



Revealing the Unmonitored Risks in your Rotating Equipment

An Opportunity for Innovation

A recent review of high-speed rotating machinery events revealed a concerning number of torsional vibration failures within the last two decades. Three examples are summarized to highlight the variety of issues and failure modes.

The steam turbine of a Pressurized Water Reactor nuclear reactor experiences an anomalous event and the machine is manually tripped due to excessive radial vibration in the low-pressure section. The investigation concludes that a blade was ejected from a low-pressure stage and that detailed inspections have revealed additional cracked blades in several stages. The root cause is determined to be excessive torsional vibration triggered by torsional excitation in the train. A later industry study of 65 Pressurized Water Reactors shows that approximately 10% of the plants had similar events involving turbine blade failures which were suspected to be caused by the same torsional vibration phenomenon. (Ref 1)

A pipeline gas transmission train experiences three coupling failures over a short duration of time. The investigation reveals that the installation of several pieces of equipment has shifted the expected torsional vibration natural frequencies. As a result, the operating speed of the train exactly matches a torsional vibration resonance. (Ref 2)

During the startup of a train, comprising of a synchronous motor driving a speed increasing gear box connected to a centrifugal compressor, the motor speed drops several times. After 12 seconds of operation, the high-speed coupler fails with component ejection. The damaged coupler spacer shows the characteristic 45o angle indicating torsional failure. It is determined that faulty wiring of the motor caused current fluctuations that excited the torsional natural frequency. (Ref 3)

Unexpected and unmonitored torsional vibration is at the heart of these recent case studies resulting in sudden failures, costly downtime and potential safety risk. This short paper will

examine the origins of torsional vibration and a few case histories to drive an understanding of the unmonitored risk existing at many industrial sites.

Torsional Vibration- What Is It?

All rotating equipment power trains found at industrial sites have vibration, usually caused by mechanical unbalance of the rotating system, shaft misalignment, or weakness in the bearing support. Characteristic vibration is experienced in one or more of three modes: horizontal or vertical (radial), axial (thrust), and twisting (torsional), see Figure 1. Bently Nevada's asset protection and condition monitoring products; probes, monitors and System 1 software, allow for the continuous monitoring of the radial and axial vibration on the rotors and casings.

Changes in the cross coupling of forces from radial vibration, unbalance, generator load variation or power grid fluctuations cause a variation in rotating speed of a machine and thus produce torsional vibration. Ultimately, torsional vibration can induce radial or axial vibrations in the rotor and attached components that causes component fatigue such as the steam turbine blades or coupler in the above case histories. Component fatigue may cause component liberation which leads to greater unbalance and in a feed positive manner will increase the torsional vibration issues. Torsional vibration in the rotor creates additional varying stresses and strains which can result in failure without warning by fatiguing the rotor material. **This represents a risk factor that, although assessed during the machine commissioning, it can be altered by future modifications and remains unmonitored for the operational life of the equipment.**

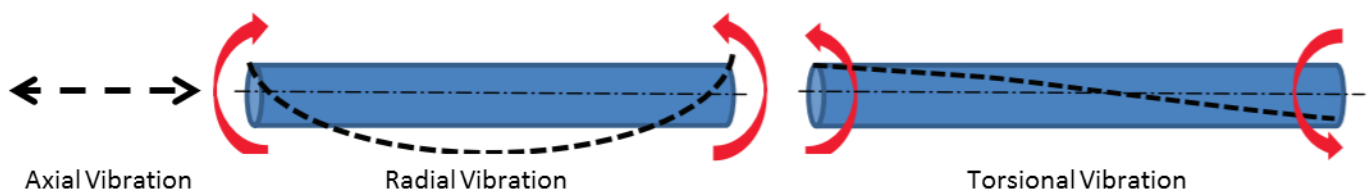


Figure 1: Vibration Modes

Torsional vibration is strongly related to the material composition and dimensions of the rotor and accompanying components. The rotor material will define such parameters as component stiffness and inertia whereas the length, diameter and coupling of the rotor will define the inertial moments.

Cross coupling refers to a condition where radial vibration can induce torsional vibration and likewise in the opposite manner. This is the root cause of the introductory example where torsional vibration caused vibration of the steam turbine blades to the point of failure.

Why does torsional vibration matter?

All rotating equipment is expected to experience variations in speed and thus are subjected to torsional vibration. Effective accurate measurement of torsional vibration allows an operator to evaluate several issues including torsional natural frequencies, dynamic stresses, torsional modes shape, component fatigue and load vibration. Torsional vibration, in some cases, can be deduced by case accelerometers but is best detected and monitored directly from the rotor. Data from direct measurements are essential to compare with dynamic model simulations. Monitoring torsional vibration as a regular part of preventative maintenance will reduce maintenance costs and may be useful in decreasing machine operating margins.

Sophisticated torsional rotor dynamics may allow one to verify three important parameters, that of the torsional natural frequency, the associated torsional mode shapes and the rotor response, sometimes referred to as the “personality” of the rotor. These calculations allow the operator to set separation margins between the desired operating speeds and torsional resonances and thus avoid possible damage and failures. Many operators desire a fourth parameter, that of a “rain fall” counter, meaning the combination of frequency of vibration, amplitude of response and stress response calculations that predict the end of life or remaining life of various rotor components.

Methodologies and Technologies for evaluating Torsional Vibration

Presently, torsional vibration is the most difficult of the three vibrations to measure and monitor. There is no commercially viable large application non-contacting continuous torsional vibration sensing and monitoring solution available. Several offered techniques involving contacting the rotor, such as zebra tape or strain gauges, or adding a component such as a stub shaft (strain gauges) or toothed gear wheel with a magnetic pickup, into the rotor train. These products remain intrusive, expensive and are often noncontinuous. (Ref 4-5)

Most commonly used for the investigation and analysis of torsional vibration, is temporary sensors installation onto the rotor such as optical encoders based on Zebra tape or strain gauges. The sensors are installed during a shutdown and operated over short power startups and excursions to gather data before removal and restarting the train.

For example, Bently Nevada Machinery Diagnostic Services (Ref 6) monitored a Gas Turbine Generator set at two locations using toothed timing speed wheels and optical zebra tape. The Bently Nevada MDS tool set was employed to evaluate the gathered data and tooth spacing variations were corrected by synchronous averaging. The expected first mode frequency of 12.5Hz at 767 RPM was confirmed within 1% by both the tooth wheel measurement, shown in Figure 2 (12.4Hz), and the zebra tape value, shown in Figure 3 (12.4Hz).

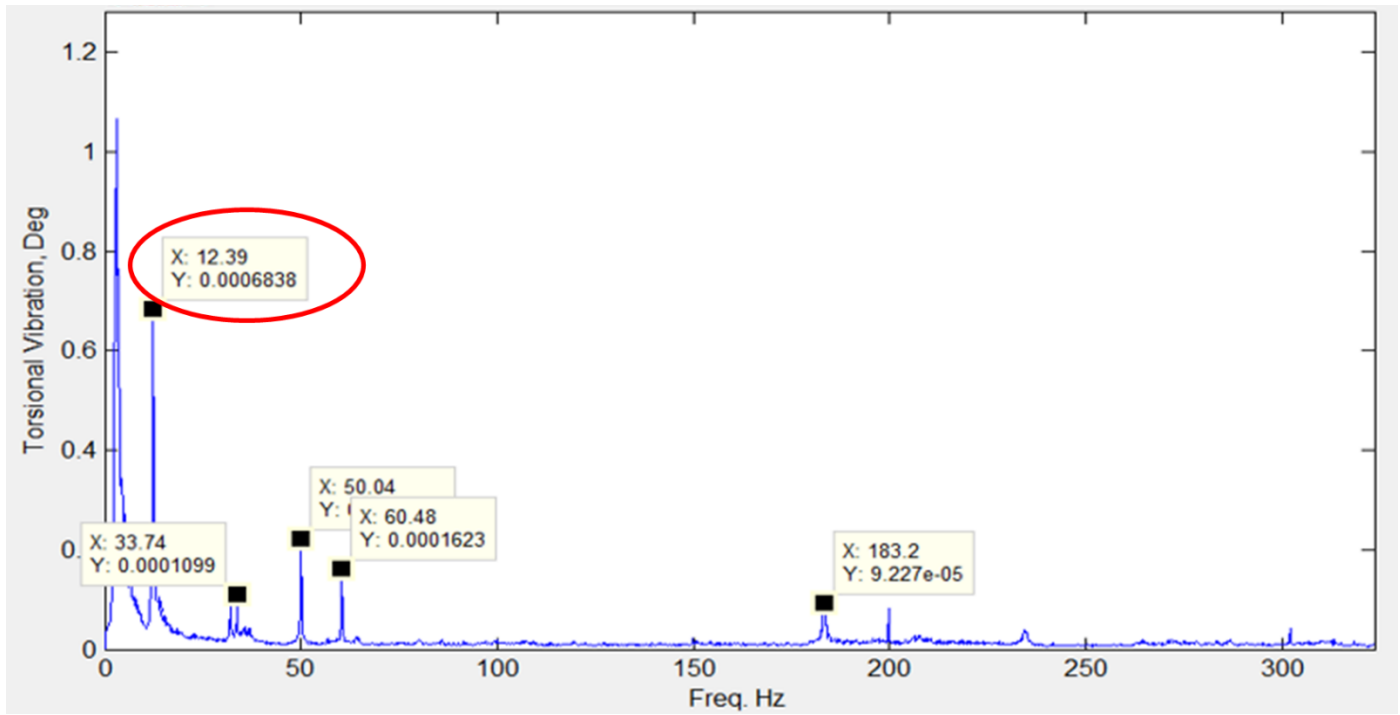


Figure 2: Corrected Data for Torsional Vibration Analysis using a Timing Wheel w/ Tooth Spaces

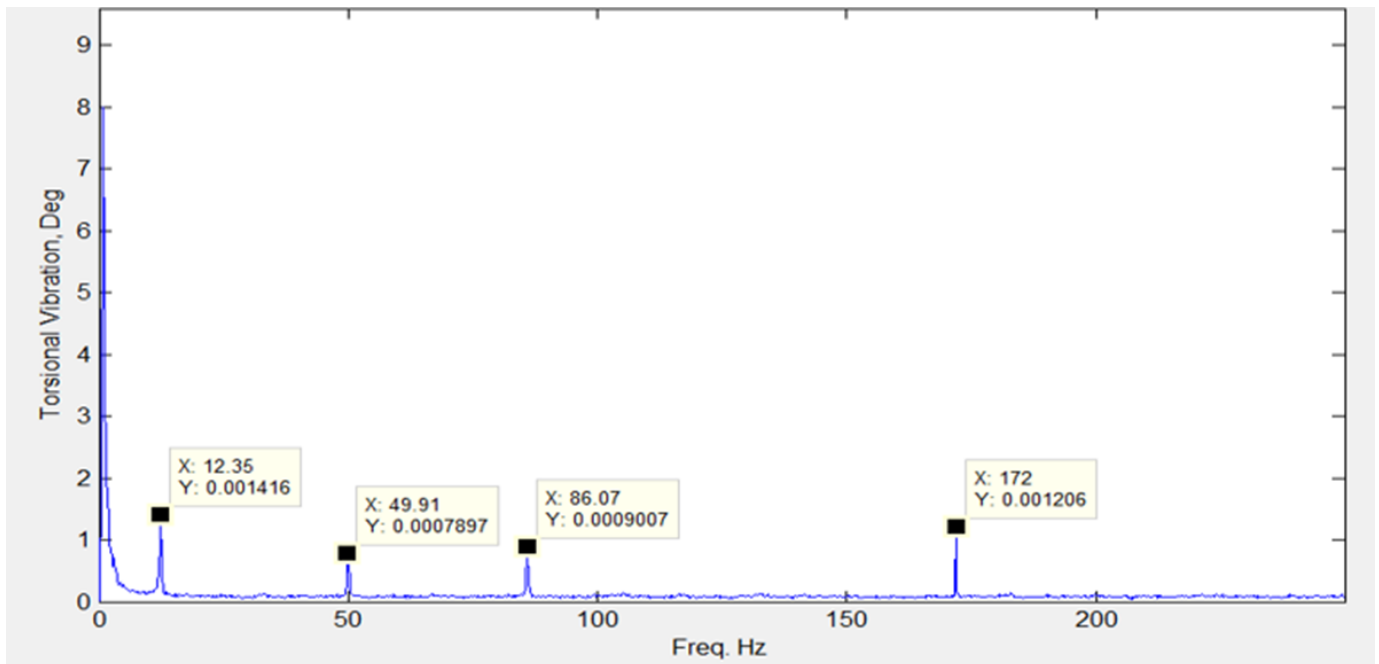


Figure 3: Torsional Vibration Analysis from Zebra Tape Encoders

In some circumstances, Bently Nevada's proximity probes and monitors have been used to infer torsional vibration measurements. For example, at one site, rotor displacement amplitudes on high-speed gearboxes were observed to enter alarm and occasionally a trip condition at low loads. This occurred on three identical aeroderivative compression trains. Bently Nevada Machinery Diagnostic Services (Ref 7) used available historical low load conditions data to create spectral plots which revealed fluctuations in direct amplitudes to be attributable to a 12.7 Hz frequency component, as shown in Figure 4. This frequency did not correspond with any rotational speed or harmonic/subharmonic. A torsional vibration model Campbell diagram, however, indicated a first torsional natural frequency at 769 CPM corresponding to 12.8Hz. Using this information, it was determined that gas heaters, firing at 20ms burst to preheat the fuel gas, caused power instability. The control system was then modified to eliminate the first torsional natural frequency excitation.

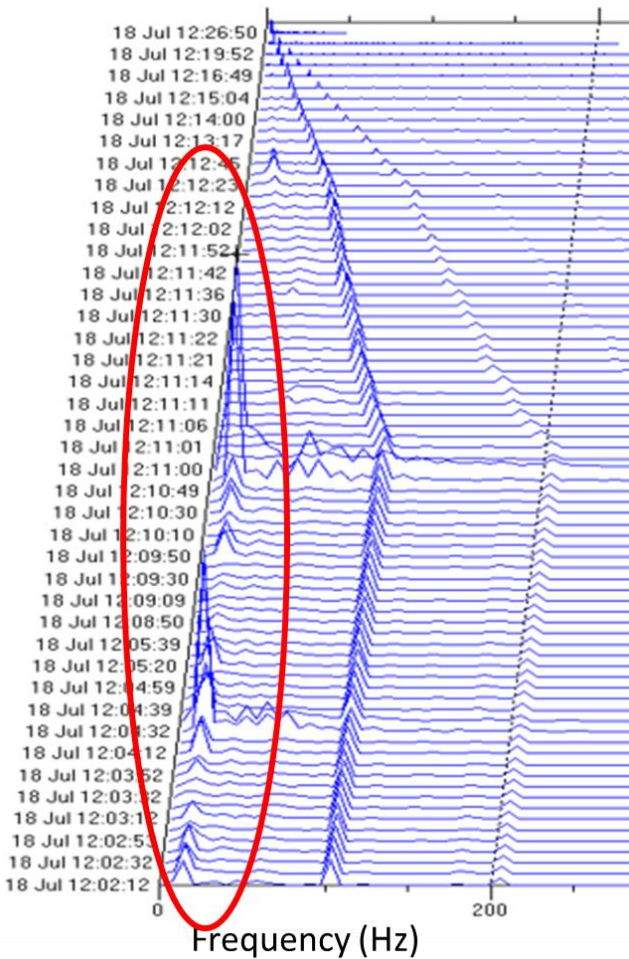


Figure 4: Half Spectrum Plot

The Effects of Torsional Vibration with Variable Frequency Drives

Motor compressor trains with attached Variable Frequency Drives (VFD) are becoming increasingly popular with OEMs and end users in the Oil and Gas, Power Generation, and Processing industries. Figure 5 describes a typical compressor/ VFD train. Since speed is directly proportional to frequency, Variable Frequency Drives enable fluctuating speed operation by sending flexible electrical frequencies and voltages into the motor. A Variable Frequency Drive receives the AC signal from a grid connected transformer and converts the signal to DC through a rectifier. A DC link passes the signal to an Inverter which converts the DC signal back to a usable AC signal to drive the motor. There are three common forms of Variable Frequency Drives; Current Sourced Inverters (CSI), using current as the DC signal and a large inductor as the DC link; Load Commuted Inverters (LSI), which are similar to an CSI and used only with synchronous motors; and Voltage Sourced Inverters (VSI), using voltage as the DC signal and a capacitor bank as the DC link.

Particularly in Current-source Inverters (CSI) VFDs, torsional vibration is a common problem in the motor train as the solid-state VFD “chopping” of A/C driving signal produces an imperfect waveform. The resulting signal notches and peaks create sidebands frequencies that can excite torsional train resonances, as Shown in Figure 6. Resonance excitation produces high amplitude torsional vibration causing compressor component damages and ultimately train failure. A continuous measurement of torsional vibration in the train rotor can highlight vibration issues affecting plant efficiency as well as present an opportunity to define skip frequencies or separation margins for the VFD programming.

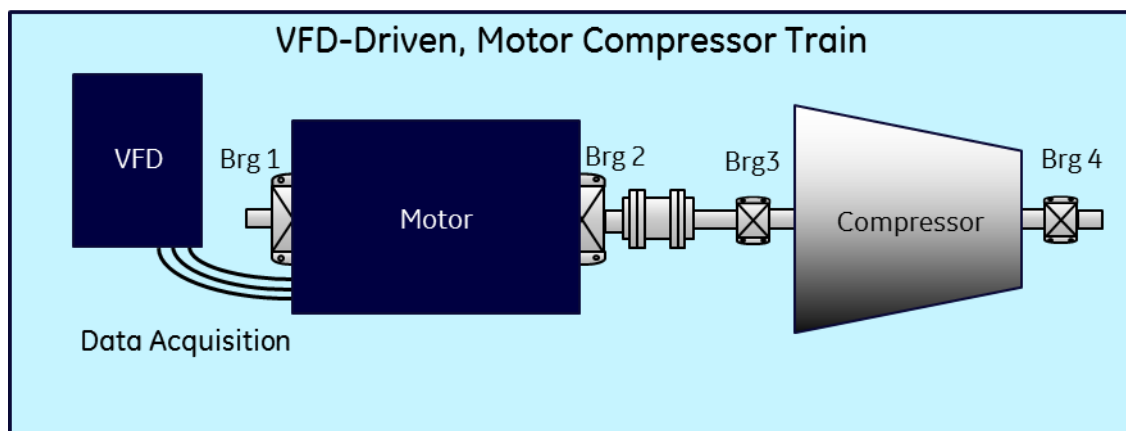


Figure 5 - VFD Motor Train

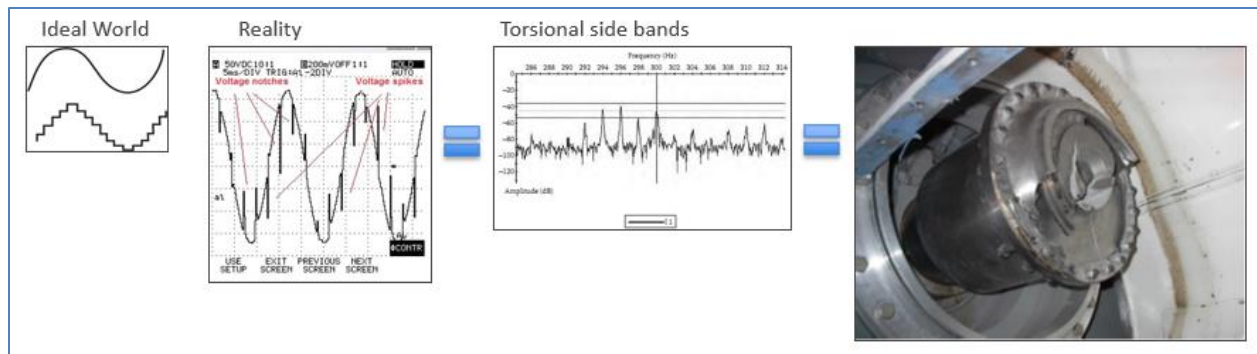


Figure 6 - VFD induced torsional vibration

Conclusion

Effective accurate measurement of torsional vibration allows an operator to evaluate several issues including torsional natural frequencies, dynamic stresses, torsional modes shape, component fatigue and load vibration. Torsional vibration, in some situations, can be deduced by case accelerometers but is best detected and monitored directly from the rotor. Presently, torsional vibration is the most difficult of the three vibrations to measure and monitor. As no industrially hardened non-contacting continuous torsional vibration monitoring system is currently widely available, investigation and analysis are usually achieved by using other direct and indirect methods. All plant operators whether at power generator or Oil and Gas locations are at risk of rotating machinery damage or unplanned plant outages due to failures by not continuously monitoring torsional vibration. This is a widespread unplanned maintenance time-bomb and provides an unparalleled opportunity for innovation.

References:

Ref 1: <https://www.nrc.gov/docs/ML0319/ML031900050.pdf>

Ref 2: Preventing Unexpected Train Torsional Oscillations, J. Corcoran et al., 39th Turbo Pump Symposium, Houston, 2010,

Ref 3: Coupling Failure due to a Motor Fault, C. McClinton et al., 43th Turbo Pump Symposium, 2014, Houston,

Ref 4: Fundamentals of Rotating machinery Diagnostics, D. Bently, 2002

Ref 5: Identifying best practices for measuring and analyzing torsional vibration, a Siemens White Paper, Siemens PLM Software, 2014.

Ref 6: Bently Nevada Case History

About Bently Nevada

Bently Nevada product line has been synonymous with machinery protection and condition monitoring for more than 60 years. Our network of global experts is dedicated to helping our customers solve some of their toughest challenges in the oil and gas and power generation industries. From refineries and petrochemical plants to hydroelectric facilities and wind farms, Bently Nevada Asset Condition Monitoring offers trusted and proven vibration monitoring equipment and a comprehensive services portfolio to help improve the reliability and performance of production assets like turbines, compressors, motors, generators, and everything in between.

Behind every suite of great products is a team of great people, and the Bently Nevada team is one of the most experienced in the industry. That experience translates into high-quality, flexible and scalable solutions coupled with a dedicated services team focused on providing proactive, consistent support throughout the lifecycle of your operations. Our domain experts can help you operate safely while maximizing plant uptime and efficiency.

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