Detection of Wind Turbine Gear Tooth Defects Using Sideband Energy Ratio™

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Abstract:

Gear tooth defect detection is an important capability of any wind turbine condition monitoring system. The Bently Nevada ADAPT.wind™ monitoring system has been designed specifically to monitor gear tooth condition and bearing health of wind turbine generators. The focus of this paper is the theory and application of gear defect detection using machine casing vibration. Sideband Energy Ratio™ (SER), a patent pending algorithm utilized in the Bently Nevada ADAPT.wind monitoring system, has been developed specifically to aid in the detection of gear tooth damage. SER calculates the ratio of side band energy to gear mesh center frequency energy and has demonstrated high sensitivity to gear damage in several cases. The theory behind SER and a case history showing successful gear tooth defect detection on parallel stage gear meshes of two wind turbine gearboxes is presented. These gearboxes were inspected, and specific gear damage was documented prior to sensor installation and data collection. These gear defects are clearly visible in the data when analyzed utilizing the Bently Nevada ADAPT.wind monitoring system and the SER algorithm.

Key Words: wind, turbine, gear, mesh, sideband

Introduction

Historically gear defects within a wind turbine gearbox have been difficult to diagnose at an early enough stage such that maintenance and repairs for these defects can be scheduled in advance. Most wind turbine gearboxes have several speed increasing stages which each produce a different gear mesh frequency. The gearboxes also transfer a very large torque from the main rotor to the generator through these gear meshes resulting in relatively high energy gear mesh frequencies when compared to the energy level of signals produced by a small gear defect. Because of the overpowering gear mesh frequencies, gear defect signatures can often be obscured in the overall vibration signal and difficult to diagnose. Recently a new algorithm, Sideband Energy Ratio™ (SER), has been developed specifically to auto-detect and distinguish gear defect signatures within an overall vibration signal and provide an early detection warning of developing gear damage.

Amplitude Modulation

To understand SER, first sidebands must be understood. Sidebands appear in a spectrum around a center frequency and generally occur as a result of an amplitude modulation of that center frequency. Amplitude modulation itself has a familiar use in AM radio in which it is used as a technique for transmitting information via a radio carrier wave. In typical amplitude modulation, the carrier signal is a single tone with frequency, f_c , similar to Eq. (1).

$$A_m = A(t)\cos(2\pi f_c t) \tag{1}$$

The amplitude, A, of the carrier signal is modulated by a lower frequency modulation signal (this is the message signal for communications), $m(t)$.

$$A(t) = A_0[1 + m(t)] \tag{2}$$

Without loss of generality, we can assume the modulation signal is a single frequency tone with frequency, f_m. Substituting this in for $m(t)$ in Eq. (2) gives the following.

$$A_m = A_0[1 + \beta\cos(2\pi f_m t)]\cos(2\pi f_c t) \tag{3}$$

Where β is called the modulation index (which is less than 1 in radio communication for better signal recovery). Expanding Eq. (3), we have

$$A_m = A_0\cos(2\pi f_c t) + \frac{A_0\beta}{2}\cos[2\pi(f_c + f_m)t] + \frac{A_0\beta}{2}\cos[2\pi(f_c - f_m)t] \tag{4}$$

As a result, this amplitude modulation produces multiple frequency components, i.e., the carrier frequency, f_c, and side bands , $f_c - f_m$, and, $f_c + f_m$, which are slightly above and below the carrier frequency. The amplitude of the carrier frequency depends on the value of the modulation index, β, as seen in Figure 1 (for modulation index less than 1) and Figure 2 (for modulation index greater than 1). This type of amplitude modulation that results in two sidebands and a carrier is often called double sideband amplitude modulation (DSB-AM). Additionally, the carrier frequency should be substantially greater than the frequency of the modulation signal. If the bandwidth of $m(t)$ is $\boldsymbol{B}$ Hz, carrier frequency f_c has to be greater than $2\pi\boldsymbol{B}$ to avoid overlap of spectra centered at f_c and $-f_c$. In many real applications, the modulation is not just a single tone but consists of multiple frequencies. Multiple frequencies in the modulation function cause multiple sidebands to appear in the spectrum as seen in Figure 3.

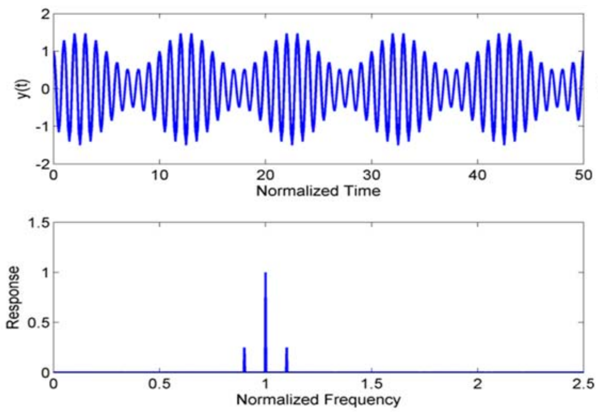

Figure 1: Timebase and spectrum plots for $\beta < 1$ amplitude modulation.

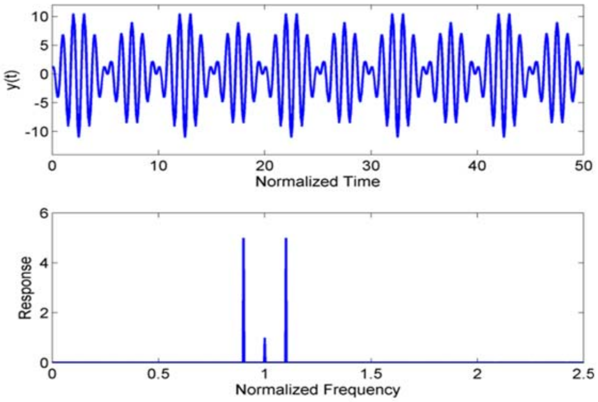

Figure 2: Timebase and spectrum plots for $\beta > 1$ amplitude modulation.

A damaged gear tooth within a gearbox can cause this phenomenon. The damaged tooth will produce an amplitude modulation of its associated gear mesh frequency each time it passes through the mesh. That amplitude modulation occurs once per revolution of the shaft that the damaged gear is mounted on. When viewed in a spectrum, this amplitude modulation shows up as a series of spectrum lines at evenly spaced frequencies on either side of the central gear mesh frequency. These sidebands occur at frequencies of $\omega_{GM} \pm n(\omega_S)$, where ω_{GM} is the associated gear mesh frequency, n is an integer of 1 or higher (although we only use $n = 1$ - 6 in the SER calculation), and ω_S is the rotational frequency of the shaft with the damaged gear. Additional harmonics of gear mesh frequencies with sideband families of their own are also generally present in the spectrum because the waveform generated by the gear mesh is usually not a pure sine wave. The case history in this paper presents several examples of this behavior.

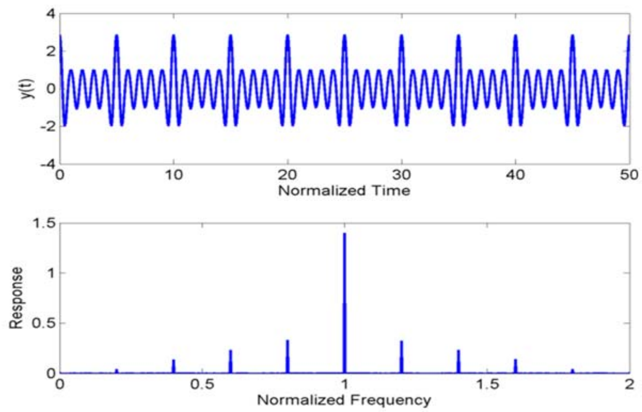

Figure 3: Timebase and spectrum plots of amplitude modulated sine wave.

Sideband Energy Ratio

SER is calculated from high resolution spectrum data. Each spectrum is created from timebase waveform data generated by an accelerometer sensor and collected by the monitoring system. Several accelerometer sensors are mounted in strategic locations on the wind turbine gearbox to monitor each gear mesh. The waveforms from each sensor are synchronously sampled so that the sampling frequency tracks changes in speed. This sampling technique produces narrow spectral lines of speed dependent frequencies, like gear mesh frequencies and associated sidebands, for variable speed machines and is essential to accurately calculate SER. Once the spectrum is generated, the SER algorithm sums the amplitudes of the first six sideband peaks on each side of the center mesh frequency and divides by the amplitude of the center mesh frequency.

$$\text{SER} = \frac{\sum_{i=1}^{6} \text{Sideband Amplitude}_i}{\text{Center mesh frequency amplitude}} \quad (5)$$

SER is sensitive to the sideband amplitudes relative to the center mesh frequency. For a healthy gear mesh any sidebands will have small amplitude compared to the center mesh frequency or may be nonexistent resulting in a low SER. The SER value is typically less than 1 for a healthy gear mesh. As damage develops on a gear tooth that passes through the gear mesh, the sidebands will increase in amplitude as well as number resulting in a larger SER value. In ADAPT.wind, the SER value is calculated for the first 3 harmonics of each fundamental gear mesh frequency

Case History

Several cases of gear damage were documented by borescope inspections on 1.5MW-class wind turbine generator gearboxes (See Figure 4 for general gearbox layout). During the inspections, damage to gear teeth on the high speed intermediate stage shaft (HSIS) pinion was discovered and photographed. The gearboxes with this documented damage were then outfitted with accelerometer sensors and data was collected and analyzed using the Bently Nevada ADAPT.wind monitoring system. The two case studies that follow illustrate successful detection of the known gear damage by the SER algorithm.

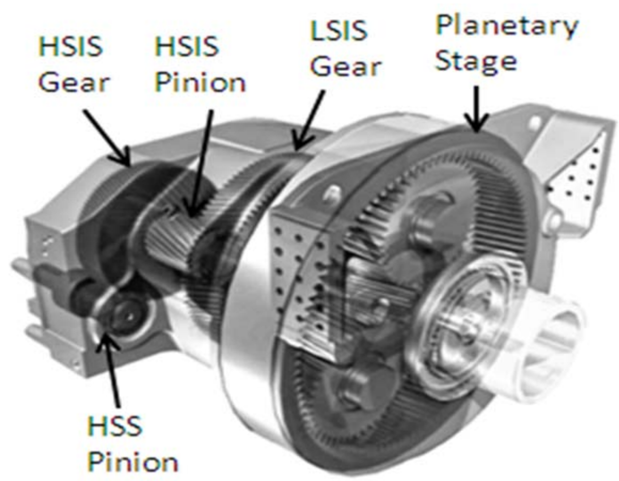

Figure 4: Gearbox Layout

Case 1: Broken HSIS Pinion Tooth

Figure 5 shows a picture of the damaged HSIS pinion tooth discovered during the borescope inspection. Figures 6 and 7 display the high resolution spectrum of the acceleration data and the acceleration timebase waveform used to generate the spectrum. All plots were generated by the ADAPT.wind software. In the spectrum plot of Figure 6 the first 3 harmonics of the gear mesh frequency are denoted as 1X, 2X, and 3X respectively. The dashed lines appearing in the plot represent the expected location of the first six sidebands on each side of the gear mesh 1X, 2X, and 3X center frequencies that would be associated with amplitude modulation occurring once per turn of the HSIS shaft. The dashed lines align perfectly with amplitude peaks in the data and in fact many more than six sidebands are present on either side of each center mesh frequency. The presence and spacing of these sidebands in the spectrum indicates that the center mesh frequency is being amplitude modulated at the frequency of the HSIS shaft. Furthermore, the gear mesh center frequency harmonics that the sidebands surround denote which gear mesh the damaged gear is passing through. These two pieces of information indicate that the damaged component is passing through the intermediate stage gear mesh (the 1X, 2X, and 3X center mesh frequency lines in the spectrum be-

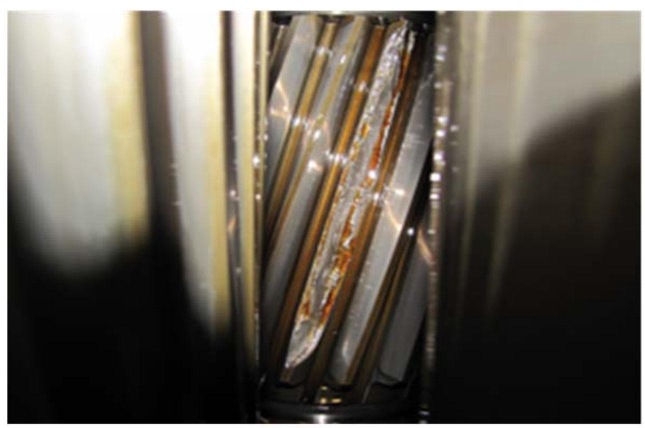

Figure 5: Case 1 HSIS pinion broken tooth

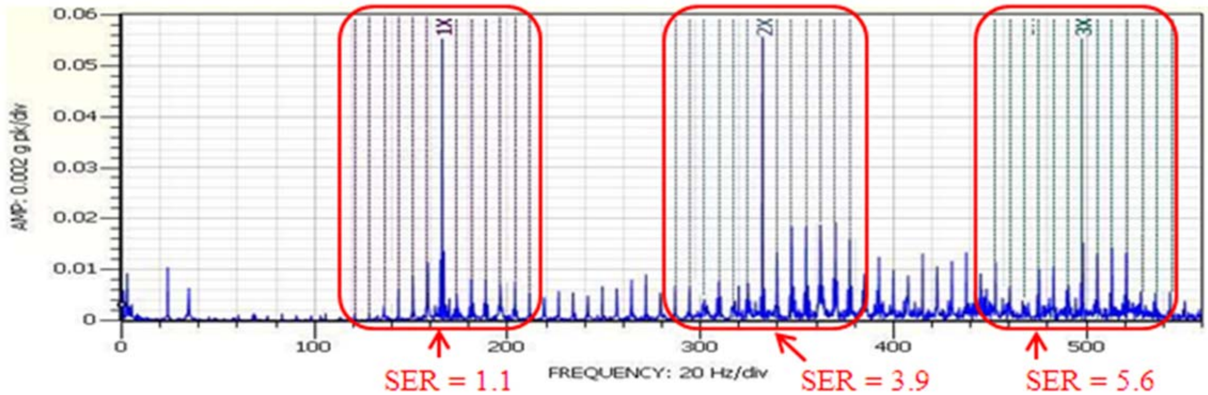

Figure 6: Case 1 spectrum showing 1X, 2X, and 3X intermediate gear mesh frequency harmonics with sidebands spaced at HSIS shaft speed indicating HSIS pinion damage.

long to the intermediate stage gear mesh) and is mounted on the HSIS shaft (the sidebands have a spacing of HSIS shaft rotational speed). This diagnosis is also supported by the timebase waveform plot of Figure 7 which shows amplitude modulation occurring once per revolution of the HSIS shaft.

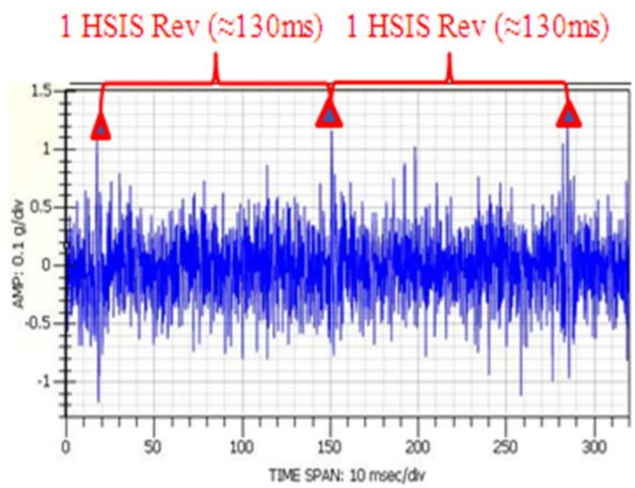

Figure 7: Case 1 timebase waveform showing amplitude spikes once per revolution of HSIS shaft.

The SER values for the 1X, 2X, and 3X center mesh frequencies for this gear mesh and sideband spacing are 1.1, 3.9, and 5.6 respectively. Typically SER values are less than 1.0 for healthy gear meshes so the SER values seen here indicate a defect on the HSIS pinion which corresponds with the damage depicted in Figure 5.

Case 2: Broken HSIS Pinion Tooth

This is another example of detection of an HSIS pinion defect inside a wind turbine gearbox. Figure 8 shows a picture of the damage present on the HSIS pinion tooth which is very similar to the previous case. Again the timebase waveform and spectrum plots of acceleration data for this wind turbine gearbox are given in Figures 9 and 10. The 1X, 2X and 3X intermediate stage gear mesh center frequency harmonics with sidebands corresponding to amplitude modulation at HSIS shaft speed are clearly visible in the spectrum. The amplitude modulation can also be seen in the timebase waveform

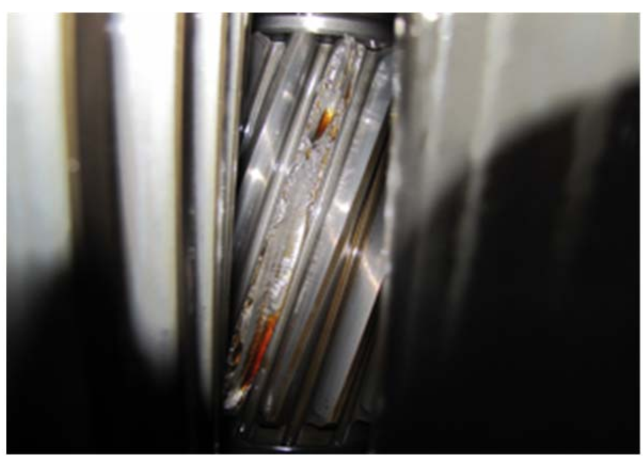

Figure 8: Case 2 HSIS pinion broken tooth

occurring once per turn of the HSIS shaft. As with the previous case, the presence and spacing of the sidebands in the spectrum indicate that modulation of the center mesh frequency is occurring once per turn of the HSIS shaft. Also, the fact that the 1X, 2X and 3X center mesh frequencies belong to the intermediate stage gear mesh indicates that the damage causing the modulation passes through that mesh. From this information we can diagnose that there is damage to the HSIS pinion in this gearbox. In this case the 1X, 2X, and 3X SER levels are 3.2, 3.5, and 6.6 respectively. These values are all well above what is typical of an undamaged gearbox indicating that there is an HSIS pinion defect within this gearbox.

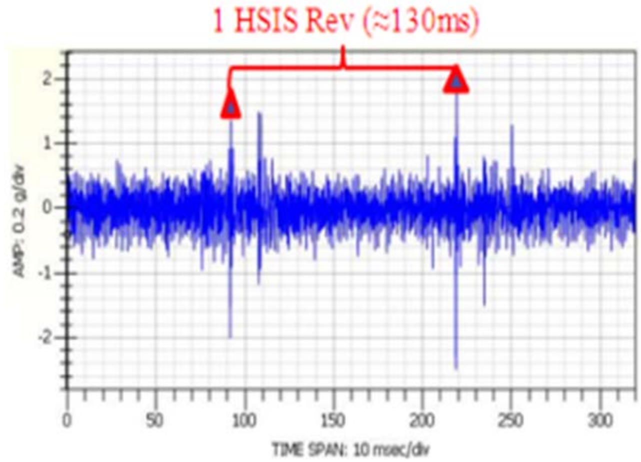

Figure 9: Case 2 timebase waveform showing amplitude spikes once per revolution of HSIS shaft.

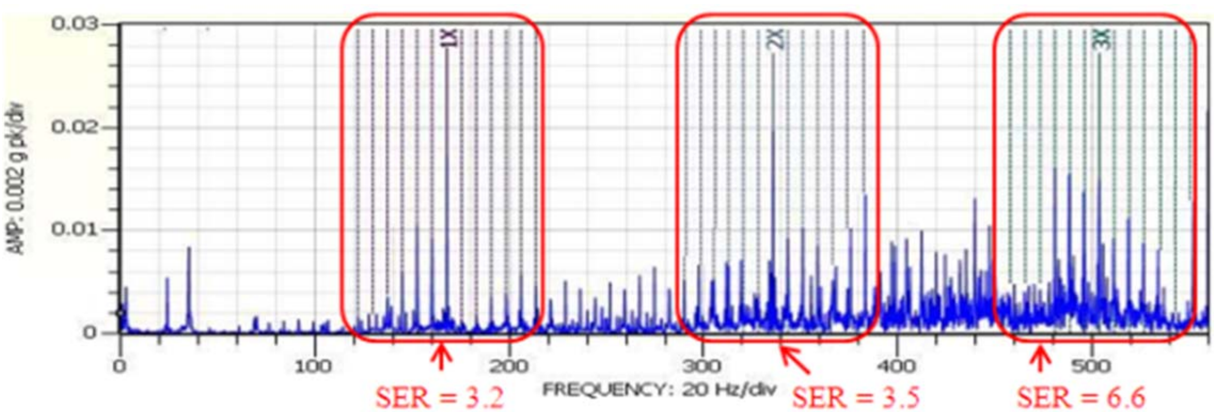

Figure 10: Case 2 spectrum showing 1X, 2X, and 3X intermediate gear mesh frequency harmonics with side-bands spaced at HSIS shaft speed indicating HSIS pinion damage.

Summary and Conclusions

The SER algorithm, recently integrated into the ADAPT.wind monitoring system, is designed to target the detection of gear related defects within a wind turbine gearbox. This is accomplished by comparing the amplitude of side-bands to that of gear mesh center frequencies in conventional spectra. The two case studies discussed in this paper provided an excellent test of the SER algorithm. In both cases the SER algorithm was successful in demonstrating not only that gear damage was present within the gearbox but also exactly which gear contained the damage. The diagnosis of HSIS pinion damage predicted by high SER values and backed up by analysis of the timebase wave-form, is confirmed by bore scope pictures of the damage in both case studies. Timely detection and diagnosis of developing gear defects within a gearbox is an essential part of minimizing unplanned down time of wind turbine generators.

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