Application Note

On-line Surveillance Monitoring of Gearboxes

By Jim Wei, Application Engineer • SKF

Background

Successful on-line surveillance based condition monitoring and evaluation of intricate industrial machinery, such as gearboxes, relies on the ability to successfully compartmentalize signals from multiple sources that are all presenting themselves simultaneously to the measurement transducer. Most industrial machines are relatively simple to monitor, as transducers are easily placed to monitor direct vibration transmission paths from the moving elements. This is true for most common machines, such as direct motor driven pumps and fans. In nearly all of these machines, transducers are positioned to “see through” a direct path to a single constrained rotating component, such as a shaft held in place by a bearing. This transducer is essentially focused on the shaft and the local bearing due to attenuation of the vibration from the shaft and opposite end bearing through a much less direct structural path. In most cases, sufficient external surface area is available to dedicate needed transducers to monitor specific internal components.

However, intricate mechanical components, such as gearboxes, are difficult to monitor, as they involve many internal components with relatively little direct external access to good vibration transmission paths. Similarly, most direct drive industrial machinery operates within reasonably narrow speed and load ranges. This is not typically the case for industrial gearbox applications, further complicating successful condition monitoring data evaluation.

This paper addresses successful gearbox condition monitoring and evaluation through examples of both field and laboratory testing of one of the most challenging gearbox applications – wind turbines.

The challenges

The intricate wind turbine gearbox mechanism

Wind turbine gearboxes are complex mechanical systems and known to be problematic. A majority of conventional wind turbines, in the 500 kW to 1,5 MW class, are equipped with three-stage gearboxes. The first high torque stage is often a planetary gearing system. The remaining two stages are typically parallel shaft drives with either spur or helical gears, as shown in **fig. 1**.

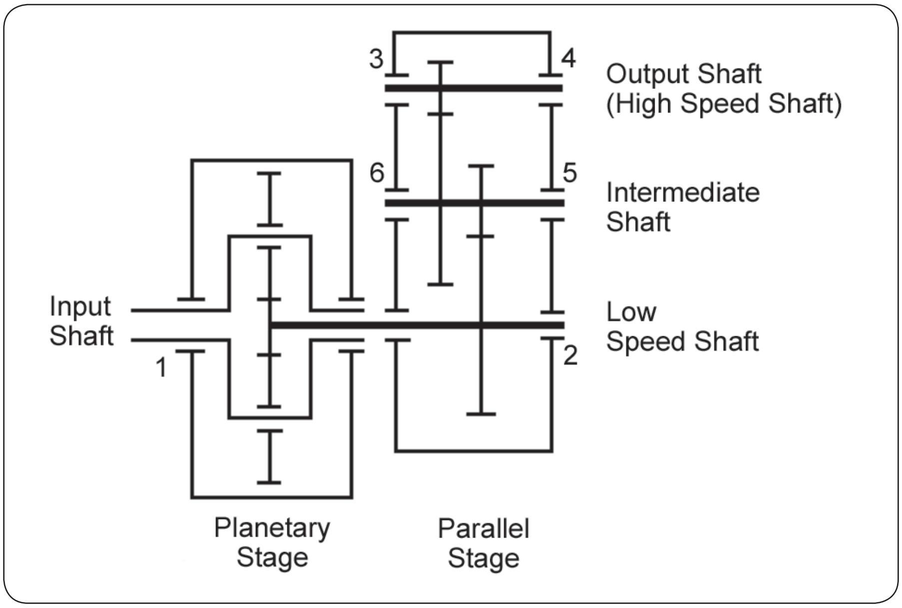

Fig. 1. Typical wind turbine gearbox configuration with transducer locations.

There are usually a dozen or so bearings, four gear wheels and a planetary gearing set including a sun gear, several planet gears and a ring gear. Any of these components could be the candidate of mechanical failure. To accurately identify the source of problem in such a complicated mechanical system is quite a challenge, especially where the components are attached internally, away from accessible bearing housings where sensors are ideally mounted.

A continually changing operating environment

Unlike other rotating machinery, wind turbines operate in a constantly changing environment. With a variable speed machine, as the inflow field changes, the load and speed of the drive train vary accordingly. Variations of turbulence intensity in the incoming wind interacts with turbine rotor systems, generating dynamic loading that greatly complicates the operating condition of the drive train, and that affects the vibration signal in such a way that a signal validation process or operating condition based alarm may be necessary.

Structurally induced variability not normally encountered in industrially mounted machinery

In addition to the difficulties mentioned so far, the turbine bedplate on which the gearbox is mounted is not likely to be as rigid as concrete pads. Dynamic deformation of the bedplate could cause excessive gearbox casing deformation. As a result, bearing housing deformation and shaft misalignment can be significant. Consequently, bearing overloading caused by deformation stress could result in an apparent damage signature that is not necessarily from existing damage, but will cause damage at some future time.

Structural resonance

Field experiences also indicate that, with variable speed drive train designs, gearbox structural resonance frequencies can easily be excited under normally occurring operating conditions. This results from gear mesh frequencies being much higher than the shaft rotating speed. As the rotor gradually changes its speed in response to a wind speed change, the gear mesh frequencies can sweep across a very large frequency band, exciting gearbox resonances in the process. The sudden dramatic increase of the vibration level due to resonance causes a conventional alarm setting strategy to produce false alarms.

Large vibration dynamic range

Very low rotational speeds at a gearbox input shaft, ranging from 10 to 20 revolutions per minute, result in very large structural vibration signals from the blades and the tower (blade and tower resonance signals), which usually dominate the spectrum when they appear. Careful measurement and alarm setup is required to separate these strong signals from the significantly more subtle bearing and gear vibration signals.

Monitoring strategy

Establishing a monitoring strategy for intricate mechanisms that are subject to any or all of the challenges faced by a wind turbine gearbox includes proper sensor selection and location and determining the types of measurements needed, including their setups and appropriate alarm criteria. A gearbox (typical of many applications) with a planetary first stage and parallel shaft second and third stages, as illustrated in **fig. 1**, requires a minimum of four piezoelectric accelerometers with constant frequency response up to 10 kHz.

The locations of these sensors are indicated in **fig. 1** at the input shaft bearing housing (1), low speed shaft bearing housing (2) and on the output shaft bearing housings (3, 4). Additional sensors at the intermediate shaft bearing housings (5, 6) should also be used, but may not be practical to install. A tachometer should be installed on the high-speed shaft (3 or 4). Shaft speeds for each individual shaft in a gearbox are obtained using gear ratio information. This information is entered into SKF's on-line software for automatic speed computation each time a measurement is performed.

Multiple measurements need to be made with each sensor. Each measurement focuses on specific frequency bands and has a specific use in determining the condition of the internal components, as the following describes.

Velocity

- Monitors low frequency rotational faults (imbalance, alignment, etc.)
- Helps detect/confirm bearing damage in later failure stages

Acceleration

- Monitors high frequency faults (gear mesh, fluid induced vibration, etc.)
- Detects high frequency structure resonance

Acceleration enveloping

- A demodulation process that enhances repetitive impact signals
- Early bearing damage detection
- Gear teeth damage detection
- Impact detection

SEE

- A demodulation process that enhances signals in the acoustic frequency band
- Incipient bearing damage detection
- Gear teeth damage detection
- Surface rubbing detection
- Lubrication degradation detection

Measurement setup includes defining the following measurement parameters

- Number of spectral lines
- Analysis frequency range, i.e., fmax and low cutoff frequency
- Acceleration enveloping band pass filter selection
- Tachometer setting
- With or without averages, number of averages, if needed
- Detection method (peak, peak-to-peak, true peak, RMS)

To achieve effective monitoring results, measurement settings are based on the individual gearbox's parameters. In general, it is recommended that the acceleration measurement fmax should be higher than eight times the focused gear mesh frequency and the acceleration enveloping fmax should be higher than five times the targeted bearing damage frequency. Data acquisition duration should be long enough to ensure at least 10 to 15 shaft rotations are acquired. Since the number of spectral lines together with the fmax setting determine the data acquisition duration, it may be difficult, in some cases, to satisfy both requirements with a single measurement (data acquisition duration and spectral line resolution).

Measurements for gearbox intermediate or output shafts should use a low cutoff frequency higher than structural resonance frequencies (blades and tower natural frequencies) to eliminate the influence of these components, which tend to reduce the measurement's amplitude resolution due to low frequency saturation.

To use band alarms, a speed reference should be correctly set up for each shaft according to the speed ratio of each shaft with reference to the shaft that has the tachometer installed.

The general rule for selecting the acceleration enveloping filter band is to ensure the high pass filter cutoff frequency is at least five times higher than shaft rotation speed. Peak-to-peak detection is recommended. Using averaging, or using higher numbers of spectral lines, has a similar effect in reducing random noise. For larger frequency ranges signals, a higher number of lines tends to produce better measurement results.

Full scale gearbox lab testing study

A full scale gearbox lab test was conducted to demonstrate gearbox monitoring using SKF's on-line monitoring hardware and software products. The gearbox was installed with SKF acceleration/SEE dual sensors, and an SKF Multilog Local Monitoring Unit (LMU) was used to acquire and process the data.

During the test, the gearbox was under constant overloading to expedite the gear teeth failure process. Periodic inspection was made to inspect the gear teeth surface for damage assessment. A bearing rolling element damage signal was also detected by the monitoring system.

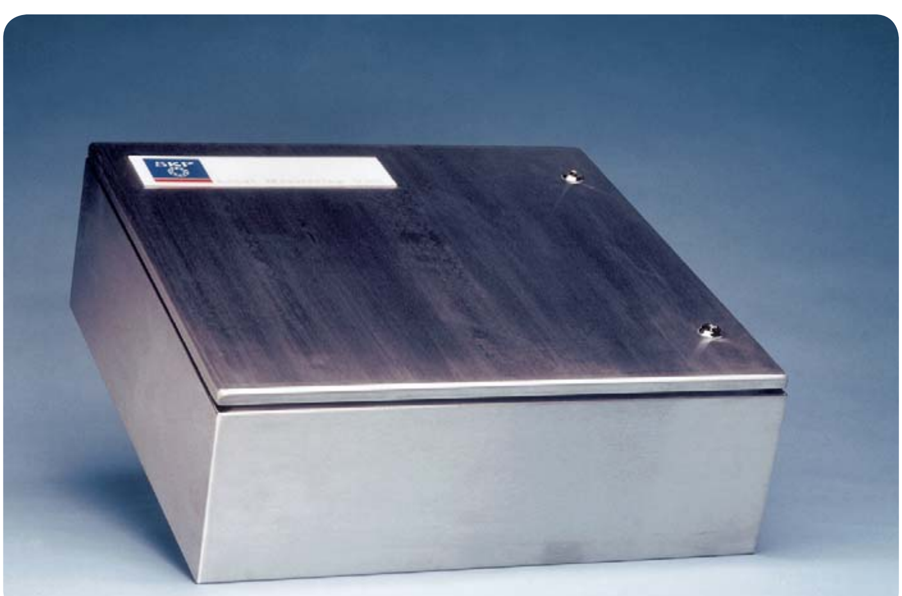

Fig. 2. SKF Multilog Local Monitoring Unit (LMU).

Some of the results of the test are presented as follows. **Fig. 3** shows the overall trend of acceleration enveloping using filter number 4 (5 to 40 kHz period) and an fmax of 8 kHz; as gear tooth surface damage progresses, the gE4 overall value increased by a factor of four. The alarm threshold levels were set by an SKF application expert and were based on experience. Notice the overall value approaching the alert level at the middle of the test and gradually working its way up and past the danger level at the end of the test.

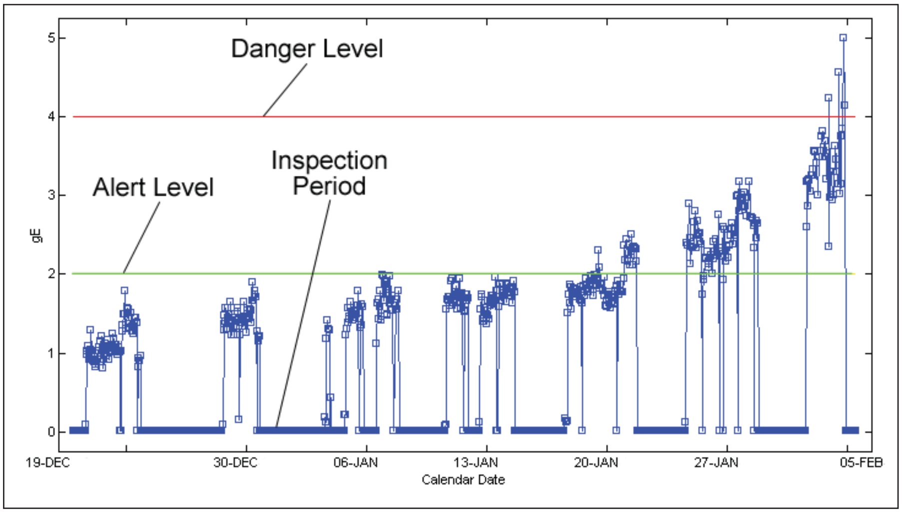

Fig. 3. Overall trending of acceleration enveloping (gE^4) measurement.

gE4 spectra measured at the beginning and end of the test are shown in **figs. 4** and **5**. Notice that the amplitude of the fundamental gear mesh frequency increased from 0,14 to 0,45 gE^4, while the amplitude of the second harmonic pass band. Over the testing increased from 0,16 to 0,35 gE^4. The third harmonic of the gear mesh frequency, not seen in the spectrum at the beginning of the test, grew to around 1,5 gE^4 at the end of the test. In addition, amplitudes of higher orders of harmonics and the noise floor of the spectrum increased significantly. All of these indicate a progressive gear tooth damage process.

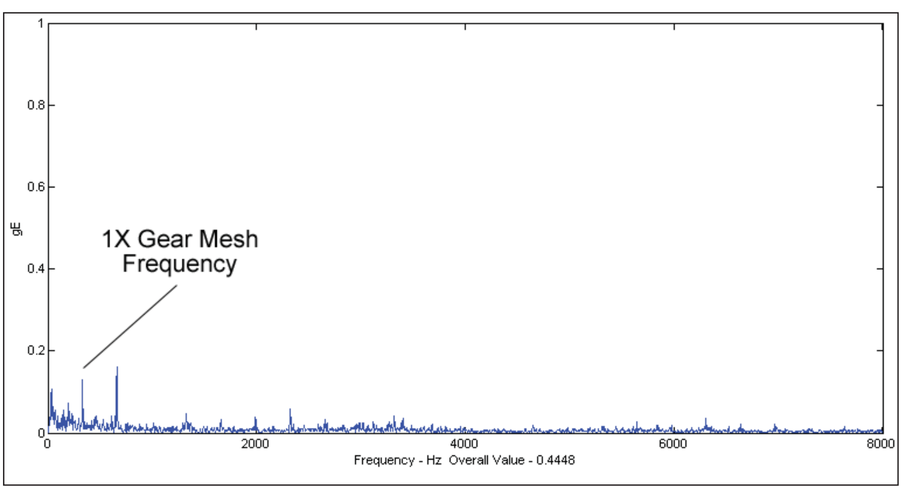

Fig. 4. gE^4 spectrum at the beginning of the test.

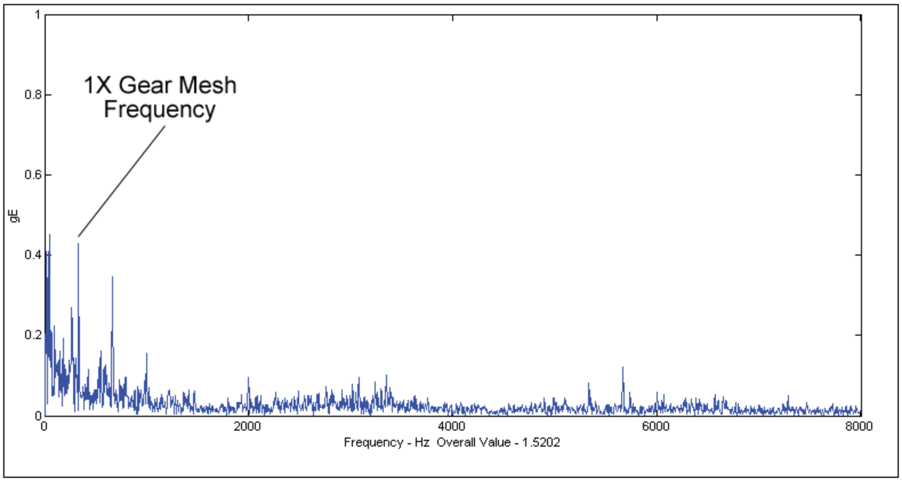

Fig. 5. gE4 spectrum at the end of the test.

Figs. 6 through **8** are the same plots for the SEE measurements. A similar pattern is observed. An interesting observation in the SEE spectrum, shown in **fig. 9**, is the clear harmonic pattern of a rolling element damage frequency, which is twice the rolling element rotational frequency. This spectrum was acquired during the early stage of the test and is an indication of an abnormal bearing condition.

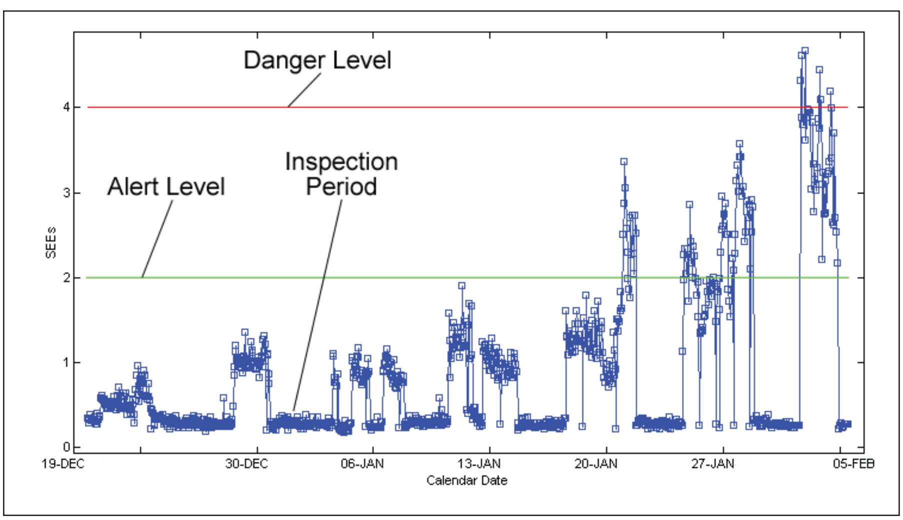

Fig. 6. Overall trending of the SEE measurement.

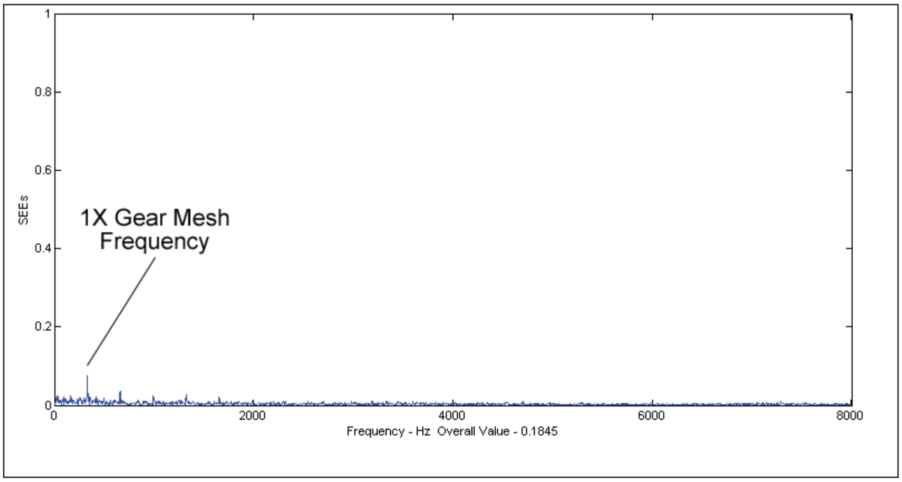

Fig. 7. SEE spectrum at the beginning of the test.

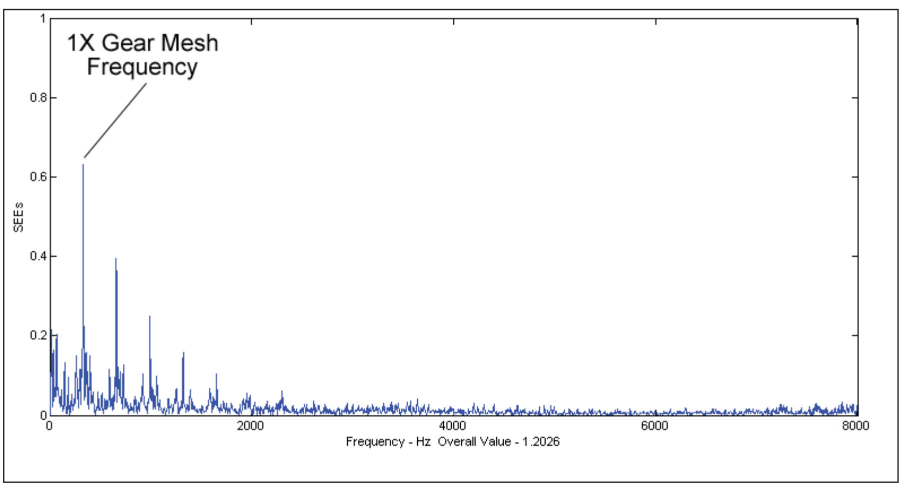

Fig. 8. SEE spectrum at the end of the test.

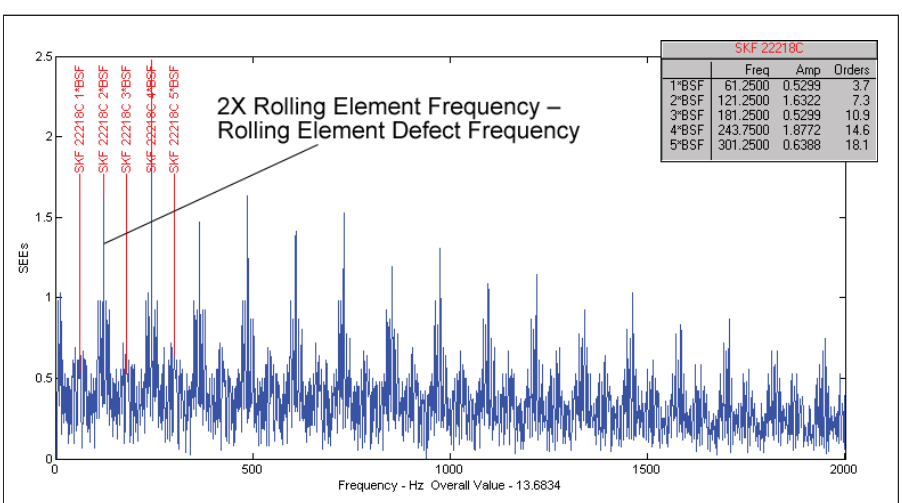

Fig. 9. SEE spectrum showing a rolling element defect signal.

Field case examples

Several projects monitoring wind turbine gearboxes in service have been conducted using the SKF Multilog Local Monitoring Unit (LMU), SKF's on-line surveillance condition monitoring instrument. The LMU is ideally suited for monitoring complex gearboxes that are subjected to varying speed and load conditions for two unique primary reasons:

- First, the LMU's data acquisition scheme is measurement focused rather than channel focused. A very large number of measurements, all focused on specific individual internal components, can be made from a single transducer without the need to compromise the quality of the data.
- Second, the LMU's built-in measurement and alarm evaluation capabilities enable it to compartmentalize measurements automatically into bins of similar operating conditions, through the advanced use of control point measurement logic.

The SKF Service organization has been providing vibration analysis /diagnosis service to various wind turbine operators throughout the world for many years. As it is impossible to present all the results here, the focus of these examples is on two recent projects using the LMU on-line surveillance monitoring system. Velocity, acceleration and acceleration enveloping measurements were used with various filter selections depending on the locations of the sensors in concern, along with SEE measurements in some installations. In installations that have variable shaft speeds, band alarms are used in evaluating the condition of mechanical components, such as bearings and gears. For variable speed turbines, the availability of shaft speeds is critical in setting up band alarms. Experiences in variable speed turbine monitoring also prove that part of the spectrum band (relative to the shaft speed) should not be included in the alarm evaluation due to resonance of the gearbox structure.

Two cases are presented in this application note. The first case is a planetary gear bearing failure case. The bearing outer race damage signal was detected in the acceleration enveloping spectrum, as shown in **fig. 10**. The unit was disassembled and inspected. **Fig. 11** is a picture of the bearing outer race with the damage clearly shown.

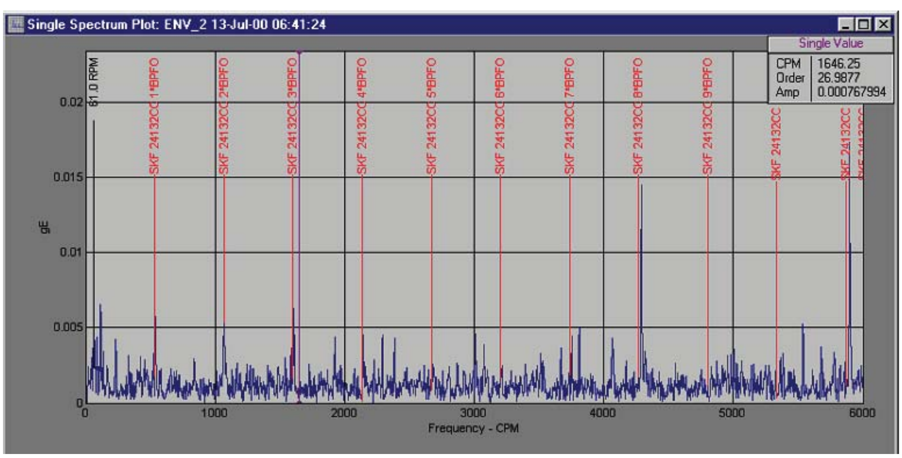

Fig. 10. gE² spectrum of a damaged planetary gear bearing.

Fig. 11. Damaged planetary gear bearing.

The second case involves a variable speed turbine where a gearbox resonant frequency was excited by gear mesh frequency harmonics. The acceleration measurement spectra are shown in **figs. 12**, **13** and **14** as shaft speed increases. Notice that the amplitude of the second gear mesh harmonic increases dramatically when the shaft speed is at approximately 1 579 r/min. Below and above this speed, the amplitude of the second gear mesh harmonics drops to a much lower level.

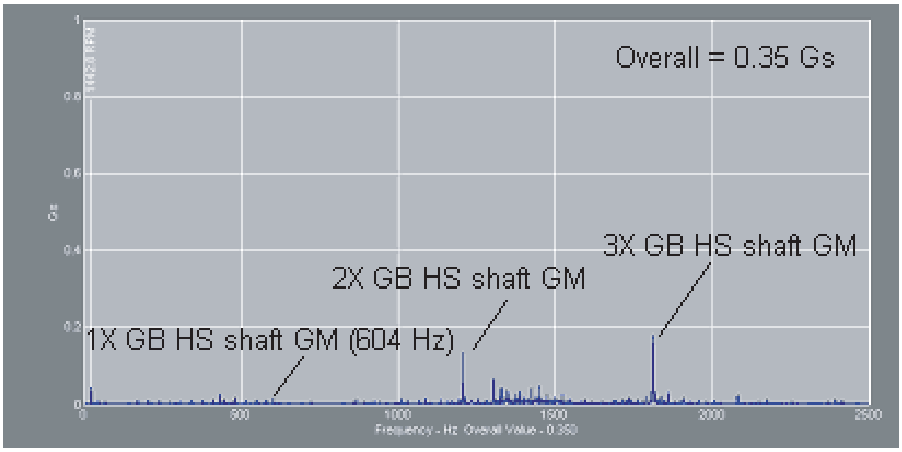

Fig. 12. Acceleration spectrum at 1 450 r/min shaft speed.

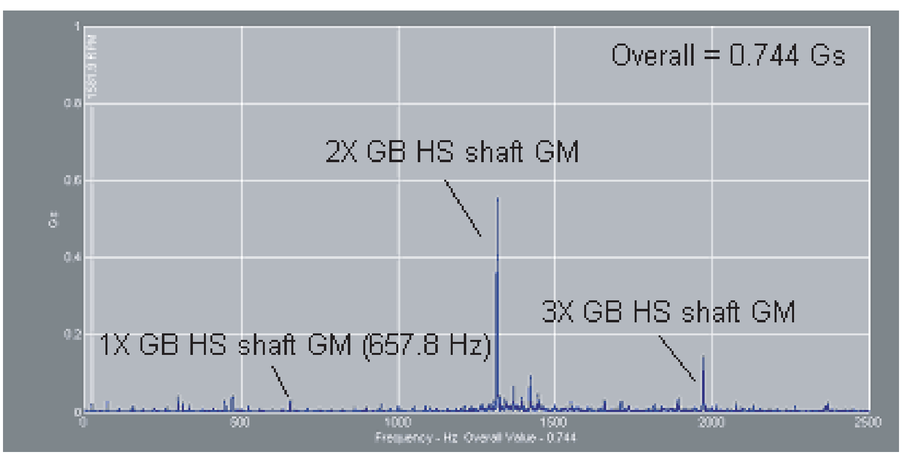

Fig. 13. Acceleration spectrum at 1 579 r/min shaft speed.

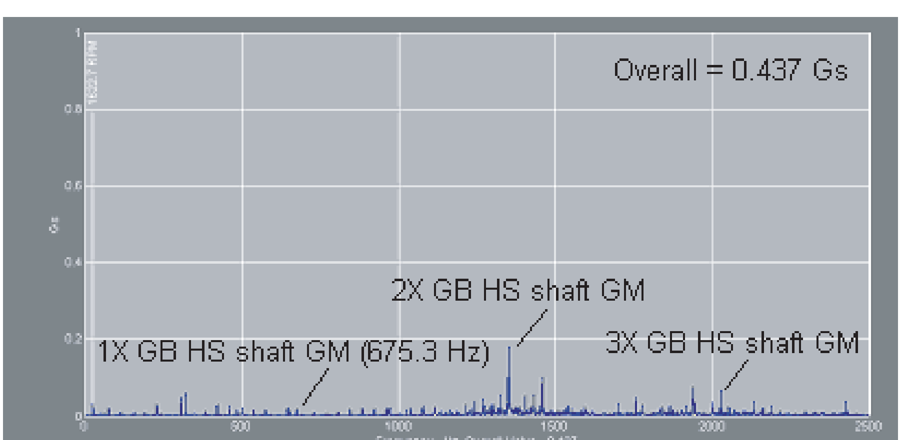

Fig. 14. Acceleration spectrum at 1 621 r/min shaft speed.

Fig. 15 shows the amplitudes of the gear mesh frequency and its harmonics as a function of shaft speed. Structural resonance at around 1 580 r/min is clearly shown. The much higher vibration amplitude at the vicinity of 1 580 r/min can easily set off spectrum band alarm. To avoid this potential false alarm, the spectrum band alarm is set such that the second harmonic of gear mesh frequency is not included in the alarm band, as shown in **fig. 16**.

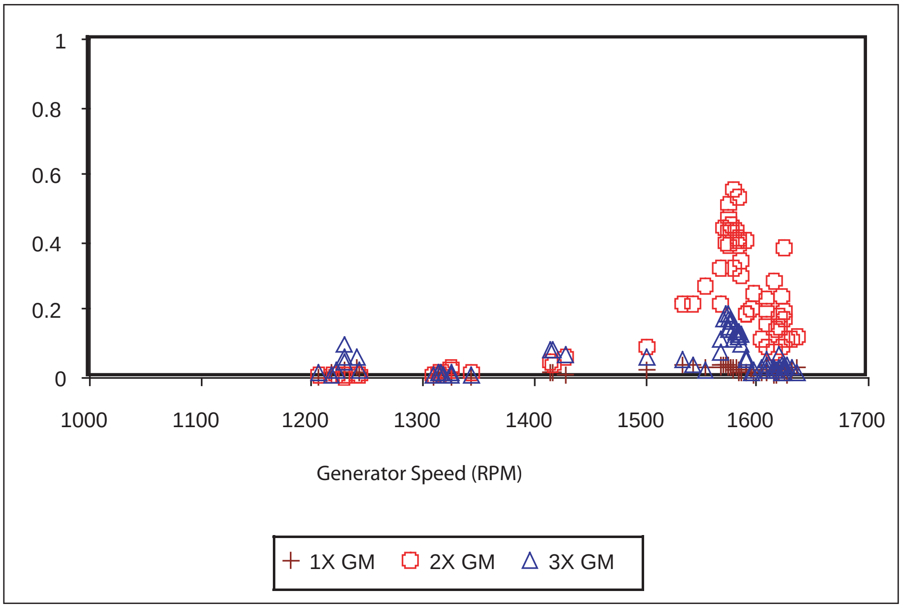

Fig. 15. Gear mesh frequency and harmonics as a function of shaft speed.

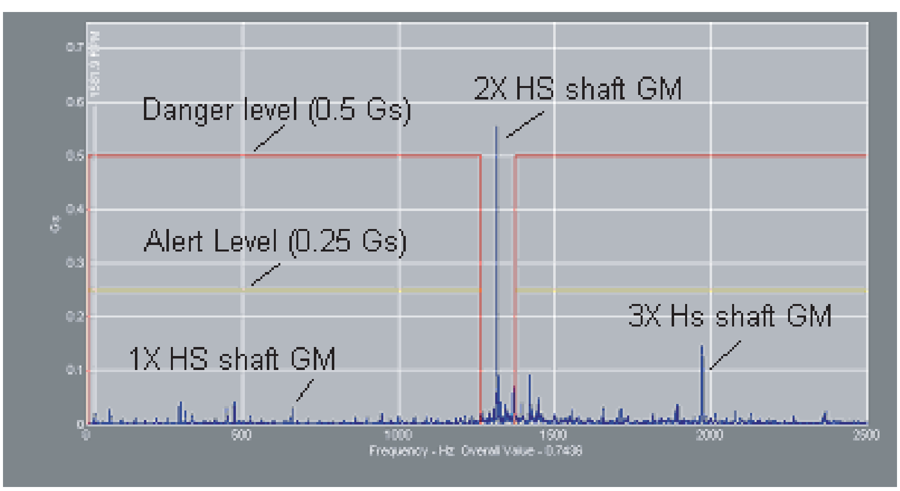

Fig. 16. Acceleration spectrum and band alarm, shaft speed = 1 581,9 r/min.

Alarm setting methodology

Setting alarms for gearbox measurements is not a simple task. There are two types of alarms for various measurements: overall and band alarms. Analysis and investigation on the data collected by SKF suggests that you should consider both methods in order to have an effective alarm strategy. In terms of determining alarm levels, a statistical tool is very useful in calculating alarm levels from real data. Vibration standards and recommendations from ISO or other organizations, such as gearbox manufacturers, automobile manufacturing companies, etc., and past SKF experiences can be used as references.

Conclusions

A complex, multi-stage gearbox can be effectively monitored using four to six accelerometers. A multiple measurement/parameter approach is critical in detecting problems that a typical mechanical drive system may develop. Knowing the characteristic structural resonant frequencies, bearing damage frequencies and gear mesh frequencies is essential in developing an effective measurement and alarm setting strategy.

Speed and load variations coupled with dynamic behavior of the gearbox can have significant effects on vibration measurements. A careful vibration measurement survey should be performed to understand the vibration pattern resulting from structure/operating condition interaction.

Band alarms are a very effective alarm setting strategy to simplify the potential drive train damage detection process. The use of statistical alarms is an effective alarm setting method when no reference or standard is available.

Please contact:

SKF USA Inc.
Condition Monitoring Center – San Diego
5271 Viewridge Court · San Diego, California 92123 USA
Tel: +1 858-496-3400 · Fax: +1 858 496-3531

Web: www.skf.com/cm

PUB CM3067 EN · January 2012