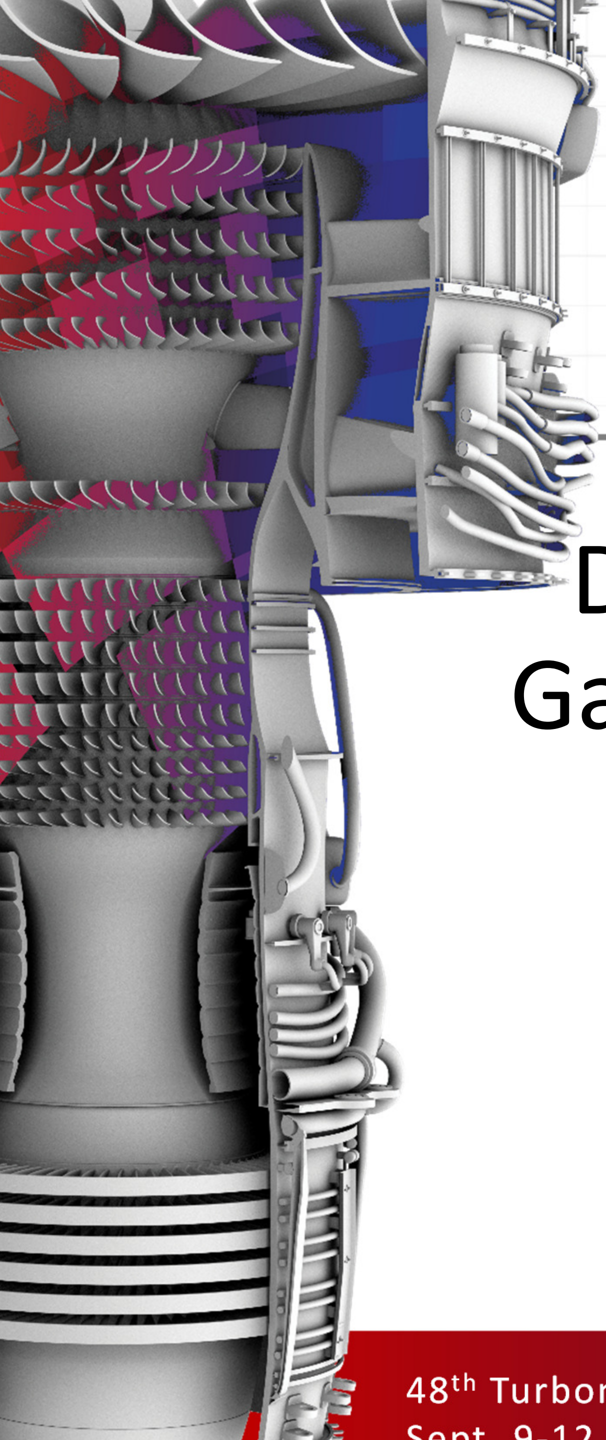


# Development and Field Testing of Strain Gauge Based Torque measurement system for Oil Pipeline Pump Application

Hemanth Satish, P.E.
Chris Barkow
Dan Phillips

# Presenter Bios

Hemanth Satish, P.Eng.

- Principal Engineer, USGO Reliability
- Specializing in rotor-dynamics, vibration, pulsation analysis, modal Analysis, RCFI, exotic metallurgy, condition monitoring and predictive analytics related to equipment for O&G industry

TC Energy

Dan Phillips, CMRP

- Technology Director, PTS Monitoring & Diagnostics
- B.S. Mechanical Engineering, University of Maryland Baltimore County
- 15 years of field experience with rotating equipment for O&G and Heavy Industries

REGAL

Chris Barkow

- B.S. Mechanical Engineering, Purdue University
- 15 years experience with Engineering Services, Preventive & Predictive Maintenance
- Previously Senior Equipment Specialist at major US steel producer

REGAL

# Short text of an Abstract (approx.80 words) to print in show guide

- As part of a PRCI (Pipeline Research Council International) project that involved developing a field testing procedure for large oil pipeline pumps, this case study focuses on the development of a system to precisely measure power at the pump shaft which paramount to the accurate estimation of the pump-motor performance. The conclusion of the case study details the lessons learned, future test plans on alternate motor-pump configurations, and the implications of transient torsional vibration on machinery health for these applications.

# Case Study Overview

- Background and Problem Statement
  - Pipeline Research Council Initiative
  - Efficiency Calculation Challenges
- Telemetry System Integration with Flexible Coupling
- Field Testing & Data Review
- Torsional Vibration for Machinery Diagnostics
- Conclusion

# Background

- Lack of industry Accepted standards and Procedure for field performance testing of large Pipeline Pumps in viscous application;
- **Lack of Standardized Accurate estimation of HP consumed on large Pipeline Pumps, making performance/efficiency estimation a challenge.**
- Pipeline Research Council International (PRCI) Initiative – Development of Pump field performance testing procedure and validation ( CPS 7-10);
- In support of the PRCI initiative there was a need to measure mechanical HP consumed for accurate performance estimation of pipeline pumps.
- TC Energy oil pumping stations used for field performance testing – proof of concept.

# Problem Statement

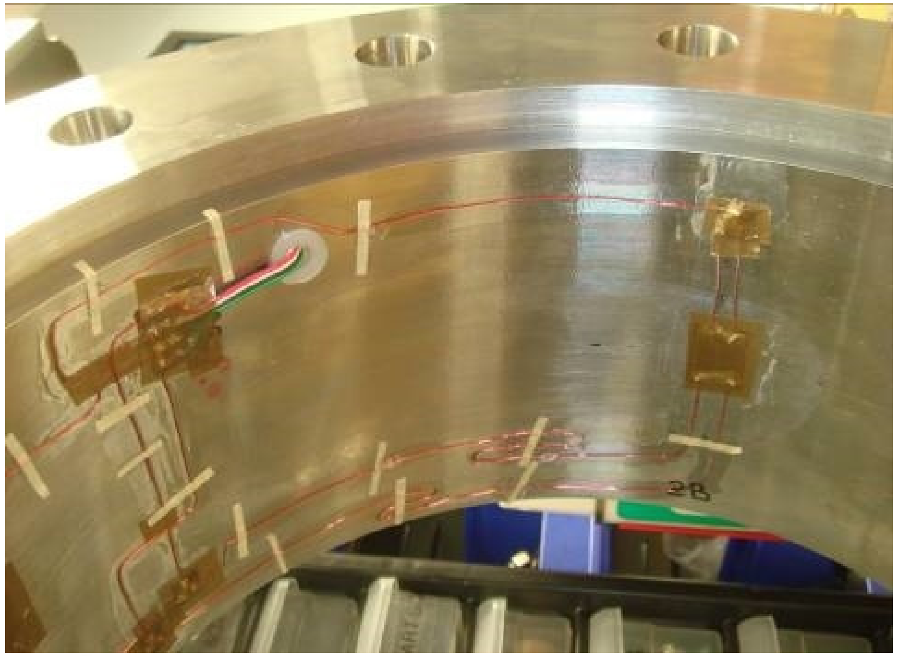
- True input torque to pump shaft needs to be measured.
- Least intrusive system needs to be used for minimizing installation and set up times – to avoid expensive line/station outages;
- Capable of continuous operation;
- No Major Modifications allowed on the pump or drive systems; use of existing coupling preferred;
- Torque measurement system should be interchangeably used on different TCE pumps (same makes);
- Simple set up, remote operation, minimal invasive cabling & portability;
- Dynamic torques measurement capability - Understand VFD oscillations, performance and effect on pump & motor;
- Capable of serving as a tool for torsional analysis with high resolution data.

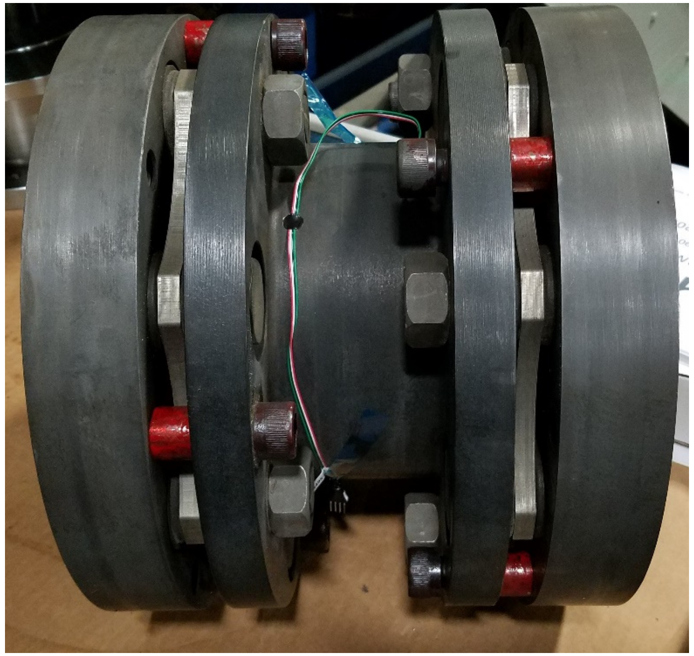
# Telemetry System – Coupling Integration

- Major Components
  - (2) Strain gage bridges mounted inside diameter of the coupling spacer
  - Transmitter mounted to the outside diameter of the coupling spacer
  - Brass hoop antenna to receive torque data from the transmitter
  - Data acquisition box which is connected to the antenna by a coaxial cable

# Telemetry System – Coupling Integration

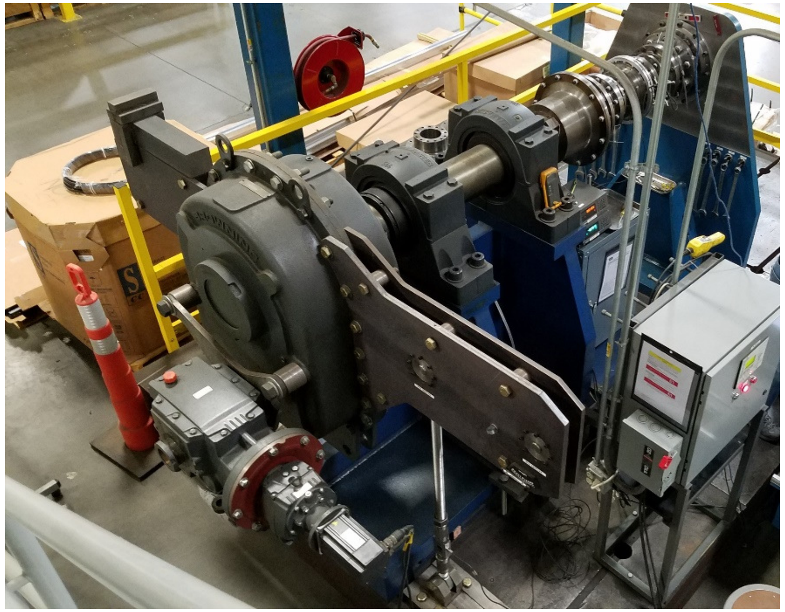
- Redundant strain gage bridges installed on inner diameter of coupling spacer
- Temperature compensation requirement of -40 to +55 deg C
- Gages constructed ‘EA’ constantan foil, are rated to -75°C (-103°F) Adhesive rated for -269°C using M-Bond 610 and protective coating rated to -75°C

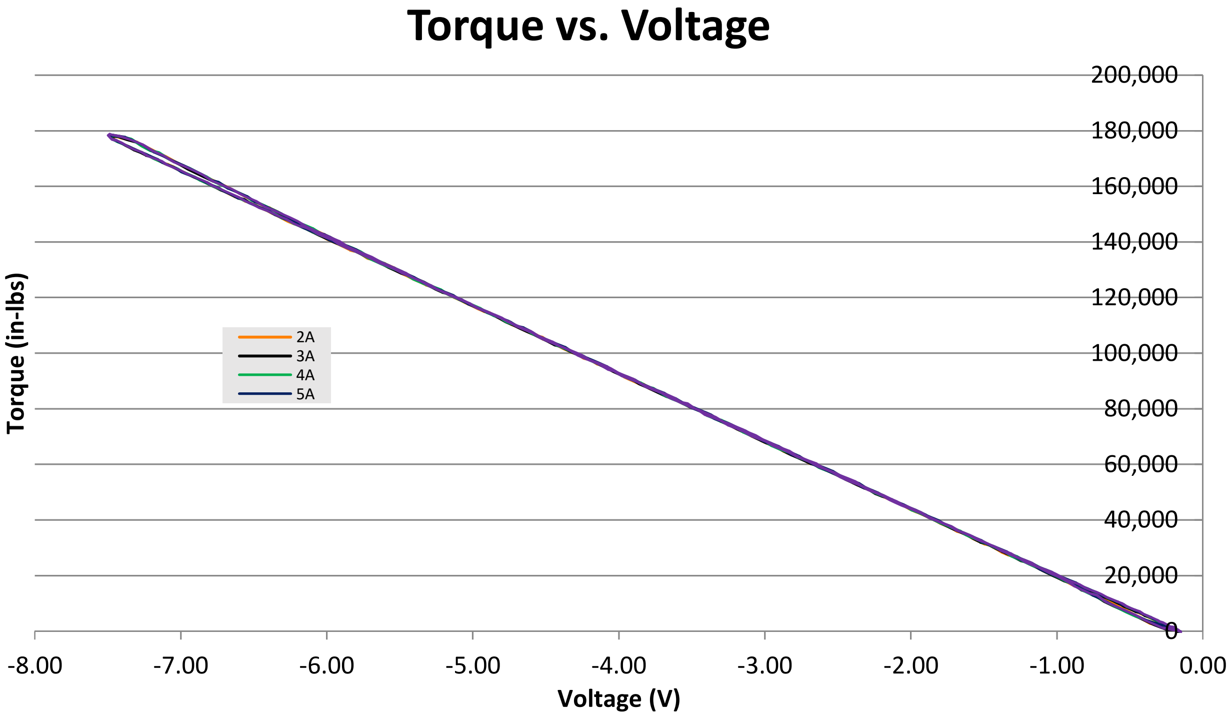




# Telemetry System – Static Calibration

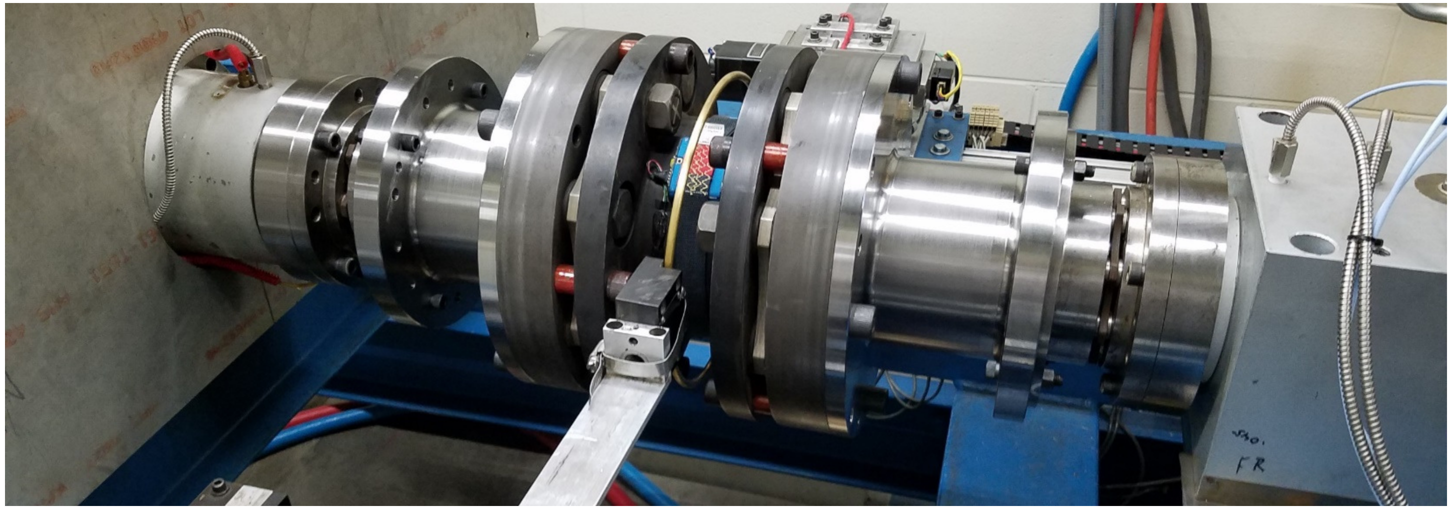
- Calibration data was taken in both rotational directions (CW and CCW)
- Torque ranged continuously from 0 in-lbs up to 177,037 in-lbs, and back down to 0 in-lbs, for each of the two strain gage outputs
- 3 complete tests were performed for each of the two strain gage outputs for repeatability
- Each test included 5 valid runs up and down in torque (Voltage below shows negative due to the bridge output)
- Verified repeatability and linearity of the gage outputs and determined the scaling factor required for each gage circuit.



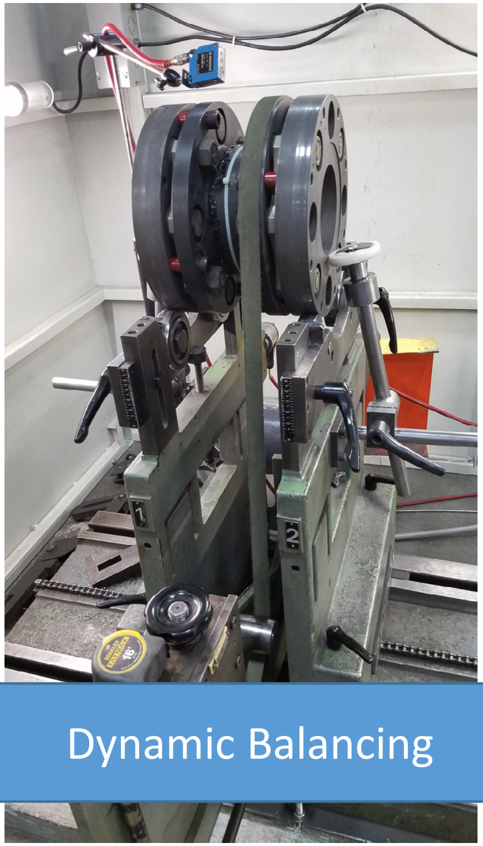


# Telemetry System – Dynamic Testing & Balancing

- Dynamic testing ensures that speed and related forces do not affect signal
- Testing help gain knowledge of the expected signal quality in the field and the possible effects of poor connections at the hoop antenna
- Dynamic balancing to API 671 standard (component balance) after instrumentation was installed



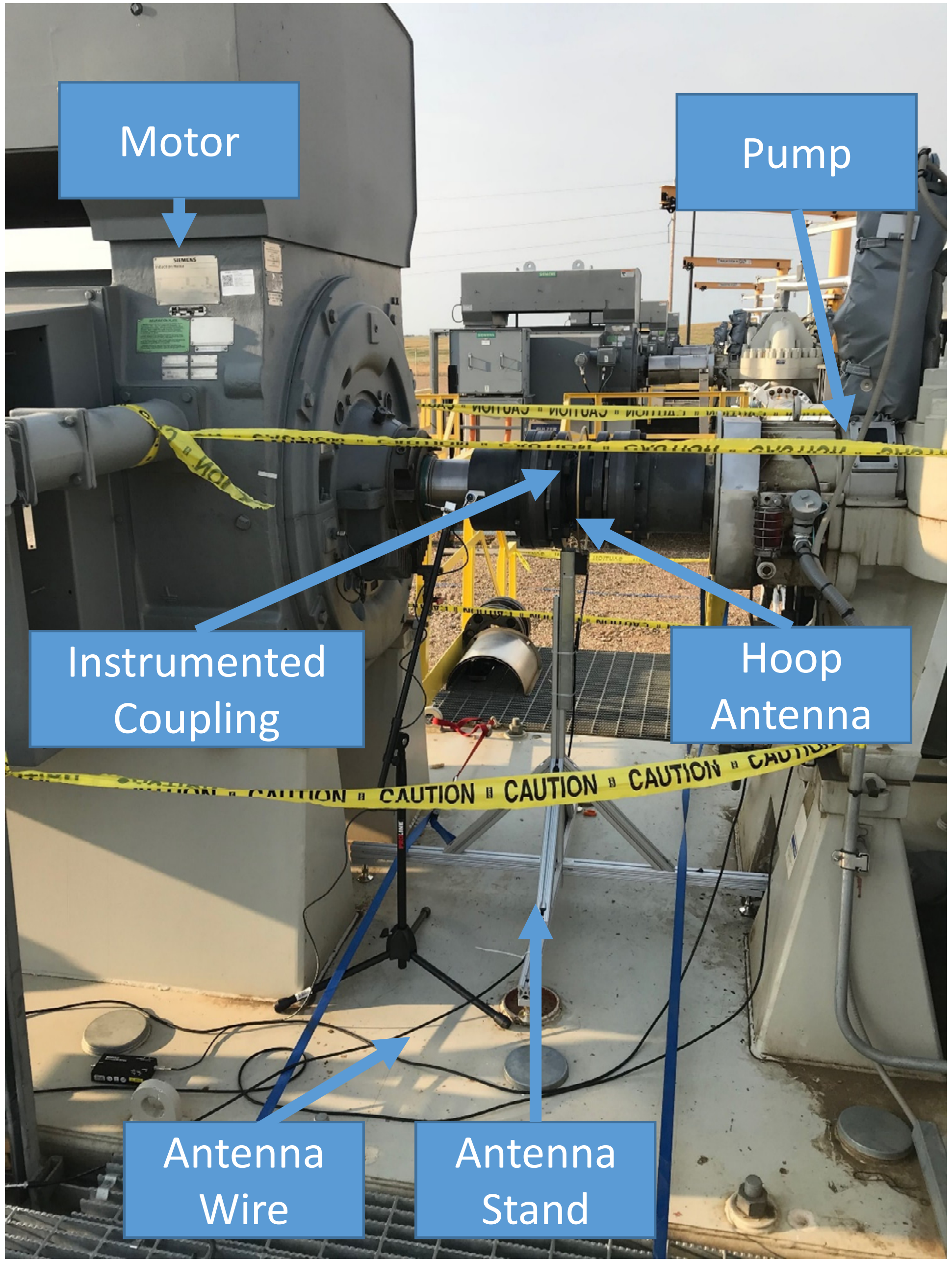
Dynamic Test Stand



Dynamic Balancing

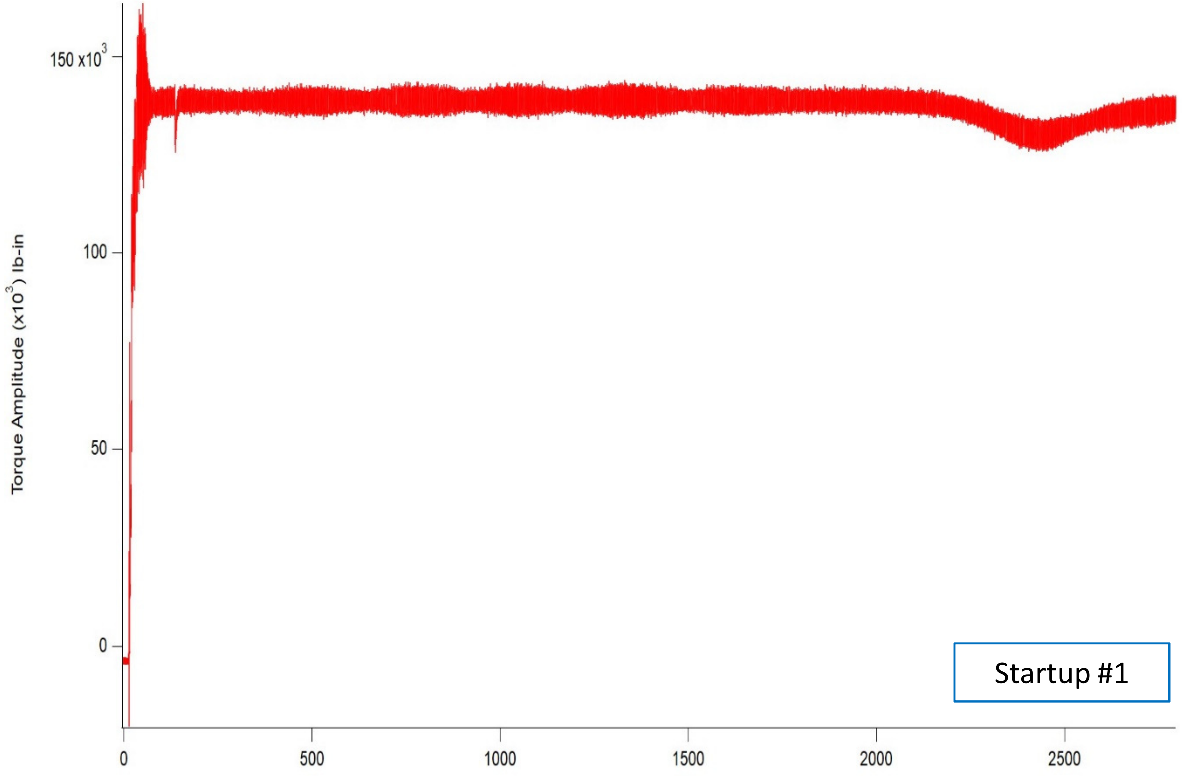
# Field Testing Setup

- Antenna support stand held the hoop antenna from the side or from the bottom of the coupling
- Field operation proved the antenna had to be held in two places to keep coupling windage and external wind forces from moving/vibrating the antenna
- A larger hoop antenna was used in the field vs testing to help clear the coupling bolt circle
- Coupling guards did not fit with the instrumentation and the area was taped off for safety during the operational testing
- The data acquisition box was set up outside of the taped off area so it was accessible for data logging

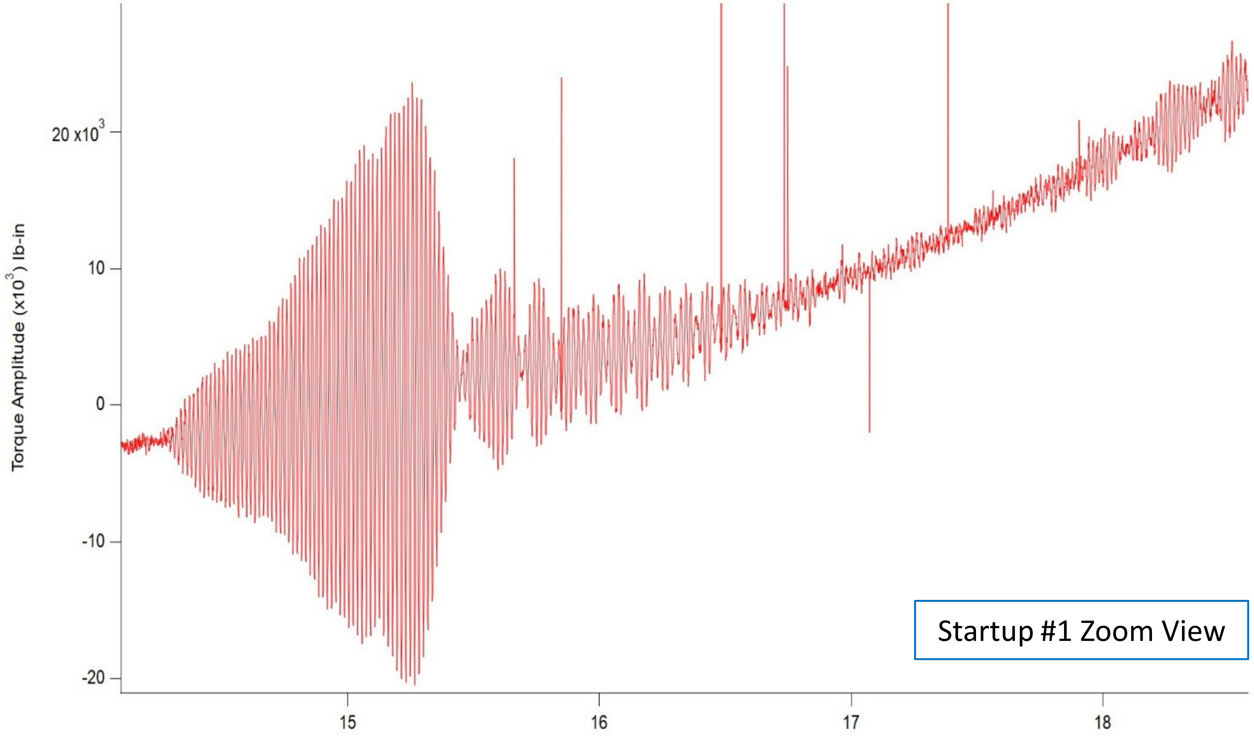


# Field Testing Results – Test Site #1 (Day 1)

- Testing site #1 was a non-VFD operated motor
- The operator had valves closed during startup(s)
- Torsional resonance at 56 Hz and reversing torques noted at startup, along with low amplitude 360 Hz oscillations
- Steady state motor speed is constant throughout the test after startup
- Variances in torque are due to valve shifts and other external factors such as fluid inertia, pumped media changes, etc



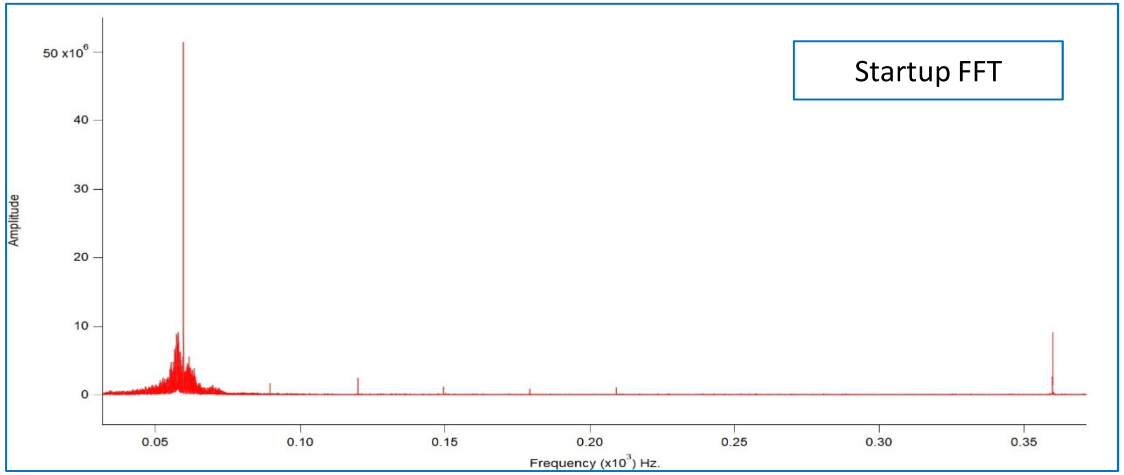
Startup #1

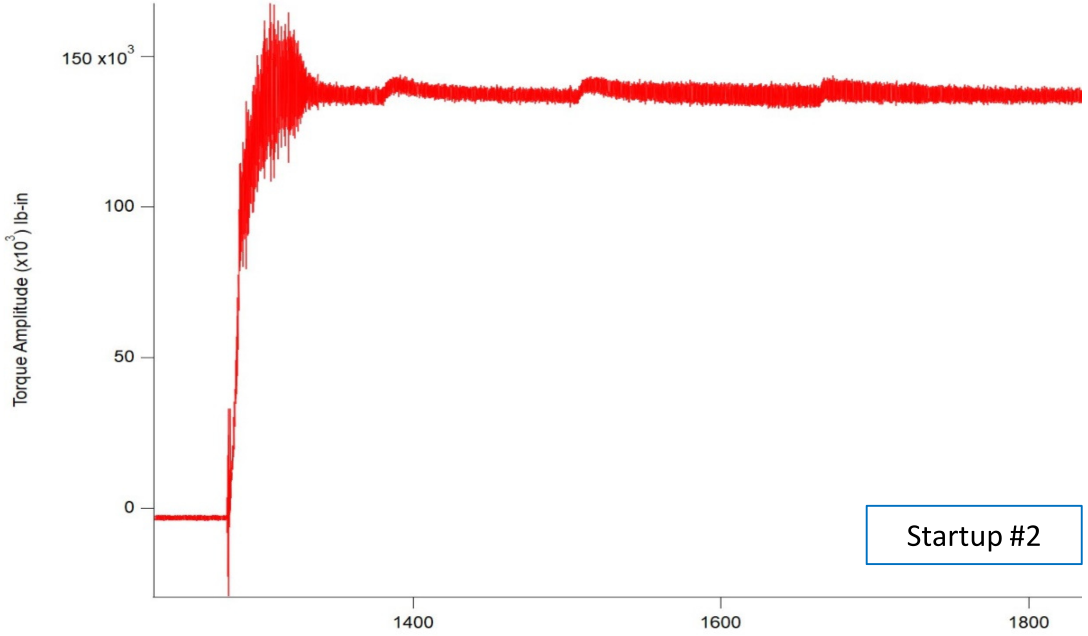


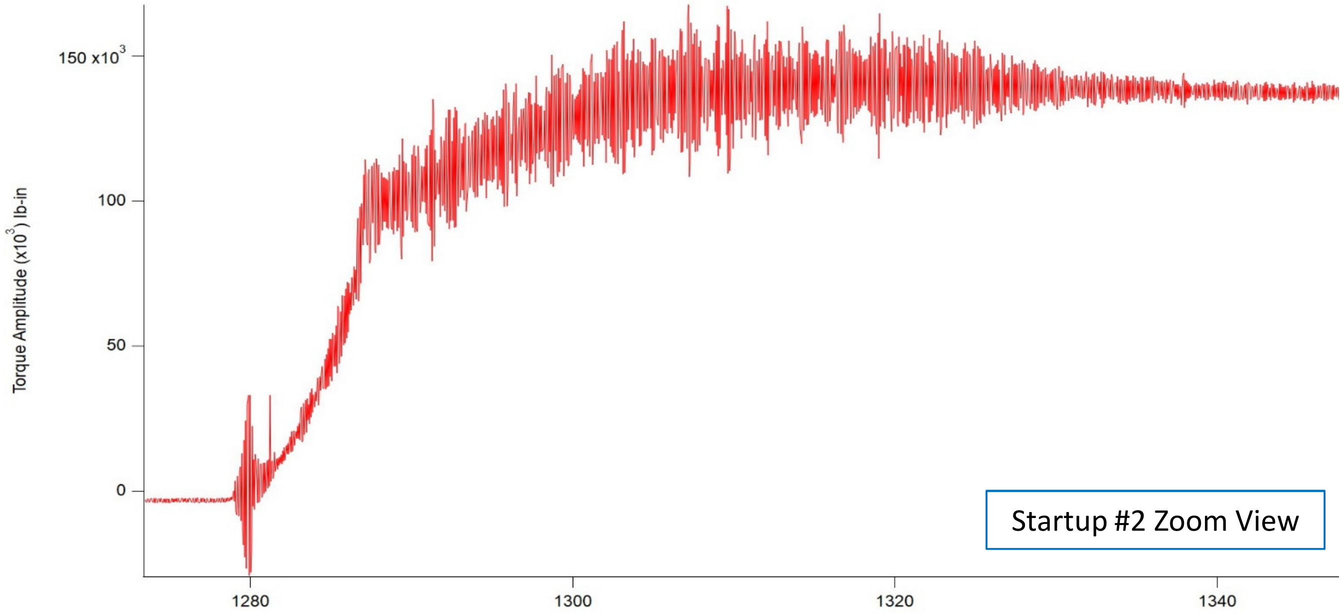
Startup #1 Zoom View

# Field Testing Results – Test Site #1 (Day 2)

- Testing site #1 was a non-VFD operated motor
- The operator had valves closed during startup
- Torsional resonance at 56 Hz and reversing torques noted at startup, along with low amplitude 360 Hz oscillations
- Speed is constant throughout the test after startup
- Variances in torque are due to valve shifts and other external factors such as fluid inertia, pumped media changes, etc


Startup FFT


Startup #2


Startup #2 Zoom View

# Field Testing Results – Test Site #2

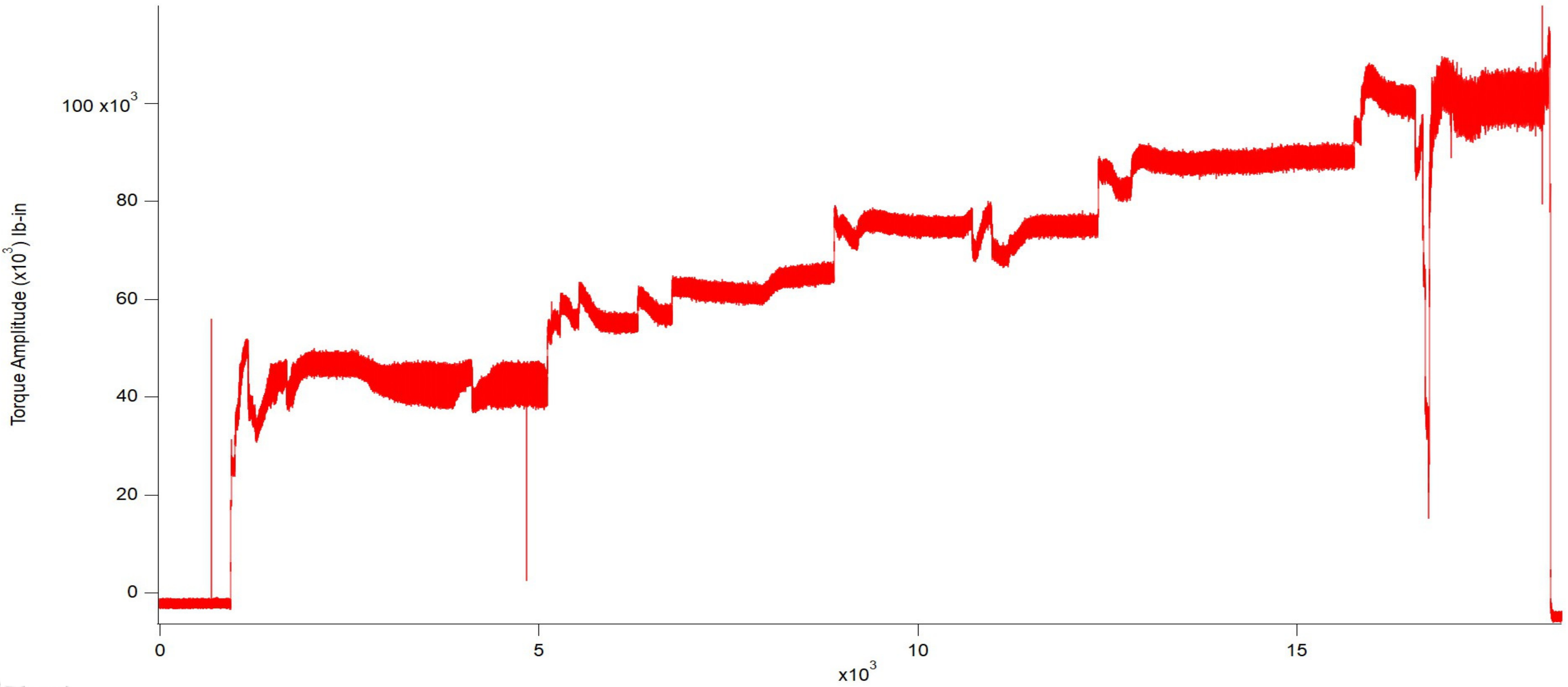
- Test site #2 utilized a VFD driven motor
- Data was collected continuously at 2,000 Samples/Sec while varying speed and loads.
- The VFD started initially at 55% motor speed and increased in steps up to 100% speed over 5 hours and 8 minutes
- Some minor adjustments occurred to the VFD controlled speed during the test.
- Torque data was continuously logged while other parameters were recorded in a notebook

| Percentage of Motor Speed | Reported Shaft Speed | Actual Time of Day | VFD Freq. | Case Pressure | Suction Pressure | Discharge Pressure | Temperature | Flow rate |
|---|---|---|---|---|---|---|---|---|
| 55% | 960 RPM | 10:41 | 31.0 Hz | 3158 kPag | - | - | 32.9 °C | 3064.0 m^3/hr |
| 65% | 1198 RPM | 12:13 | 39.6 Hz | 3304 kPag | - | - | 32.9 °C | 3038.0 m^3/hr |
| 67% | 1230 RPM | 12:22 | 41.0 Hz | 3363 kPag | - | - | 32.9 °C | 3061.5 m^3/hr |
| 77% | 1400 RPM | 12:54 | 46.7 Hz | 3578 kPag | 2459 kPag | 3598 kPag | 32.9 °C | 3116.0 m^3/hr |
| 75% | 1351 RPM | 13:25 | 45.1 Hz | - | 2513 kPag | 3561 kPag | 32.9 °C | - |
| 77% | 1397 RPM | 13:45 | 46.6 Hz | - | 2550 kPag | 3675 kPag | 32.9 °C | 3170.0 m^3/hr |
| 84% | 1520 RPM | 13:53 | 50.6 Hz | - | - | - | 32.9 °C | - |
| 87% | 1573 RPM | 14:37 | 52.4 Hz | 3911 kPag | 2445 kPag | 3951 kPag | 32.9 °C | 3186.0 m^3/hr |
| 95% | 1733 RPM | 14:51 | 57.3 Hz | - | - | - | - | - |
| 100%* | 1809 RPM | 15:14 | 60.3 Hz | 3123 kPag | 1031 kPag | 3149 kPag | 32.5 °C | 2775.0 m^3/hr |

Table 1 – Overview of data collected from torque telemetry system and on-site test notes

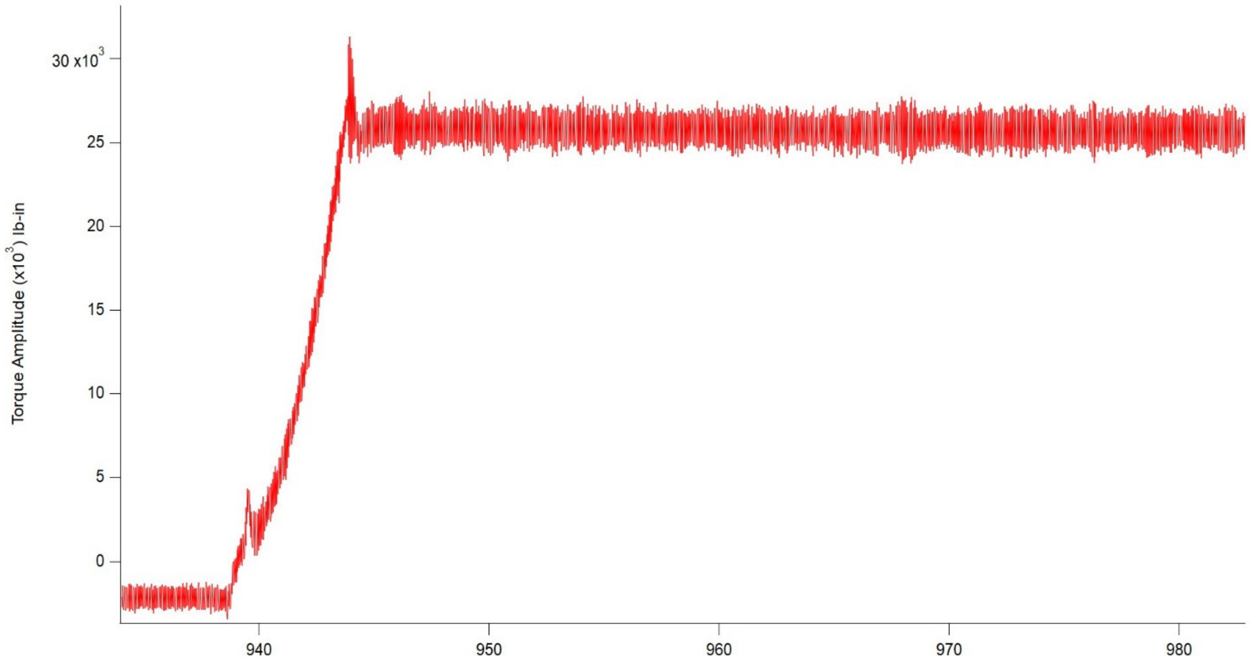
# Field Testing Results – Test Site #2

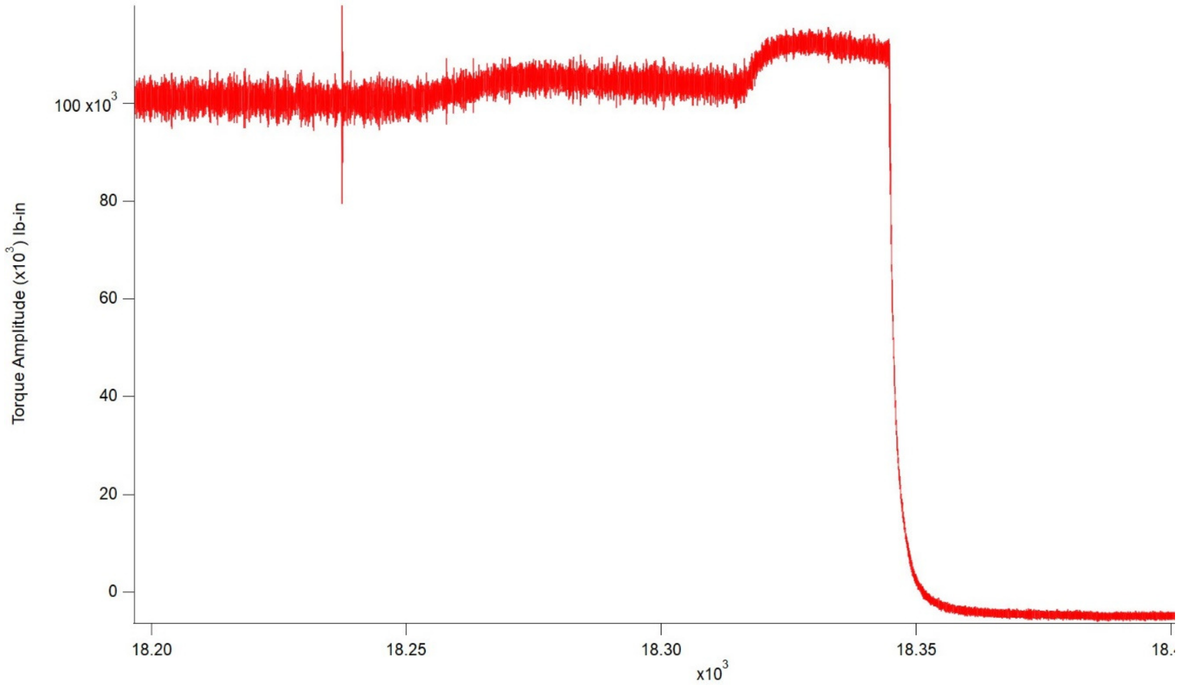
- Steady state coupling torque increases linearly with VFD frequency
- A direct relationship exists, once the pumped fluid gains inertia, which can be used in efficiency calculations



# Field Testing Results – Test Site #2

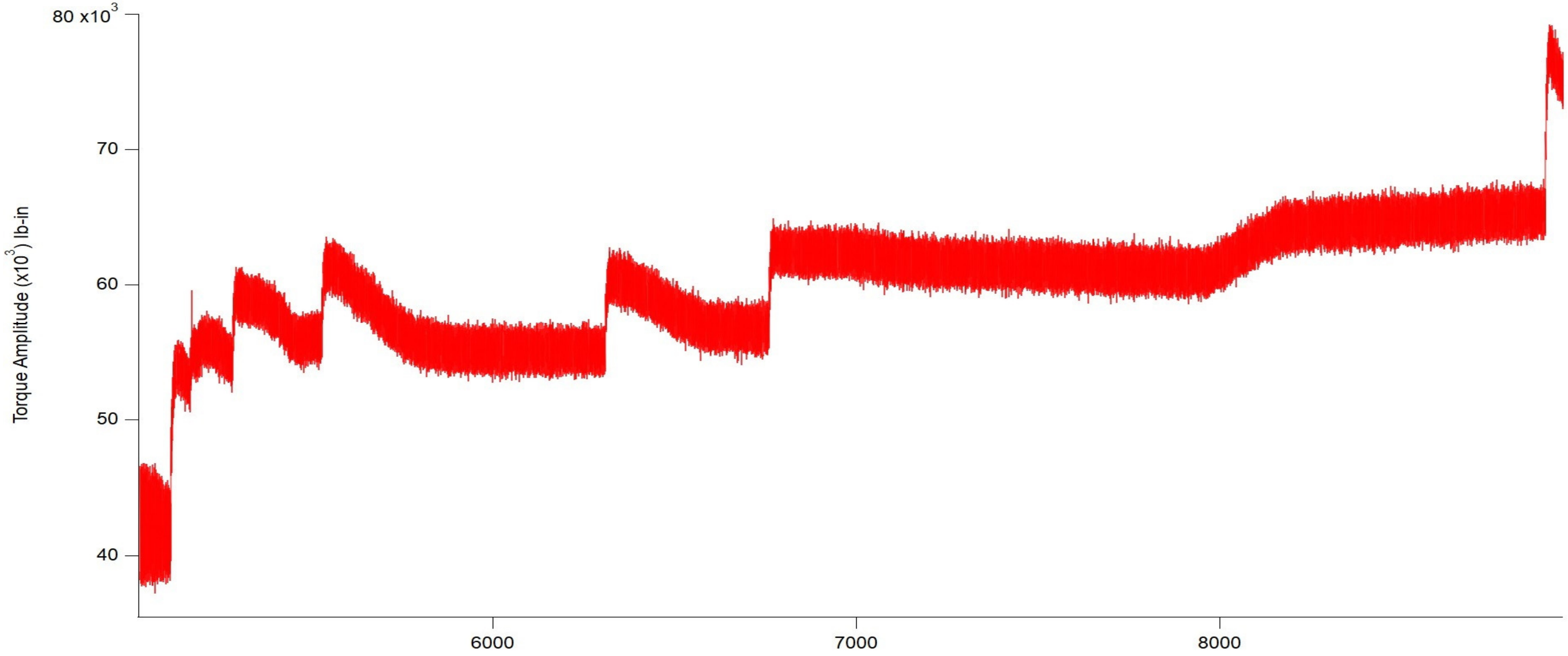
- Torsional oscillations at 60 Hz and 2x the VFD operational frequency can be seen in transient torque data
- Steady state torque amplitudes for pipeline pumping systems falls within a range for each speed. This may be related to varying suction and discharge pressures dependent on ancillary pumps/conditions
- No reversing torques or torsional resonance seen during startup compared to the non-VFD data from testing site #1, likely due to valves being open during startup at testing site #2





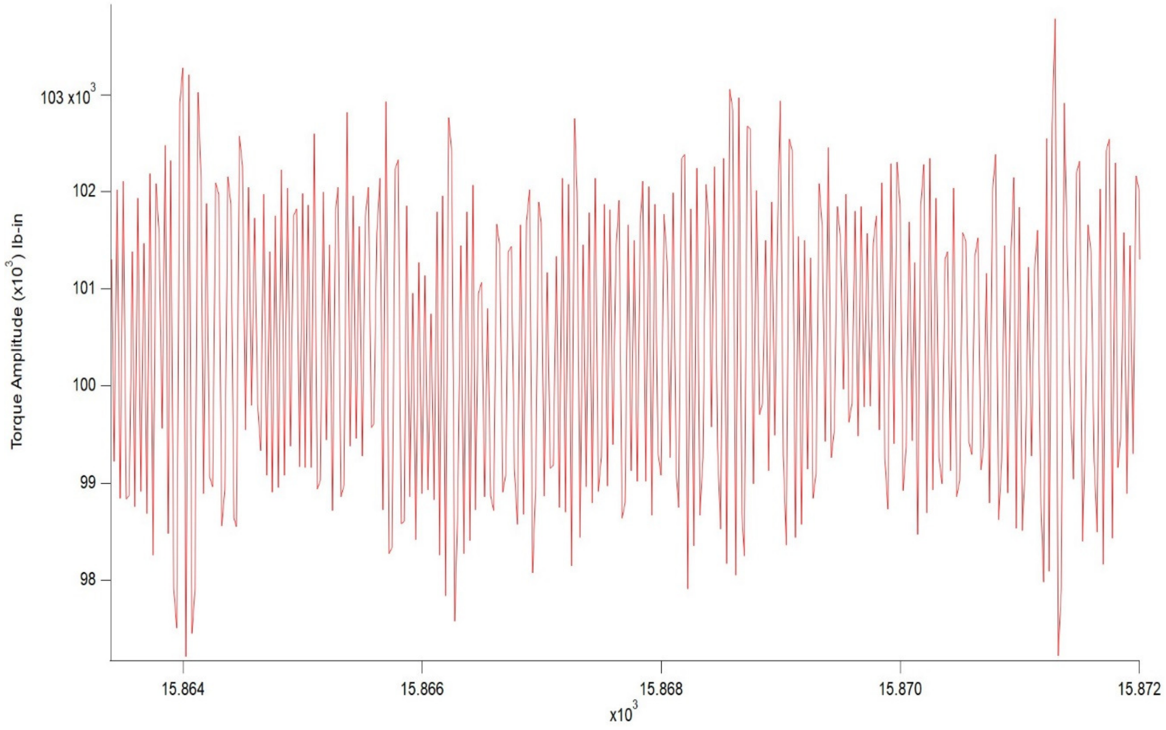
# Field Testing Results – Test Site #2

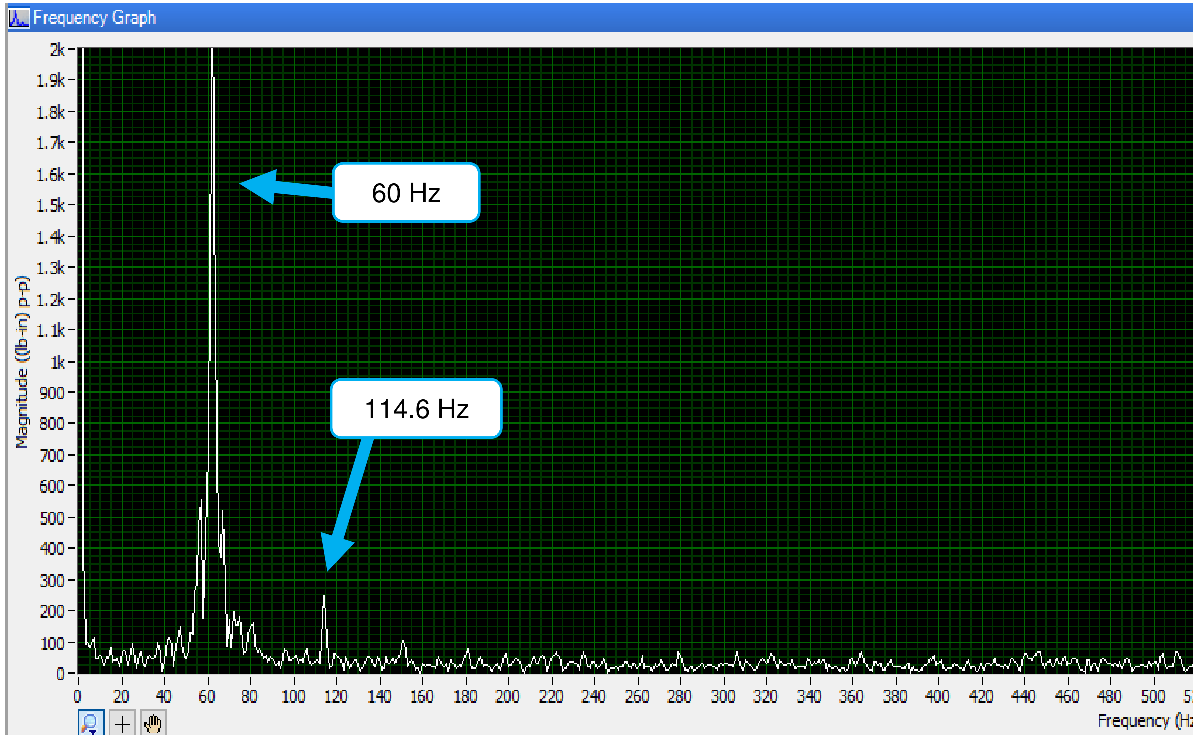
- A sample of transient torque data from Hour 2 of VFD driven testing is shown in the figure below
- Small speed adjustments can be noted to cause spikes in torque
- Torque spikes up, then decreases in magnitude as pumped fluid gains inertia
- A variance is seen from initial steady state torque to final steady state torque of around 500 in-lb
- The difference from the peak average torque spike amplitude to the final average steady state amplitude is around 11% of the steady state value. Peak-to-peak oscillations were around 3750 lb-in at steady state.



# Field Testing Results – Test Site #2

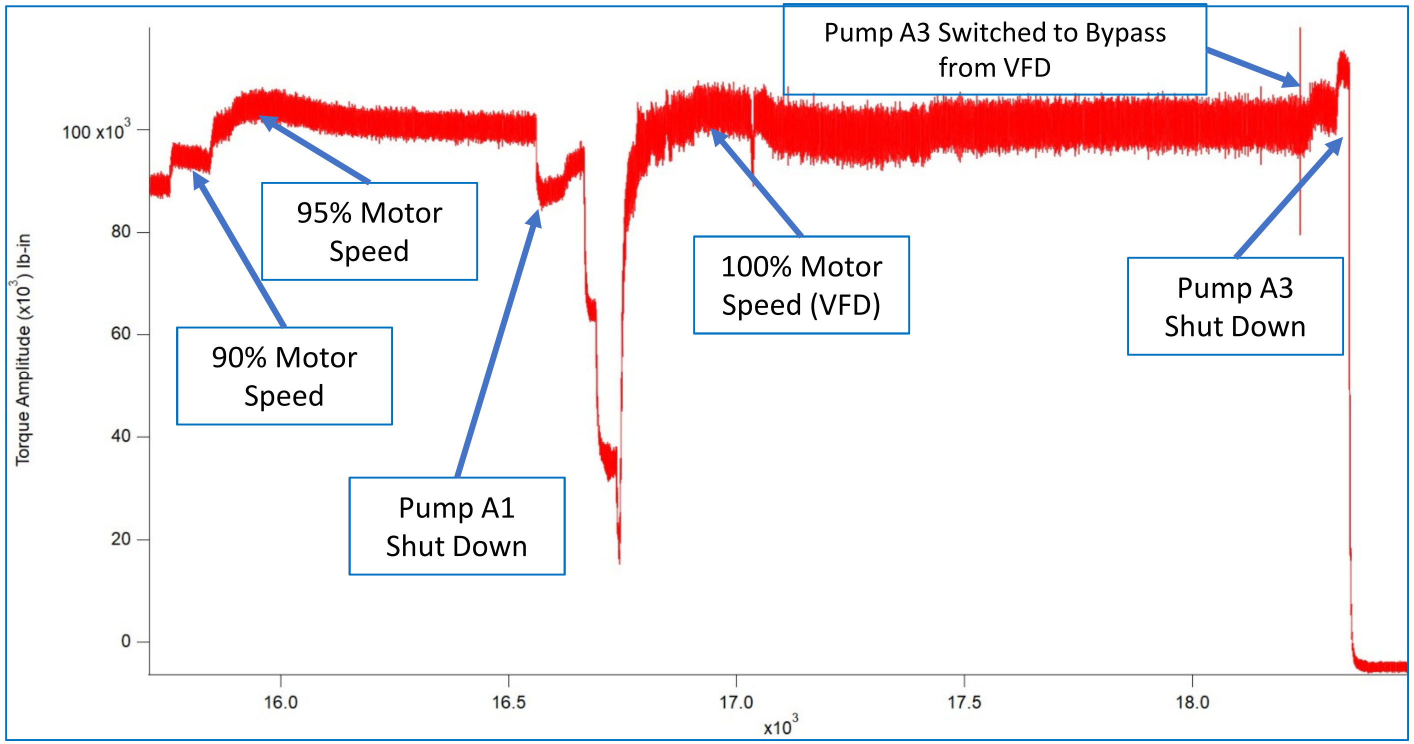
- A zoomed in view of torque data where oscillations at 60 Hz and 114.6 Hz are noted in the FFT shown in the below figure
- The VFD is at 57.3 Hz in this test segment
- A clear 2x VFD frequency exists at every speed step during testing, until the pump runs from line voltage at the end of the test
- Oscillations at steady state showed an average peak-to-peak amplitude of 3750 in-lb in the VFD driven data and non-VFD data across the full range of torque amplitudes (at both sites)





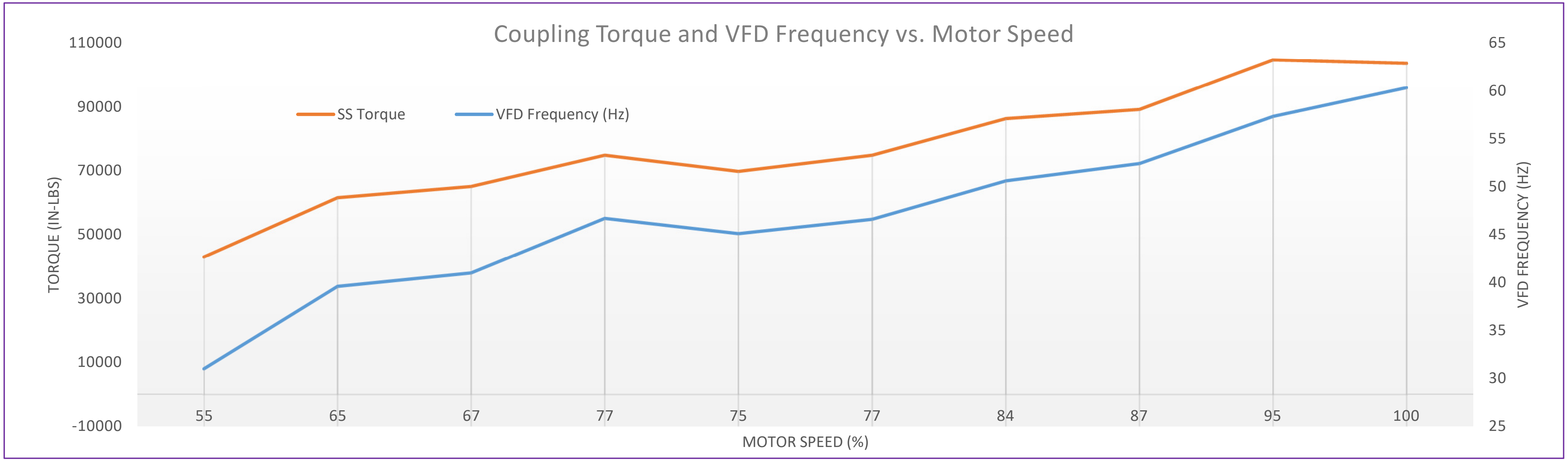
# Field Testing Results – Test Site #2

- Pump A1 was shut down during the last speed step of the test (Hour 5)
- Pump A3 was the test subject which had the instrumented coupling spacer installed
- Torque and speed at A3 were affected by the shutdown of pump A1
- The amplitude of the peak-to-peak torsional oscillations at A3 increased after A1 was shut down, through torque at steady state was nearly the same
- Decreasing steps in torque are due to the operational procedure during pump A1 shutdown

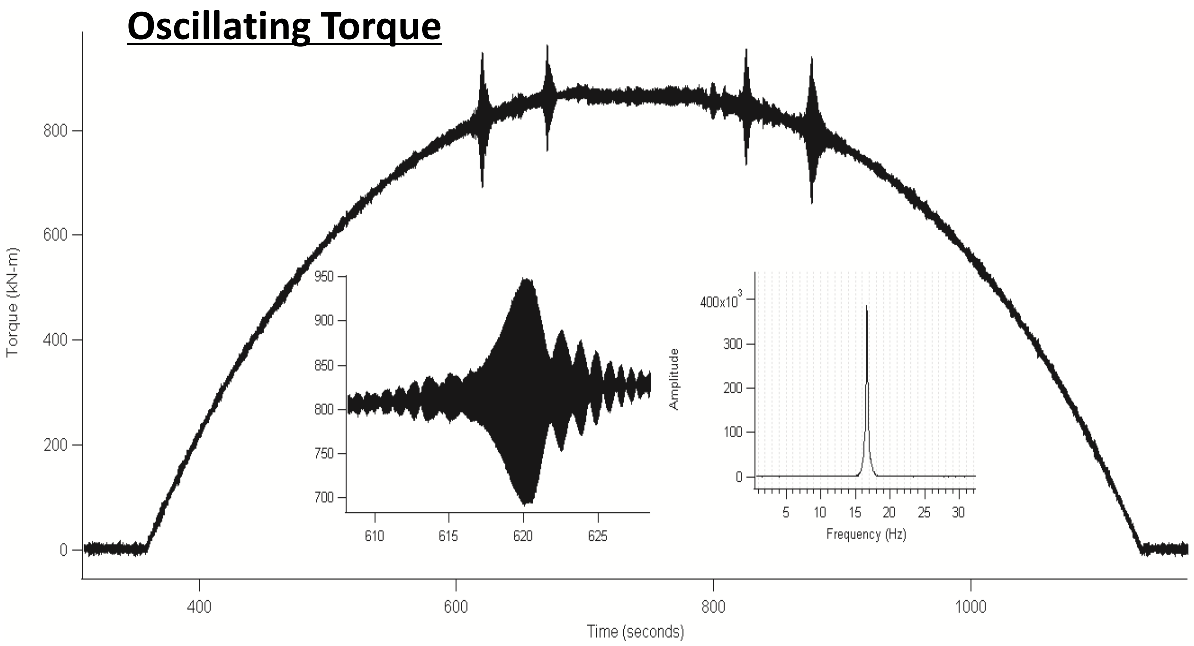


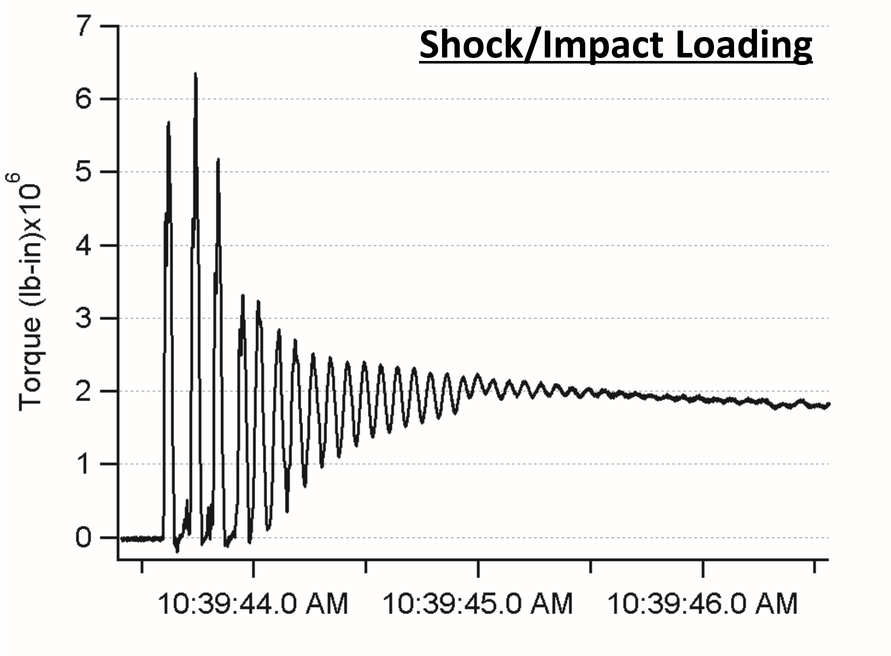
# Field Testing Results - Overall

- Testing was initially done with valves closed (Test Site #1), which resulted in torsional oscillations at startup resembling intermittent resonance at a natural frequency and included some reversing torques down to -20k in-lb spikes
- Testing site #1 operated at a fixed speed; no VFD was used at the site
- Further testing at Test Site #2 with an alternate operator, VFD controlled motor, with valves open and no torsional resonance was noted during startup
- The testing site #2 utilized a VFD operated motor and was able to gradually increase pump speed (shown below)



# Transient Torque Measurement for Machinery Diagnostics

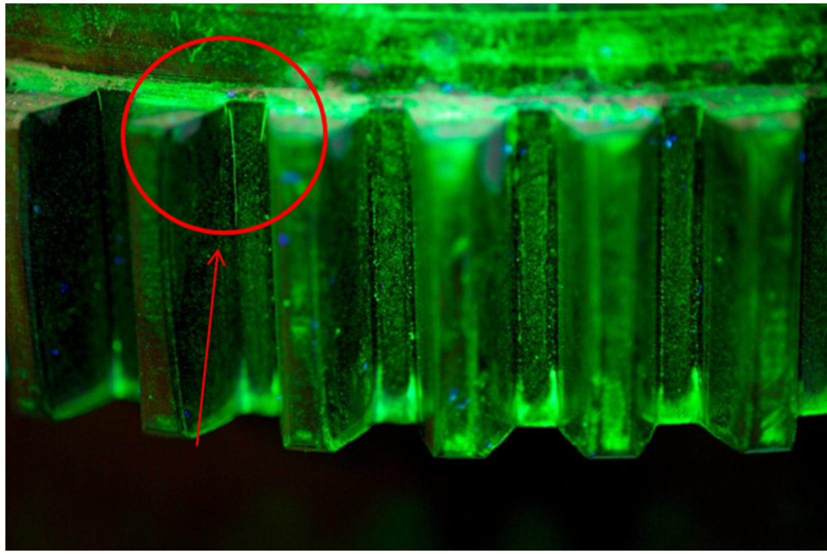

**Oscillating Torque**

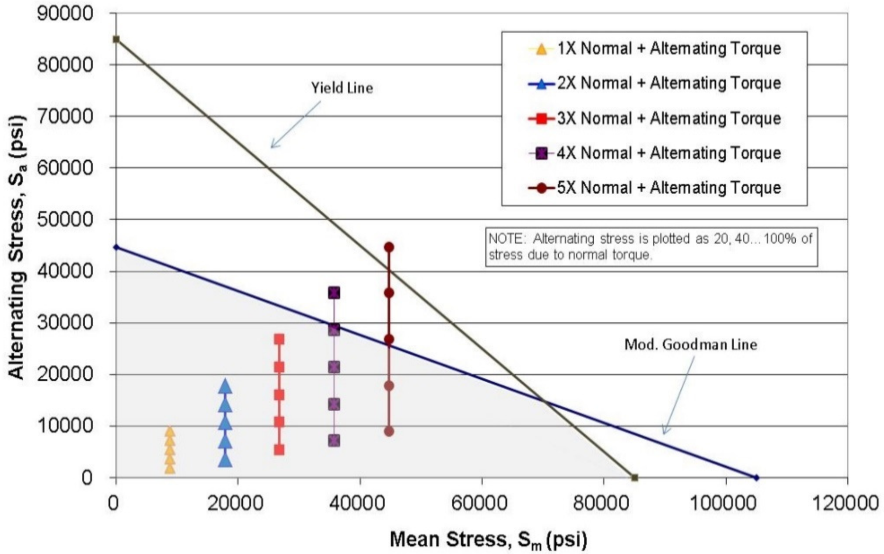

**Shock/Impact Loading**

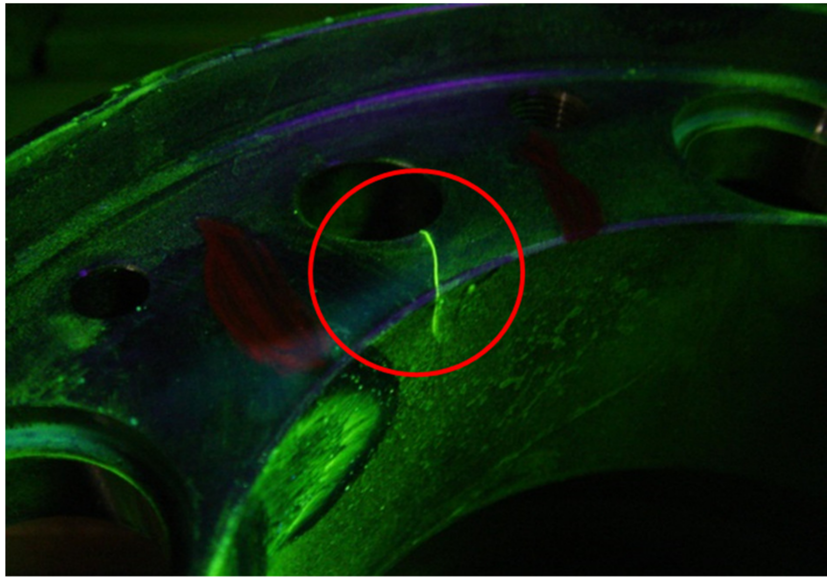
- Torsional vibration can be observed as oscillations (vibratory) or sudden peaks
- Magnitude determines severity (i.e. stress), frequency identifies source
- Potential sources: resonance, operational/process faults, start-up/shut-down, electrical

# Transient Torque - Effect on Rotating Equipment

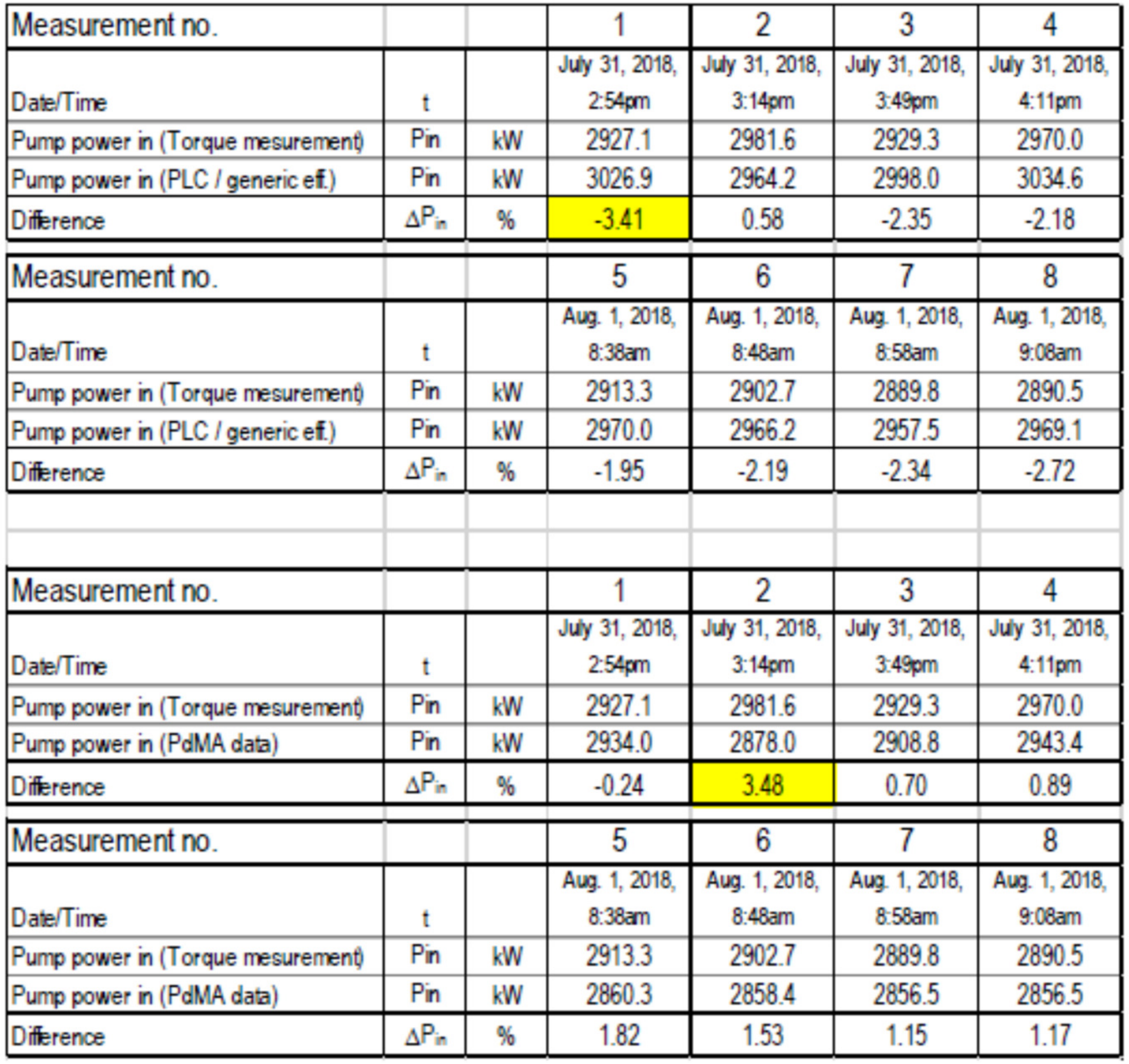
- Torque is directly related to the mechanical stress which it induces in a drivetrain component.
- Damage occurs when stresses in the load-transmitting material exceed the endurance limit or yield limit.
- Simple geometries can be analyzed with classical stress calculations
- Complex geometries typically require finite element analyses to determine allowable torque levels







# Pump Field Performance Testing Results

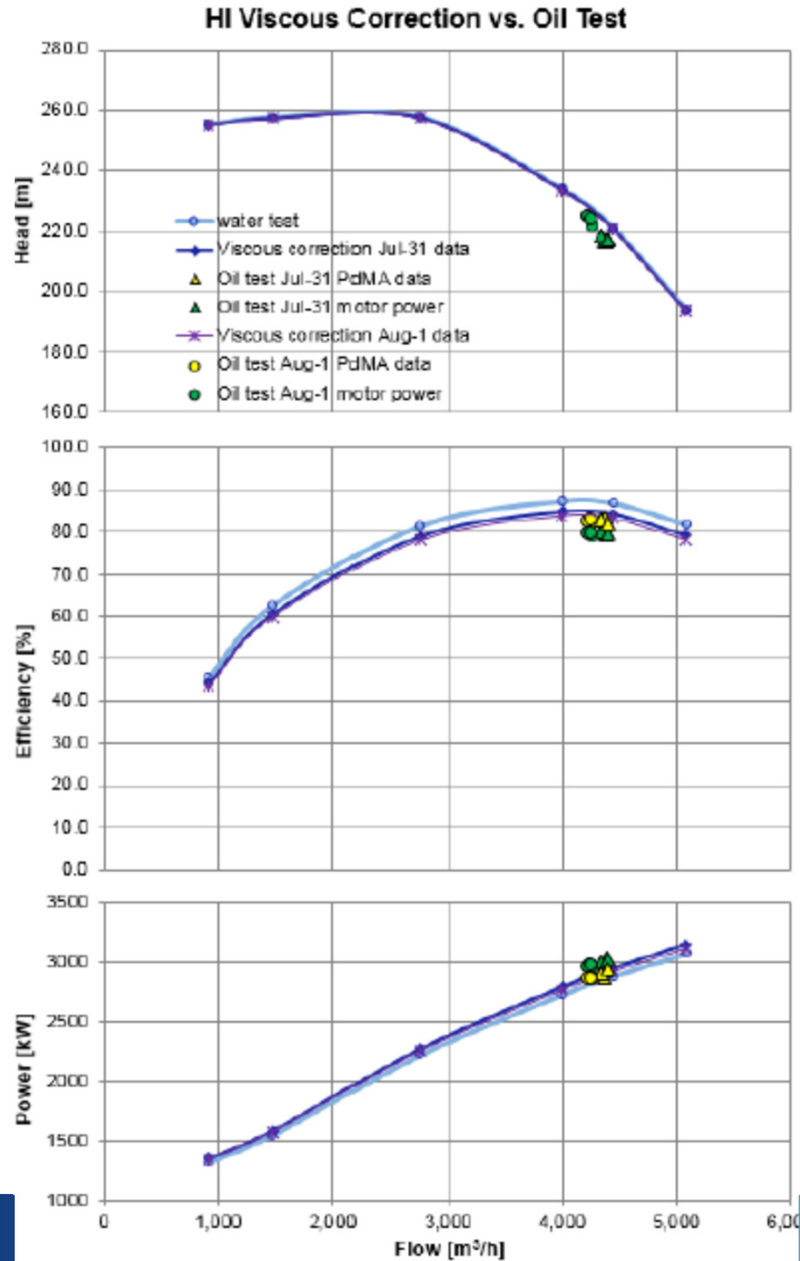


| Measurement no. | | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| Date/Time | t | | July 31, 2018, 2:54pm | July 31, 2018, 3:14pm | July 31, 2018, 3:49pm | July 31, 2018, 4:11pm |
| Pump power in (Torque mesurement) | Pin | kW | 2927.1 | 2981.6 | 2929.3 | 2970.0 |
| Pump power in (PLC / generic eff.) | Pin | kW | 3026.9 | 2964.2 | 2998.0 | 3034.6 |
| Difference | $\Delta P_{in}$ | % | -3.41 | 0.58 | -2.35 | -2.18 |

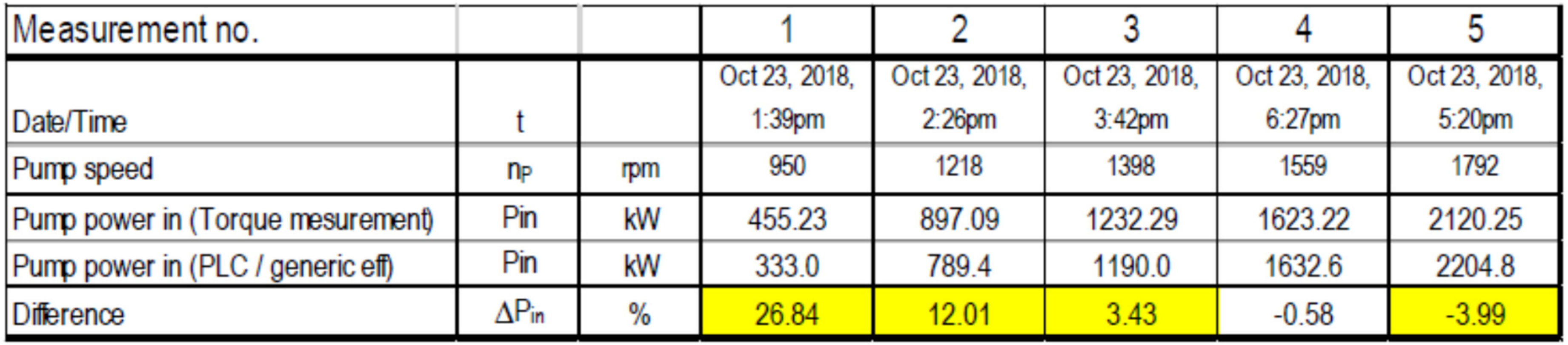
| Measurement no. | | | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|
| Date/Time | t | | Aug. 1, 2018, 8:38am | Aug. 1, 2018, 8:48am | Aug. 1, 2018, 8:58am | Aug. 1, 2018, 9:08am |
| Pump power in (Torque mesurement) | Pin | kW | 2913.3 | 2902.7 | 2889.8 | 2890.5 |
| Pump power in (PLC / generic eff.) | Pin | kW | 2970.0 | 2966.2 | 2957.5 | 2969.1 |
| Difference | $\Delta P_{in}$ | % | -1.95 | -2.19 | -2.34 | -2.72 |

| Measurement no. | | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| Date/Time | t | | July 31, 2018, 2:54pm | July 31, 2018, 3:14pm | July 31, 2018, 3:49pm | July 31, 2018, 4:11pm |
| Pump power in (Torque mesurement) | Pin | kW | 2927.1 | 2981.6 | 2929.3 | 2970.0 |
| Pump power in (PdMA data) | Pin | kW | 2934.0 | 2878.0 | 2908.8 | 2943.4 |
| Difference | $\Delta P_{in}$ | % | -0.24 | 3.48 | 0.70 | 0.89 |

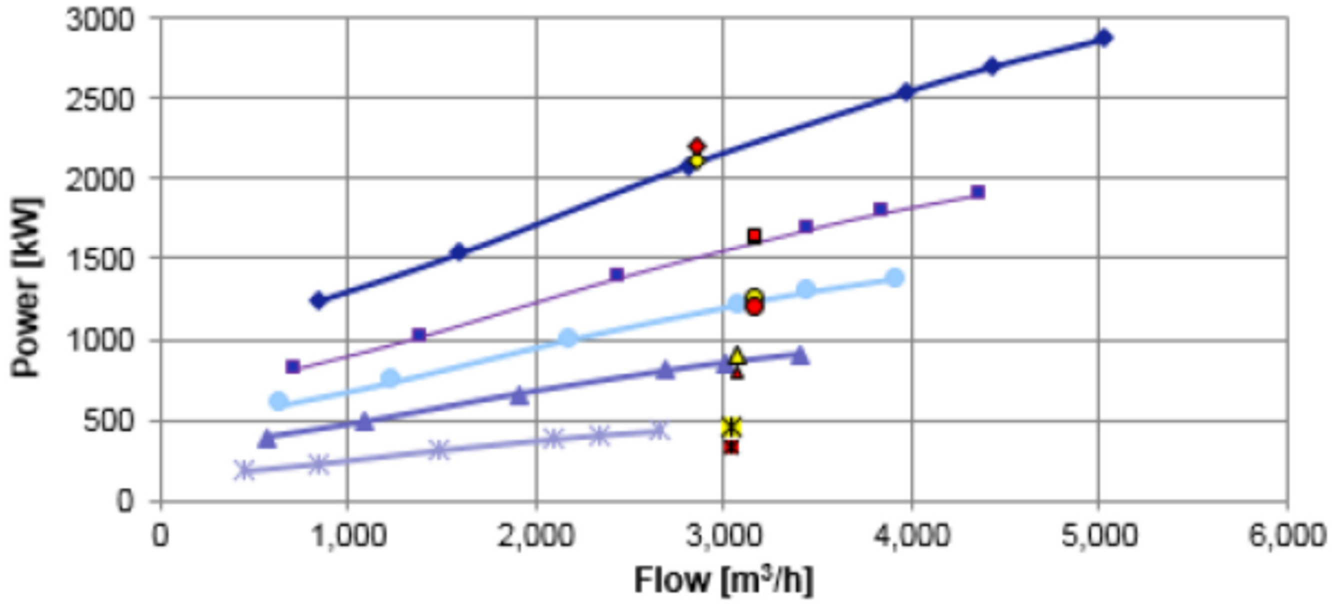
| Measurement no. | | | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|
| Date/Time | t | | Aug. 1, 2018, 8:38am | Aug. 1, 2018, 8:48am | Aug. 1, 2018, 8:58am | Aug. 1, 2018, 9:08am |
| Pump power in (Torque mesurement) | Pin | kW | 2913.3 | 2902.7 | 2889.8 | 2890.5 |
| Pump power in (PdMA data) | Pin | kW | 2860.3 | 2858.4 | 2856.5 | 2856.5 |
| Difference | $\Delta P_{in}$ | % | 1.82 | 1.53 | 1.15 | 1.17 |



# Pump Field Performance Testing Results



| Measurement no. | | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| Date/Time | t | | Oct 23, 2018, 1:39pm | Oct 23, 2018, 2:26pm | Oct 23, 2018, 3:42pm | Oct 23, 2018, 6:27pm | Oct 23, 2018, 5:20pm |
| Pump speed | $n_P$ | rpm | 950 | 1218 | 1398 | 1559 | 1792 |
| Pump power in (Torque mesurement) | Pin | kW | 455.23 | 897.09 | 1232.29 | 1623.22 | 2120.25 |
| Pump power in (PLC / generic eff) | Pin | kW | 333.0 | 789.4 | 1190.0 | 1632.6 | 2204.8 |
| Difference | $\Delta P_{in}$ | % | 26.84 | 12.01 | 3.43 | -0.58 | -3.99 |

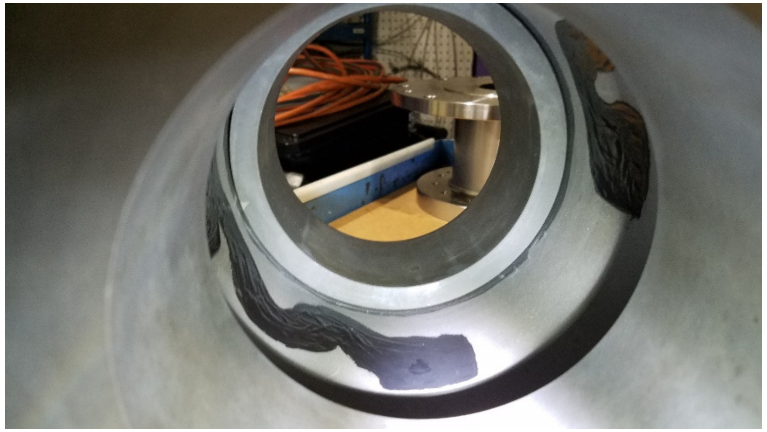


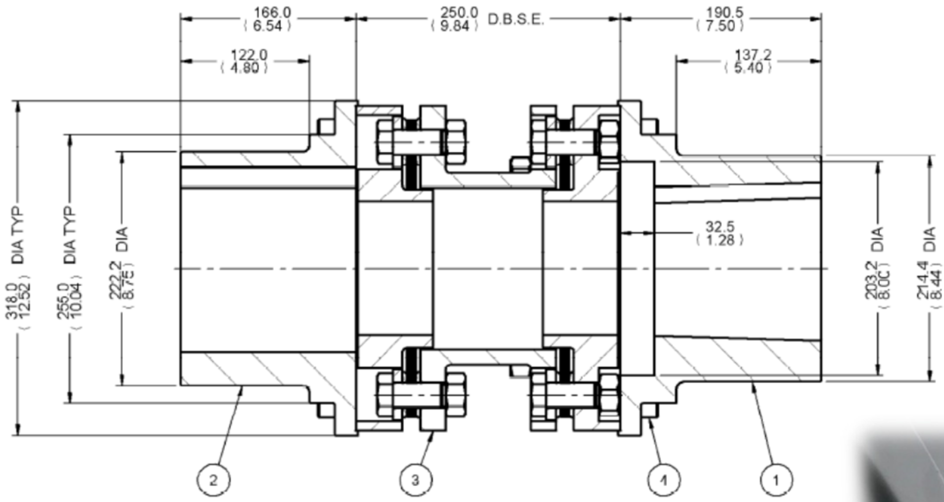
# Conclusions

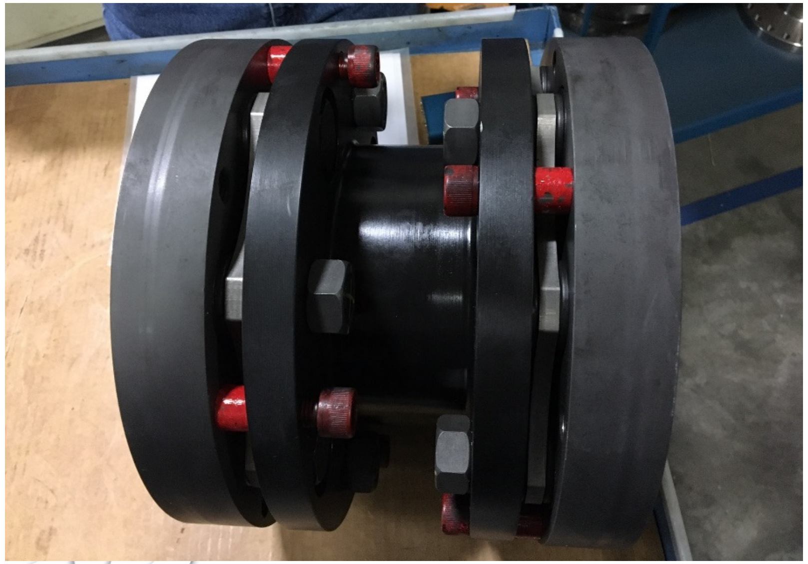
- A custom dynamic torque measurement system developed to meet the project objectives.
- Torque measurement system provided accurate power measurements – verified by secondary electrical power measurements and PDMA testing;
- System facilitated identification of efficiency discrepancy b/w motor name plate and measured values;
- System facilitated VFD- Motor- Pump Train mechanical operation validation; VFD excitation estimated to be within the tolerance;
- Demonstrated case study to use the system as a troubleshooting tool to pin point performance degradation on VFD or Motor or Pump.
- Can be used for performance guarantee by accurate HP – efficiency estimation during new pump installs and brownfield modifications to the pump.

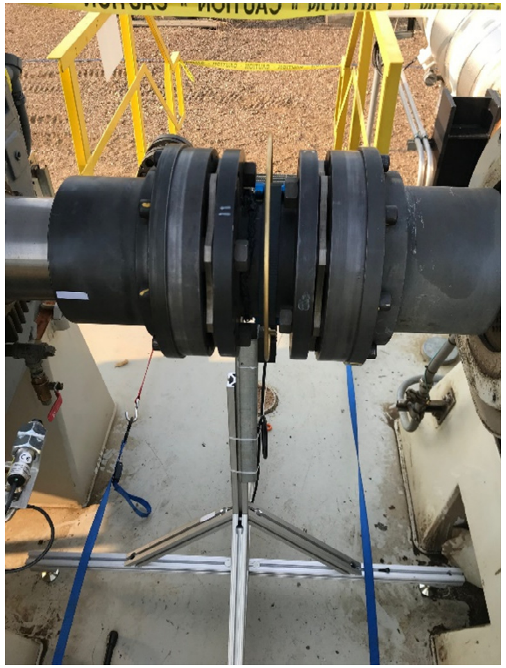
# Appendix

# Telemetry System – Additional Images









# Effect on Rotating Components – Alternate Photos

# Telemetry System – Future Integration

- Fully enclosed housing encapsulating wireless transmitter, battery cells, and strain gages, benefits includes:
  - Decreased windage
  - Improved balance characteristics
  - Increased battery life
  - Simplified field installation - no hoop antenna