White Paper

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Torsional Issues: Stop Guessing and Measure the Problems Directly

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INTRODUCTION

Failure mechanisms such as misalignment, balance, or lubrication issues can cause machinery failure. Many of these problems can be identified using standard non-destructive testing (NDT) methods including vibration analysis, infrared thermography, and tribology.

Torsional transmission issues are the source of a large percentage of problems and damage to rotating equipment and may be the cause of many “mysterious” repeat, chronic drive component failures.

Excessive peak torque loads and torsional resonances are frequently the cause of torsional related failures. Unfortunately, torsional issues are difficult to detect using standard NDT methods. Direct measurement of the torque on the shaft using strain gages is the only accurate technique to assess the torsional conditions.

DISCUSSION

Motor Current and Torque

Directly measuring the transmitted torque utilizing strain gage based torque telemetry is the most accurate method of measuring the actual torque on a shaft. Many process engineers and other professionals incorrectly assume that measuring motor current will provide an excellent analysis of torsional characteristics. The current that flows through a motor is a function of the responses to the dynamic drivetrain conditions, drive control parameters and the physical properties of the motor. It is not necessarily a function of the actual torque on the motor shaft. The motor current can provide a reasonable estimate of the torque at steady state conditions. However, it cannot measure the actual driveshaft torque during transient or larger torsional dynamic events. During these conditions, only direct measurement of the torque can provide a truly accurate assessment of the torsional characteristics. Additionally, even during steady-state conditions, the motor current cannot characterize the torsional conditions in complex drivetrains with multiple driven shafts.

Figure 1 illustrates the motor torque at a hot rolling mill during the rolling of a steel slab. The blue trace (SG) is the directly measured torque using strain gages. The red trace (CT) is the torque measurement based on the motor's current transducer. During the middle of the slab, both traces have a similar amplitude at steady state conditions. Observing the slab entry, however, there is a significant difference between the strain gage measurement and the motor current measurement.

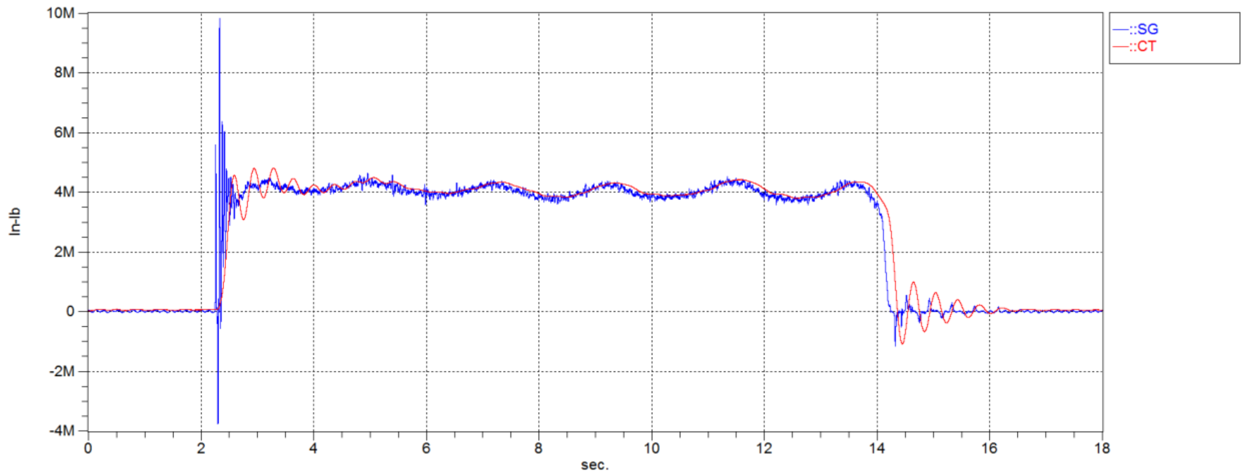

Figure 1

A closer examination of the slab entry **(Figure 2)** illustrates two potentially damaging conditions to which the motor current signal is “blind." First, the actual peak torque is 9.82 Million Inch-pounds (M In-lb), whereas the motor current transducer only sees a peak torque of 4.80 M In-lb. In this case, the motor current signal is just detecting half of what the actual torque is. Second, there is a sizeable torsional reversal (negative torque) event that occurs at slab entry. A reversing torque of -3.76 M In-lb was recorded using the strain gage measurement. Reverse torque conditions can be extremely damaging to drive components, including shafts, keyways, and gearing. Again, the motor current transducer did not detect the reversing torque condition.

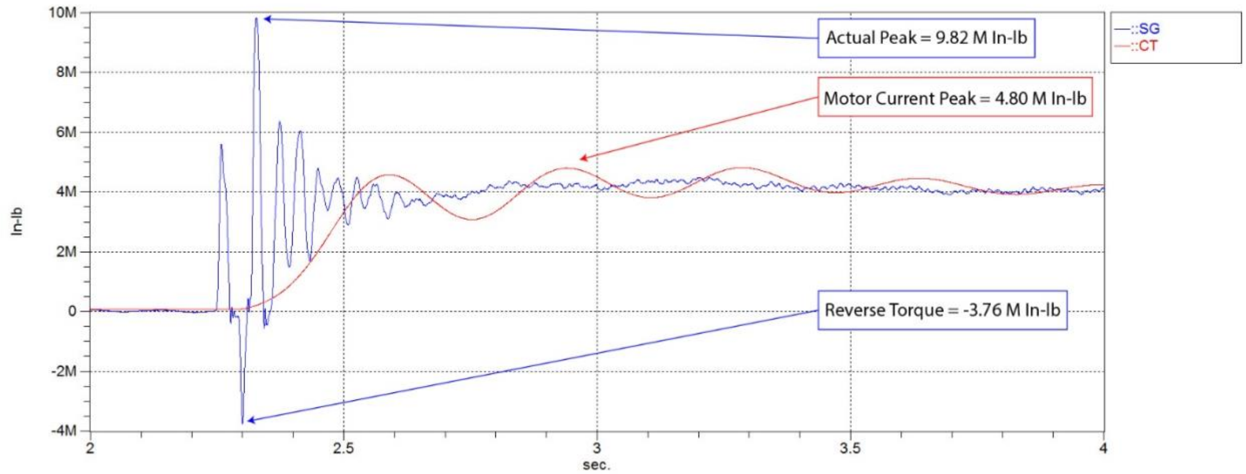

Figure 2

Relying on the motor current measurements for an indicator of actual torsional conditions can lead to incorrect assumptions of operating conditions - especially for machinery that may be experiencing repeated failures or unsatisfactory performance.

Strain Gage Based Torque Telemetry

The use of and technology behind strain gages has been well established for decades. The strain gage orientation and configuration can be designed to measure specific types of loading including axial, bending, or shear loading. Since torsional loading acts in the angular direction, it creates shear type loads at 45 degrees to the axis of the shaft. The general relationship between torque and shear stress is shown in **Equation 1** where *T* is the torque, τ is the shear stress, *J* is the Polar Moment of Inertia, and c is the distance from the center of the shaft:

$$T = \frac{\tau * J}{c}$$

Equation 1

This equation can be rewritten to calculate the torque as a function of shear stress and reduced to be specific for solid circular shafts, which is shown in **Equation 2** where *d* is the shaft diameter:

$$T = \frac{\tau * \pi * d^3}{16}$$

Equation 2

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A similar equation can also be derived for hollow shafts.

Properly oriented and configured strain gages can be installed to measure the shear stress as a result of torsional loads while negating other types of loads such as bending or axial. **Figure 3** shows a partial torque strain gage installation. A second strain gage is installed 180 degrees around the shaft. Note that the active elements of the strain gage are oriented at 45 degrees to the shaft axis. The orientation of the strain gage is then designed to measure the shear stress as a function of torsional loads.

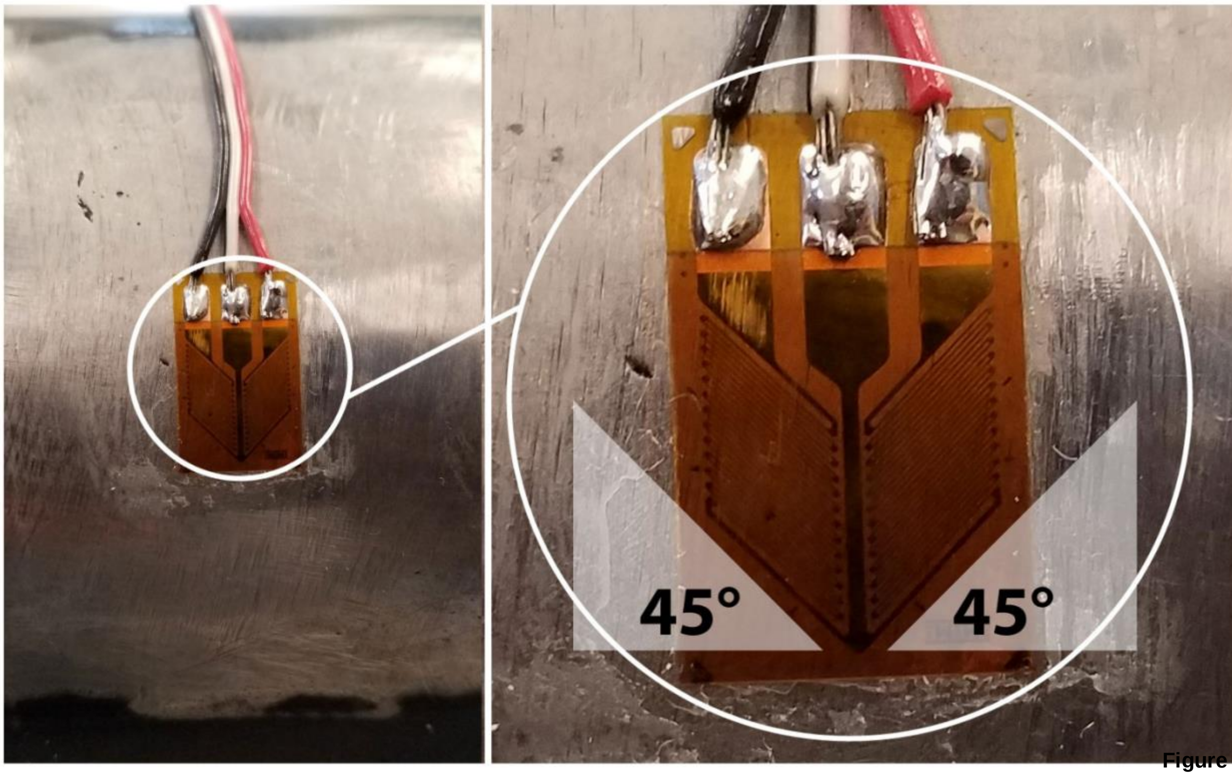

Figure 3

The installed strain gages are wired to an electronics package that consists of a power supply and signal conditioner for the strain gage, an analog to digital converter, and a digital transmitter. This is referred to as the telemetry portion of the system and is installed on the rotating shaft. Power is provided by using a battery pack on the rotating shaft for temporary systems or an inductive power loop for permanently installed systems. A stationary receiver antenna is mounted to receive the signal from the rotating telemetry system. The torque on the shaft can be measured directly as a function of the shear stress using strain gage based telemetry. The frequency response of modern strain gages and digital telemetry systems can reach into kilohertz (kHz), which provides ample data points to observe and measure torsional events precisely.

Figure 4 illustrates a basic battery powered strain gage based torque telemetry system installed on a motor output spindle.

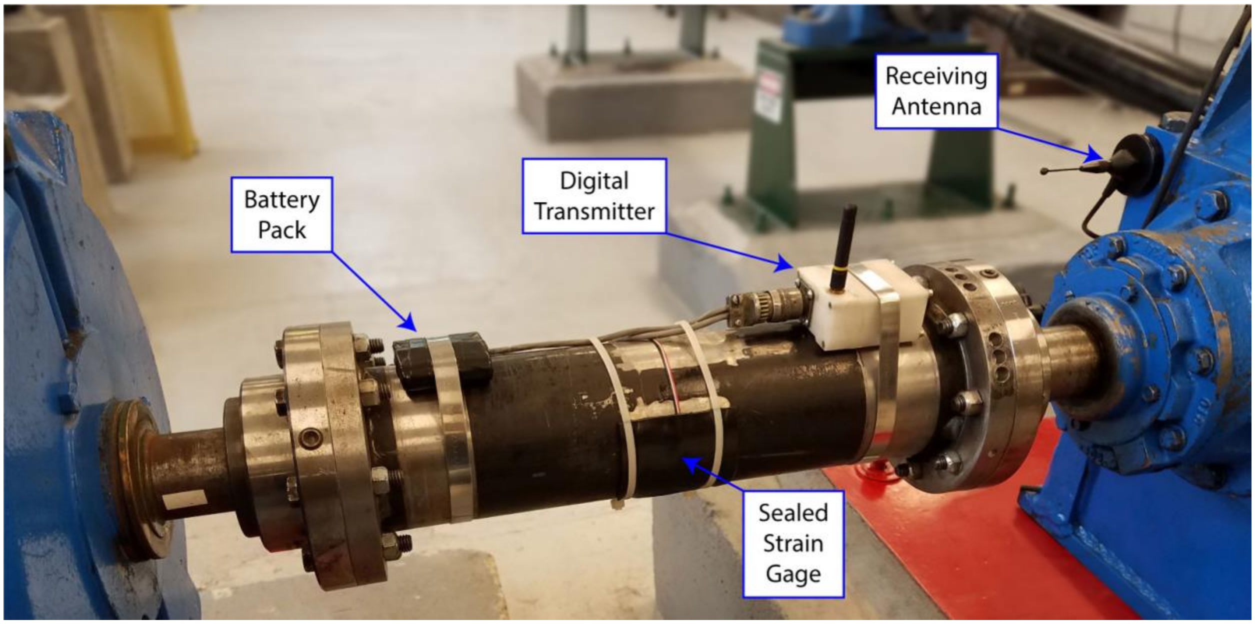

Figure 4

Torque and Vibration

Vibration measurements can be an extremely useful tool in detecting a wide variety of machinery faults. However, torsional events are not easily identified using vibration sensors. Since torque acts in a rotational or twisting direction as opposed to a linear path, it typically does not generate a vibration response that can be used to characterize torsional events. Large torque spikes may not cause a representative vibration spike, particularly if the clearances and backlashes are already taken up. Torsional vibration issues such as torsional resonance also may not generate a mechanical vibration that can be detected using standard vibration sensors. In these cases, a direct measurement of the torque on the shaft will be required to determine the magnitude of the torque.

One example of this is a compressor startup. The measured torque and motor vibration of the compressor startup are shown in **Figures 5 and 6,** respectively. The blue trace is the motor torque measured directly with strain gages. The green and orange traces show the motor outboard vibration in the axial and horizontal directions. In both figures, the red trace is a motor speed profile scaled for each chart.

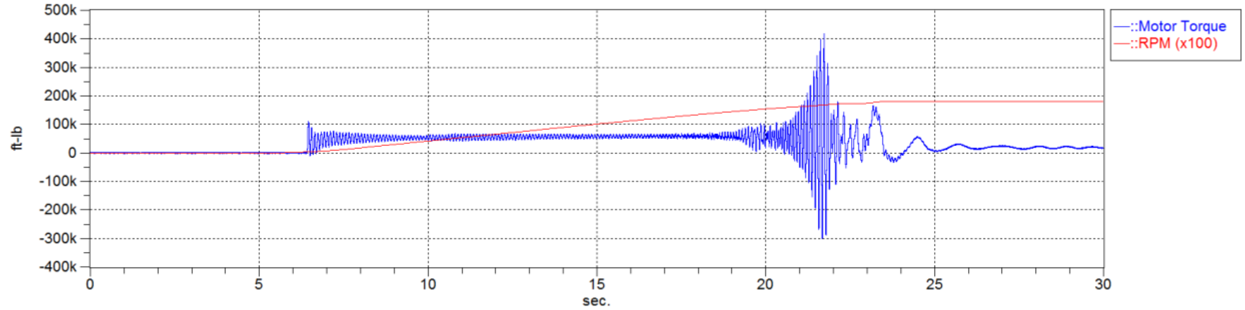

Figure 5

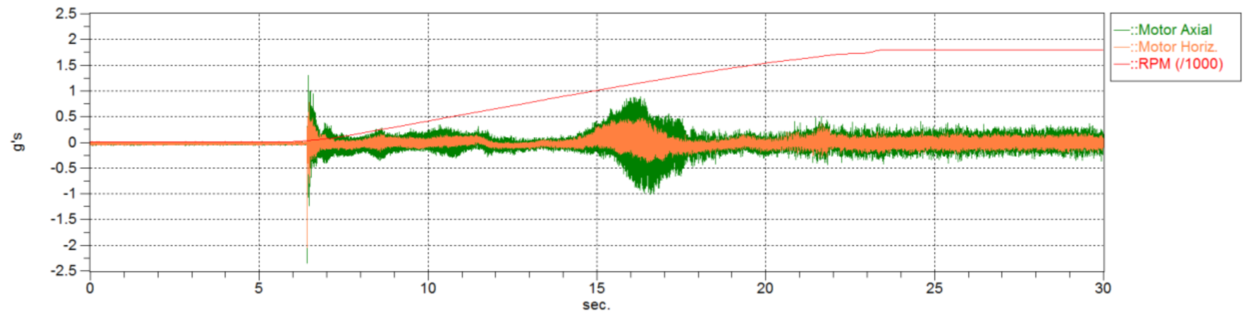

Figure 6

Upon evaluation of the motor torque data, there is a sizeable torsional oscillation that occurs at 21 to 22 seconds. The standard operating torque for this compressor is approximately 34,000 ft-lb, but during this event, the peak torque is 418,000 ft-lb (over 1200% normal load) while also experiencing reversing torques of -301,000 ft-lb. The cause of this torsional oscillation is a torsional resonance centered at 10 Hz that is excited during the start of the compressor. The motor vibration does not detect any indication of the torsional resonance-induced oscillation at 21 to 22 seconds. There is a vibration response between 16 and 18 seconds, but this is a result of the motor control PID loop that excites the motor at 44 Hz.

Figure 7 is a waterfall plot (frequency vs. amplitude as a function of time) of the motor torque, and **Figure 8** is a waterfall plot of the motor axial vibration. The waterfall plot of the motor torque shows a large peak centered at 10 Hz. This is the torsional resonance oscillation at 21 to 22 seconds. The waterfall plot of the motor vibration does not show any indication of a response near 10 Hz. Since the torsional energy is acting in the angular direction, the vibration sensors do not detect what can be an extremely damaging torsional condition.

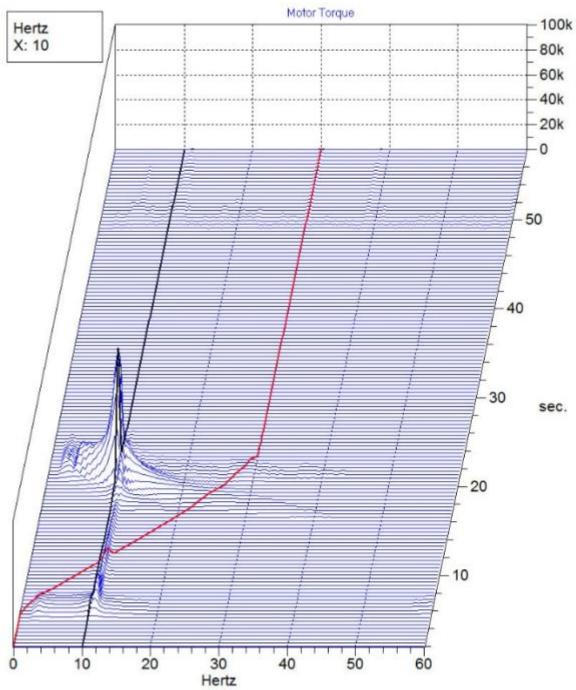

Figure 7

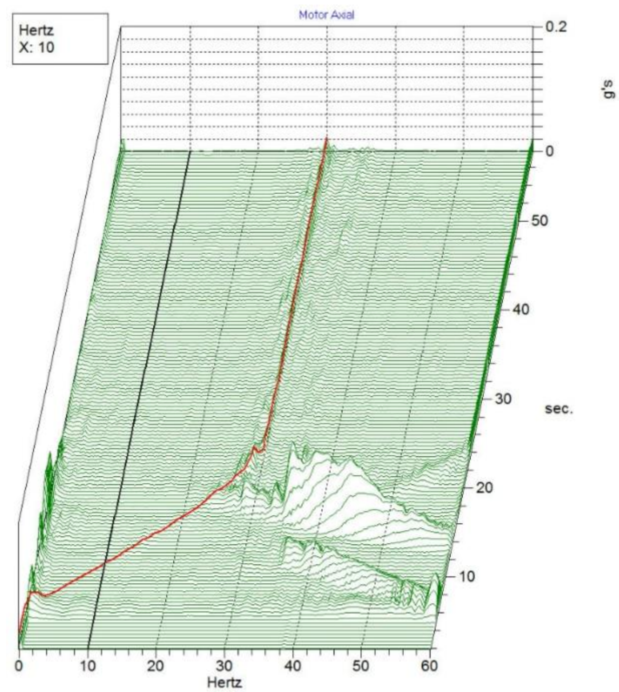

Figure 8

Torsional resonances do not only manifest during startup of equipment, but can be present through the operating range of variable speed machinery. Similar to structural resonances, torsional resonances can be excited by many forcing functions, such as shaft speed and harmonics, blade or vane pass frequencies, and gear mesh frequencies. Multiple forcing functions in variable speed machinery can create challenges when trying to operate the machinery as intended, yet avoid damaging torsional conditions that can reduce the reliability of the machine.

An example of this is a positive displacement reciprocating pump. In this case, one torsional resonance centered at 40.8 Hz is excited by two times motor speed (2X Motor) as well as two, three, four, and five times the pump pulsation frequency (2X, 3X, 4X, and 5X PPF). Each of these forcing functions can excite the resonance based on the operating speed.

The measured torque and motor vibration of the pump during a speed ramp test are shown in **Figures 9 and 10,** respectively. The blue trace is the motor torque measured directly with strain gages. The green and oranges traces show the motor outboard vibration in the axial and horizontal directions. In both charts, the red trace is a motor speed profile that has been scaled for each chart.

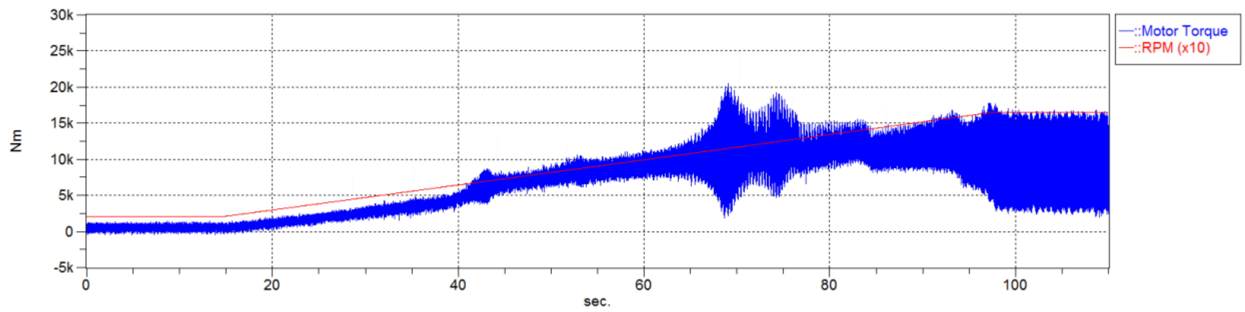

Figure 9

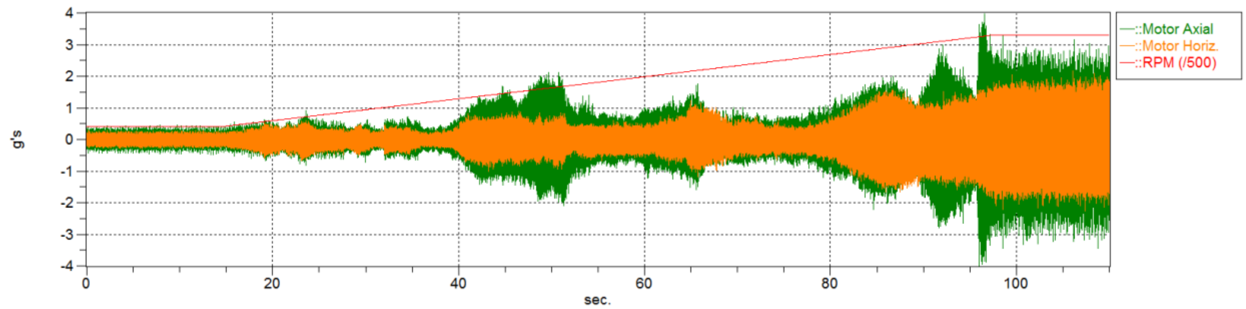

Figure 10

The speed ramp data encompasses the entire operating range of the pump from 200 to 1650 RPM. After evaluating the motor torque data, there are several instances when torsional oscillations occur during the speed ramp: 43 sec., 69 sec., 74 sec., and beyond 97 seconds. During each of these occurrences, the oscillation is caused by excitation of the 40.8 Hz torsional resonance, but in each instance, a separate forcing function excites the resonance. The excitation of the resonance, in this case, does not necessarily cause higher than allowable torque or reverse torque conditions. However, the torsional oscillations can cause accelerated cyclic wear of the mechanical components as well as undesired pump performance. Since torque is directly related to horsepower, unstable torsional conditions can create unstable delivered horsepower conditions, resulting in poor pump performance at certain speeds. In this case, pump speeds near 1150 RPM, 1240 RPM, and full speed (1650 RPM) would need to be avoided to prevent accelerated mechanical wear and unstable performance.

Once again, the motor vibration is responsive at other times, primarily at higher frequencies, and does not detect any indication of the torsional resonance. The waterfall plot of the motor torque shown in **Figure 11** illustrates the torsional resonance centered at 40.8 Hz. The red cursors mark the forcing functions that excite the torsional resonance: 2X PPF, 3X PPF, 4X PPF, 5X PPF, and 2X motor speed.

The waterfall plot of the motor vibration shown in **Figure 12** does not show any indication of a response near 40.8 Hz. It can be seen that the vibration at full speed (1650 RPM) is primarily 1X motor speed at 27.5 Hz.

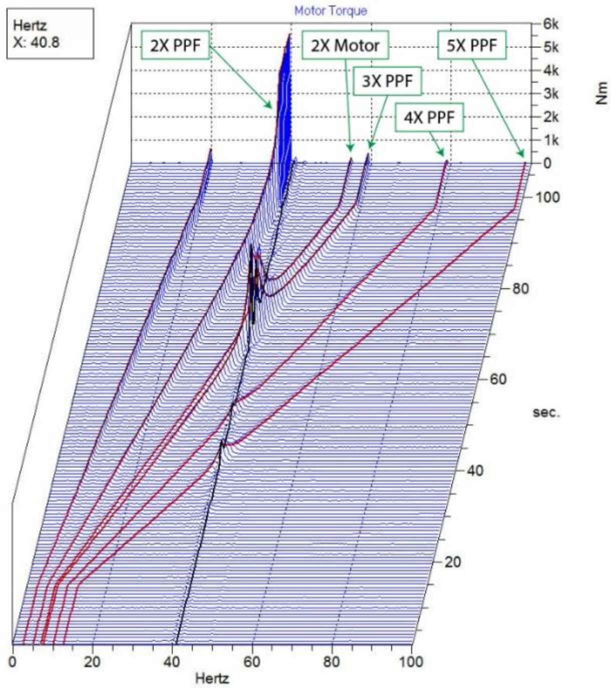

Figure 11

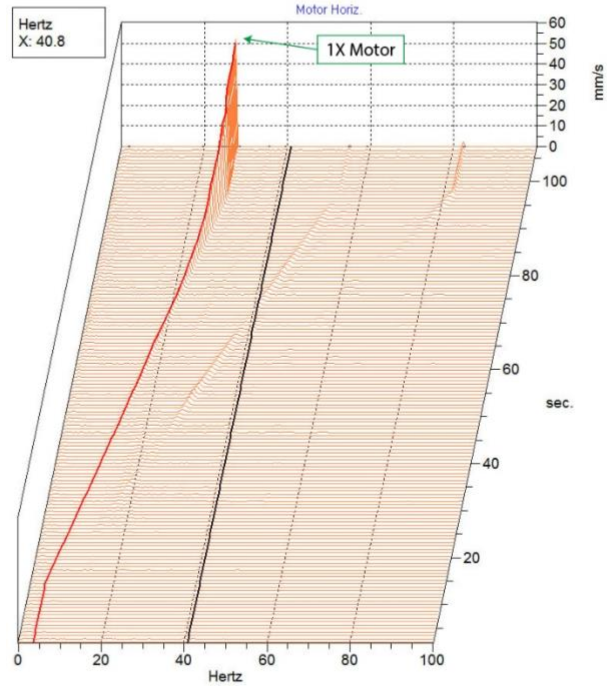

Figure 12

An Interference Diagram (Campbell Diagram) is shown in **Figure 13** to illustrate the multiple forcing functions that can excite the 40.8 Hz torsional resonance through the speed range.

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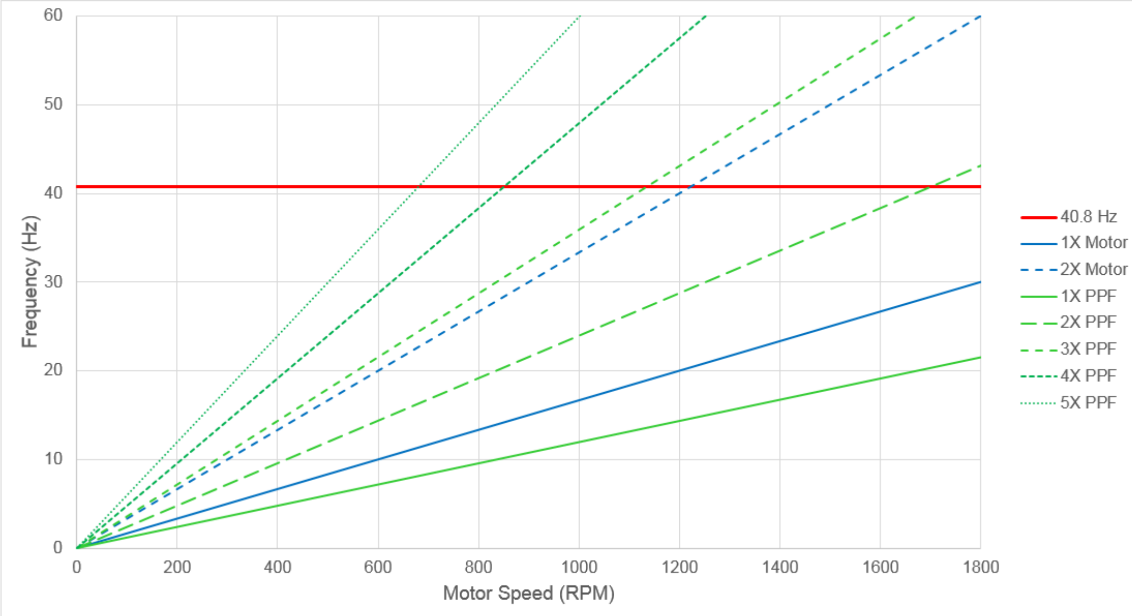

Figure 13

CONCLUSION

Torsional issues can cause a wide variety of machine failures, operational instability, and product quality issues. These issues can exist in a wide range of machinery with rotating components. As discussed previously, the only way to accurately measure and detect torsional issues is a direct measurement of the torque on the shaft using strain gage based telemetry technology. One should not assume that monitoring motor current is sufficient in understanding the true torsional characteristics of a machine. The motor current is only a response to various factors of the system and typically reacts more slowly than many torsional events. Additionally, torsional issues can easily go undetected using other NDT technologies such as vibration. As W. Edwards Deming stated: “Without data you’re just another person with an opinion.”

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