Shaft Crack Detection

Trends in machine use and design are causing shaft cracks to become increasingly more commonplace than 20 years ago.

The current trend among machinery users is to extend the life of rotating machinery. Rather than replace 20- to 30-year old machinery, many companies are using life assessment and inspection techniques to operate their machinery up to or beyond its original design life.

Today's operating practices--particularly on machines in power generation service--also impose severe thermal and mechanical stress on the rotors. One such practice is the runup and rundown of machines two or more times per day. When operated in this manner, some rotors become susceptible to age-related cracking.

Another trend over the past 10 years has been to design larger turbine generators--even greater than 1,000 megawatts. These larger machines are more susceptible to various machine malfunctions, including shaft cracks, according to an Electric Power Research Institute (EPRI) study.

Consequently, the number of shaft crack incidents has increased dramatically.

One machine manufacturer has logged more than 28 incidents in North America over the past 10 years in the power generation industry alone. And the manufacturer indicates this is a partial list only.

Cracks, which develop in new or overhauled rotors because of faults in design, tend to develop early in the life of the rotor after commissioning or rebuilding. These cracks are often caused by increased stress introduced by poor machining techniques.

Cracks can also develop in rotors that have run many thousands of hours without failure, because of corrosion damage, severe misalignment preloads, and other factors. These problems can develop on many types of rotating machinery, both large and small.

As the number of shaft crack incidents has increased, so, too, has the need for early detection of shaft cracks.

The reason is simple. The consequences of shaft cracks are catastrophic. Companies--from a monetary, safety, and public image point of view--cannot afford to have a shaft crack incident.

According to an EPRI report, one utility paid $6.2 million to purchase replacement power alone during an outage caused by a shaft crack on a turbine. The cost of instrumentation to diagnose the shaft crack was $100,000.

Early Shaft Crack Detection On Rotating Machinery Using Vibration Monitoring and Diagnostics
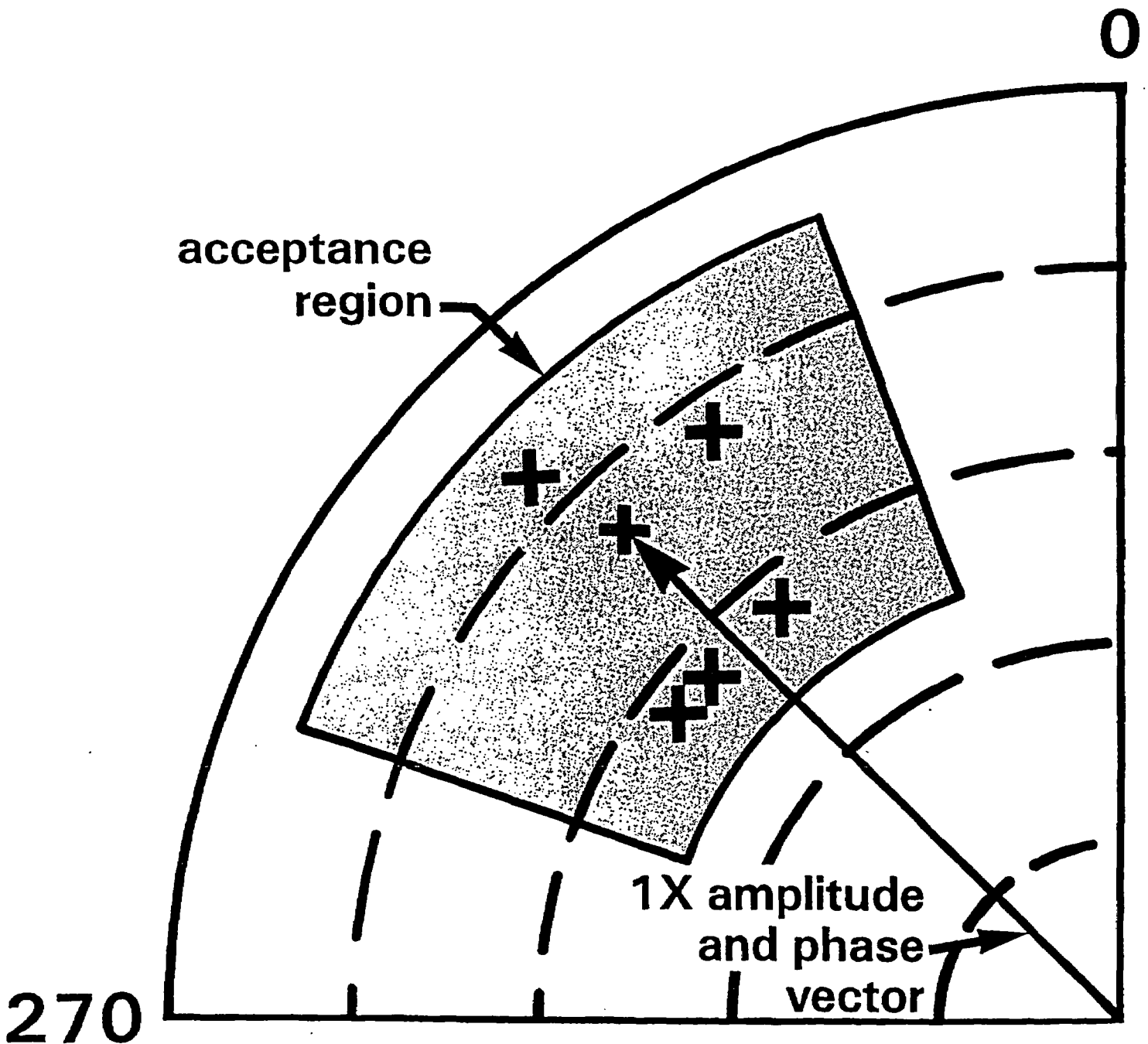
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acceptance
region

1X amplitude
and phase
vector

270

Because other malfunctions can cause the machine to exhibit similar symptoms as those experienced under a shaft crack condition, it's important to understand that proper diagnostic methods must be used to diagnose a shaft crack.

There are two fundamental symptoms of a shaft crack:
1) Unexplained changes in the synchronous speed (1X) shaft relative amplitude and phase and/or slow roll bow vector, and
2) The occurrence of twice rotative speed (2X) vibration.

The vital and primary symptom is changes in the synchronous (1X) amplitude and phase and/or slow roll bow vector. This symptom, which has been observed on large turbine generators with shaft cracks, is the most important indicator of a shaft crack. Shaft measurements are the only effective method for measuring changes in the synchronous (1X) amplitude and phase and/or slow roll vector.
The changes in synchronous (1X) amplitude and phase are caused by the shaft bowing due to an asymmetric transverse crack (Figure 1). In this situation, the synchronous (1X) amplitude and phase changes-- either higher or lower.

The secondary, and classical, symptom--the occurrence of the 2X component--is due to asymmetry of the shaft.
The 2X component is due to a combination of a transverse crack--which causes shaft asymmetry--and a steady-state radial load--such as gravity, in the case of horizontal rotors.
The 2X frequency component is especially dominant when the rotative speed is in the region of half of a rotor system natural frequency. Figure 2 shows a spectrum cascade plot and the corresponding orbits, which identify this classical shaft crack behavior as well as the bow/nonlinear response.

The change in synchronous (1X) amplitude and phase can be monitored under normal operating conditions to provide alarming and early warning of a shaft crack.
The polar plot provides an excellent format for documenting the shift in synchronous (1X) amplitude and phase. The shift is monitored at operating speed and at slow roll. A normal operating range of the 1X vibration vector is determined within the plot to form what is called an "acceptance region." The actual 1X vibration vector is then plotted. Deviation of the 1X vibration vector from the acceptance region can be a vital warning of a shaft crack, even though other rotor disturbances can also cause some deviation from the acceptance region (Figure 3). Similar techniques apply to changes in the slow roll bow vector.
Changes in synchronous (1X) amplitude and phase must be analyzed in conjunction with other vibration information--including the twice rotative speed (2X) machine behavior--to determine whether the shifts were caused by an asymmetric transverse crack or other factors, such as load, field current, steam conditions, or other operating parameters.

Acceptance regions also can be plotted for the twice rotative speed (2X) component during startup and shutdown to provide further evidence of the possibility of a shaft crack.

The polar plot format is used to document increases in the twice rotative speed (2X) component within an acceptance region. We recommend that the maximum amplitude of the acceptance region for the twice rotative speed (2X) component be established at 2 mils peak-to-peak (pp), based on our experience with shaft cracks and other machine malfunctions. When relative changes of the twice rotative speed (2X) component exceed 2 pp mils, it is an indication of a severe machine malfunction.

It is important to note that the 2 pp mil level may not be appropriate for all machines. The type of machine and the location of the proximity probes on the machine must be considered when establishing the acceptance level.

Even though the appearance of the 2X component has been described in technical papers for the past 50 years, only one of four recent shaft crack saves exhibited this classical phenomenon.

In that case, the plant engineers and manufacturer's engineer observed and acted upon the following information on a vertical pump used in nuclear power plant service to accomplish an excellent save:
1. Increasing overall vibration levels.
2. Large 1X and 2X frequency vibrations.
3. 2X frequency vibration that remained after the machine was trim balanced. The 1X frequency vibration was significantly decreased by trim balancing.

The engineers used the vibration information to determine whether the machine response was caused by other possible malfunctions, such as unbalance, misalignment, etc. After eliminating the other possible malfunctions, the engineers determined there was a high probability of a shaft crack. The machine was taken out of service and inspected. Inspection confirmed their diagnosis.

Observation of orbits is also useful for revealing a shaft crack.

Figure 4 shows the typical orbit patterns for a shaft with a large 1X component, caused by a crack as well as a steady-state preload, such as gravity. The orbit patterns show that the rotor moves toward the direction of the preload twice during each shaft rotation. This results in a 2X component. Future changes in the orbit pattern are dependent on the phase lag relationship between the 1X and 2X components.

When these orbit patterns are detected, other machine malfunctions must be eliminated to determine whether a shaft crack is the root cause of the problem.

A large 1X component can be caused by a shaft thermal bow as well as a shaft crack. A preload--due to misalignment--as well as a shaft crack can cause large 1X and 2X components.

3

When the thermal bow is removed, both 1X and 2X components disappear. When only the steady-state load is removed, the orbit becomes a 1X circle without a 2X component. The two separate methods of 2X formation may, of course, occur together when both situations are present (see Figure 3).

To obtain the vibration information for detecting shaft cracks, mode identification XY proximity probes--located at various longitudinal positions along the rotor--and a Keyphasor® reference are required. These probes make it possible to reliably observe the significant indicators of a shaft crack--the action of the shaft vibration patterns and bow changes at low rotative speed--as well as to identify nodal point regions and rotor mode shapes.

The mode identification XY proximity probes should be used to continuously monitor machines that are susceptible to shaft cracking. The use of these probes also overcomes the potential danger, when only a single set of XY proximity probes is used, of locating the probes at a nodal point along the rotor.

What to do when your machine experiences any of the shaft crack symptoms...

As we stated before, because other malfunctions can cause the machine to exhibit similar symptoms as those experienced under a shaft crack condition, the proper methodology must be used to diagnose a shaft crack.

Two recent shaft crack saves illustrate this point. The engineers originally suspected imbalance as the cause of the problem, but the machine did not respond properly to several balancing attempts.

Difficulty in trim balancing often is a warning sign of a cracked shaft. Further analysis of the symptoms is required to determine the root cause of the problem.

Bently Nevada possesses the capabilities to assist you in identifying the symptoms and detecting cracked shafts.

We know numerous machines are now operating with at least small cracks and are using a three-pronged approach--research, services, and instrumentation--to detect shaft cracks.

Research, conducted by Bently Rotor Dynamics Research Corporation, has resulted in the definition of shaft crack symptoms and the development of methodology for diagnosing shaft cracks.

# THE FUNDAMENTAL ACTION OF
A TRANSVERSE CRACK
IS THAT IT

BOWS THE SHAFT

Orbit of shaft bow
caused by transverse
crack (1X frequency)
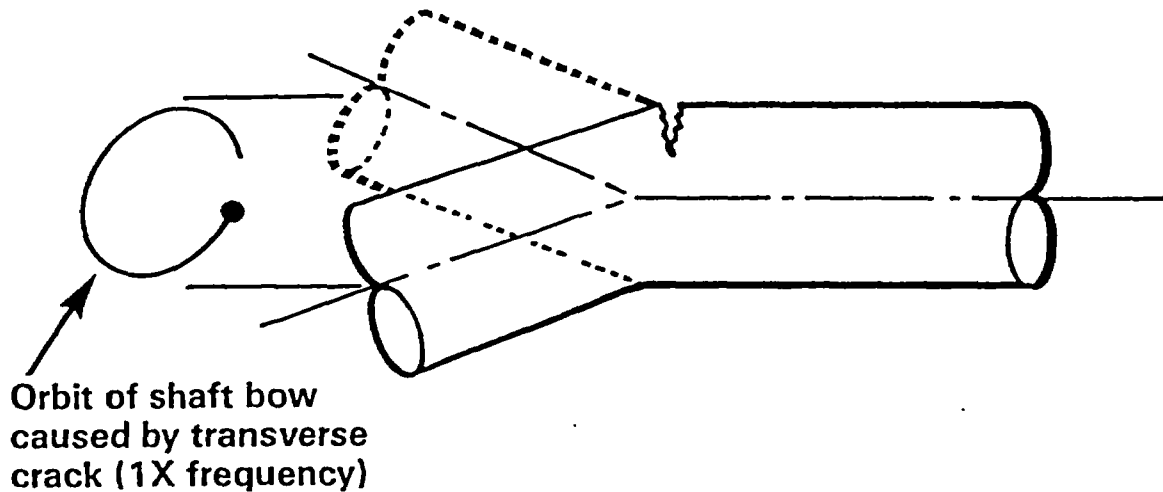
This causes: (1) Changing 1X (synchronous) vibration behavior at speed and load.

(2) Erratic response to attempted balancing.

(3) Changes in the slow roll bow vector (at low rotative speeds).

Further, as the bow increases, a totally different type of 2X behavior may occur. (See spectrum cascade of cracked shaft).
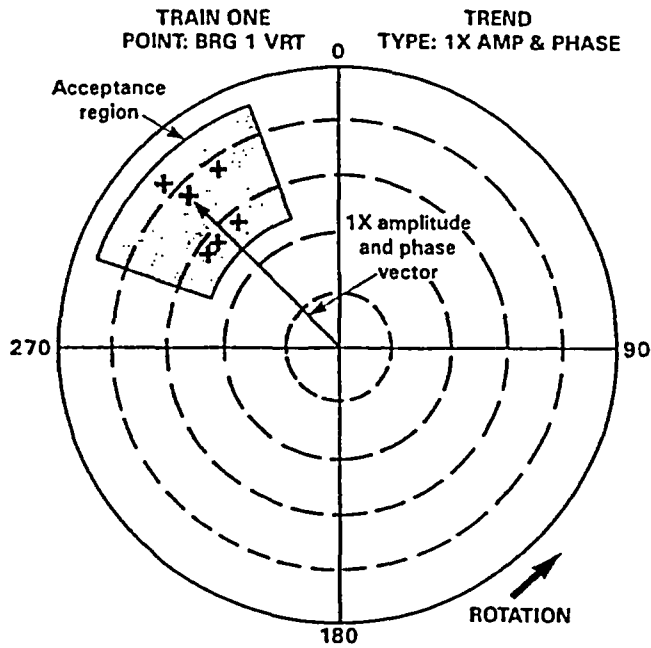
Figure 1
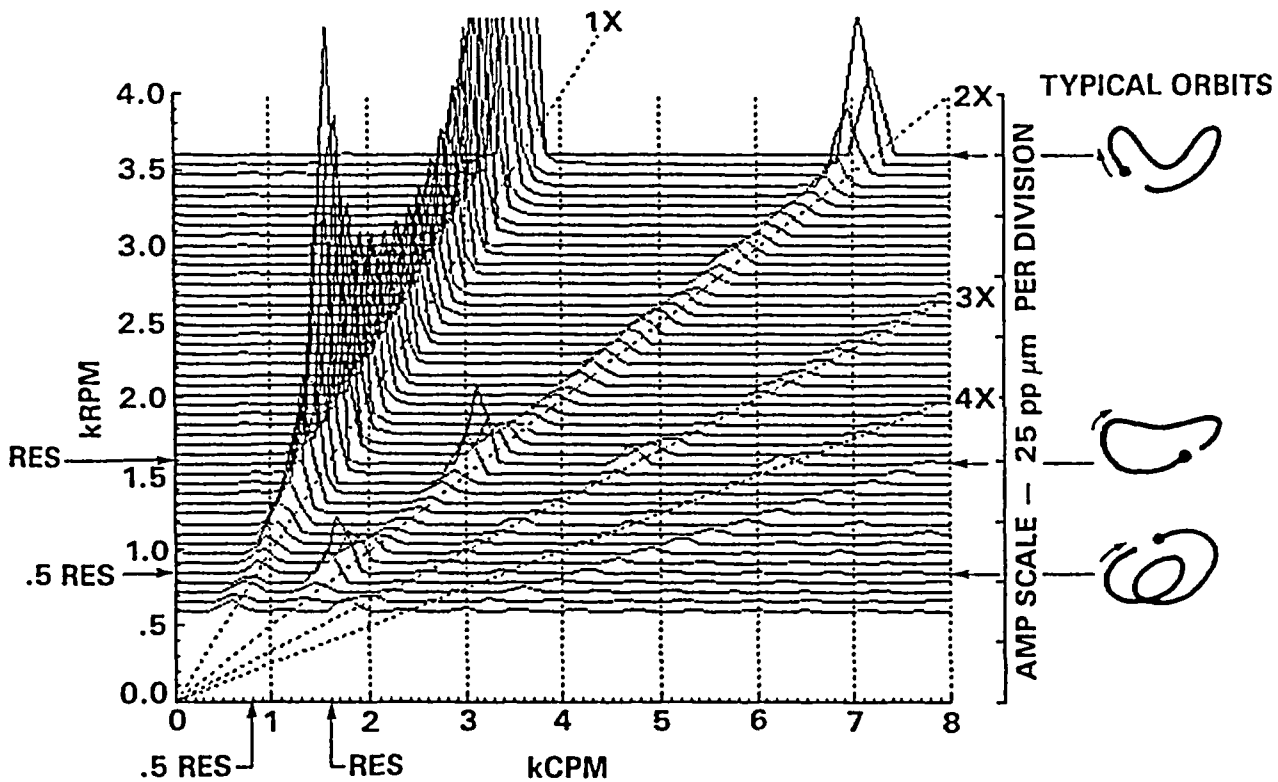
**SPECTRUM CASCADE
OF CRACKED SHAFT**

The above spectrum cascade plot shows the vibration response (amplitudes and frequencies) from a proximity displacement transducer at different speeds during a shutdown of a rotor with a cracked shaft. Two types of 2X components caused by a cracked shaft can be observed in this example.

When the rotative speed (800 rpm) is at half the resonance speed (1600 rpm), the 2X frequency component has its resonance. The orbit shows the typical inside loop. This 2X motion is driven by a preload (like gravity) and shaft nonsymmetry due to a crack. The 2X component is present even though the 1X component is small.

When the shaft bow gets large as the rotative speed approaches the resonance speed a steady state preload causes the rotor reaction shown by the orbit at 1600 rpm. Notice that the 2X, 3X, and 4X harmonics are also incurred. This 2X motion is driven by the 1X and therefore, is only present when large 1X orbiting occurs.

At 3600 rpm a large 1X vibration again occurs (second resonance). In conjunction with the preload, it causes the resulting 2X frequency component. The corresponding orbit is shown.

Figure 2

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TRAIN ONE   TREND
POINT: BRG 1 VRT   0   TYPE: 1X AMP & PHASE

Acceptance region

1X amplitude and phase vector

270 ——————— 90

ROTATION

180

The polar plot is a presentation of vector monitoring. The 1X (or 2X) amplitude and phase vector is monitored to ensure it remains within an acceptance region. When the vector moves outside the acceptance region, further diagnostics are necessary. This is especially important for monitoring for cracked shafts.

Figure 3
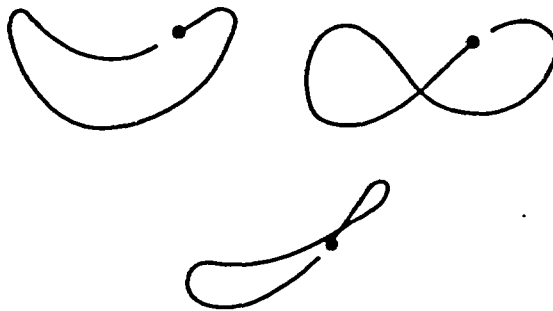
Examples of orbits of a rotor with a cracked shaft and resulting shaft bow combined with a stead-state preload, such as gravity.

Examples of orbits of a rotor with a cracked shaft where the 2X frequency component results primarily from a preload, like gravity. These are the classical 1X and 2X orbits for a cracked shaft, at a half first balance resonance speed.

Figure 4

The methodology is taught at our Customer Training seminars.

In a machine save involving a shaft crack at a public service utility, engineers from the utility had attended a Bently Nevada seminar, which helped them better interpret the information from their 7200 Series Monitoring System and ADRE® (Automated Diagnostics for Rotating Equipment) system. Based on the vibration data, they stopped the machine. Inspection revealed a 400 degree spiral crack.

The shaft crack methodology is also applied by Bently Nevada's Mechanical Engineering Services in performing machine analysis for customers.

In a recent case, MES engineers' superior methodology made the difference in correctly diagnosing the problem. Bently Nevada's MES engineers analyzed the rotative speed (1X) and the twice rotative speed (2X) data and determined there was a high probability of a severe crack. The machine was disassembled. Inspection revealed a 90 to 95 percent crack through the rotor that was visible to the eye.

Bently Nevada's MES engineers are trained to detect shaft cracks and diagnose other machine malfunctions.

They also are trained to perform balancing--using modern techniques--and to document the response vectors during the balancing process for the user's records.

Several Bently Nevada instruments are available today for use in early shaft crack detection:

□ ADRE System to observe and document the machine response under transient conditions. The ADRE is especially useful for observing 1X and 2X polar plots

□ 7200 Series Dynamic Data Manager® system to continuously observe and trend 1X and 2X amplitude and phase components as well as to observe and document spectrum information.

□ 7200 Series Monitoring System with the 72730 Digital Vector Filter (DVF-R) to continuously observe 1X amplitude and phase components.

□ Digital Vector Filter 2 (DVF 2) and Balance Master™ to take periodic readings of 1X and 2X amplitude and phase components.

□ Keyphasor Multiplier, an accessory to the DVF 2 and Balance Master™, which can be used to multiply the Keyphasor frequency to observe 2X components.

□ Snapshot® to take periodic readings of 1X and 2X amplitude and phase components and to plot data in spectrum, time base, and orbit formats.

NOTES

For more information on Bently Nevada products and services for detecting shaft cracks, please contact your local Bently Nevada office or the Customer Information Center, P.O. Box 157, Minden, Nevada 89423. Or call 800-227-5514, Ext. 7438.

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