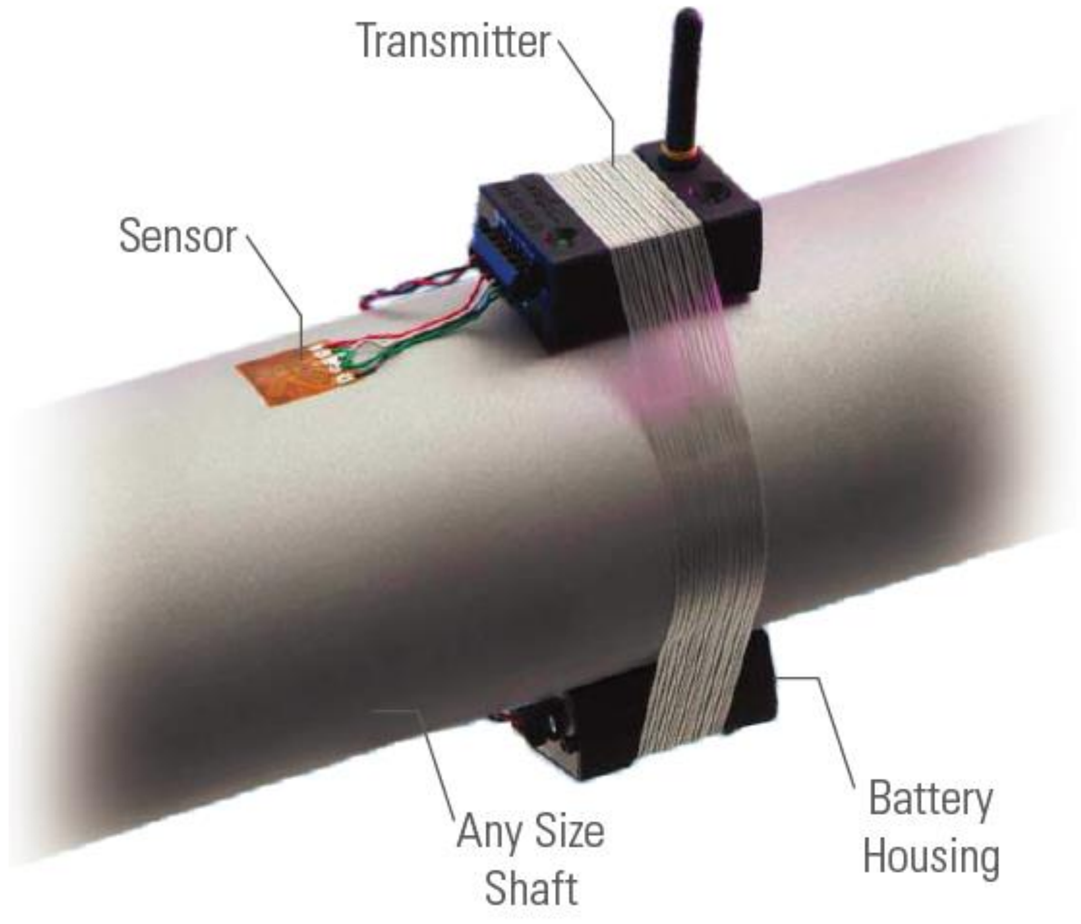
https://dsp.stackexchange.com/questions/44710/hilbert-transform-of-an-fm-signal

Strain Gauge Setup

- Strain gauge is installed on the shaft
- Wireless telemetry system used to transmit strain while the machine is running
- Half or full bridge configurations to measure torsion are applied
- Can eliminate unwanted quantities such as bending or thermal expansion

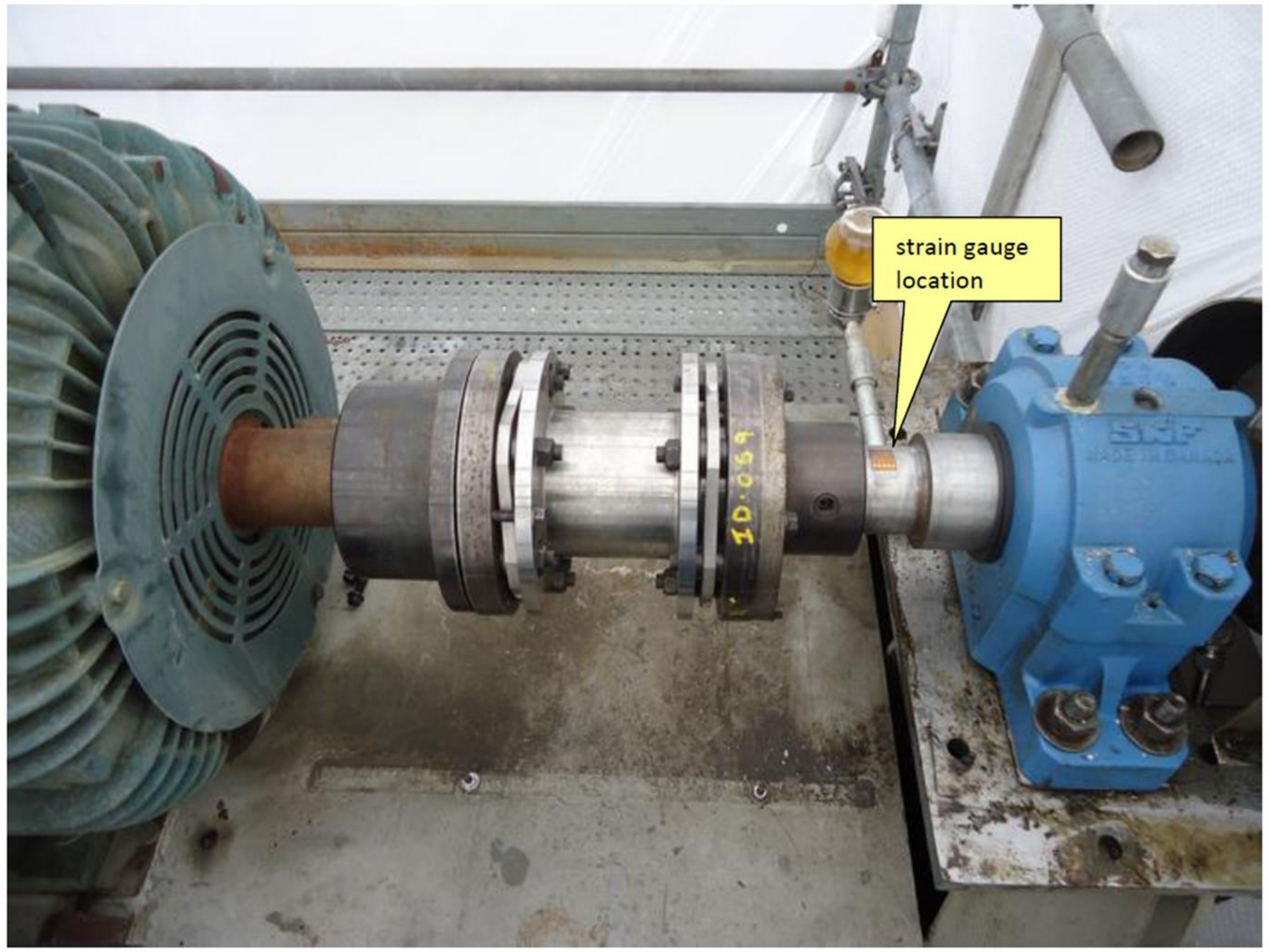


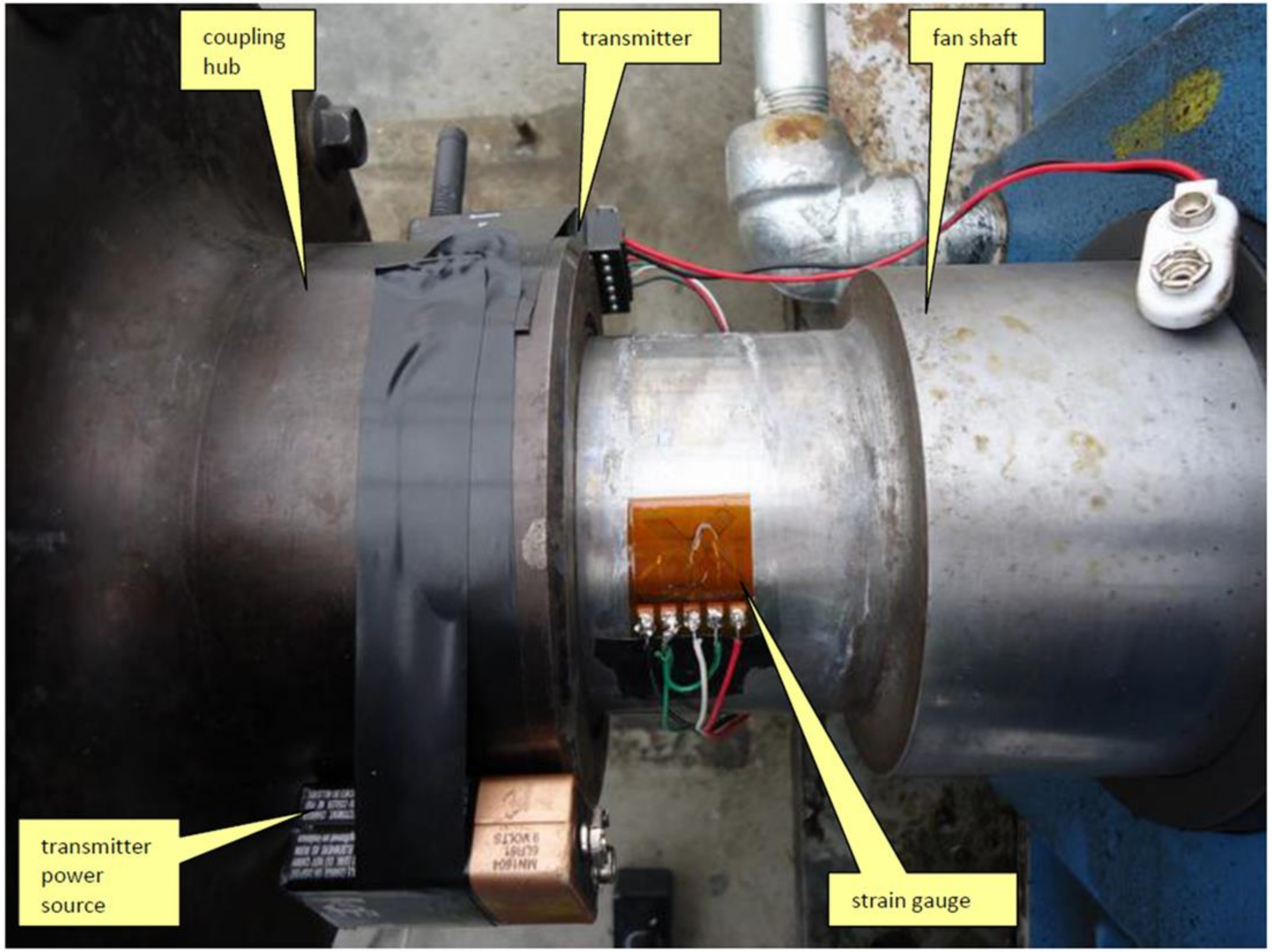
Strain Gauge Setup



Binsfeld TX 10K

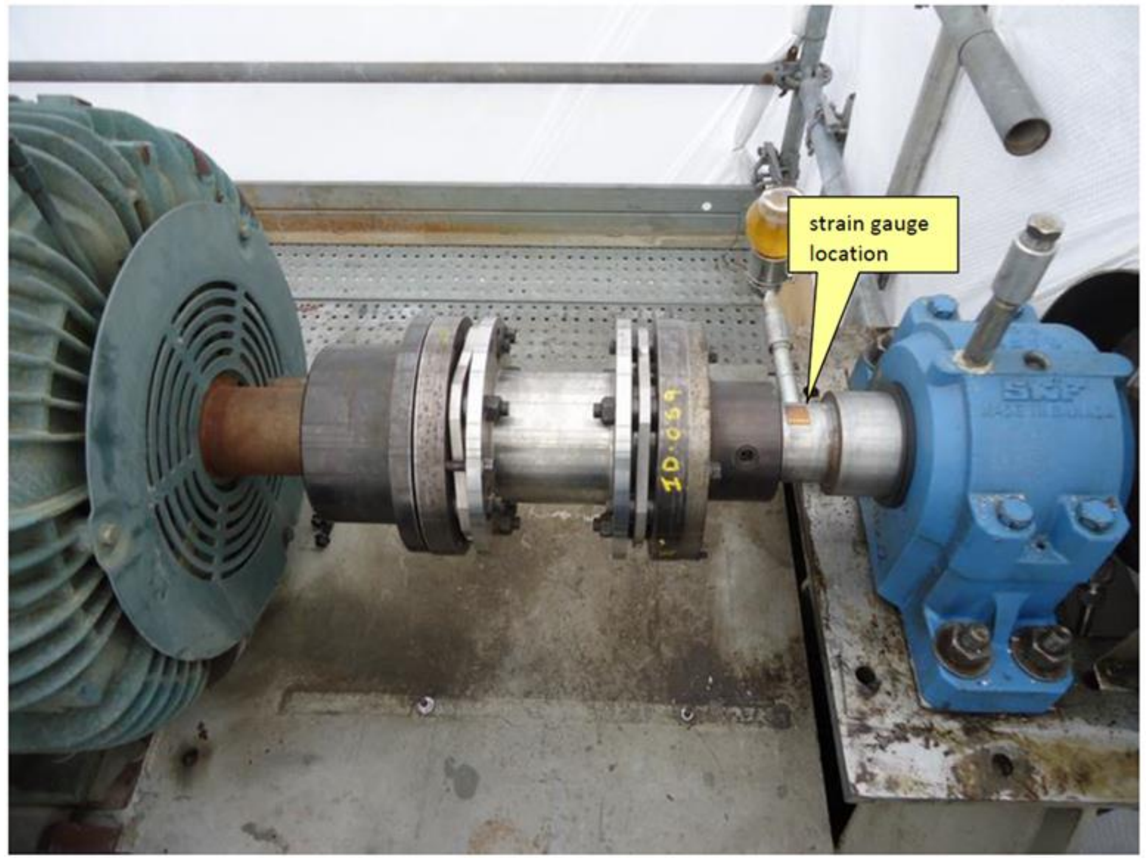
Strain Gauge Setup on Motor/Fan System

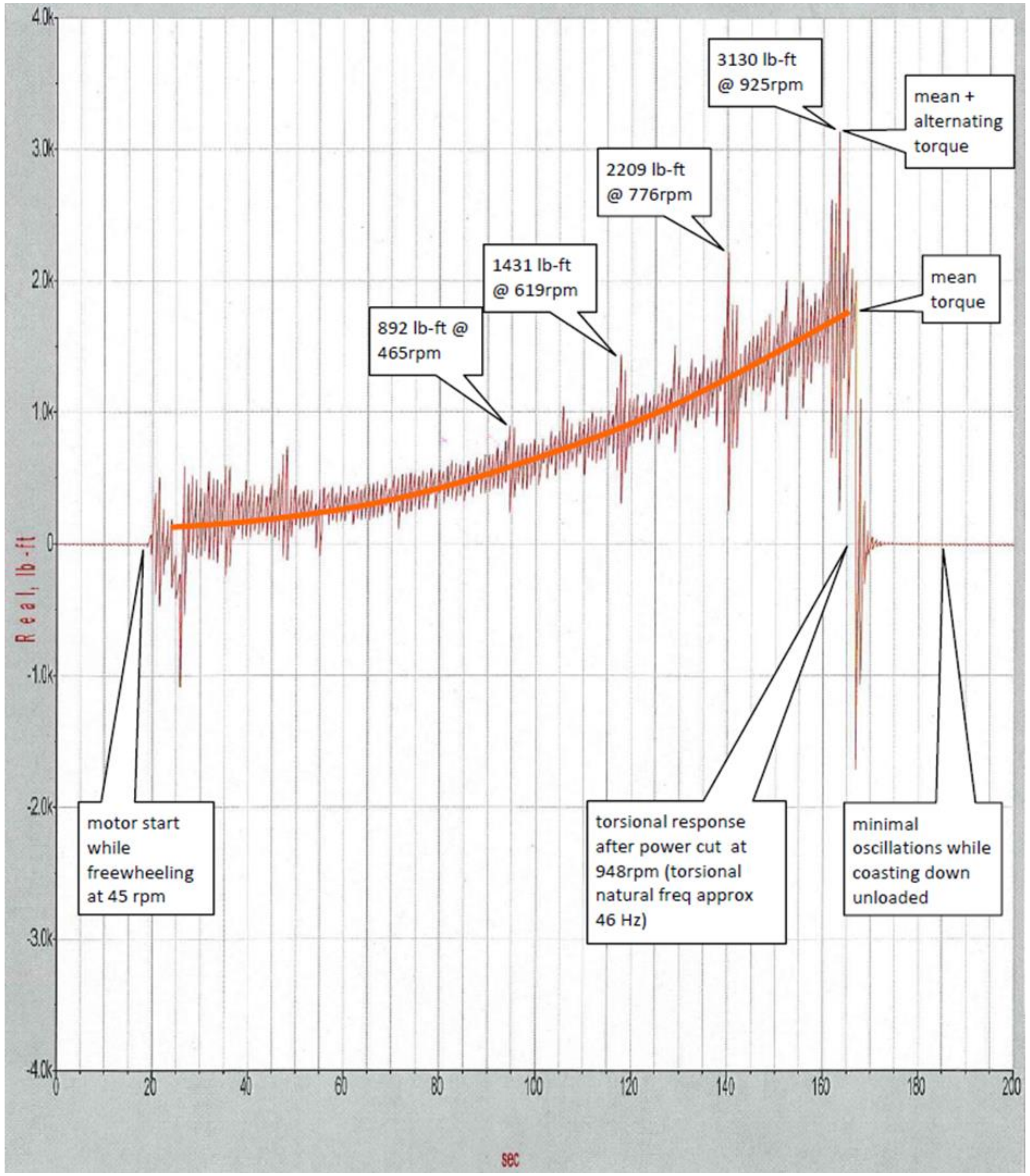




Strain Gauge Setup

- Mean + alternating torque measured directly
- Can apply FFT to determine Torsional Natural Frequencies (TNFs)



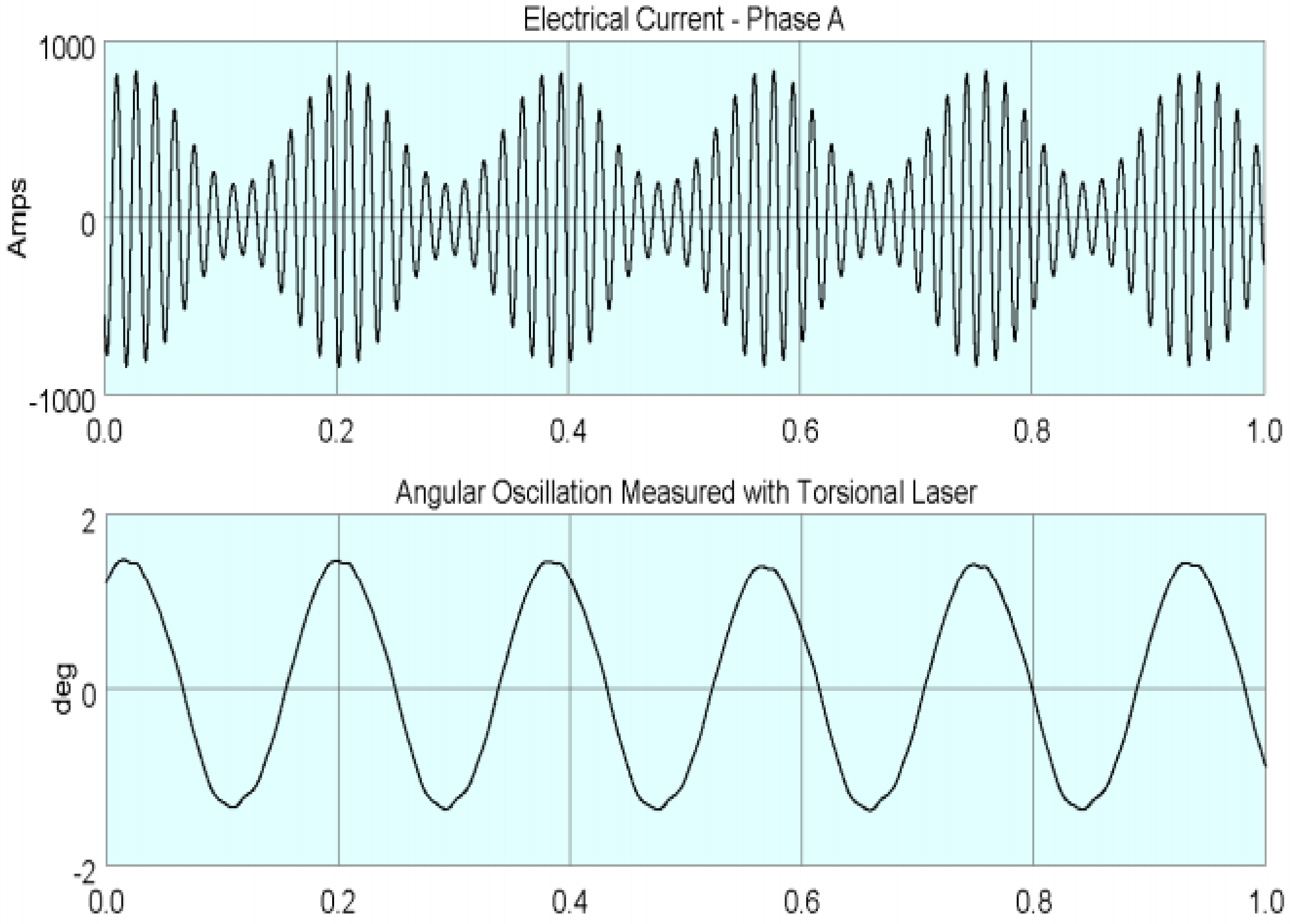


Laser Vibrometer Setup

- Retro-reflective tape must be installed on the shaft
- Dual laser beam is used to determine the instantaneous shaft angular velocity
- Low sensitivity to shaft translation vibration
- Expensive device
- Requires clear access

Motor Current Pulsation

- Motor Current Pulsation: The NEMA MG-1 specification states that current pulsations should not exceed 66% for synchronous motors. API 618 specifies a 40% limit for induction motors.
- Because of a significant drop off in performance due to high current pulsations, the API 618 guideline is recommended.
- Note that the percent current pulsation is compared to full load amps (FLA) of the motor.
- High-efficiency induction motors with their lower slip factors can experience higher current pulsations



Applying API and NEMA Specifications to Limit Electrical Current Pulsation and Torsional Vibration of Synchronous Motors Driving Reciprocating Compressors, Troy Freese - Engineering Dynamics Inc., Mark Fanslow - TECO-Westinghouse

Torsional Vibration Measurement Considerations

Torsional Vibration Measurement

- Time domain (raw) torsional vibration is collected using any of the previously discussed methods
- Torsional vibration is captured using data acquisition hardware during:
  - Machine startup (crank to idle ramp up)
  - Ramp Up or Coast Down through normal operating speed range (typically in steps or slow speed sweep)
  - Machine shutdown (controlled or uncontrolled ESD shutdown)
- Analysis of (raw) time domain signal is required to:
  - Compare to screening limits
  - Determine the frequency content and amplitudes

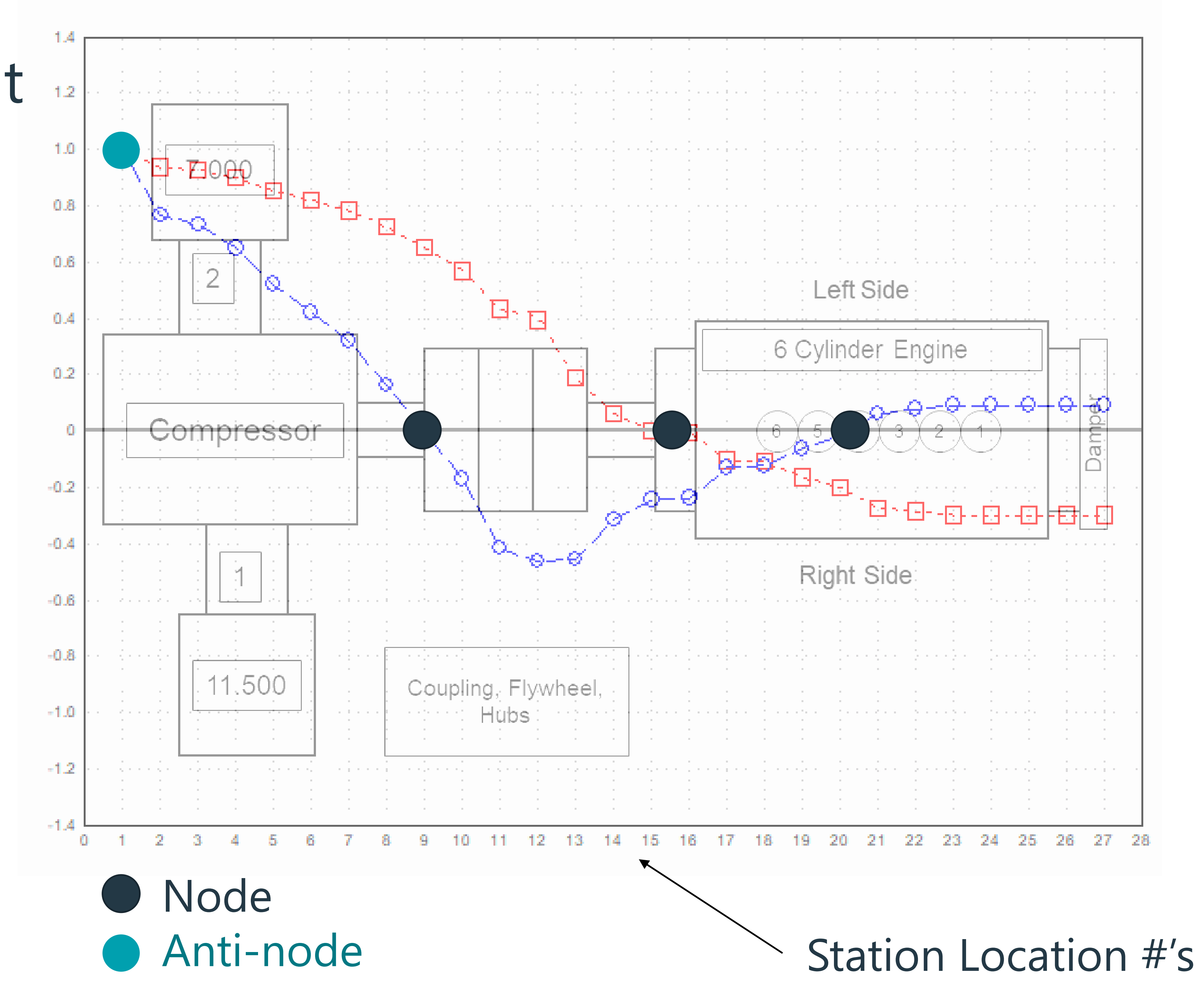
Torsional Vibration Measurement Location

- The torsional system and measurement locations must be understood before the measurement is completed
- Different locations along the machine will have different torsional amplitudes

- Strain gauge measurement:
  - Strain gauge measurement will be most accurate at a nodal location
  - This is where torsional velocity/displacement is lowest, BUT strain is highest
- Other methods
  - Require location where torsional velocity/displacement is an anti-node
  - This will result in higher torsional vibration (velocity/displacement) amplitude

Torsional Mode Shape

- Mode shape plot is shown on the right
- Which location would be ideal for a strain gauge?
  - Ideal location around #14/15
- Which location would be ideal for an encoder measurement?
  - Ideal location around #1



Synchronous Motor Starts

- Larger HP motors
- Create large torque fluctuations at startup
- Frequency of torque fluctuations is twice the slip frequency
- 120 Hz to 0 Hz
- Excellent for identifying TNFs
- May cause other issues

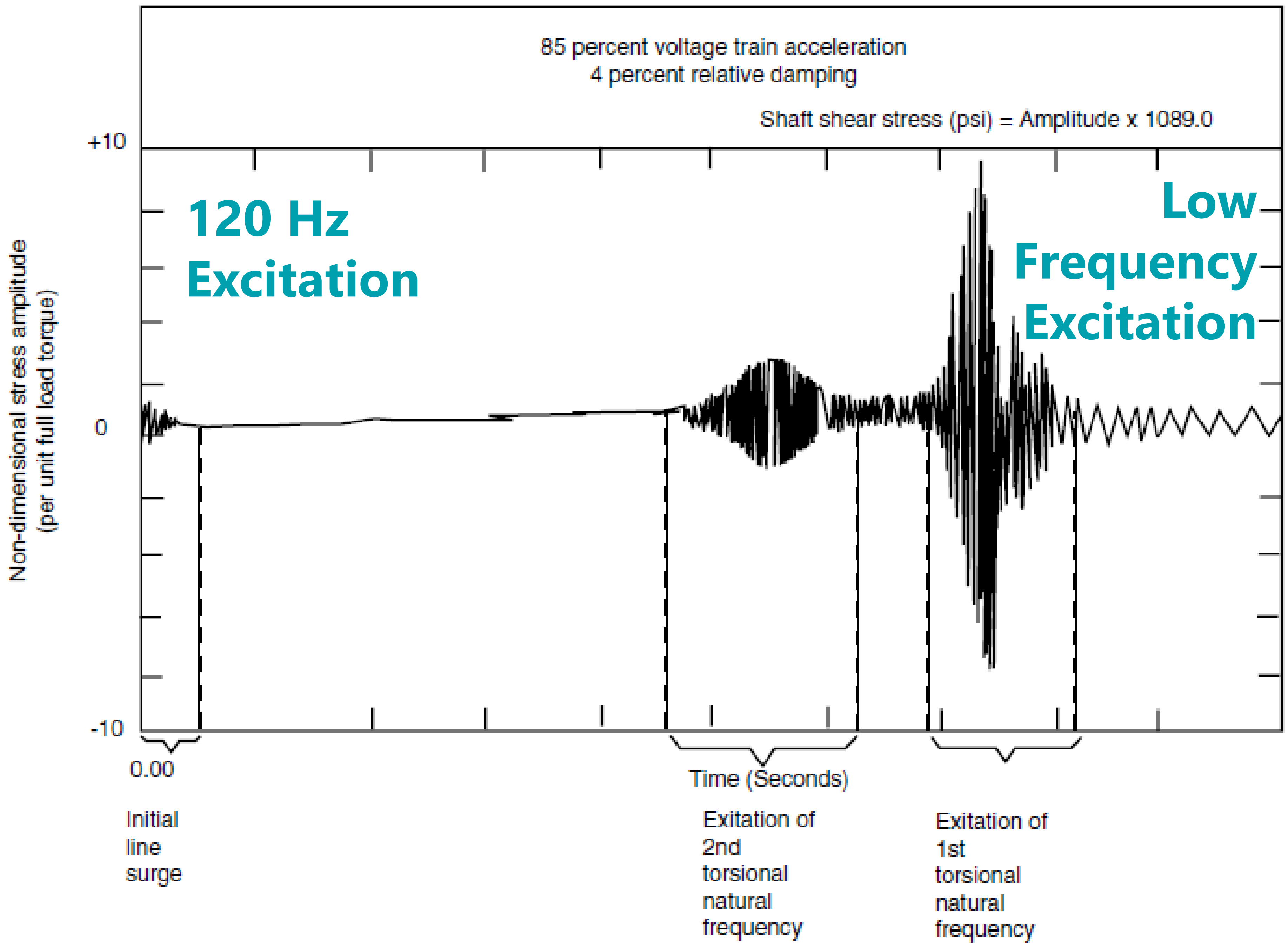


Figure 4-43—Transient Torsional Simulation of a Synchronous Motor-Driven Compressor Train

Reference: API-684

Torsional Vibration Guidelines

A presentation by Wood.

Torsional Vibration Limits

- Many manufacturers provide safe torsional vibration limits
- The limits are provided at a specific location of the machine, i.e. the compressor auxiliary end
- The torsional vibration limits can be provided in:
  - Time domain (overall) amplitude, or
  - Frequency domain (individual frequency peak) amplitude
- Some OEM’s provide a vibratory shear stress limit
- In other cases, the stresses must be compared to an appropriate shear stress endurance limit for the material
- GMRC Torsional Guideline:

1. Limit of 2% velocity amplitude overall (zero-to-peak), based on full load rated speed, anywhere in the compressor shafting (typically would be the free end). For the class of compressors covered by this specification, this limit will reduce the risk of lateral vibration problems caused by torsional-lateral vibration coupling.
2. Limit of 0.75% velocity amplitude overall (zero-to-peak), based on full load rated speed, in an induction motor, to avoid problems with current pulsation.

Torsional Vibration Limits

- Previous guidelines are difficult to meet at auxiliary end.
- GMRC Torsional Guideline also provides following (from an OEM):

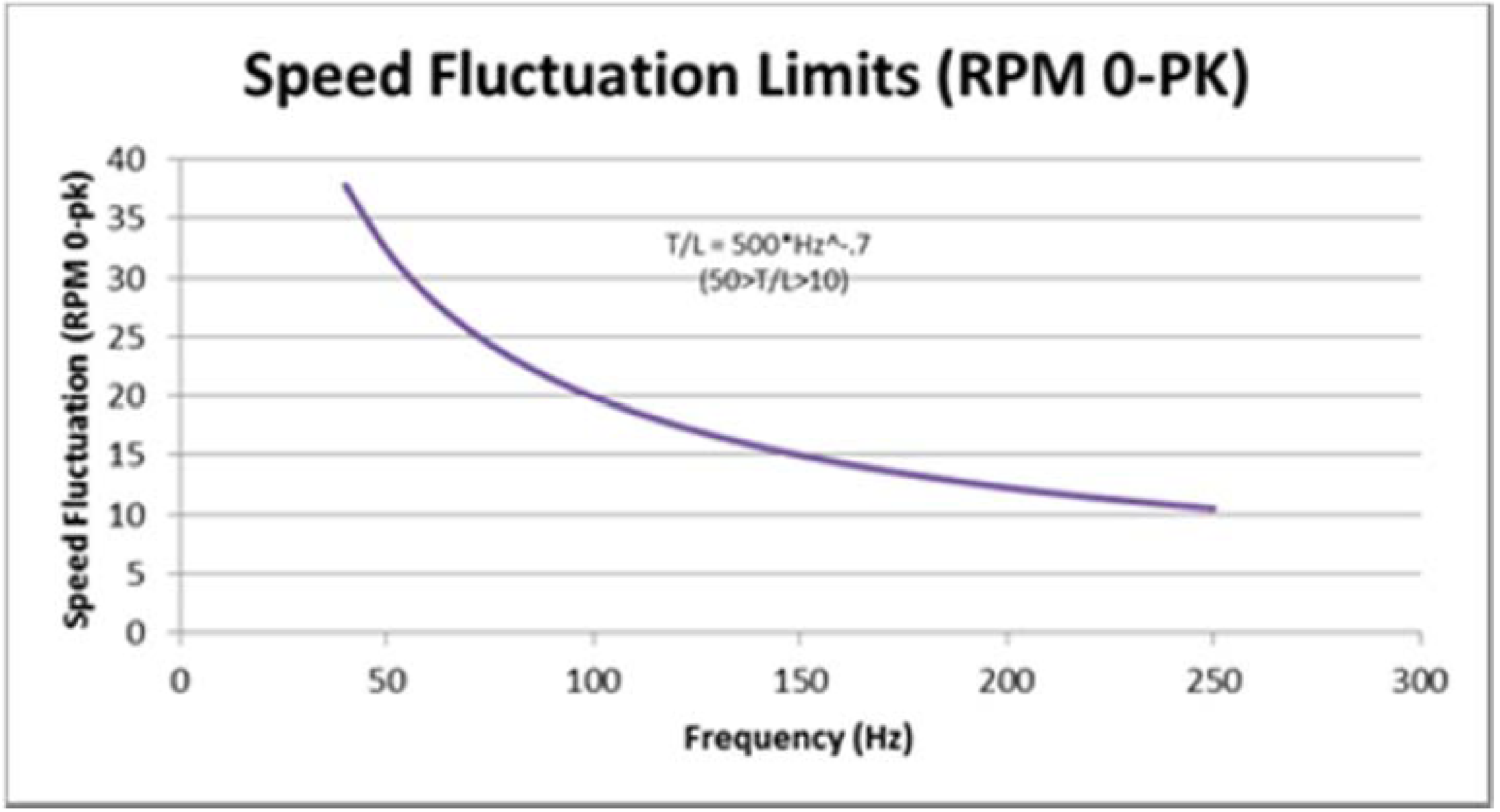


Figure 3-2. Compressor Angular Velocity (Speed) Limits

Torsional Vibration Math

- D is angular displacement in degrees 0-pk
- V is angular velocity in degrees/s 0-pk
- A is angular acceleration in degrees/s^2 0-pk
- f is vibration frequency in Hz.

$$V = 2\pi f D \qquad D = \frac{V}{2\pi f}$$

$$A = 2\pi f V \qquad V = \frac{A}{2\pi f}$$

- (Degrees/second)/6 = RPM
- Be careful about 0-pk versus pk-pk

$$A = [2\pi f]^2 D \qquad D = \frac{A}{[2\pi f]^2}$$

Example to try:

We measure angular velocity of 35 RPM 0-pk @ 50 Hz, at 1000 RPM (3.5%). What is this in angular displacement degrees pk-pk?

Torsional Vibration Math Example

- First convert velocity RPM to degrees/second:

$$35\ \frac{Rev}{Min}\left(\frac{360\ degrees}{rev}\right)\left(\frac{min}{60\ seconds}\right) = 210\ \frac{degrees}{second}\ 0 - pk$$

- Convert velocity to displacement:

$$D = \frac{V}{2\pi f}$$

$$D = \frac{210\ degrees/sec}{2 * \pi * 50\ 1/sec} = \ .668\ degrees\ 0 - pk$$

$$1.3\ degrees\ pk - pk\ Torsional\ Displacement$$

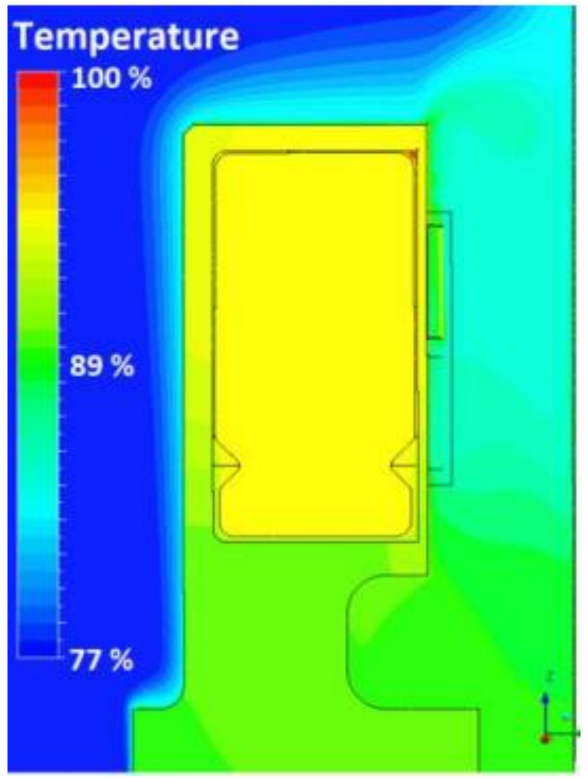
Torsional Vibration Torque Limits

- Rexnord coupling catalog provides:
  - https://www.rexnord.com/contentitems/techlibrary/documents/2000_catalog
  - Max. continuous torque
  - Additional evaluation required to determine the static and dynamic limits
  - Design analysis can be used to calculate torsional vibration limits to meet allowable torque

- Other Torsional Considerations:
  - Heat Load dampers and soft couplings
  - Current Pulsation

Type AMR Spacer Coupling — Rexnord Thomas Flexible Disc Couplings Catalog (#2000)

Coupling Size	Max. Horsepower per 100 RPM Service Factor 1.0	③ Max. RPM	Max. Continuous Torque (lb-in)	⑦ Peak Overload Torque (lb-in)
162	9.1	2,500	5,740	6,888
200	17.5	2,500	11,030	13,236
225	24.7	2,500	15,575	18,690
262	33.4	2,500	21,038	25,245
312	37.5	2,500	23,650	28,380
350	83.8	2,300	52,800	63,360
375	126	2,200	79,442	95,330
425	140	2,000	88,000	105,600
450	216	1,900	136,125	163,350
500	319	1,800	200,750	240,900
550	436	1,800	275,055	330,066
600	569	1,800	358,875	430,650



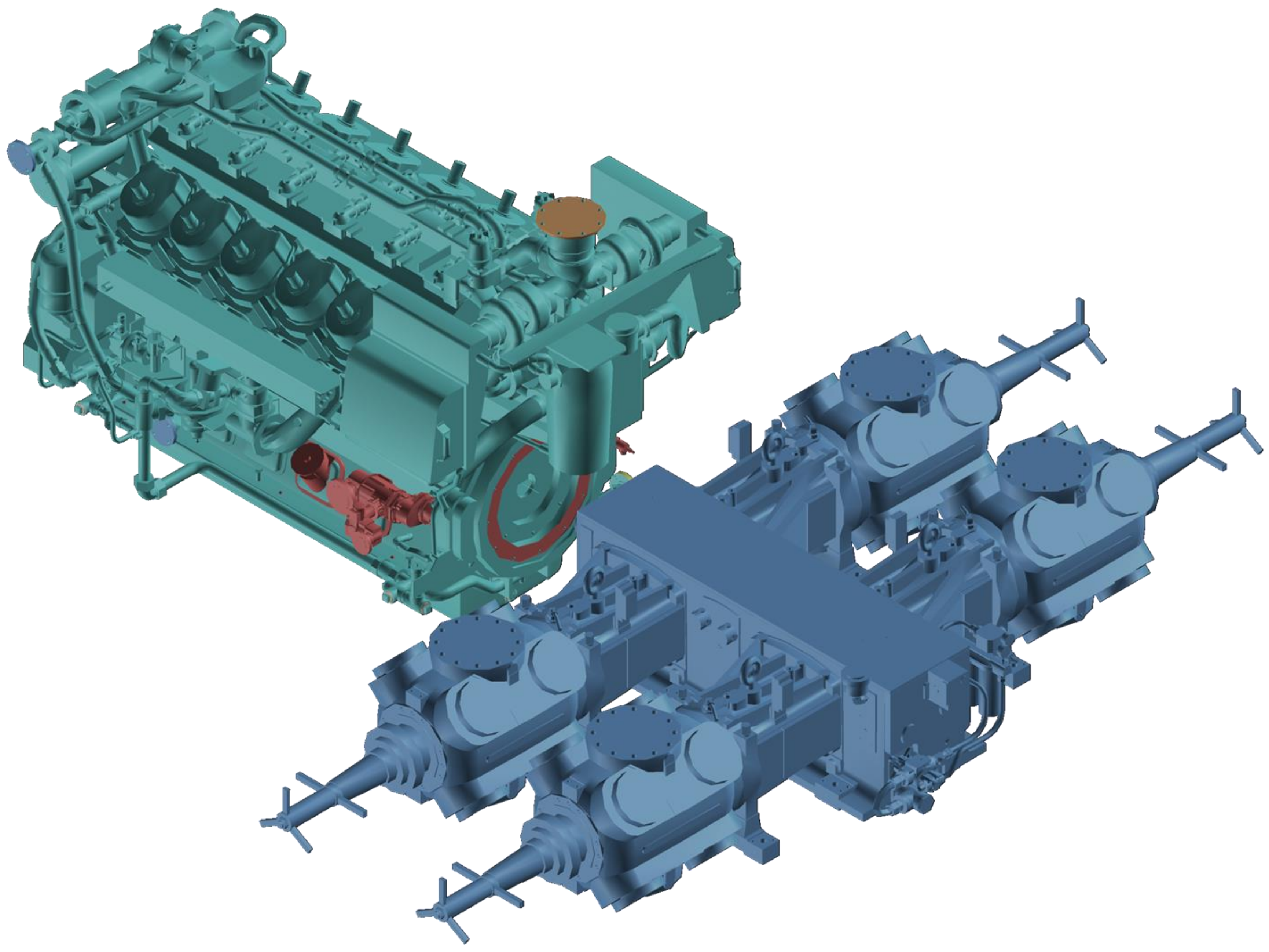
Reference: Introduction to Design and Analysis of Torsional Vibration Dampers in Vehicle Industry, M. VENCZEL1, Á. VERESS

Case Study

Torsional Startup Check

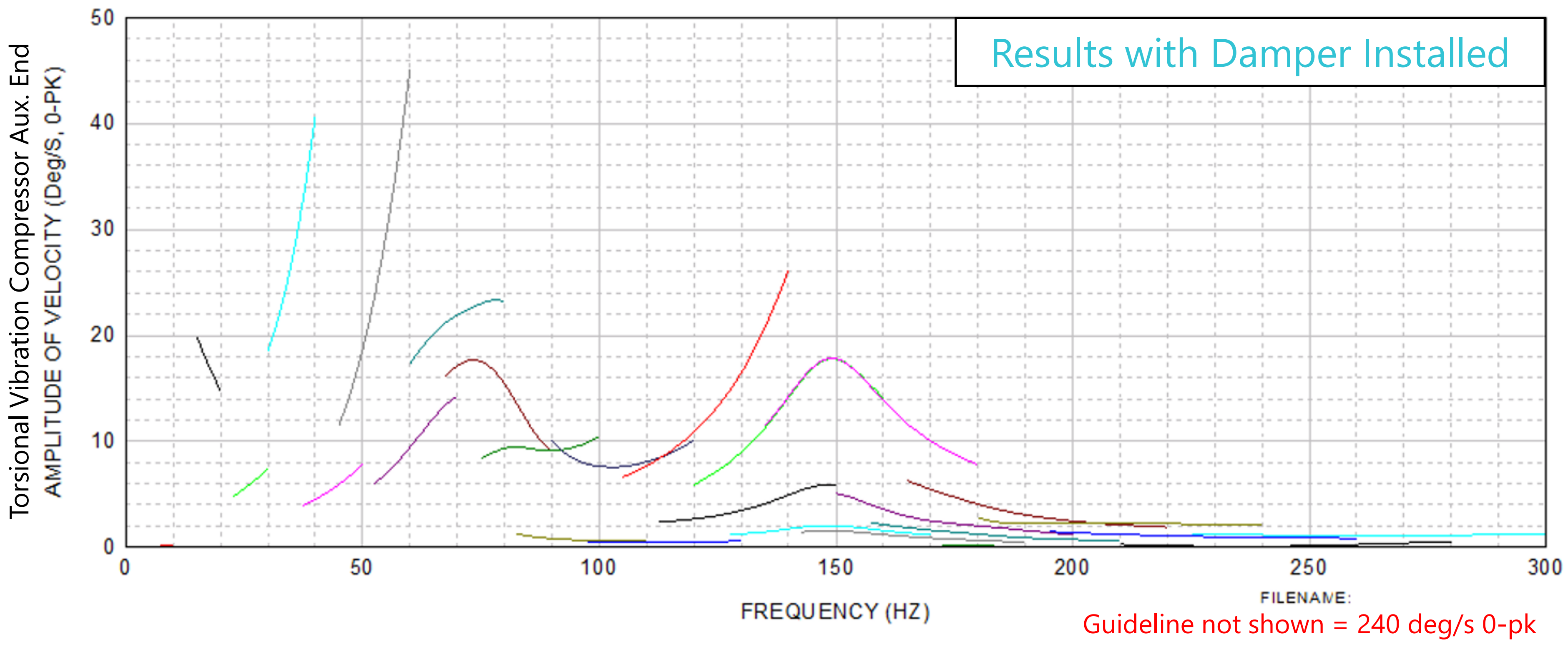
Introduction

- Four (4) throw, one (1) stage reciprocating compressor
- Driven by an engine
- 850 – 1200 rpm operating speed range
- Unit start-up check following unit commissioning
- Design analysis completed by Wood VDN during construction
- Analysis included:
  - Torsional vibration analysis (TVA)
  - Acoustical and mechanical analysis



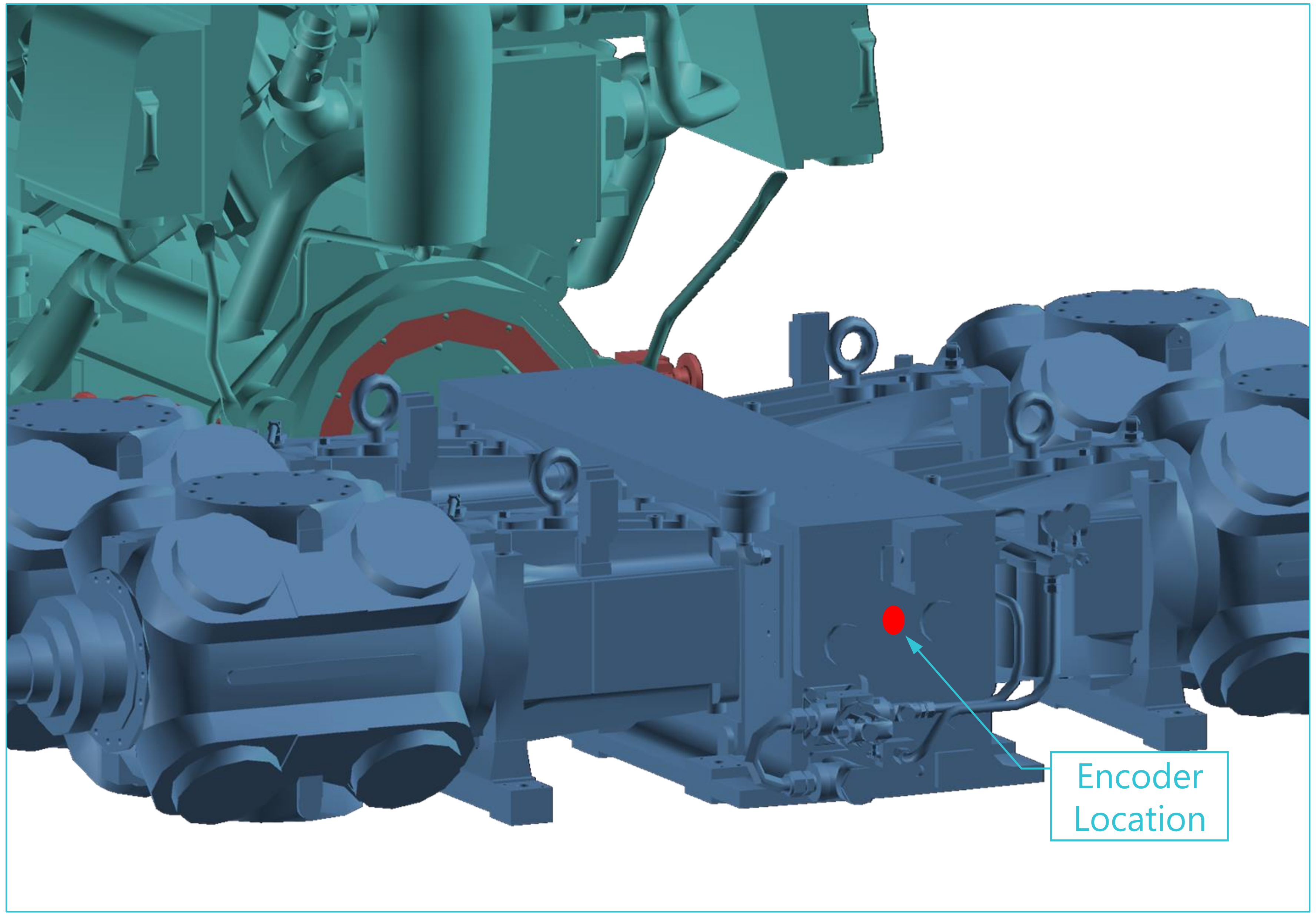
Torsional Vibration Analysis (Design Results)

- Torsional vibration analysis (TVA) completed by Wood VDN
- TVA confirmed
  - Compressor auxiliary end damper required
  - Flywheel and coupling design acceptable
- Torsional amplitudes at engine and compressor predicted to be acceptable
- Stresses in shafts acceptable



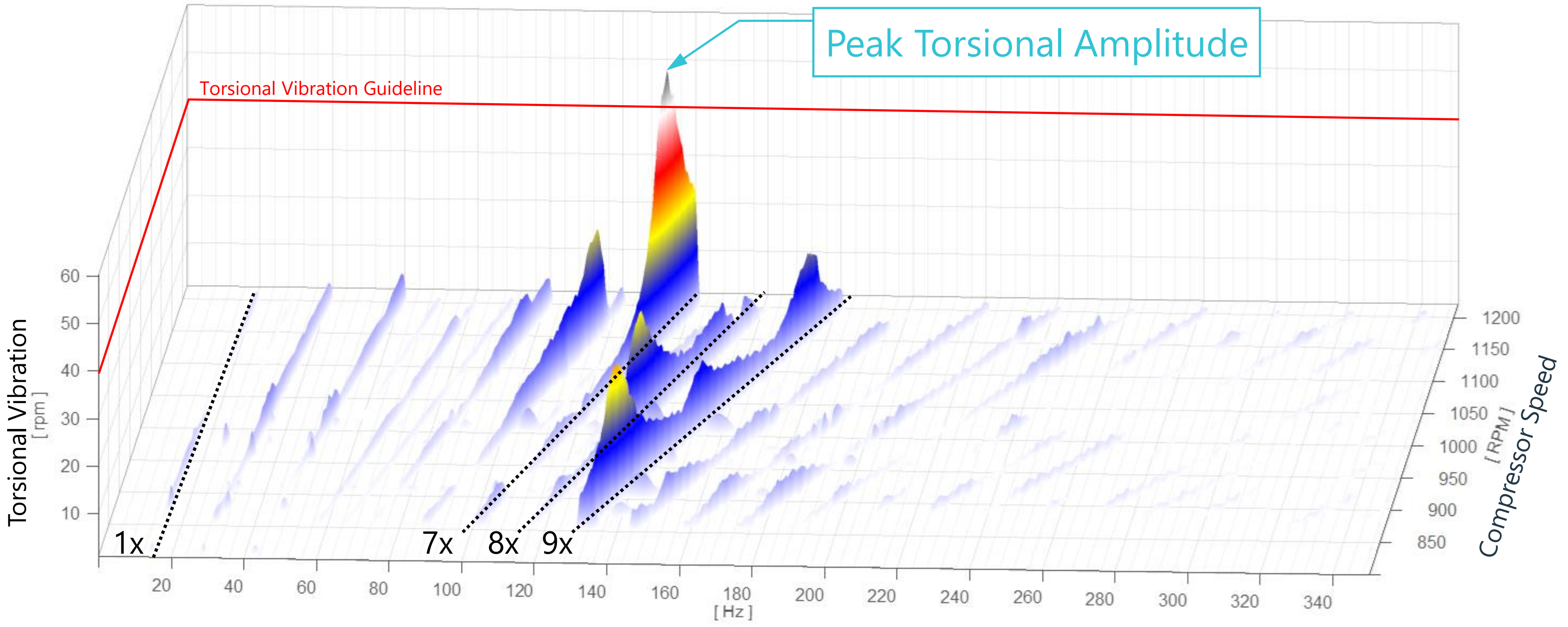
Field Torsional Vibration Data Collection

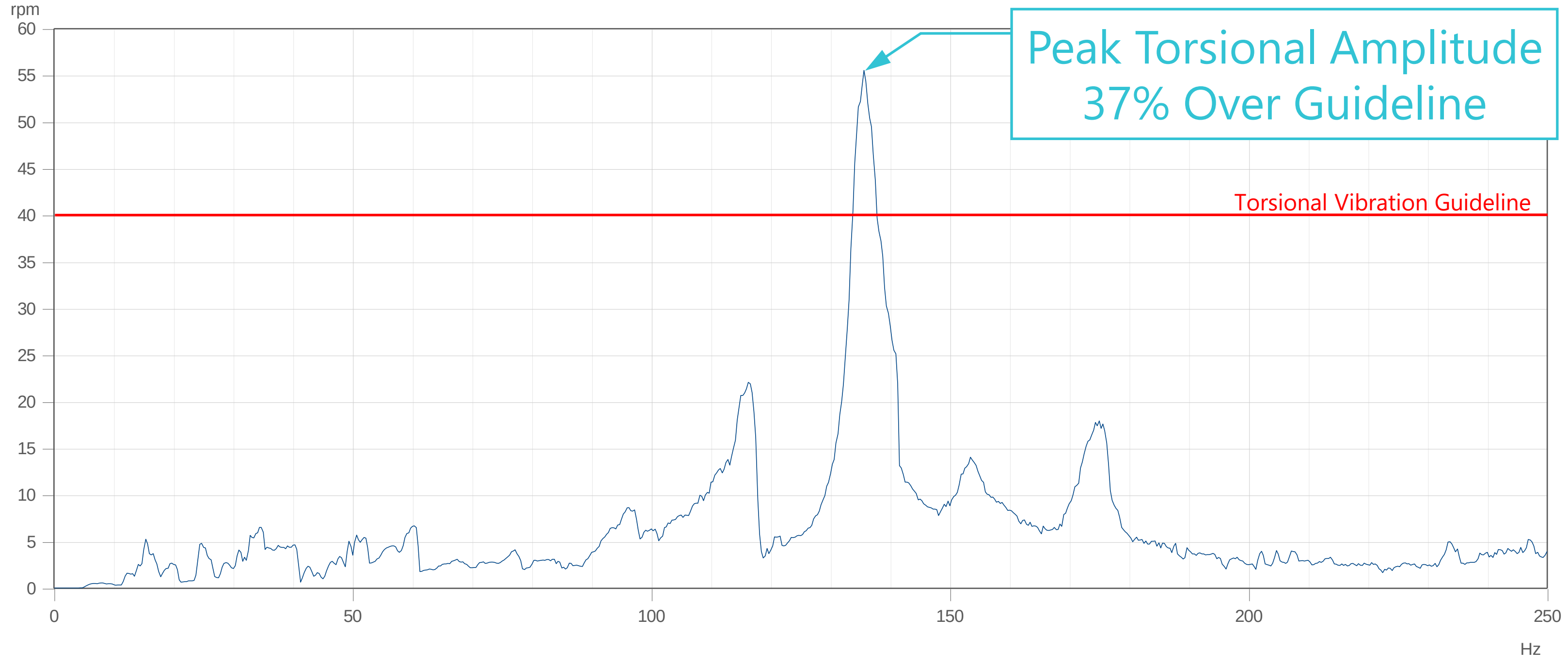
- Wood VDN asked to complete baseline torsional vibration measurement
- Torsional vibration collected through the full speed range
- Non-drive (auxiliary) end encoder was used on compressor crankshaft extension



Field Start-up Check Results

- High torsional vibration was observed
- Maximum torsional vibration observed around 1160 rpm
- Corresponds to 7x (135 Hz) compressor operating speed
- Amplitude significantly higher than predictions at design stage
- End user preference was to run units at full speed

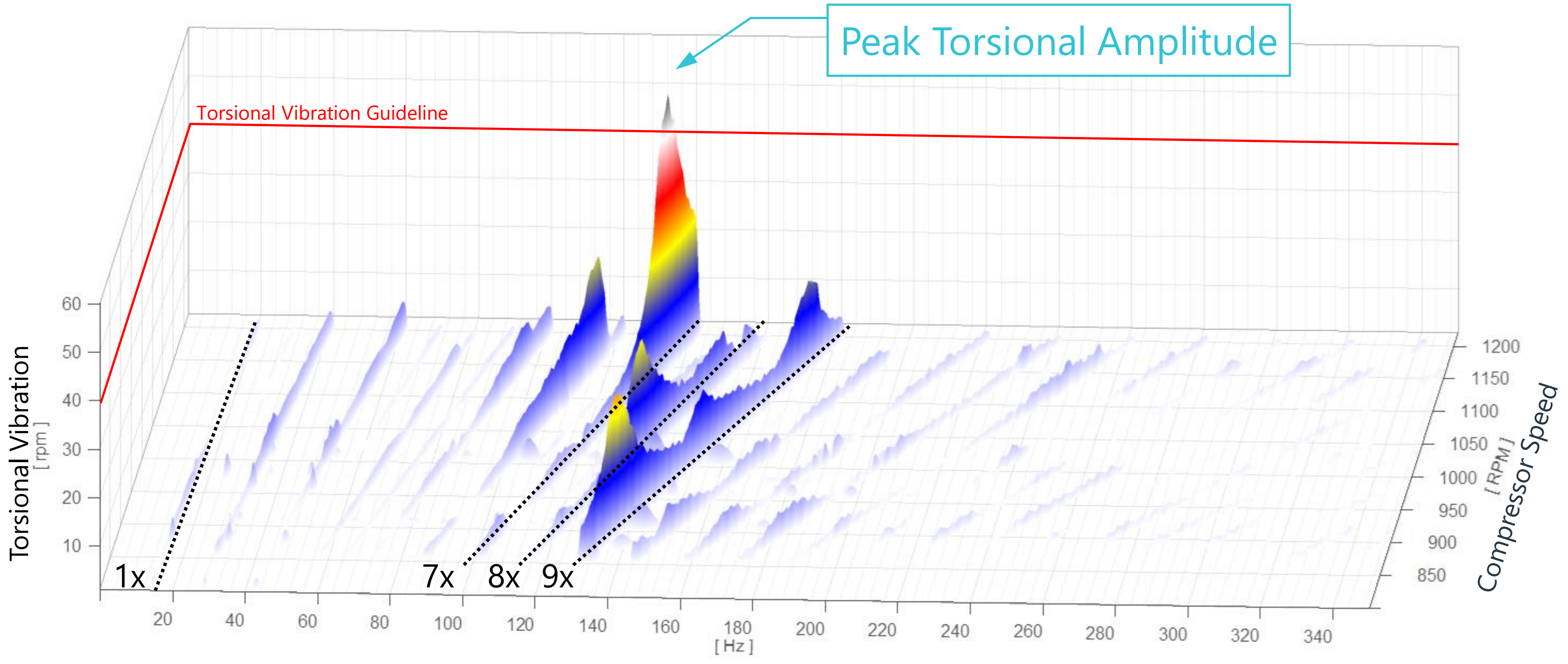


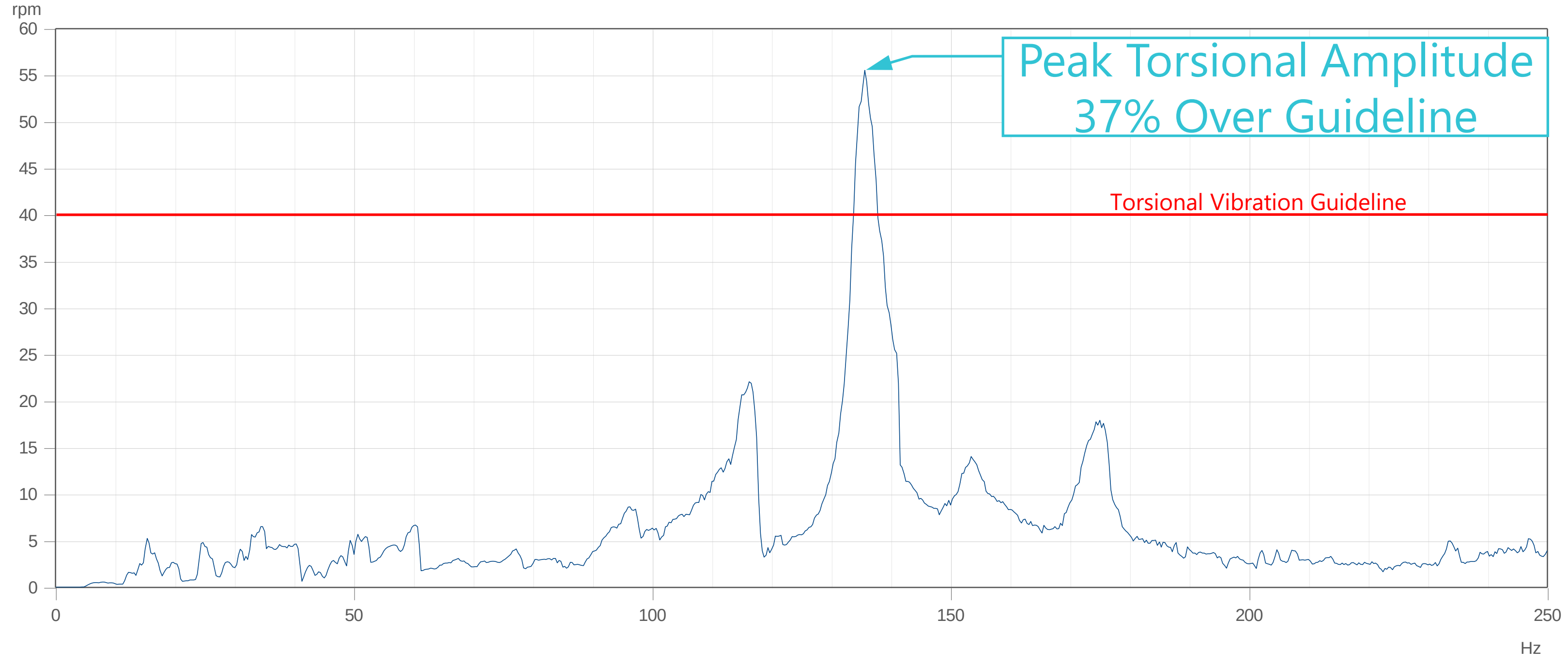


Field Start-up Check Results (continued)

- High torsional vibration:
  - Could have resulted in failure in short amount of time
  - Potential issues with oil pump, coupling, or crankshaft failure
  - Would result in blocked speed range

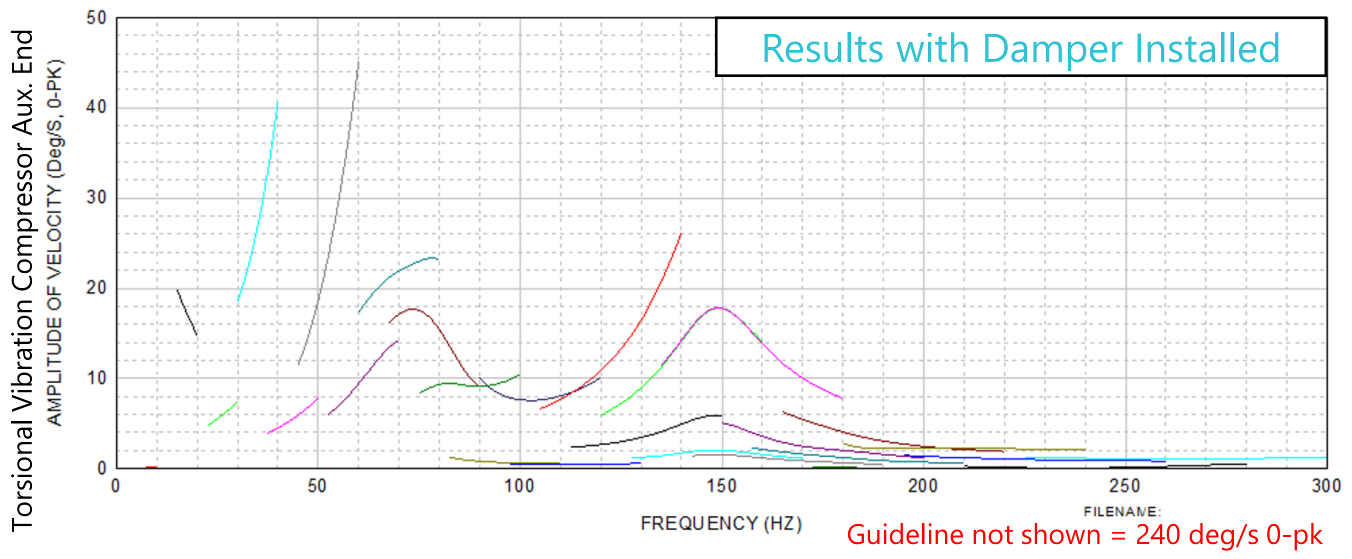
- Why is the torsional vibration so high?

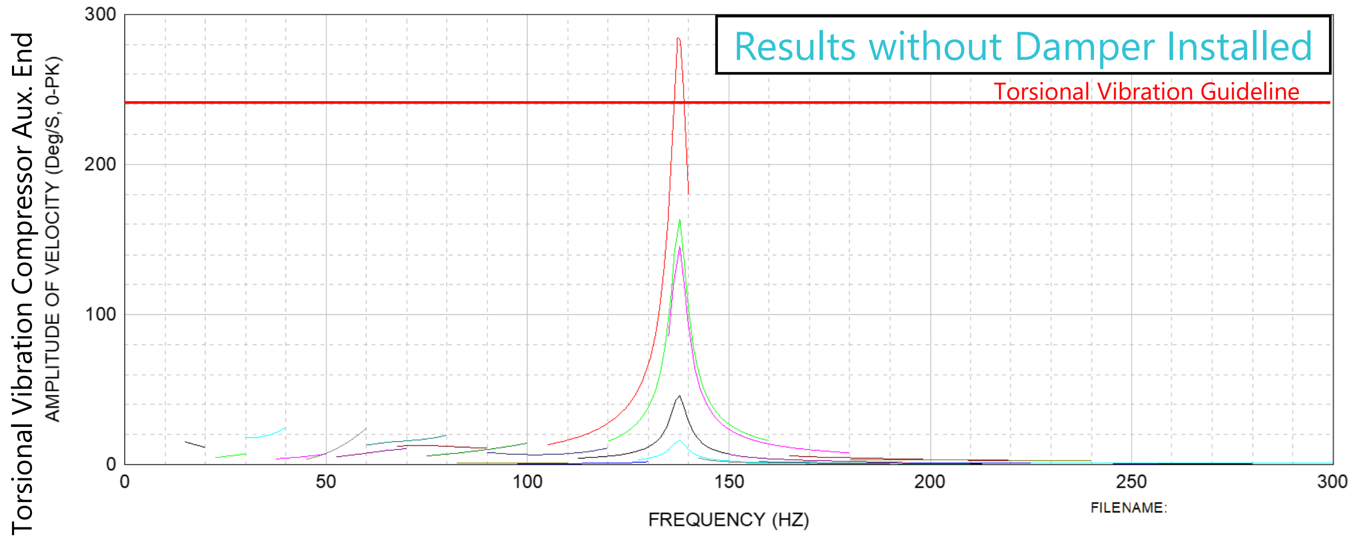


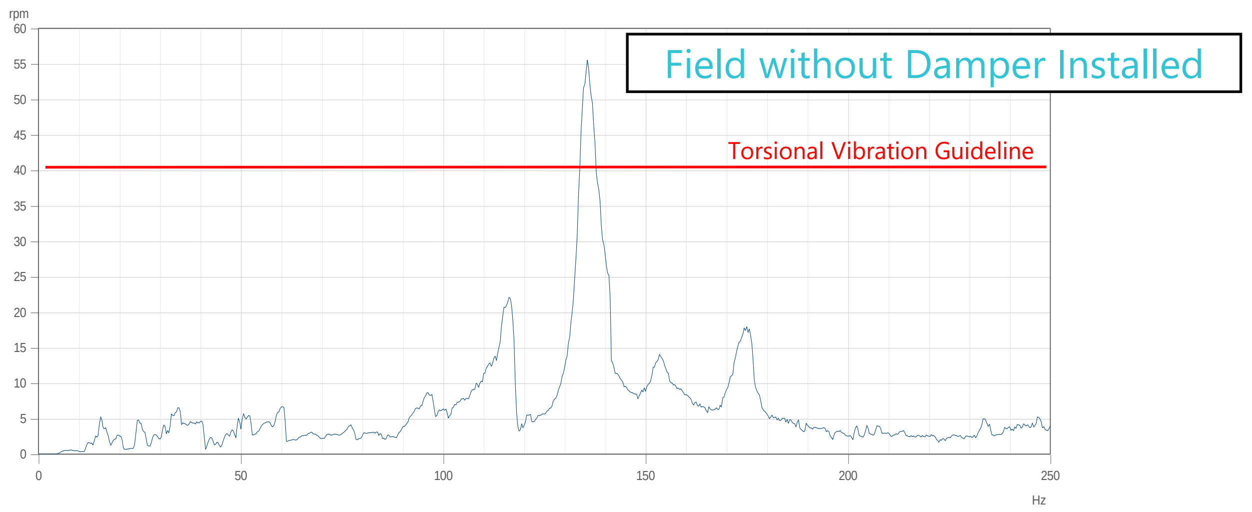


Why is the vibration high?

- Field results prompted discussion between us, OEM, packager, and end user
- Discussions reviewed:
  - The design and the analysis
  - The implemented (as-built) design
  - The part list including review of additional modifications
- Review found:
  - Compressor non-drive end damper was not installed
  - Damper is standard part of this frame model

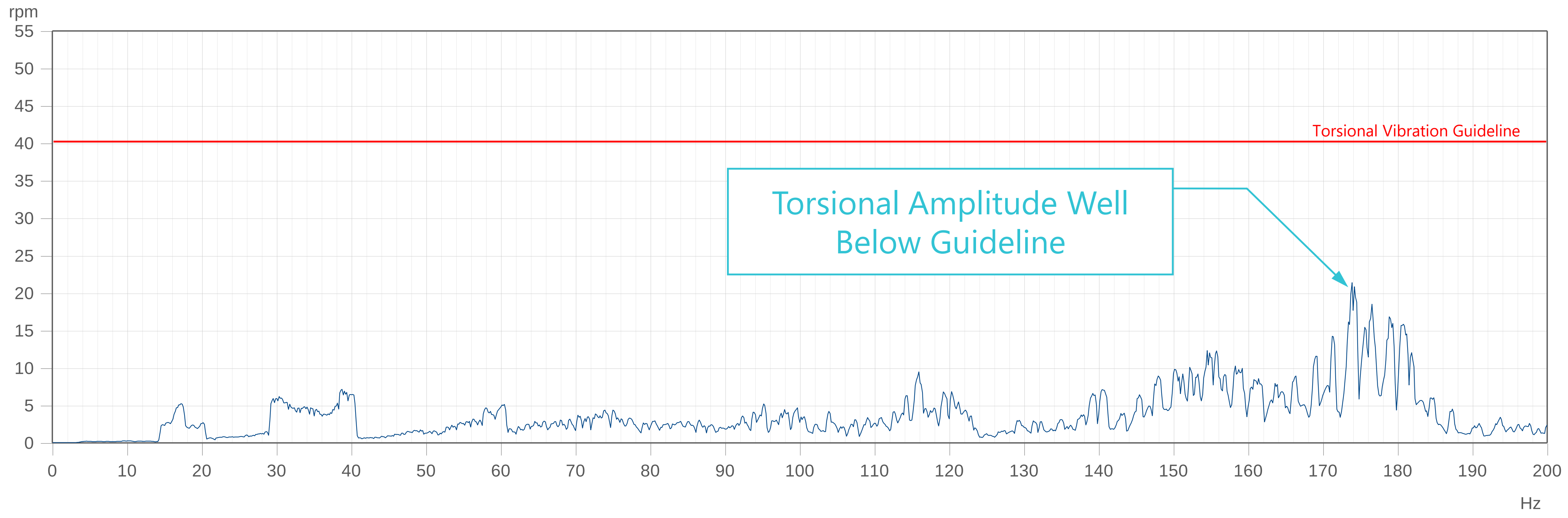






Resolution

- Compressor frame damper was installed
- Located at the non-drive end of compressor crank shaft
- Resulting torsional vibration was measured:
  - Was found to be acceptable as shown on the right
  - Amplitudes in line with design predictions



Case Study Conclusion

- Start-up check can be very important to confirm:
  - Torsional natural frequencies (TNFs)
  - Torsional vibration amplitudes
  - The as-built package matches the design
- Simple check to protect the equipment investment
- Prevent quick failure due to lack of physical symptoms of the condition

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