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30th Pump SYMPOSIA
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DRIVE SHAFT FAILURE ANALYSIS ON A MULTISTAGE VERTICAL TURBINE PUMP IN RIVER WATER SUPPLY SERVICE IN A NICKEL AND COBALT MINE IN MADAGASCAR - BASED ON ODS AND FEA

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Problem Statement

- Pumps installed in 2011. One drive shaft suffered a catastrophic failure on 12/10/11 and was shortly followed by another on 1/26/12.
- Prior to any analysis by the authors, cladding and extra bracing were added to the engine support structure to reduce vibration on all three pumps. Additionally, plates were welded along the I-beams supporting the pump to the discharge on all three pumps. Lastly, grout was added to the internal cavity created by the cladding on one pump.
- The gearbox on one of the pumps suffered a crack on one of its centering feet after one drive shaft incident.
- The goal became to determine the root cause of the drive shaft failure, including identification of any resonance or other stress creators over the pump operating speed range. Based on this, a practical fix would be identified.

Photos Drive Shaft Failures






Failures located at the male end weld (same location each incident) at the engine-side of the assembly.

Outline Drawing

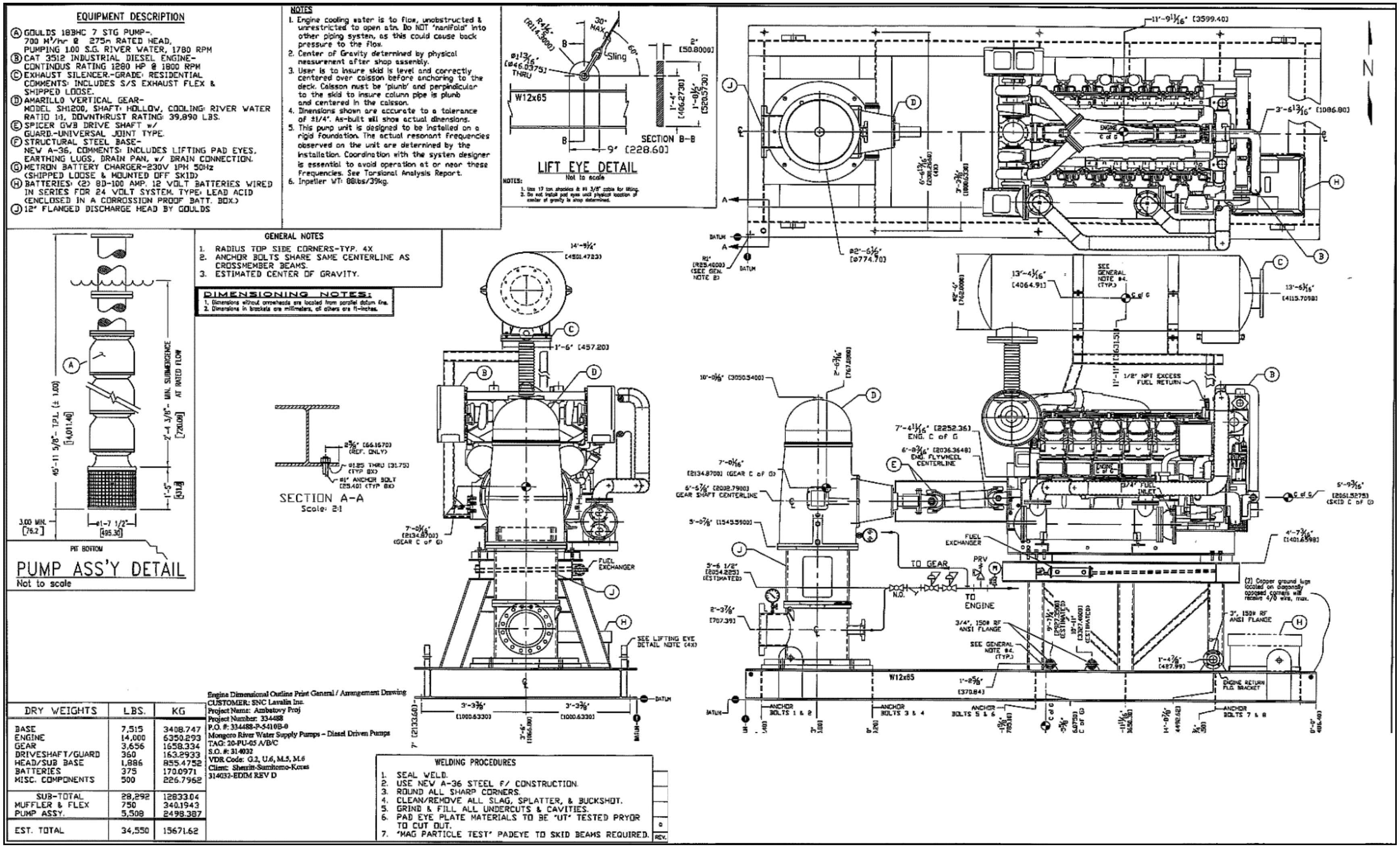
COS Pump Speed: ***1760 rpm***

COS Engine Speed: ***1800 rpm***

Condition of Service (COS)

Engine Cylinders: ***12***

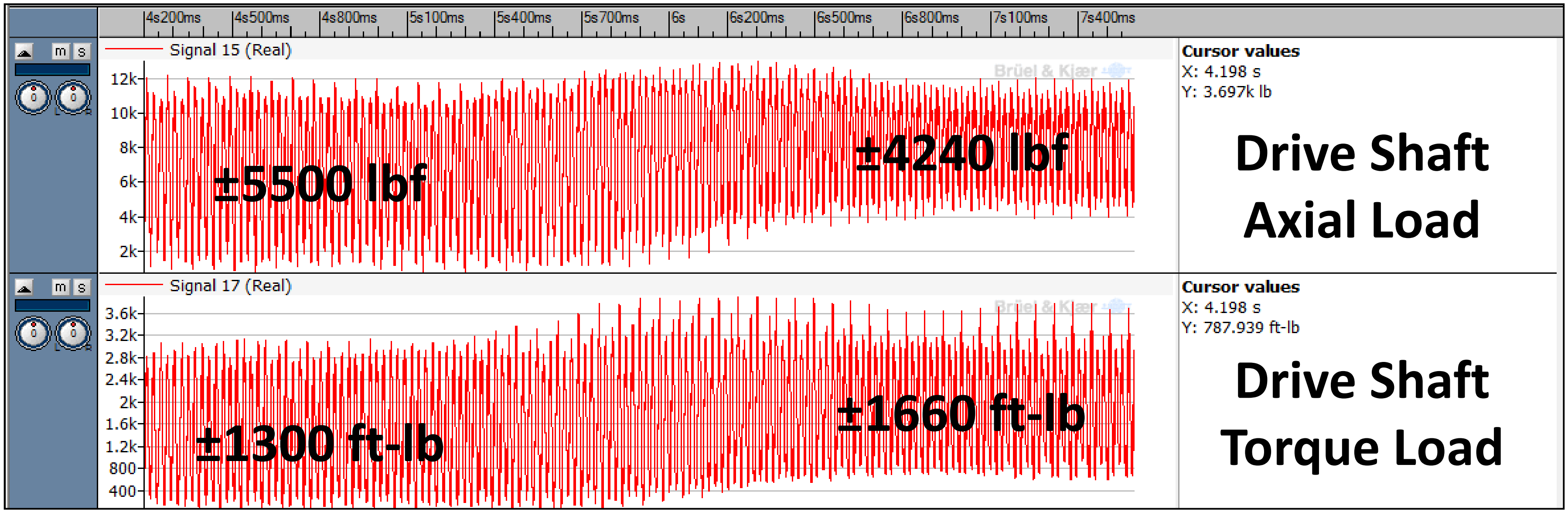
Gearbox Ratio: ***1:1.0217***

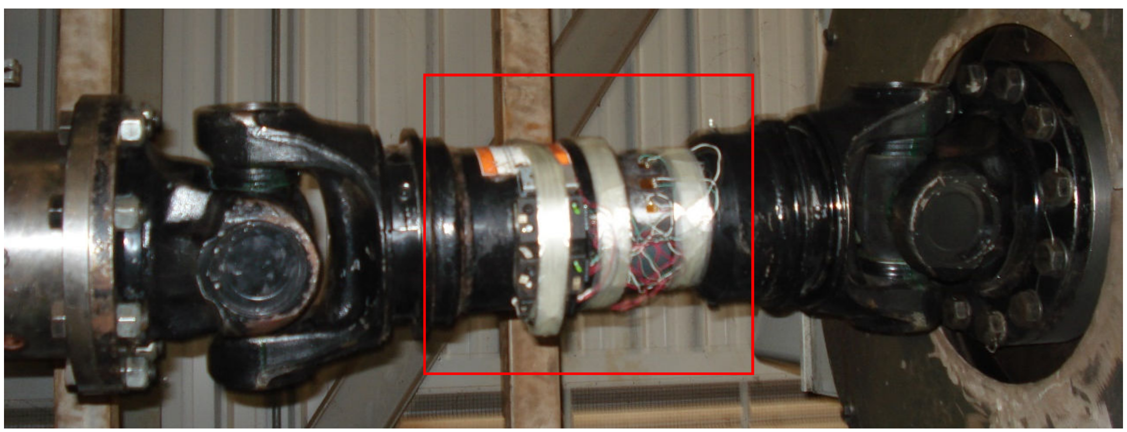


Analysis Method and Steps Taken

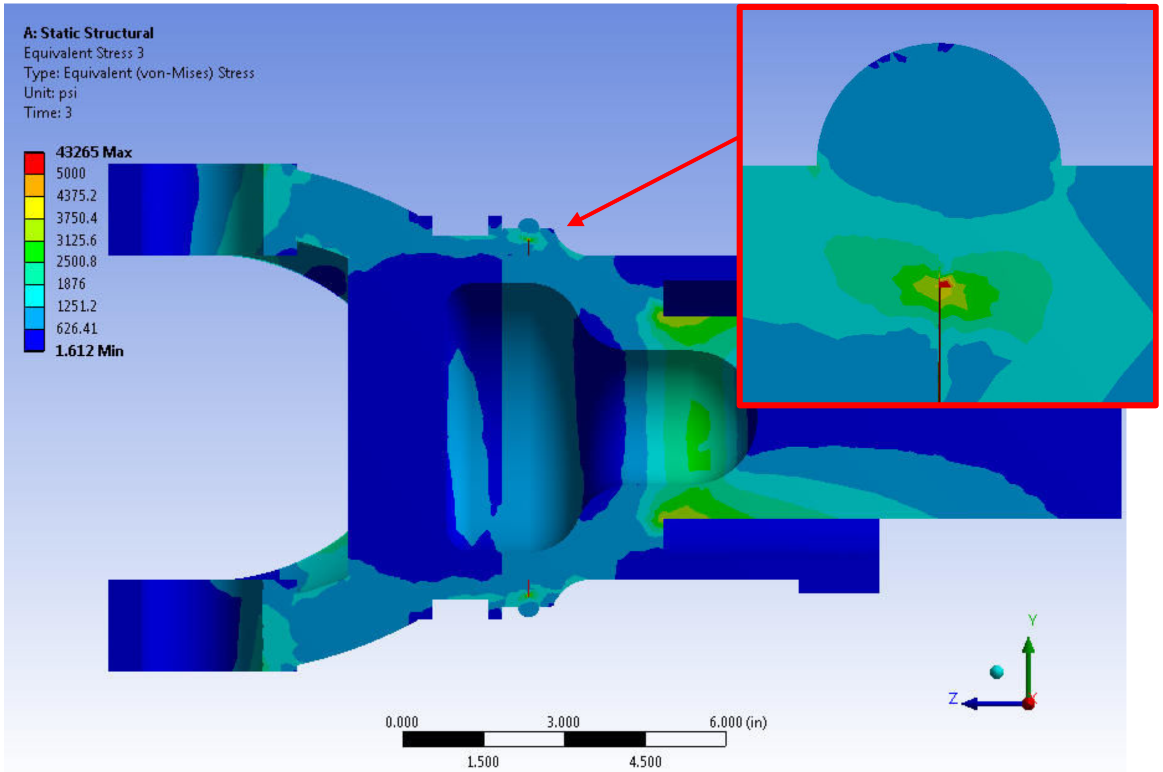
- Radio Frequency (RF) telemetry strain gauges measuring axial bending and torque were installed on the driveshaft of one pump.
- Time-transient vibration testing results on the pump, gearbox, drive shaft, and engine were collected using accelerometers and shaft sticks.
- An Operating Deflection Shape (ODS) test was performed to reveal dynamic behavior of the entire pump system.
- Experimental Modal Analysis (EMA) data was collected to find natural frequencies of the different system components.
- A test-calibrated Finite Element Analysis (FEA) based fracture mechanics analysis approach was used to predict the ability of detected stresses in the drive shaft to encourage initiation and propagation of the crack.

Time Domain Plots/ Drive Shaft 1,650 - 1,820 rpm





Finite Element Analysis



Stress Linearization Through Weld Bead

Results	
Membrane	1407.2 psi
Bending (Inside)	1739. psi
Bending (Outside)	1739. psi
Membrane+Bending (Inside)	3118.1 psi
Membrane+Bending (Center)	1407.2 psi
Membrane+Bending (Outside)	535. psi

If the weld on the driveshaft did not penetrate to the inner diameter of the welded components in the region near the weld, this would create a geometry that is basically a crack around the circumference of the shaft. This creates a high stress concentration at the inner edge of the weld. Such a circumstance can be quantitatively evaluated with Linear Elastic Fracture Mechanics (LEFM).

Fracture Mechanics Calculation

The peak membrane plus bending stress located at the region near the "crack" was calculated from the FEA model to be 3118 psi due to the observed alternating torque and axial loading.

Fatigue Analysis Due to Alternating Torque and Axial Load

Alternating Torque Load Stress $\sigma_a := 3118.1$ psi

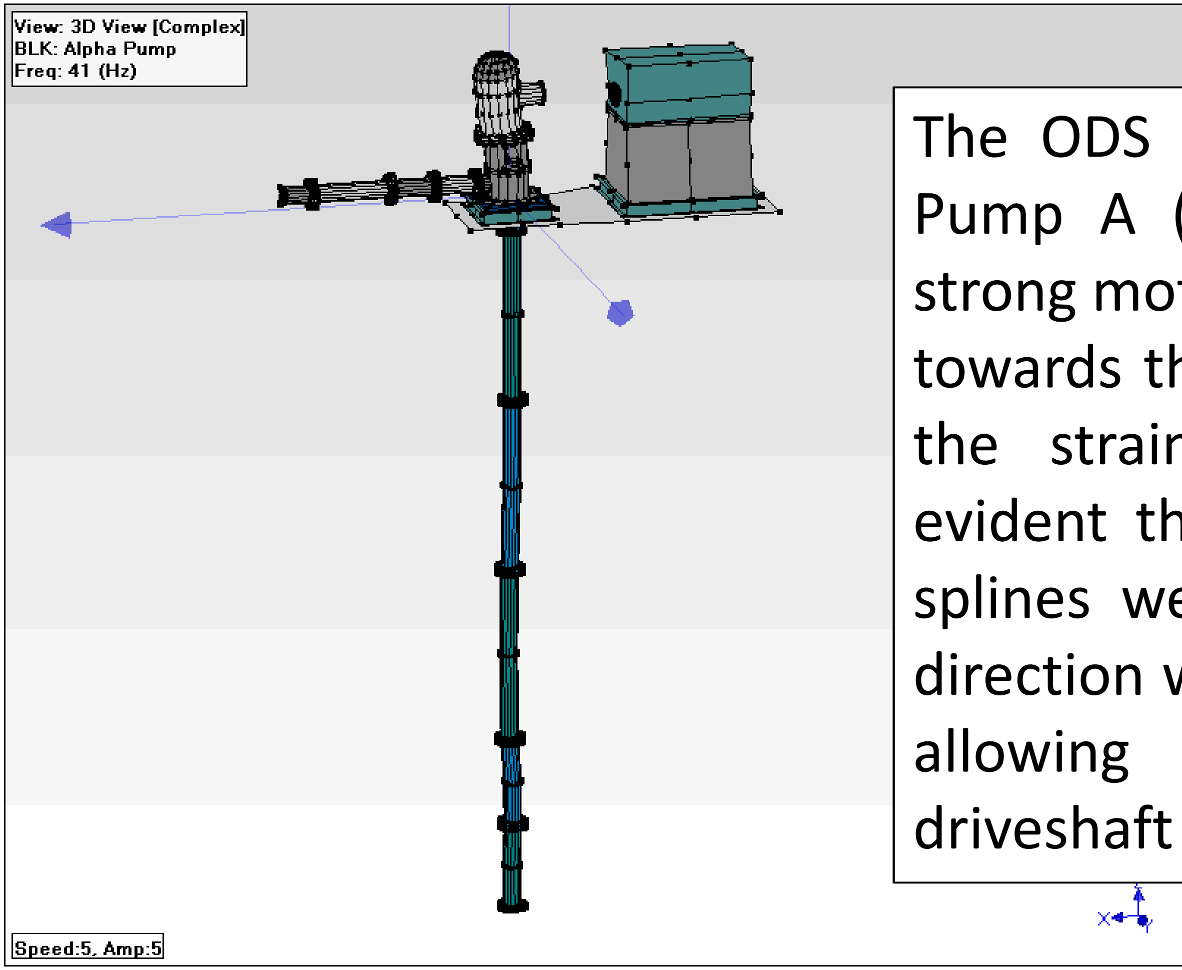
Crack Length $a := 3.3$ inches

Geometry Correction Factor $Y := 1.1$

Stress Intensity Factor $k_I := \sigma_a \cdot Y \cdot \sqrt{\pi \cdot a} = 1.104 \times 10^4$

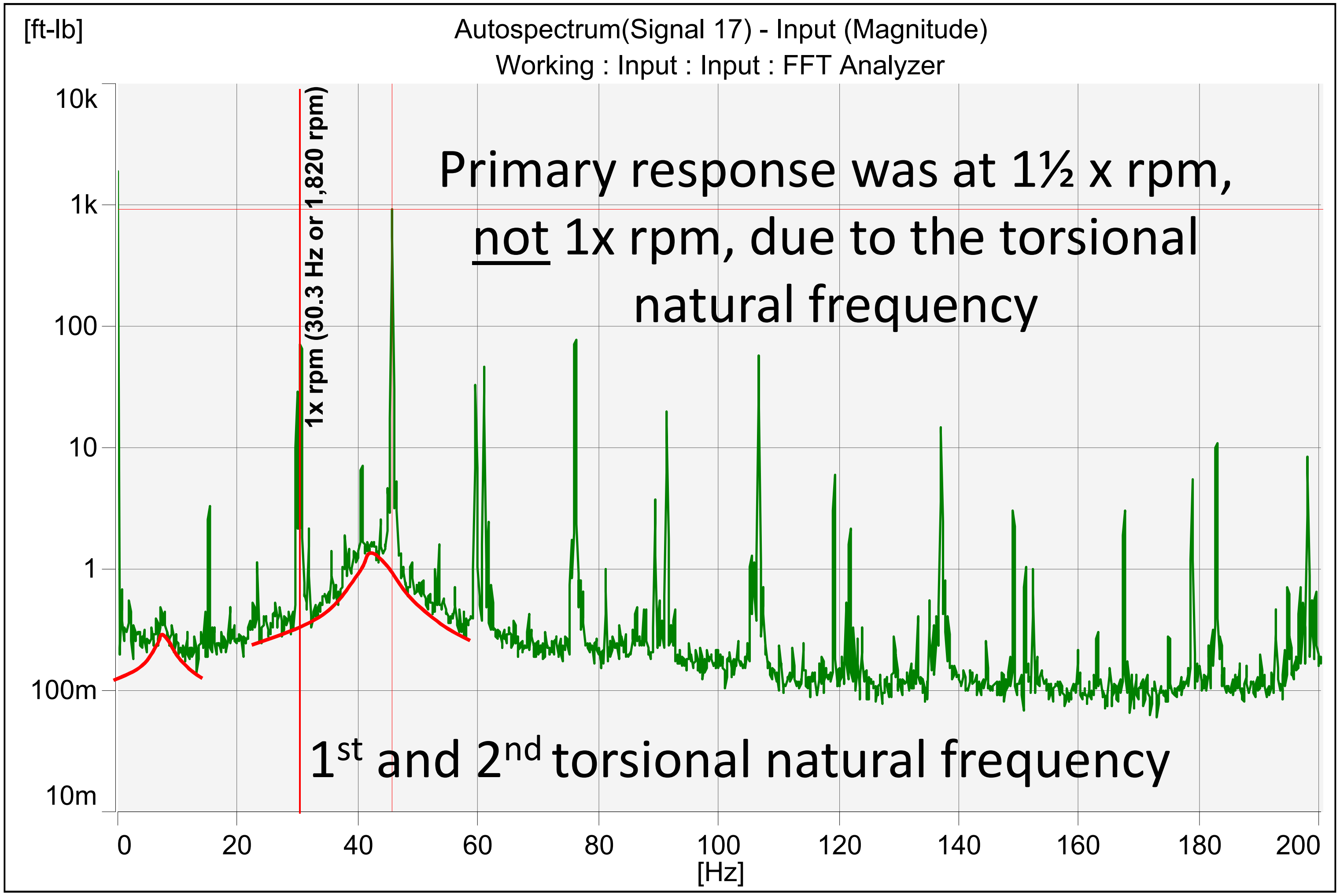
For carbon steels, exceeding a critical stress intensity factor of about 10,000 psi(in)$^{0.5}$ indicates that the crack or material flaw of radial length "a" has the ability to propagate under alternating load. This analysis calculated a possible k_I value of 11,040 which indicates significant but "borderline" probability of failure from fatigue loading of the weld bead.

Computer Model Using ME'Scope Program Plotting ODS Test Results



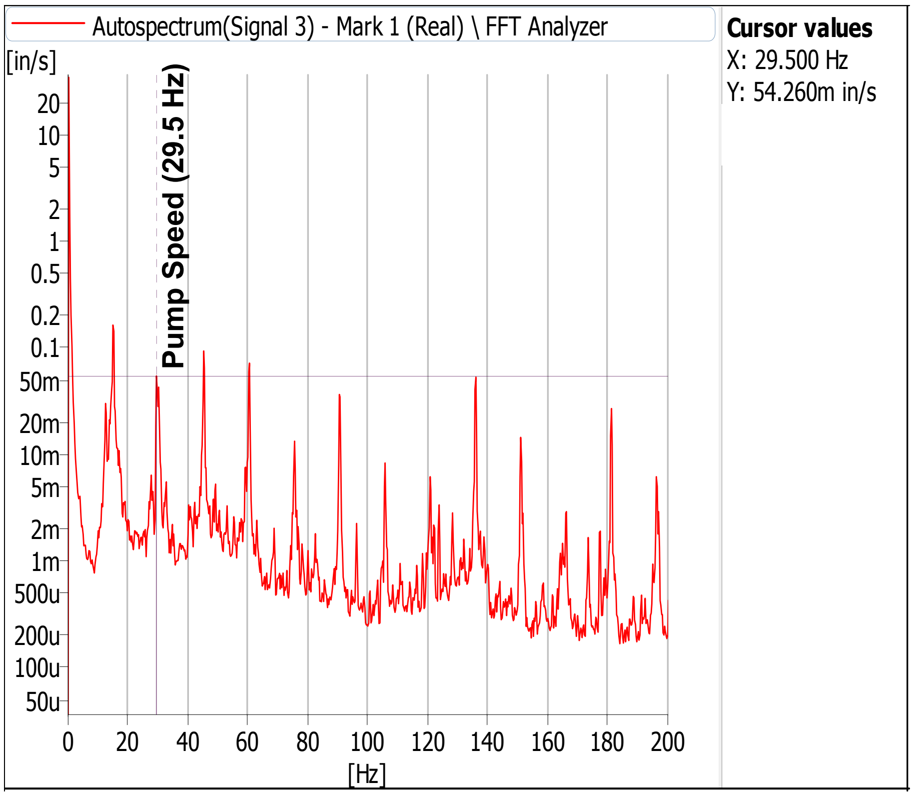
The ODS animation at 41 Hz on Pump A (1.5x RPM) indicated a strong motion of the gearbox head towards the engine. According to the strain gauge data, it was evident that the drive shaft axial splines were binding in the axial direction when under torque load, allowing this mode to enable driveshaft failure.

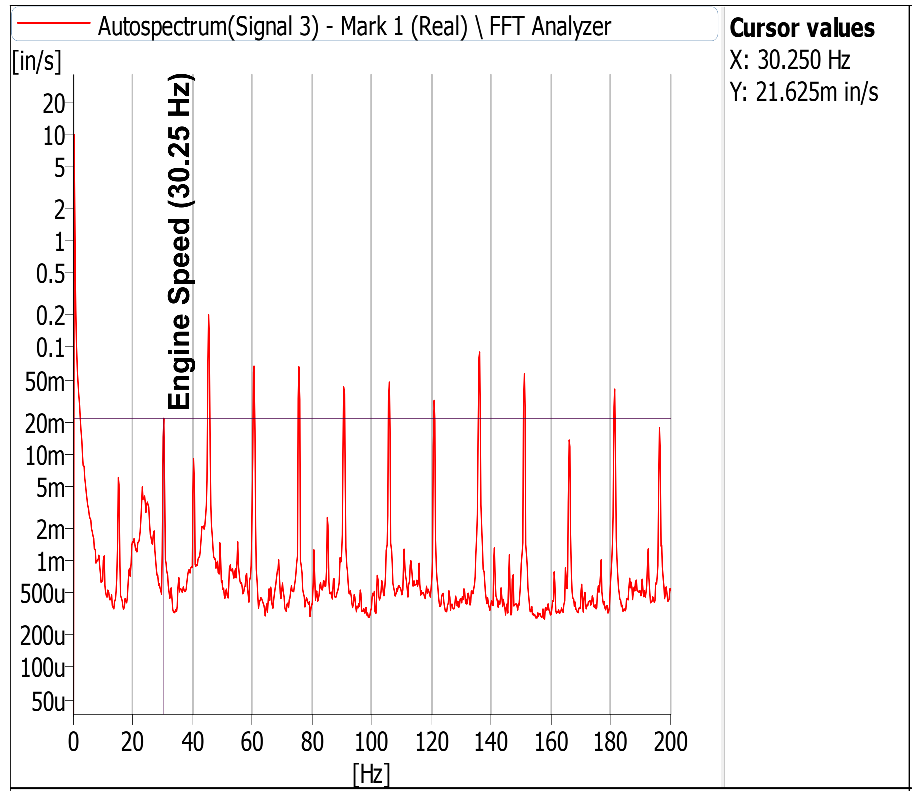
Strain Gage Test



Drive Shaft Torque Spectrum and Torsional Natural Frequencies
Natural frequencies at 7.25 Hz and 42 Hz.

FFT Spectra of Vibration at Gearbox and Engine Top





Gearbox Top,
Input Shaft End

Engine Top,
Drive End

Notice that the ½ x rpm harmonics appear in both the engine and gearbox.

Mangoro Station Pump C Vibration vs. Speed

Signal #	Eng. Speed (rpm)	Pump Speed (rpm)	1x Pump (Hz)	Amp 1x in/s rms Pump	1.5x Eng. (Hz)	Amp 1.5x in/s rms Pump	Overall in/s	Mean Torque Load (ft-lb)	Power (HP)	Torque Oscillation (ft-lb) 0-pk	Oscillating Torque Load (%) 0-pk	Mean Axial Load (lbf)	Axial Oscillation (lbf) 0-pk	Oscillating Axial Load (%) 0-pk	Separation Margin (%) between 42 Hz and 1.5x
3	800	783	13.0	0.12	20.00	0.01	0.14	289	44	250	87%	2,414	1,500	62%	-52.94%
4				0.04		0.02	0.11								
3	1200	1174	19.6	0.14	30.00	0.01	0.20	600	137	550	92%	4,052	2,750	68%	-28.57%
4				0.07		0.02	0.18								
2	1650	1615	26.9	0.17	41.25	0.21	0.32	1,480	465	1,300	88%	6,827	5,500	81%	-1.79%
4				0.09		0.09	0.53								
2	1808.5	1770	29.5	0.09	45.21	0.11	0.35	1,490	513	1,400	94%	7,974	5,350	67%	7.65%
4				0.04		0.04	0.56								
2	1820	1781	29.7	0.07	45.50	0.15	0.24	1,900	658	1,660	87%	8,045	4,240	53%	8.33%
4				0.04		0.03	0.50								
2	1884	1844	30.7	0.08	47.10	0.16	0.48	1,910	685	1,625	85%	7,957	4,065	51%	12.14%
4				0.05		0.04	0.52								

Signal 2 – Top of the gearbox parallel to the discharge

Signal 3 – Top of the gearbox perpendicular to the discharge

Signal 4 – Top of the pump discharge head parallel to the discharge

*1,750 rpm column piping vibration was interpolated

Conclusions / Observations

1. The failure mechanism of the drive shaft was caused by the elevated axial and torsional oscillation loads in combination with the jammed driveshaft spline.

2. The situation became severe because an axial (horizontal parallel to the crankshaft) pump natural frequency and torsional shaft assembly natural frequency were simultaneously in resonance with an unexpectedly high 1.5x running speed harmonic, which appeared due to a poorly tuned engine (resulting in a 1/2x rpm fundamental and its harmonics).

3. The 2nd torsional natural frequency of the drive shaft was determined to be at 42.0 Hz (Pump C). The separation margin from 1.5x running speed is within 5% from both the pump and engine speed.

4. The torsional oscillation was observed to be as high as 94% zero-to-peak of the mean torque value.

Conclusions / Observations

5. The measured axial force oscillation imposed on the drive shaft peaked at 11,000 lbf pk-pk.

6. Since the weld on the driveshaft did not penetrate to the inner diameter of the material the region near the weld, this created effectively a crack around the circumference of the shaft. This resulted in a high stress concentration at the edge of the weld. The peak oscillating membrane plus bending stress amplitude located at the region near the "crack" was calculated from the FEA model to be 3118 psi due to the observed alternating torque and axial loading.

7. For carbon steels, exceeding a critical stress intensity factor of 8,000-10,000 indicates the effective initiated crack length "a" has the ability to propagate under alternating load. This analysis calculated a stress intensity factor value of 11,040 which explained the failure from fatigue loading on the weld bead.

Recommendations/ Results

1. The engine was re-tuned due to the observed mis-firing, since it was providing unusually strong torque impulses or "shocks" at the rate of 1/2x RPM, which caused strong frequency harmonics. This left no place to “park” the system natural frequencies to avoid resonance.

2. A torque shock absorbing coupling between the engine and the drive shaft was implemented. The entire drive shaft and coupling assembly was replaced including the u-joints at each end.

3. The highest vibration level dropped from 24 mm/s pk at the gearbox horizontal measurement location near the input shaft to 7.8 mm/s pk after change to a flexible coupling. Failures ceased.