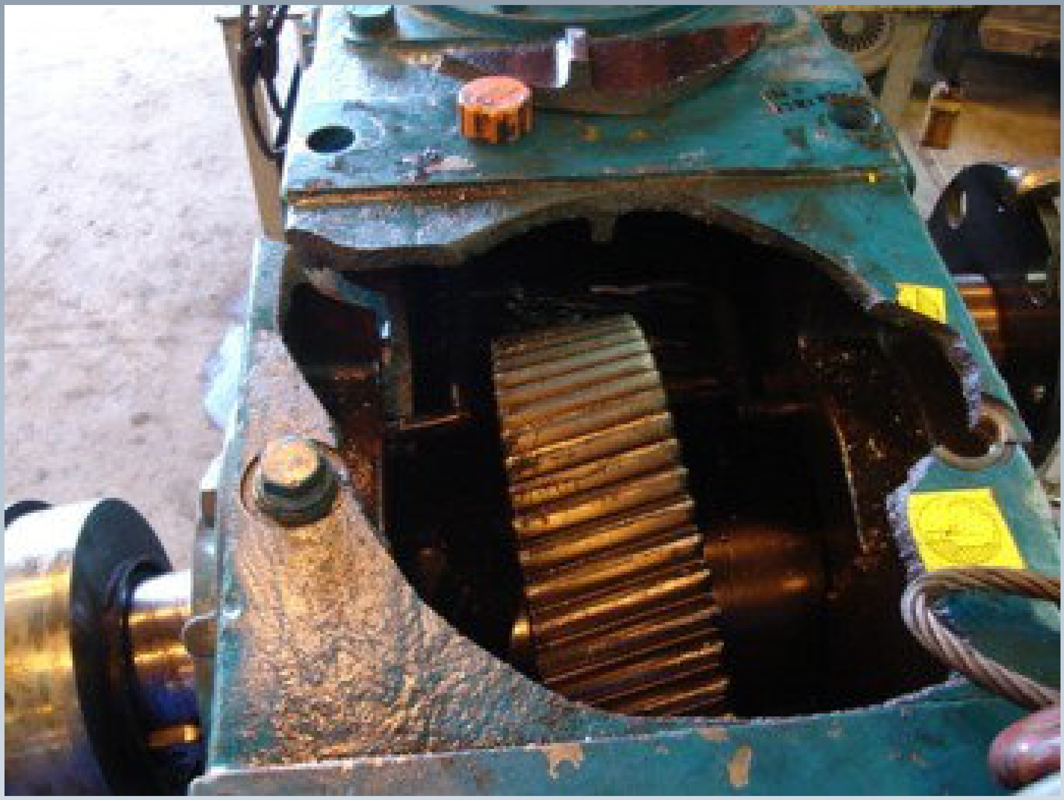
BINSFELD ENGINEERING INC.



TORSIONAL VIBRATION ANALYSIS

A Beginner's Guide

BINSFELD. MEASUREMENT MADE EASY.

INTRODUCTION

Of the vast array of torque measurement applications, one of the most intriguing is the measurement of torsional vibration. Torsional vibration measurements allow engineers to better understand the dynamics of their rotating equipment, enabling them to troubleshoot and/or validate performance. While this remains a largely specialized field, the concepts behind torsional vibration measurements are relatively straightforward and can be mastered by those with a basic understanding of the principals of vibration and how it correlates to equipment performance. With a better understanding of the reasons and methods to measure torsional vibration, the right instrumentation, and a helpful partner, you will become better positioned to make the decisions you need to decrease downtime and increase productivity. In this guide, we explain the basic concepts behind torsional vibration analysis including what it is, how to do it, and why it's important.

CONTENT

FAQ

Frequently Asked Questions

What is torsional vibration?

Torsional vibration is angular vibration that occurs about the axis of a shaft. It is different than lateral vibration (which occurs in the radial direction) and axial vibration (which occurs along the shaft length). Torsional vibration involves speed fluctuations of various components and the twisting of shaft sections while the machinery is rotating.

Excessive torsional vibration can lead to failures of such items as shafts, couplings, fans, gears, engine dampers, and compressor oil pumps. These failures typically occur at a 45-degree angle to the shaft axis. Unfortunately, torsional vibration problems may not be apparent until after a failure occurs.

Figure 1. *A cracked coupling due to excessive torsional vibration on VFD motor - ID fan [Courtesy of Engineering Dynamics Inc (EDI)]*

FAQ

Frequently Asked Questions

What is torsional vibration analysis (TVA)?

Some people use the term torsional vibration analysis (TVA) to mean taking measurements. However, TVA more commonly refers to calculations performed with a computer program. Some industries such as oil and gas require TVA of new equipment per American Petroleum Institute (API). For example, mass-elastic data are used to calculate torsional natural frequencies (TNFs) and mode shapes, interference diagram, and forced response. Other industries such as municipalities may specify analysis in the design stage and testing during commissioning of water pumps.

Why is torsional vibration analysis & torsional vibration testing important?

Torsional vibration and testing may be necessary to determine separation margin from torsional natural frequencies (TNFs) or to verify previous calculations. If a torsional problem is found, the system may need to be modified. Once the mass-elastic model has been normalized to match the measurements, the torsional vibration analysis software can be used to evaluate any proposed solutions. To avoid torsional resonance, this may require changing the torsional stiffness of the coupling, the inertia of a flywheel, etc.

Figure 2. *A vibration consultant measuring torsional vibration [Courtesy of ED)]*

Torsional vibration measurements help engineers increase the reliability and safety of rotating equipment.

FAQ

Frequently Asked Questions

What equipment is needed for torsional vibration analysis & torsional vibration testing?

An accelerometer is used to measure lateral vibration, but special equipment is needed to measure torsional vibration. Torsional vibration can be measured using a torsiograph, encoder, or laser vibrometer. These devices will determine angular oscillation and/or angular velocity. Some people have even detected high torsional of a disc pack coupling vibration using a simple strobe light to view warping or "pop canning" of the elements during operation.

Telemetry systems (such as the TorqueTrak 10K) can be used to measure shear torsional strain. The torsional strain value can then be converted to stress and/or torque by knowing the geometry and material properties of the shaft section. For example, the transmitted torque can be determined from the average value of the time wave form. The alternating torque can likewise be determined from the time wave form. The peak-to-peak value would be maximum – minimum. The alternating torque is usually expressed as zero-peak or (maximum-minimum)/2. These measured torque levels can then be compared to the rating of a coupling.

The optimal location for measurement depends on the torsional mode shape. For alternating torque, it is best to measure near a node crossing. For the first torsional natural frequency (TNF) this is usually near the coupling. Whereas a torsiograph, encoder, or laser vibrometer should be used near an anti-node (point of maximum angular oscillation).

FAQ

Frequently Asked Questions

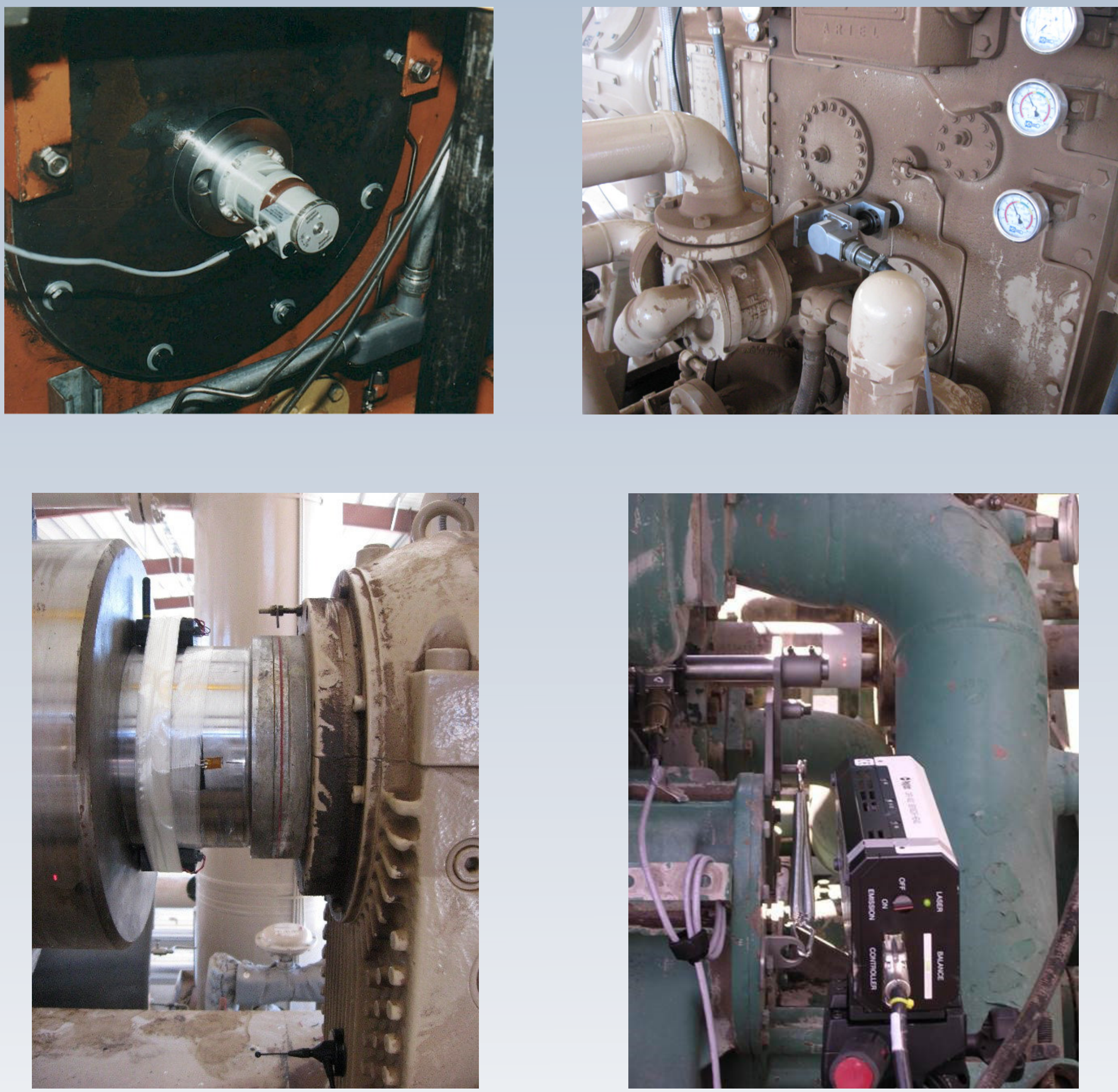


Figure 3. *A torsiograph (upper left), an encoder (upper right), a telemetry system (lower left) and a laser vibrometer (lower right), all used to measure torsional vibration [Courtesy of EDI]*

FAQ

Frequently Asked Questions

What are common applications that require torsional vibration analysis & testing?

Situations where torsional testing may be required could include the following:

[Excerpt from 2009 Turbomachinery Paper "Prevention of Torsional Vibration Problems in Reciprocating Machinery" by T. Feese and C. Hill]

- If a failure of a component occurs, testing of the repaired system is recommended to investigate the cause(s).
- If a system poses unusually high risks to life, other machinery, or plant processes, testing should be performed to ensure reliable operation. This could include a prototype machine or an existing model operating at higher speeds or pressures than previously designed.
- This could include systems with torsionally soft rubber couplings and/or wide speed ranges or operating conditions. If many assumptions had to be made in the torsional analysis phase due to lack of drawings and technical information, testing should be used to confirm the results.
- Newly designed systems that will be mass produced should be tested under load. It is much easier to correct a problem with an initial unit at the factory than it is to retrofit many units that have already been shipped to customers.
- Systems that have been modified or put into a different service, such as re-staging and/or changing operating conditions, should be re-analyzed or tested.
- Many municipalities have specifications that require torsional vibration testing of new units by a professional engineer.

FAQ

Frequently Asked Questions

What are common applications that require torsional vibration analysis & testing? (Continued)

In industrial applications, the most common equipment where torsional vibration testing is important is with variable frequency drive (VFD) motors driving large inertia fans and reciprocating engines/compressors. For VFD's, problems can occur due to tuning of the drive. Reciprocating engines and compressors can have much higher excitation than rotating machinery. Having a wide operating speed range will be more likely to encounter a torsional resonance.

In marine applications, torsional vibration testing is often required on propellar shafts to troubleshoot propulsion problems or to quantify excessive vibrations predicted in a computer torsional vibration model. Torsional vibration measurements are often required to meet meet certain classifications for new build or re-powered ships. Section 7.9 of the ABS Guidance Notes on Vessel Vibration highlights: "If measurement is conducted as per 4-3-2/7.5.8 of the ABS Steel Vessel Rules, torsional vibration measurements are to be taken either at the free end of the propulsion machinery, using a suitable torsional vibration transducer, and/or on the main shafting, using strain gauges. Alternatively, depending on the system characteristics, a mechanical torsiograph, driven from a suitable position along the shafting or free end, may be used for this purpose. "

FAQ

Frequently Asked Questions

How is torsional vibration analysis & testing performed?

Testing should be performed during startup, shutdown and over the range of operating conditions. Time wave forms can be helpful to determine transmitted torque and overall alternating torque. Time wave forms can also be used to capture peak torque during a transient event such as synchronous motor startup or emergency shutdown (ESD) of a reciprocating compressor. Appropriate sampling rate needs to be used to capture the data. For example, if a telemetry system is set to 0-500 Hz range, then the data is typically sampled at 5000 Hz with the data acquisition (DAQ) system. Fast Fourier transform (FFT) is needed to determine the frequency content of the signal. By varying the operating speed and making a waterfall plot, the TNFs can be determined. A waterfall plot can also be made during a slow startup or unloaded coastdown.

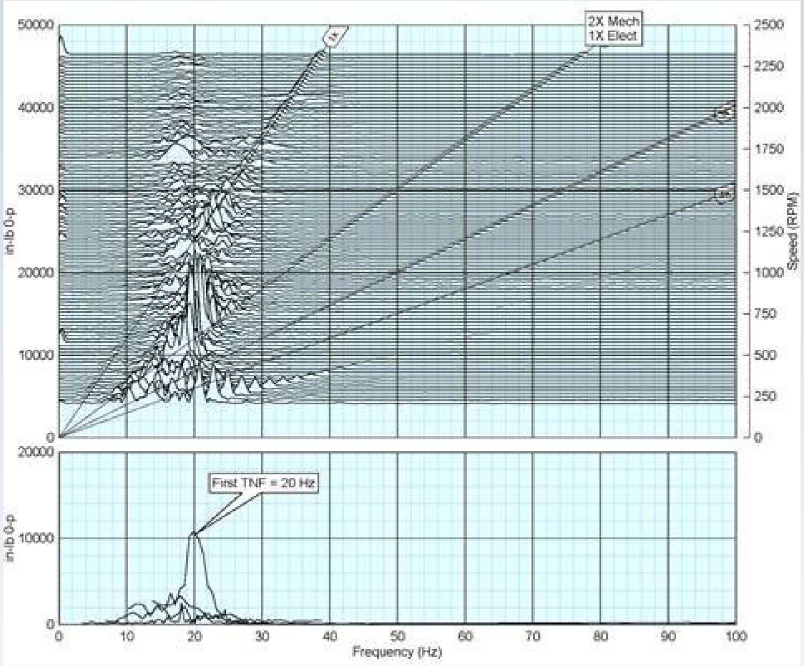


Figure 4. *A waterfall plot indicating a torsional natural frequency at 20 Hz. [Courtesy of EDI]*

Using Torque Telemetry

For Torsional Vibration Analysis

As discussed, telemetry can be an invaluable tool for torsional strain measurements in torsional vibration analysis. The recommended configuration from Binsfeld Engineering is the TorqueTrak 10K telemetry unit with the OPDAQ Field Test 2 data acquisition system. The TorqueTrak 10K will provide the torsional measurements and the OPDAQ Field Test 2 data acquisition system will store the data on a PC using a built-in high-frequency mode that enables data capture at rates up to 2400 Hz. The user could then do a frequency analysis (FFT) on the data to determine the resonant frequencies where torsional strain is the greatest and, if necessary, implement a corrective action to minimize that torsional strain to a safe level.

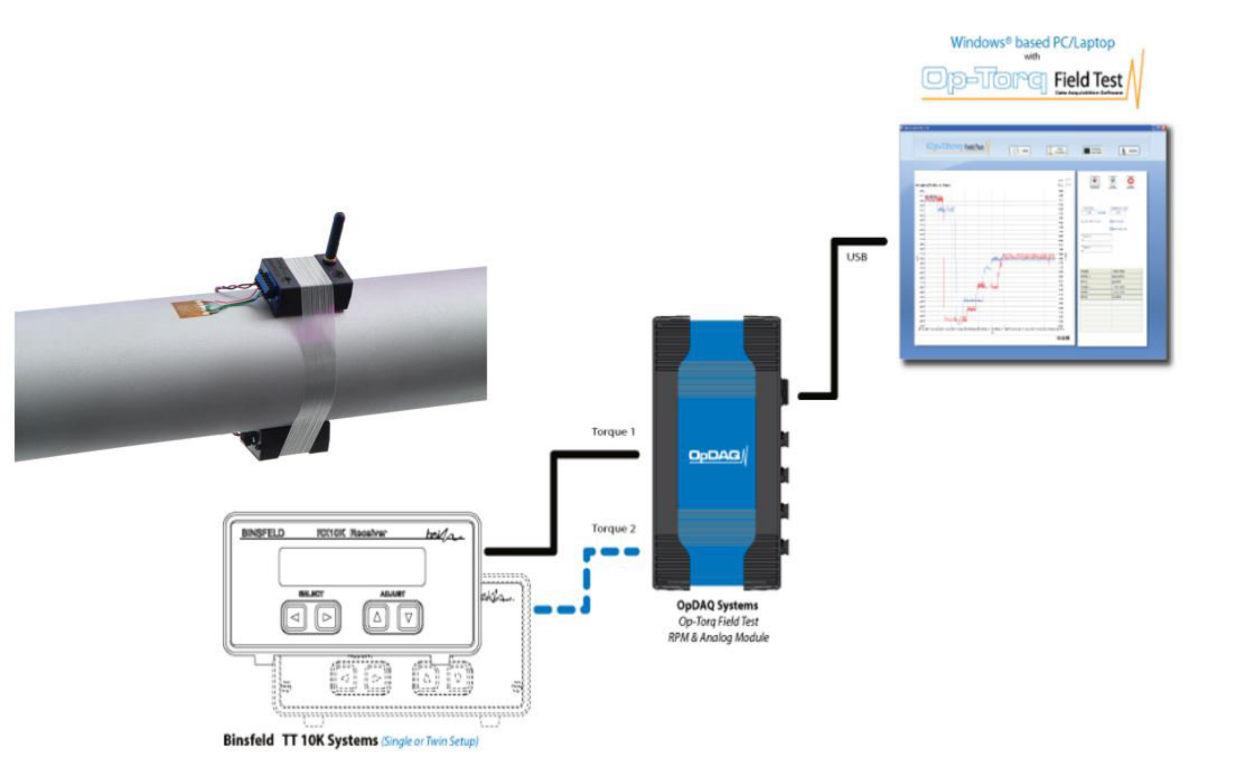


Figure 5. *Torsional vibration testing kit from Binsfeld Engineering.*

Using Torque Telemetry

For Torsional Vibration Analysis

Most often, the amplitude of the torsional vibration data is directly related to shaft speed (RPM). Torsional vibration causes premature wear and sometimes even damage to equipment, such as bearings and couplings. Therefore, it should be identified and de-tuned, if necessary. On big equipment, torsional vibration can be de-tuned by placing extra inertia on the shaft at a specific location. On ships, there is what is known as the "barred speed range." This is a shaft speed (RPM) range where torsional vibration is the greatest and the ship Captain knows to pass through the "barred speed range" as quickly as possible.

Additional examples of torsional systems where Binsfeld's TorqueTrak 10K telemetry system has been used for torsional vibration analysis and testing include:

- VFD motor driving various types of fans (ID, FD, and MVR).
- VFD motor driving centrifugal compressor for gas pipeline
- VFD motor driving pumps for fresh water and wastewater plants
- Reciprocating compressors systems driven by motors or engines
- Belt driven multiphase compressor for oil and gas industry
- VFD motor driven winder at paper mill
- VFD motor driven 310-ton crane at nuclear facility
- Engine driven firewater pumps
- Motor – gearbox – reciprocating compressor system at refinery
- Back-to-back motor testing at shop
- Kiln drive at cement plant
- Mixer rotors at plastics plant
- Propellar shafts on marine vessels

Using Torque Telemetry

For Torsional Vibration Analysis

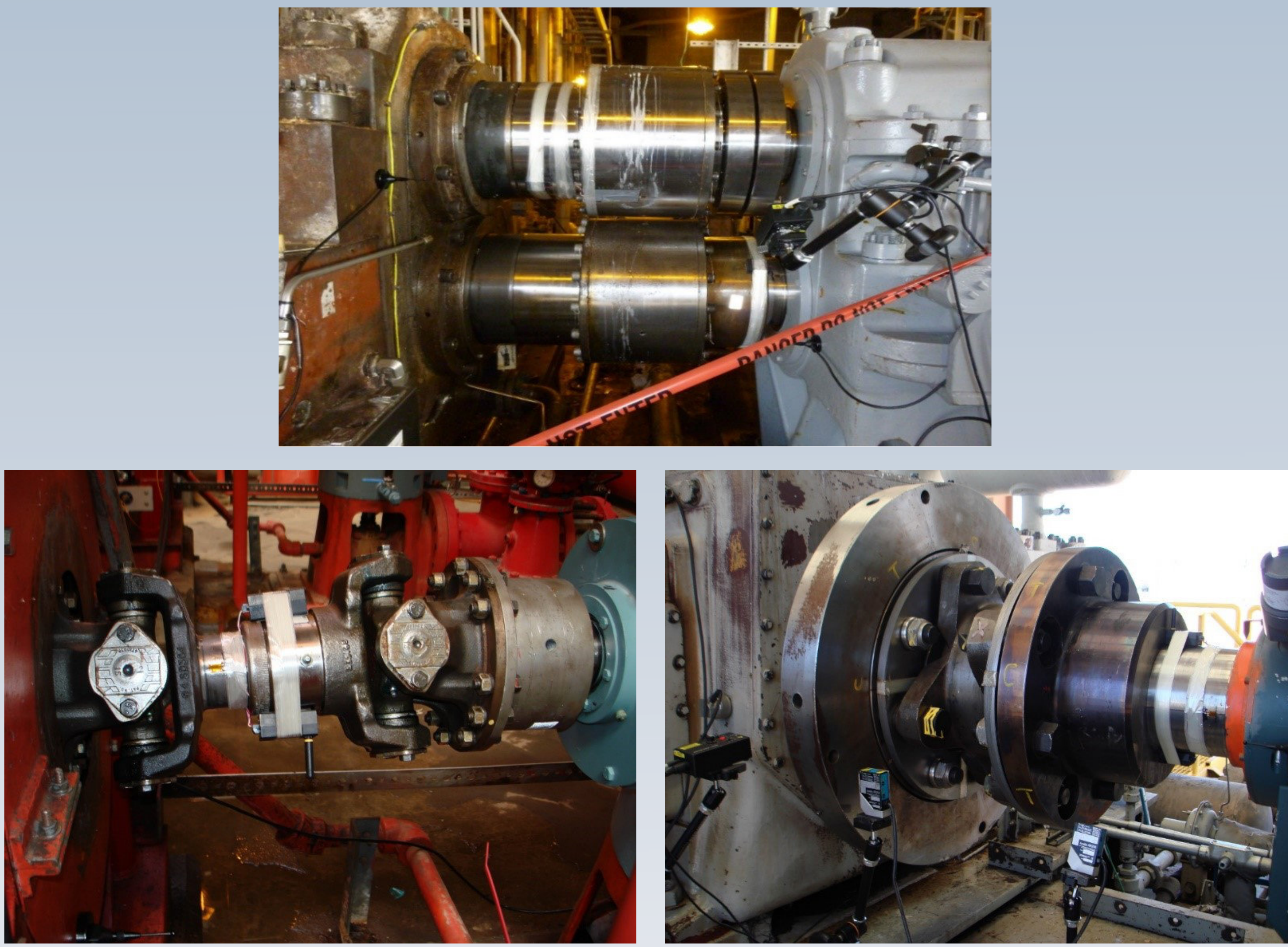


Figure 6. *Binsfeld's TorqueTrak 10K used for TVA on a variety of equipment including rotors, engine-driven pumps, and reciprocating compressors. [Courtesy of EDI]*

Using Torque Telemetry

For Torsional Vibration Analysis

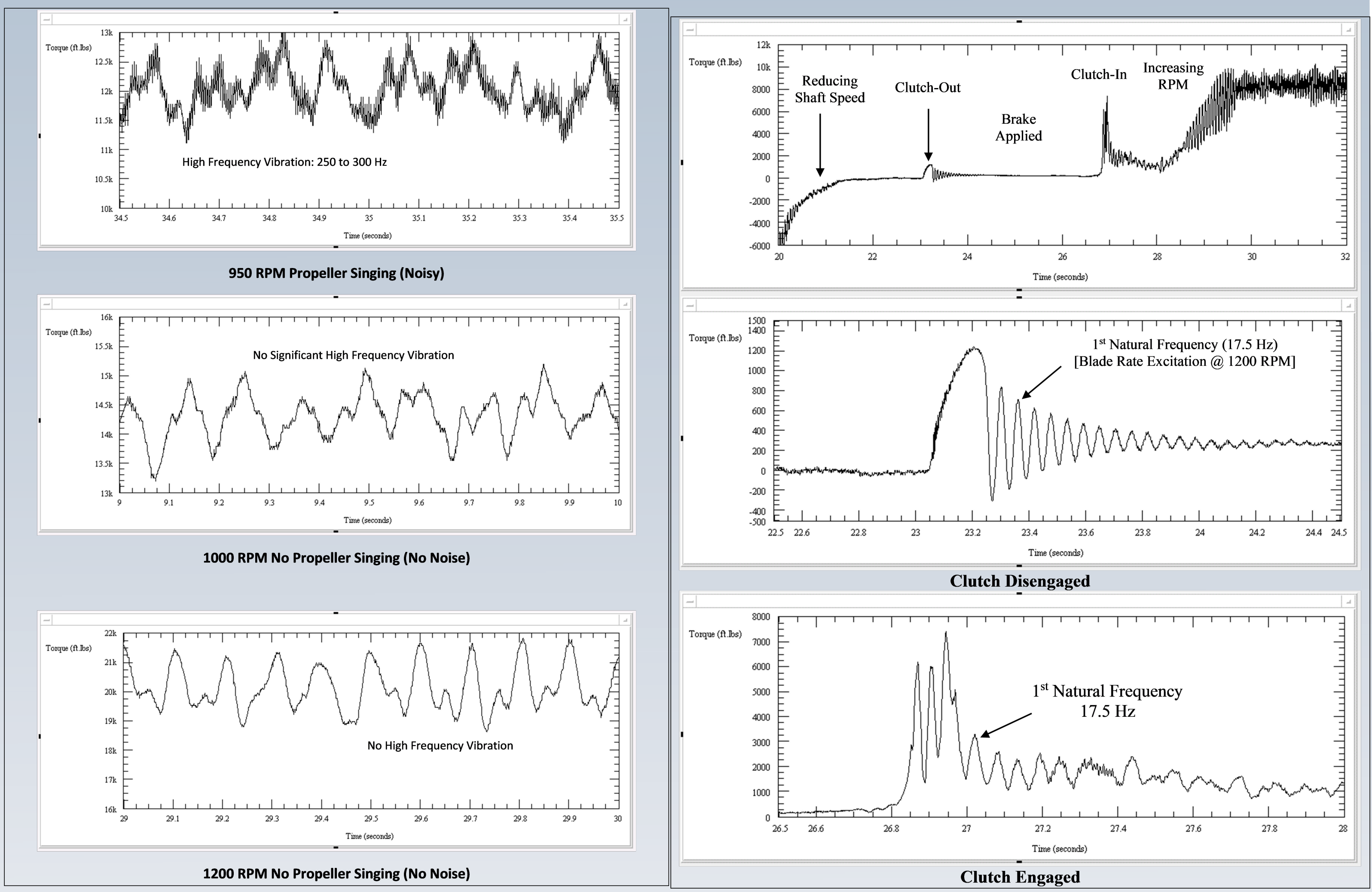


Figure 7. *Sample plots of torsional vibration testing done with a TorqueTrak 10K unit on a ships propellar shaft. [Courtesy of Lamalo Technologies]*

Using Torque Telemetry

For Torsional Vibration Analysis

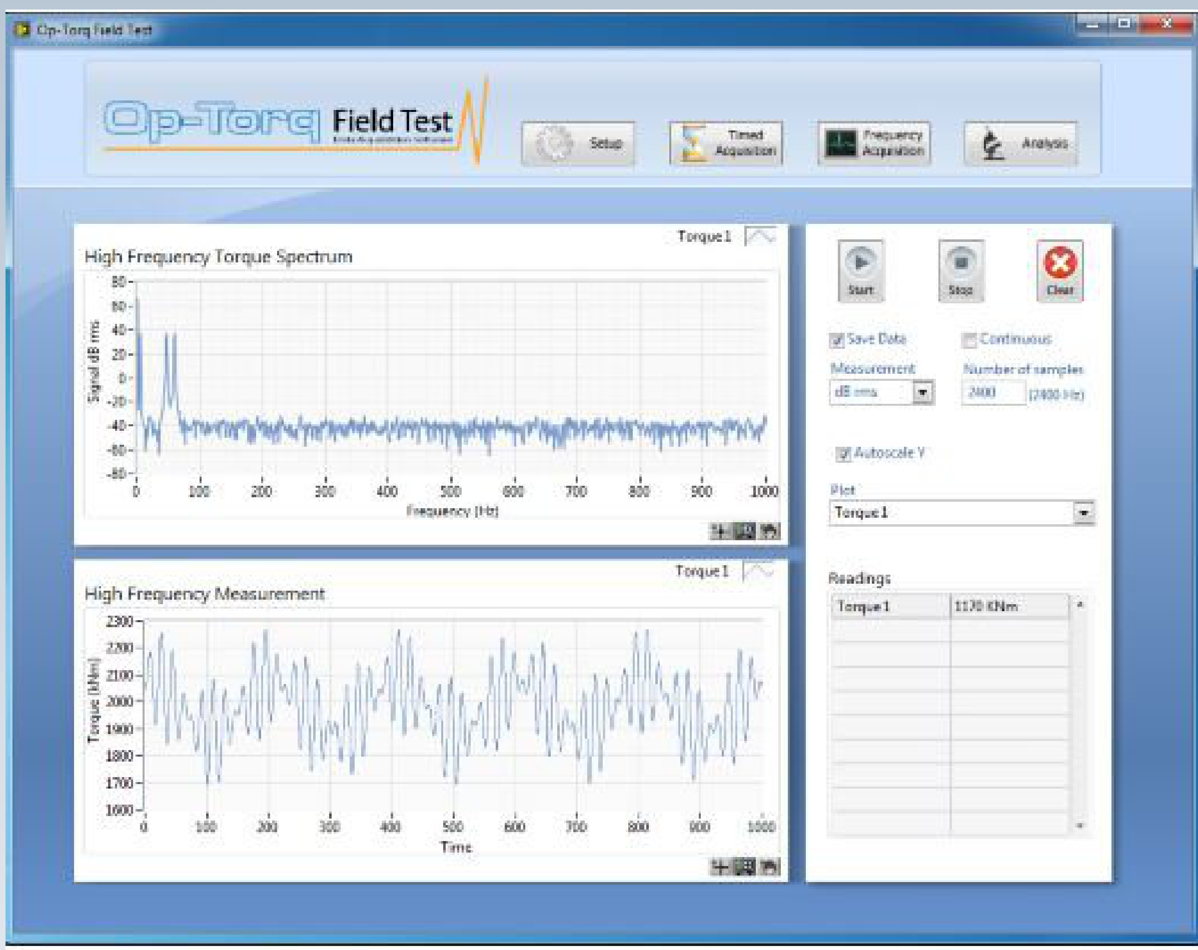


Figure 8. *A sample high-frequency plot from the OPDAQ Field Test 2 system.*

CASE STUDY

TORSIONAL VIBRATION ANALYSIS ON REFINERY ID FAN COUPLING

The Client

Engineering Dynamics Incorporated

Engineering Dynamics Incorporated (EDI) is an independent engineering firm offering consulting services to a large range of industries. The corporation was established in 1982 by a core group of six engineers, and today has offices in both San Antonio and Houston, TX. The team at EDI is a cohesive and consistent engineering staff which is crucial to maintain experience, especially in a technical specialized business. EDI is a recognized leader in providing engineering expertise for clients in the petrochemical, refinery, paper, power generation, gas processing/transmission, and various other industries. (Website: www.engdyn.com)

The Challenge

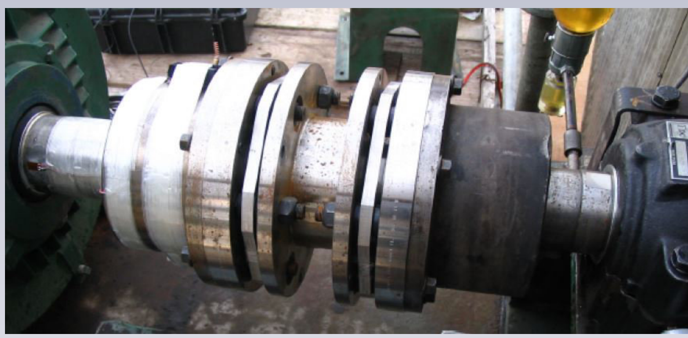
Refinery ID Fan Coupling Failures

EDI was called in to troubleshoot the cause of repeated failures on couplings in an induced draft (ID) fan system at a large refinery. The fan was driven by a 350 HP VFD-controlled induction motor and was part of an atmospheric furnace that heated approximately 152,000 barrels of crude per day. The trouble began when the motor was changed out for one of similar electrical performance, but of different physical size.

Inspection of the broken couplings revealed a crack propogation angle of 45 degrees at the bolt holes, indicative of the system hitting a harmonic torsional vibration mode. EDI needed to quantify and implement a solution as quick as possible to help the facility **reduce downtime** and **increase operational efficiency**.

The Solution

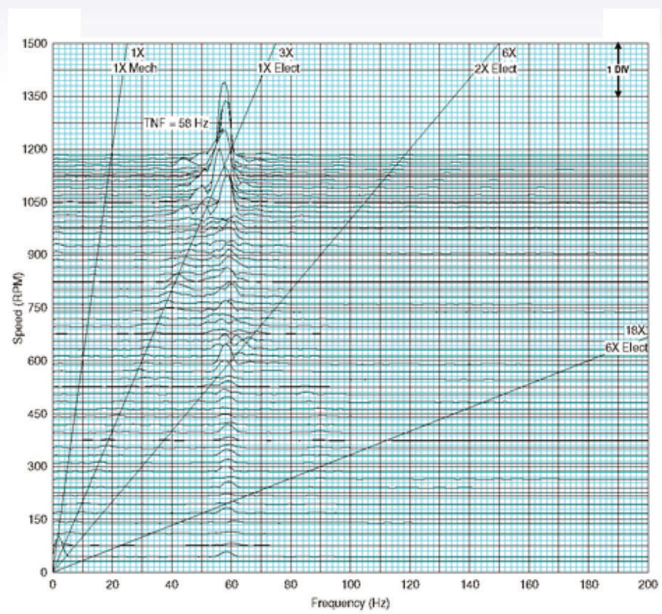
THE TORQUETRAK 10K



The **TorqueTrak 10K** torque telemetry system was to measure the torsional vibration on the driveline. Field Engineer Troy Feese explains, "One of the best tools for taking torsional measurements in the field has been the Binsfeld TorqueTrak 10K. It is easy to install and provides a clean torque signal".

The Impact

ACCELERATED TROUBLESHOOTING & REDUCED DOWNTIME



Torsional vibration data from the TorqueTrak 10K was used to confirm the presence of a torsional vibration natural frequency (TNF) in the drive system near 58 Hz, which was being excited by 1× electrical frequency of the VFD. This resulted in high dynamic torque in the coupling when operating the fan at 1000 – 1200 RPM. EDI selected an alternate coupling with standard rubber blocks in compression to detune the TNF away from the 1× electrical frequency of the VFD. The new coupling was installed and the equipment has continued working over many years . The TorqueTrak 10K helped to diagnose the problem and validate a solution quickly, resulting in **reduced downtime** for the refinery.

Reference: Feese, T. (2013, August/September). Torsional Vibration Problem with VFD Motor/ID Fan. Uptime Magazine.

"As a vibration consultant, for a long time I have been looking for a simple, efficient and reliable instrument for measuring torsional vibration, and I found it in the Binsfeld TorqueTrak instrumentation. Torsional vibration is absolutely necessary in reciprocating, gear transmission, electric motors and generating machinery."

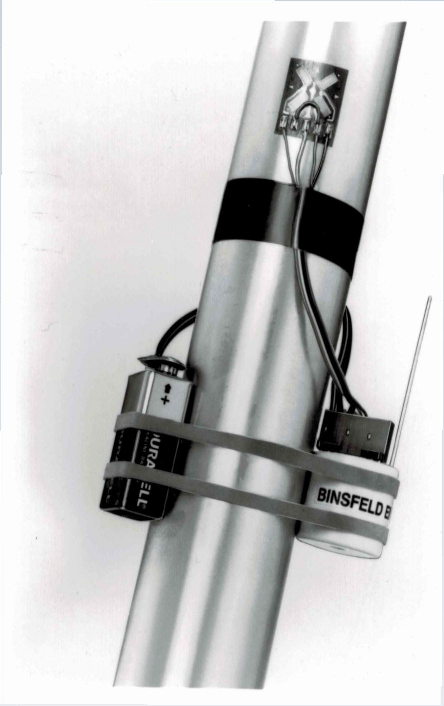
Vibration Analysis Consultant
Dyna

"One of the best tools for taking torsional measurements in the field has been the Binsfeld TorqueTrak 10K. It is easy to install and provides a clean torque signal. We have used it to successfully troubleshoot torsional failures of many systems such as VFD motors, reciprocating compressors, couplings, etc. We have also used the TorqueTrak 10K to measure axial thrust in vertical pump systems. In fact, we like the TorqueTrak 10K so much that EDI currently owns six of them!"

Troy Feese
Senior Staff Engineer, P.E.
Engineering Dynamics Inc.

BINSFELD. MEASUREMENT MADE EASY.

At Binsfeld, we understand that managing and servicing rotating equipment is hard enough. The last thing you should have to worry about is getting the data you need. Having started in the field ourselves almost 50 years ago, we understand the challenges you face, which is why we developed easy-to-use torque telemetry instrumentation backed by personalized one-on-one support from our experts, so you can spend less time measuring and more time focusing on what matters most.



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Torsional Vibration Problem with VFD Motor/ID Fan

Troy Feese

An induced draft (ID) fan system at an oil refinery experienced a failure of the spool piece in the flexible disc coupling between the motor and fan shafts. The fan system is part of an atmospheric furnace that heats approximately 152,000 barrels of crude oil per day.

The ID fan is driven by a 350 HP induction motor (Figure 1). To improve efficiency, the fan speed is varied instead of using inlet dampers to control the exhaust flow from the furnace. The motor speed is controlled by a low voltage variable frequency drive (VFD) from 0 to 1200 RPM. Any unscheduled downtime would be costly and could quickly outweigh the energy savings from using the VFD instead of inlet dampers. Therefore, it is imperative that this fan system have high reliability.

Tap to get more information

FIGURE 1

The failure of the flexible disc coupling consisted of a cracked space piece, which appeared to originate at a bolt hole (Figure 2). Initially, maintenance was blamed for possibly over tightening the coupling bolts. However, the 45 degree angle of the crack through the coupling spacer (Figure 3) is typical of a failure caused by high torsional vibration.

Torsional vibration is referred to as silent because it occurs in the shaft axis of rotation where conventional vibration monitoring equipment, such as accelerometers and shaft proximity probes, would not normally detect. Coupling chatter and shim pack deformation are common indicators of a torsional vibration problem. However, problems are usually not detected until after failure occurs. Therefore, special test equipment is needed to measure torsional vibration.

Field tests were performed to diagnose the cause of the coupling failure. The transmitted torque was measured using a wireless strain gage telemetry system mounted on the motor shaft extension near the cou-

FIGURE 2

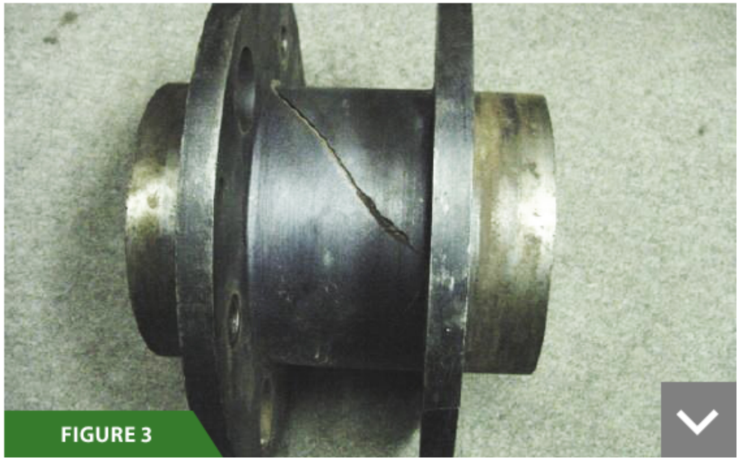


FIGURE 3

pling hub as shown in Figure 4. The waterfall plot in Figure 5 shows the measured frequency spectra of the alternating torque versus speed. The first torsional natural frequency (TNF) of the system was identified at 58 Hz.

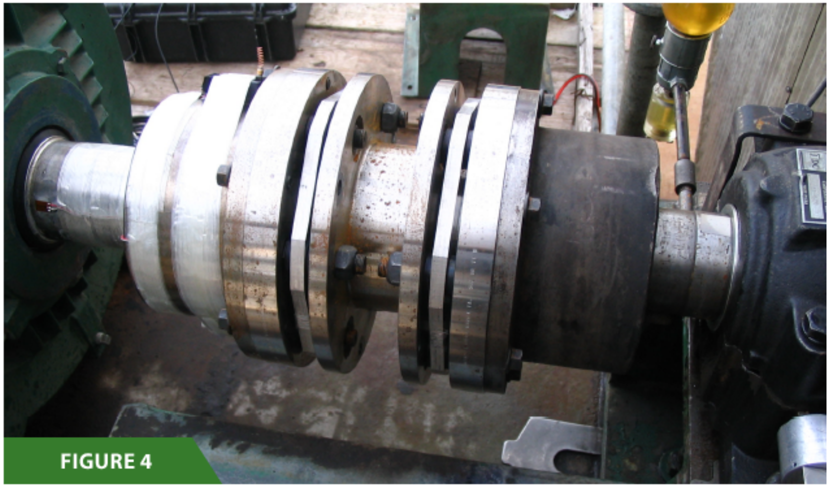


FIGURE 4

Torsional resonances occur when energy at multiples of mechanical running speed and electrical harmonics from the VFD intersect a TNF. Because the motor has six poles (three pole pairs), the mechanical frequency will be approximately 20 Hz (1200 RPM) when the fundamental VFD frequency is 60 Hz, neglecting a slip of the induction motor. High dynamic torque in the coupling was found when operating the fan in the 1000 RPM to 1200 RPM speed range due to VFD excitation, a 1× electrical frequency.

VFDs control motor speed by varying the electrical frequency. In the U.S., electrical power is supplied at 60 Hz. The VFD first rectifies the input AC power to the DC bus. The VFD then inverts from DC back to AC power at the required electrical frequency to drive the motor at the desired speed. The output frequency from the drive can range from 0 to 60 Hz, or even higher frequencies. Because the output waveform is no longer a pure sine wave, torque ripple can be produced. Some newer VFD technologies, such as pulse width modulation (PWM), can produce smoother waveforms and thus reduce excitation at electrical harmonics.

Because the refinery normally operates the fan from 1000 RPM to 1200 RPM, which was the speed range where excessive amount of dynamic torque was measured, this is believed to be the reason for the coupling failure. For example, the VFD excitation was approximately five percent of the full load torque (FLT) and at torsional resonance, the dynamic torque is amplified by a factor of thirty. Therefore, the maximum alternating torque was approximately 150 percent of the transmitted torque, which exceeded the rating of the coupling.

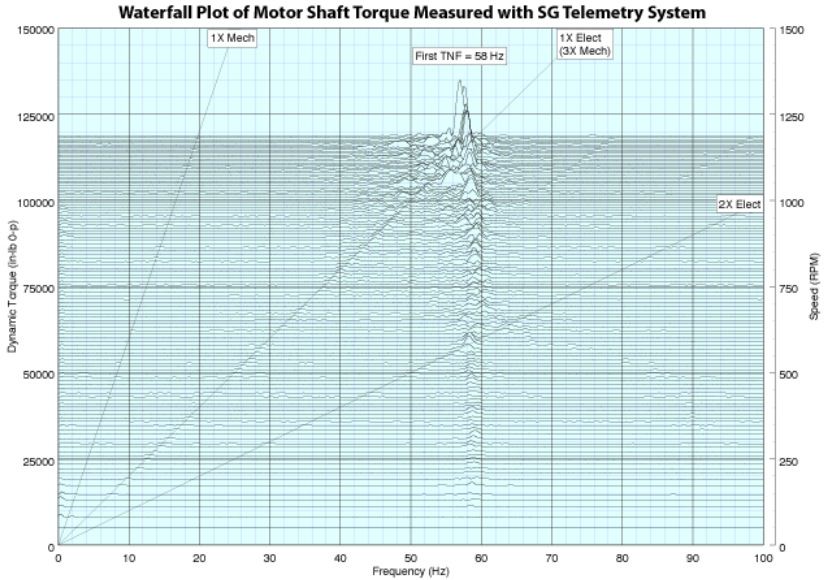


FIGURE 5

Because of the large diameter size and weight involved, the inertia of the fan is many times greater than the inertia of the motor. For the first torsional mode, the motor core is typically near an anti-node and acts like a torsional pendulum. The fan, on the other hand, is usually near the node and acts as an anchor. The drive infers load changes by monitoring motor current, which could also contain variations from the first TNF. In a torsionally stiff, lightly damped system, the first torsional mode is very sensitive to any harmonic excitation or sudden speed adjustments from the VFD motor. The references listed at the end of this article provide additional information and examples.

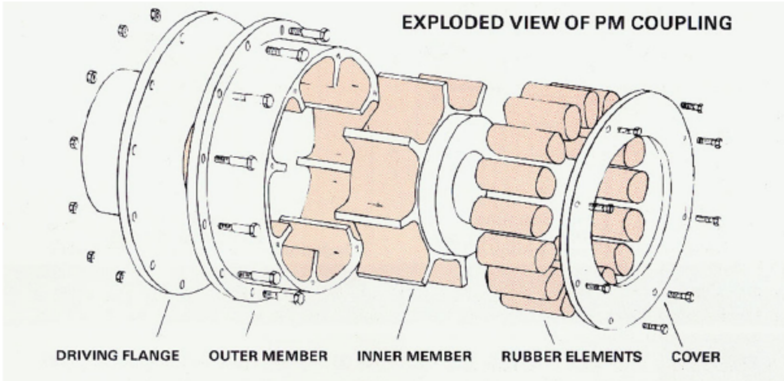
After further discussion with plant personnel, it was determined that the fan was originally driven by another motor from a different manufacturer. Repairs were needed on the original motor and would have taken longer than the plant could accept. Therefore, an alternate motor from a different manufacturer was installed. This new motor was similar in electrical performance, but was vastly different in physical size and inertia. Unfortunately, the electrical engineers did not communicate with the mechanical engineers that this change was being made and did not realize the effect on the mass-elastic torsional system.

AMERICAN PETROLEUM INSTITUTE (API) RECOMMENDS THAT A TORSIONAL ANALYSIS BE PERFORMED IN THE DESIGN STAGE TO PREVENT FAILURES.

American Petroleum Institute (API) recommends that a torsional analysis be performed in the design stage to prevent failures. A separation margin (SM) of at least 10 percent between the torsional natural frequencies and the excitation frequencies is recommended to avoid running at a torsional resonance. This is required unless safe operation can be demonstrated at resonance. Often times, satisfying the 10 percent SM is impractical for VFD motor systems, which typically operate over a large speed range.

Unfortunately, a torsional analysis of the fan system was not performed with either motor. Therefore, the location of the first torsional natural frequency was unknown and could not be avoided. After the coupling failure, the inertia values of the two motors were compared. It was found that the replacement motor had a much lower inertia (WR2) value than the original motor. Reducing the motor inertia caused the first TNF of the system, which was originally below the minimum speed, to increase into the normal operating speed range of the fan.

Since it was not possible to switch back to the original motor, a temporary solution was recommended where the running speed would be limited to a maximum motor speed of 1000 RPM (VFD frequency of 50 Hz) to avoid exciting the first TNF at 58 Hz. This provided a SM of approximately 13 percent between the VFD excitation frequency and the first TNF of the system. The plant was able to run the fan in a safe condition until a long-term solution could be developed.



(Illustration courtesy of Holset Coupling Catalog)

FIGURE 6

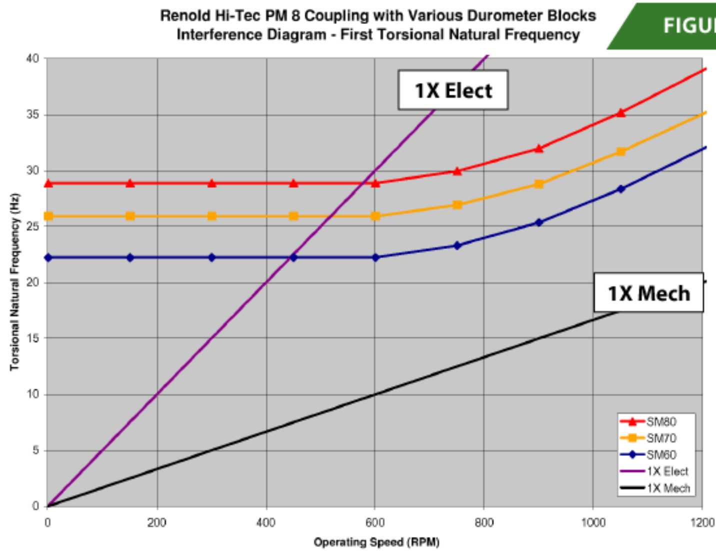
A torsional analysis of the system was performed and normalized to match the measured field data. Based on the results of the computer analysis, an alternate coupling was selected to detune the TNF away from the 1× electrical frequency of the VFD. A coupling with rubber blocks in compression (Figure 6) generally has a lower torsional stiffness than a steel flexible disc coupling and provides additional damping. The damping limits the dynamic torque when operating near resonance. Rubber couplings in compression are commonly found on large VFD motor/fan systems at power plants.

The torsional stiffness of the coupling is non-linear and sensitive to shore durometer (hardness) of the rubber blocks. Therefore, when using this type of coupling, it is important to compute the TNFs using various rubber durometers (SM60, SM70, SM80) over the entire operating range. The interference or Campbell diagram shown in Figure 7 illustrates how the first TNF varies with speed/load for various rubber durometers. With SM60 blocks, the torsional resonance was predicted well below the normal operating speed range. Fortunately, a suitable coupling with proper size and durometer blocks was located within a short delivery time.

The new coupling was installed and the fan system has been operating satisfactorily for five years. This case study shows the importance of performing a torsional analysis on a new system in the design stage and whenever the system is modified. Variables in the system include motor inertia and coupling torsional stiffness. The inertia was significantly different between the old and new motor models.

It is interesting to note that the VFD excitation was higher than reported by the manufacturer. For a smoother VFD producing only one percent torque ripple, the rubber coupling may not have been required. To achieve a reliable design, adequate safety factors must be considered to account for possible variation in the supplied information.

FIGURE 7



Troy Feese *is a Senior Project Engineer at Engineering Dynamics Incorporated (EDI) in San Antonio, Texas. He has 22 years of experience performing torsional vibration, lateral critical speed, and stability analyses as well as evaluating structures using finite element methods. He conducts field studies of rotating and reciprocating equipment. He is a lecturer at the annual EDI seminar and has written technical papers on torsional vibration, lateral critical speeds, and balancing. He is a member of ASME, Vibration Institute, and is a licensed Professional Engineer in Texas.*

Website