Improved Fault Detection by Appropriate Control of Signal Bandwidth of the TSA

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ABSTRACT

Vibration analysis is perhaps the longest serving technology used in condition monitoring. It is usually assumed that higher sampling rates improve fault detection due to the increased bandwidth of the acquisition. That said, increased bandwidth may decrease the signal to noise, impairing fault detection. Alternatively, if the fault features' bandwidth is greater than the system bandwidth, the fault cannot be observed. One tool of vibration analysis is the Time Synchronous Average (TSA) analysis. Statistics of the TSA itself can be used as a fault feature, or statistics based on analysis performed on the TSA (energy operator, residual analysis, amplitude/frequency modulation analysis) are used as fault features. Additionally, the computation of the TSA requires a tachometer signal for zero crossing, which has its own bandwidth effect on the TSA analysis. This paper discusses bandwidth control techniques to improve fault detection using the TSA. The techniques are validated using real world pinion data. These techniques have other advantages for embedded condition monitoring systems.

1. THE TIME SYNCHRONOUS AVERAGE

Time Synchronous Averaging (TSA) was developed by (McFadden 1987), revolutionizing vibration analysis of rotating equipment. The TSA is integral for helicopter Health and Usage Monitoring System (HUMS) design (McInerny et al., 2003). Analyses, such as FM0, NA4, NB4, etc., based on the TSA, are now commonly used for vibration analysis in a number of different condition monitoring applications (Lebold et al 2000; Samuel and Pines 2005).

For a given shaft, the vibration model is defined as:

$$x(t) = \sum_{k=1}^{K} X_k \left(1 + a_k cos(2\pi k f_m(t) + \phi_k(t) + \Phi_k)\right) + b(t) \quad (1)$$

Where:

- X_k is the amplitude of the k^{th} mesh harmonic,
- $f_m(t)$ is the average mesh frequency,
- $a_k(t)$ is the amplitude modulation function of the k^{th} mesh harmonic,
- $\varphi_k(t)$ is the phase modulation function of the k^{th} mesh harmonic,
- Φ_k is the initial phase of harmonic k,
- While $b(t)$ is additive background noise.

The mesh frequency is a function of the shaft rotational speed: $f_m = Nf$, where N is the number of teeth on the gear and f is the shaft speed. Due to the finite bandwidth of the feedback control of the gearbox under analysis, or variation in power (as in the case of a wind turbine, where torque is a function of the wind speed) there will be variation in the shaft speed. This change in speed will result in smearing of amplitude energy in the frequency domain. The smearing effect, and non synchronous noise, is reduced by resampling the time domain signal into the angular domain:

$$m_x(\theta) = E[x(\theta)] = m_x(\theta + \Theta) \quad (2)$$

The variable Θ is the period of the cycle to which the gearbox operation is periodic, and $E[x(\theta)]$ is the expectation (e.g. ensemble mean). The transformation from time (t) to (θ) angle is done by resampling. For example, in one revolution, the time domain data is resampled (e.g. interpolated) such that the angular displacement over the shaft is constant. For example, if in a given revolution one sampled 827 data points, this would be interpolated to 1024 samples over the shaft revolution.

One important assumption is that $m_x(\theta)$ is stationary and ergodic. This results in non-synchronous noise reduced by

$1/\sqrt{rev}$, where *rev* is the number of cycles measured for the TSA. A number of interpolation techniques are available: linear, comb filter, polynomial or cubic spline. In (Decker, 1999), a comparison of these techniques was conducted: effectively no difference in TSA fault detection performance was found. However, there was a measurable difference found in computational loading. This researcher has found that spline and polynomial interpolation had an order of operation 6x of linear interpolation.

In (Bechhoefer, 2012), an enhancement for the TSA was developed, which allowed correction for changes in shaft speed within one revolution of the shaft under analysis. For the TSA using linear interpolation, the TSA can resample data that is linearly increasing or decreasing in shaft rate over the shaft revolution. Spline interpolation can resample for one change in shaft rate (e.g. sign change in dθ/dRev). Unfortunately, there are many cases where within one revolution, the shaft changes speed multiple times, such as

- the 2/revolution change in main shaft associated with blade flapping motion in the helicopter, or
- the 3/revolution change in main shaft associated with wind turbine tower shadow.

The inter-revolution resampling allowed accurate resampling of the shaft, which improved the performance of the TSA. This was seen in the Fourier domain with superior resolution of gear mesh frequencies and side band, especially at higher harmonics. Since side band modulation is one indication of gear fault, this technique resulted in improved gear fault detection.

2. BANDWIDTH REDUCTION OF THE TSA

Generally speaking, because the radix-2 Fast Fourier Transform (FFT) is easy to code and has less computation burden than an arbitrary length discrete Fourier transform, the TSA is implemented based on the radix-2 length. That is, the number of measured data points in one revolution is resampled to the next larger power of 2. The average number of points in one revolution is then a function of the acquisition system sample rate (*sr*) divided by the shaft rate (Hz):

$$NPnts = 2^{ceil\,(log_2(sr/Hz))} \tag{3}$$

For example, given a shaft rate of 6.57 Hz, and a sample rate of 48,828 samples/sec, the number of points in the TSA is 8192. On average, there are 48828 / 6.57 Hz = 7432 data points per revolution. These 7432 are interpolated to 8192 data points.

In the Fourier transform of the TSA, each bin represents 1 shaft order, e.g. 6.57 Hz. In the example, the pinion on this shaft has 28 teeth, so that in the spectrum of the TSA, bin 29 would (DC + 28) be the gear mesh energy. Nyquist for the sample data is *sr*/2 or 24,414 Hz. The Nyquist for the TSA would be 4096, but bins greater than 24,414/6.57 Hz = 3714 will have only noise.

More importantly, because of system jitter (due to the rising edge of the tachometer signal, limitations of the TSA algorithm, etc.), the practical limits of signals associated with the 28 tooth gear is no more than 10 or 20 harmonics. This means that in the Fourier domain, bins 560 to 4096 (in the example of a 8192 point TSA) are effectively noise.

In general, for a given white noise signal, the relationship between RMS noise and bandwidth is:

$$RMS \propto \sqrt{bandwidth}$$

Thus, by reducing the bandwidth by a fourth (e.g. decimating the 8192 TSA to 2048), the RMS noise would be cut in half, or alternatively, this will improve the signal to noise ratio by 3 dB.

Because of the radix-2 length of the TSA, it is a simple matter to use Fourier domain decimation to reduce bandwidth of the TSA.

2.1. Mechanization Issues

Because of the relationship between sample rate, shaft rate and TSA length, one can ask the question as to why not use a lower sample rate? In the given example, the sample rate of 48,828 for the 6.57 Hz shaft resulted in an 8192 length TSA. The 1024 length TSA could be calculated directly by sampling at 6104 sampling per second. There are a number of reasons why this is not a good solution.

- For a given FFT bin, the noise is proportional to $1/\sqrt{n/2}$, where n is the FFT length. Since the bandwidth reduction occurs in the Fourier domain, the 8192 TSA reduces the noise in the FFT bin 0 through 511 by 4.5 dB over the 1024 point FFT.
- Further, Shaft and gear analysis is not performed alone, but with bearing analysis. Envelope analysis is the demodulation of high frequency resonance associated with bearing damage. The frequency is dependent of the bearing material stiffness and mass. Typically, one sees resonance for these bearing between 4 and 15 KHz. The Nyquist theorem requires the sample rate to be twice the highest frequency of interest. Sampling at 6104 would likely be too low to measure bearing faults.
- As an experiment, the raw time domain data was resampled from 48828 to 6104 sps. The resulting TSA displayed no fault indications. Evidently, features associated with the fault have a frequency greater than 3052 Hz.

The mechanization of efficient bandwidth reduction is performed by:

- Taking the real FFT (positive frequency only) of the TSA(Press et. al, 1992)
- Zeroing the real and imaginary values from bin 512 to original TSA/2 length
- Taking the inverse FFT
- Reordering the TSA by mapping every, r^{th}= *TSA Length/1024* (e.g. 8196/1024 = 8^{th}) data point into the new TSA.

Other advantages to this method are a large reduction overall order of operations. This is achieved because the TSA is the waveform that is used for all other gear analysis. Thus, reducing the TSA length to 1024, of 8196 (in this example) reduces the overall computation burden by a significant amount, since this all of the subsequent analysis are reduced by a factor of 8.

2.2. Tachometer Signal Jitter

A tachometer signal is used to synchronize the vibration data with the shaft position over time. If there is one target on the shaft under analysis (i.e. a key phasor), then the phase of a vibration signal can be calculated. However, it is usually the case that the tachometer signal is not taken from the shaft under analysis, and that there is more than 1 target. For many applications, the speed sensor target is a pinion within the gearbox (e.g. 18 tooth pinion), or on an external shaft coupling.

It is assumed that the spacing of the targets is uniformly spaced. Additionally, it is assumed that the sensor itself will trigger identically as target passes it. If either of these assumptions is poor, the jitter this adds to the zero crossing time will degrade high frequency components of the TSA. In Figure **1**, the tachometer target is taken for a 3 point shaft coupling.

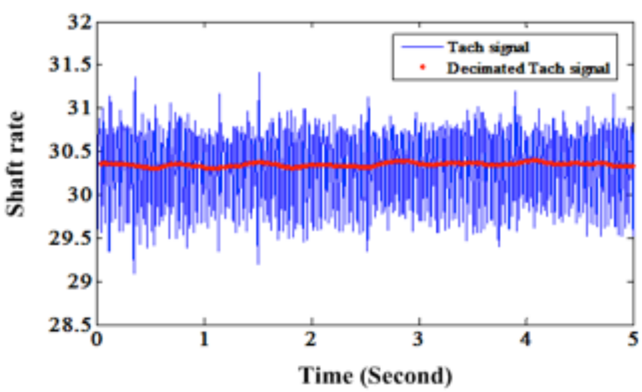

Figure 1. Variation is Calculated Shaft Speed due to Tach Jitter

While it is assumed that the targets are evenly spaced at 120 degree, due to machining errors, the targets are spaced 119 and 121 degrees, respectfully.

2.3. Effect of Bandwidth on the Narrowband Analysis

For gear tooth faults, a powerful analysis is the Amplitude and Phase Demodulation (McFadden, 1986). The analysis is based on an ideal band pass filter is applied to the TSA (defined as the Narrowband, (NB) signal). The amplitude-demodulated (AM) signal is derived by taking the absolute value of the Hilbert transform of the NB signal. The phase demodulated (FM) signal is calculated from the pseudo derivative of the argument of the Narrowband signal. The argument is calculated by taking the arctangent of the ratio of the imaginary to real component of the Hilbert transform of the NB signal.

The selection of the bandwidth of the NB is a somewhat ad-hock method, based more on experience than theory. Note that the feature of the AM/FM analysis is different than that of TSA statistics or energy operator/residual. These analyses are sensitive to 1/Rev impact events, such as seen with a soft/cracked tooth (Figure 1).

Consider the phenomenology of a soft tooth. When the tooth comes into the load zone (e.g. engaging mesh), because the tooth has less stiffness, the load is transferred to the other teeth in mesh contact. This results in two phenomena. The periodic displacement of the gears (which results in vibration) is dissimilar in the area surrounding the soft tooth (AM feature). The angular velocity of the gear will be dissimilar in the area surrounding the soft tooth (speeding up then slowing down, FM feature).

Thus, the bandwidth of the NB signal needs to be wide enough to capture this phenomenology, but narrow enough to filter noise not associated with the gear. This researcher typically used a bandwidth of 2. That is, when Fourier domain, all real/imaginary values greater than +/- 2 bins around the gear tooth, are set to zero, and then the inverse FFT is calculated.

For example, the following analysis can be performed on the TSA for gear fault detection:

- Gear Residual Analysis (1 FFT, 1 IFFT)
- Gear Narrowband Analysis (1 FFT, 1 IFFT)
- Gear AM Analysis (1 Hilbert Transform)
- Gear FM Analysis (1 Hilbert Transform)
- Each Hilbert transform calls a FFT, and the IFFT.

3. CASE STUDIES

These examples are taken from operational wind turbines, where the site ID is identified as A, B or C. Site A has gear fault in low speed shaft, whereas site B and C are nominal. The low speed shaft has a frequency 6.57 Hz and the pinion on it has 28 teeth. The sampling frequency is 48,828 Hz.

There are 3 pulses per revolution for the tachometer signal. From Eq. 3, the TSA length is 8192. Clearly, the fault is more visible as the TSA is decimated to 4096, 2048 and finally to 1024 points (Figure 2)

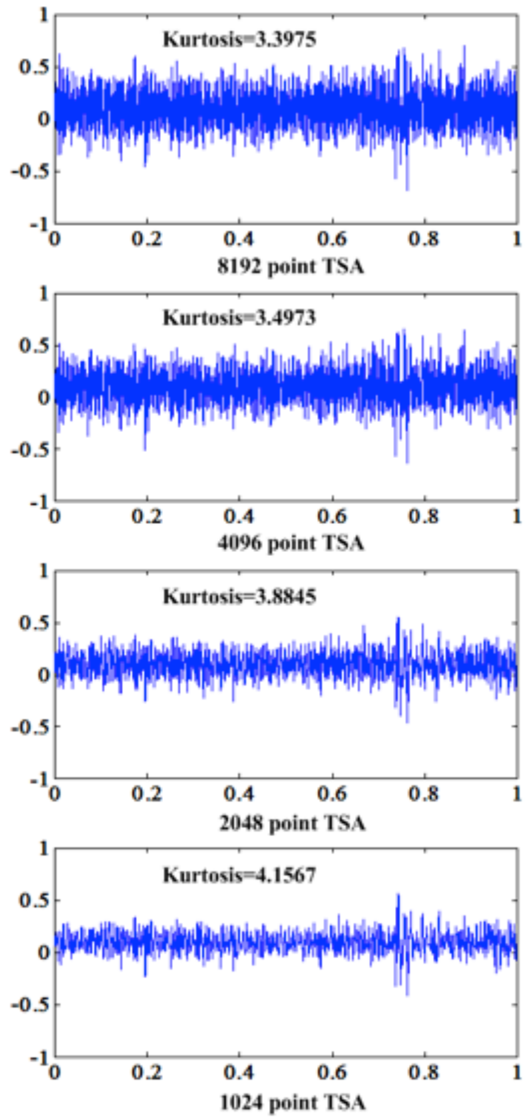

Figure 2. TSA at 8192, 4096 (1.5 dB), 2048 (3 dB) and 1024 (4.5 dB)

The 8x reduction in the TSA length (e.g. 4.5 dB improvement to SNR) at approximately 0.7 Rev. Note that the kurtosis went from 3.3975 in the 8196 point TSA to 4.1567 for the 1024 point TSA. Similar improvements to the Energy Operator signal were observed. Note that with the reduction in bandwidth, the fault is clearly seen in the energy operator. The kurtosis for the energy operator (8196 point) went from 7.8 to 30.4. The large increase in kurtosis improves the probability of fault detection.

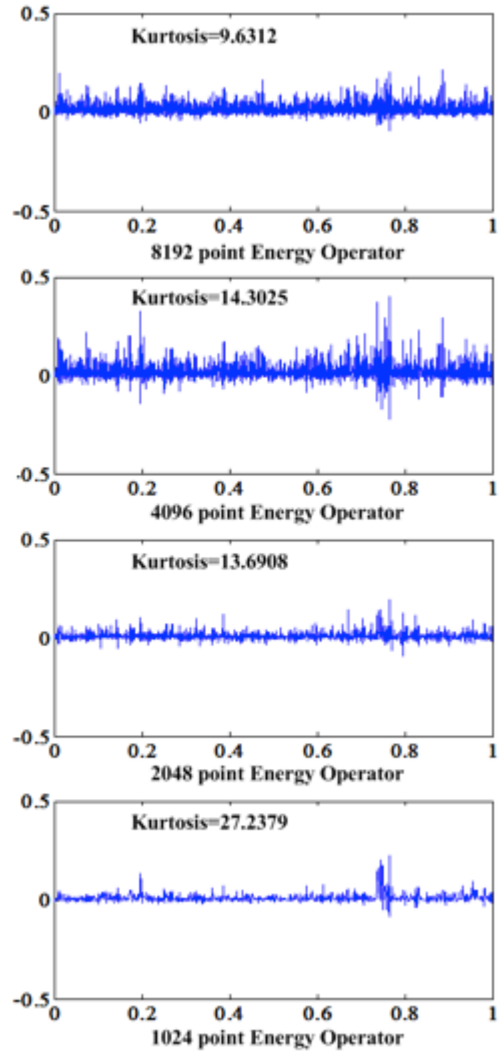

Figure 3. Energy Operator of the TSA at 8192, 4096, 2048 and 1024 points

The improved probability of detection can be demonstrated by comparing the condition indicator population statistics for residual kurtosis. Here the bad pinion (A) is compared to platforms with nominal gear (B and C). Note that large difference in the population of the residual kurtosis in going 8196 to 1024 points. At 8196, there is effectively no difference between the CI. This would result in a missed detection. However, 4.5 dB increase in SNR significantly improves the fault detectability. Without bandwidth reduction, the fault cannot be detected from the population of the bad pinion.

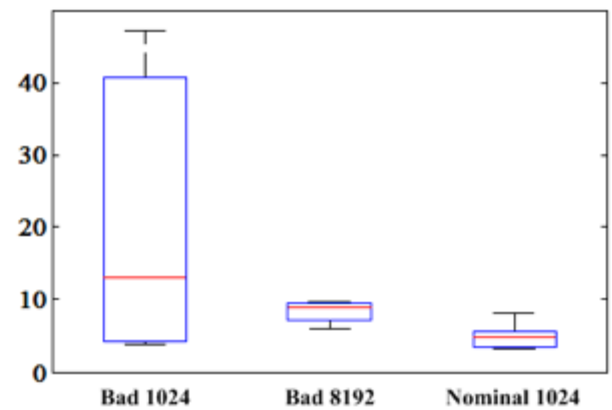

Figure 4. Comparison of the residual Kurtosis for the bad Gear 1024 points, the bad Gear 8192 points, and nominal

3.1. Effect of Jitter on the TSA

In this example, the tachometer target is 3 pulses per rev, where it is assumed that the targets are evenly spaced at 120 degrees. The decimated tachometer (i.e., using ever 3rd pulse, so that there is in effect 1 pulse per revolution) TSA has more energy than the full bandwidth TSA (Figure **5**.)

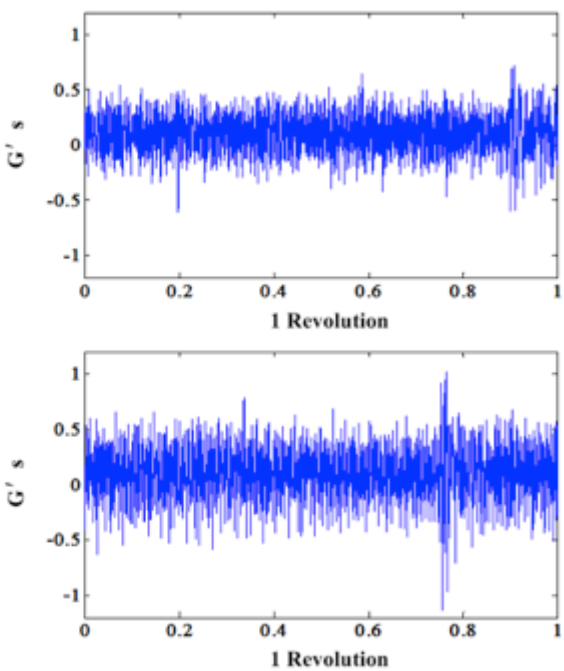

Figure 5. Full vs. Decimated Tachometer Signal

The difference is more evident in the Fourier domain, where it is clear that the jitter due to the tachometer has caused an attenuation of the high frequency TSA content associated with the gear mesh. Further, the jitter, because it is periodic due to a manufacturing error in the spacing of the targets, has added frequency content (see Figure 6)

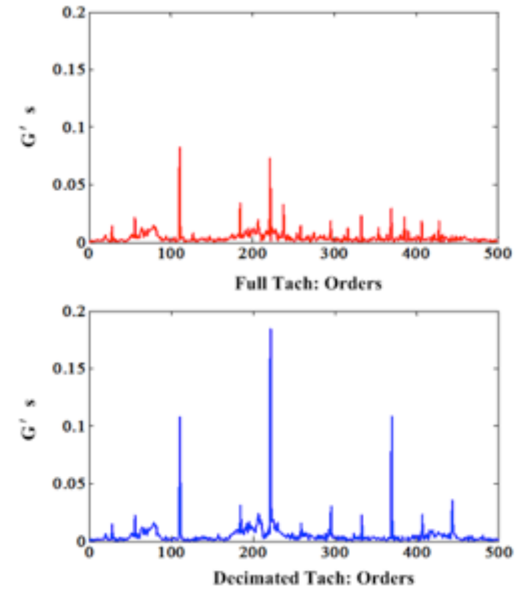

Figure 6. Full Tach Attenuates Gear Mesh Frequencies and adds frequency content due to Jitter

3.2. AM/FM Analysis Verification using High Speed Gear Fault Data

A recent high-speed pinion fault was detected on a 3 MW wind turbine. Raw data was collected once per day on the damage pinion, and nominal data was taken from two other machines. This allows an investigation of determining the bandwidth of the NB signal, which maximized the separation between the bad pinion from the good ones. The number of teeth on the pinion is 32. The sampling frequency is 97,656 Hz. The tachometer takeoff had 8 pulses per revolution. Figure 7 compares a bad pinion to the nominal pinion for NB bandwidth from 1 to 10 bins (i.e., changing the bandwidth from 1 to 10 of the Narrowband Signal) for AM RMS analysis. Figure 8 is the comparison of FM RMS analysis. With the increase in the bandwidth, the separation between the bad pinion and the nominal pinions increases. While the fault can be detected with a bandwidth of 2, the separability is much greater at higher bandwidth. This means that the fault is more reliable detected with AM/FM analysis with a higher bandwidth, such at 8 or 10.

From this analysis, it is suggested the bandwidth of floor (number of teeth/4) should be used. For this example bandwidth of 8 is used given the 32 teeth pinion. The AM and FM analysis of the damage pinion is compared to a nominal pinion in Figure 9.

Figure 9 is instructive that the relationship of the damage tooth (seen at 0.7 revolution in the TSA) and the distribution of load (AM analysis) and frequency modulation (FM analysis) are clearly observable. Note the phase change of the pinion, indicating the pinion slowed then increase in speed as the gear mesh passes over the damage area of the pinion. Figure 10 is an image of the damage pinion.

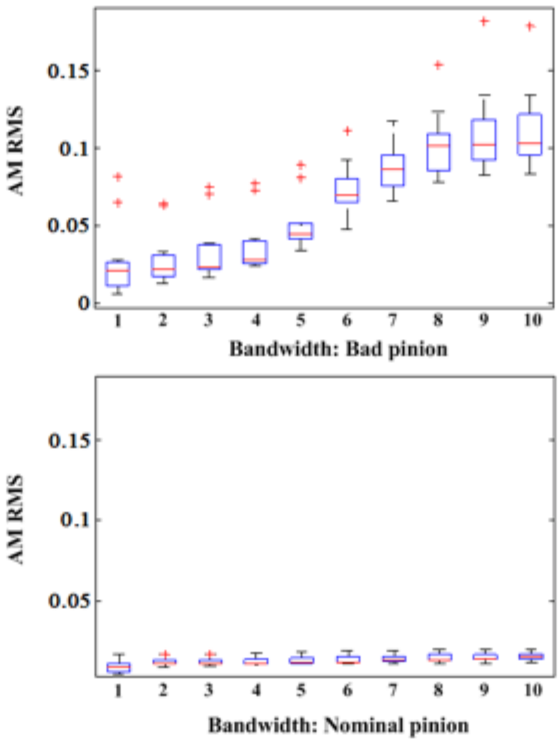

Figure 7. AM RMS for Bandwidth 1 to 10

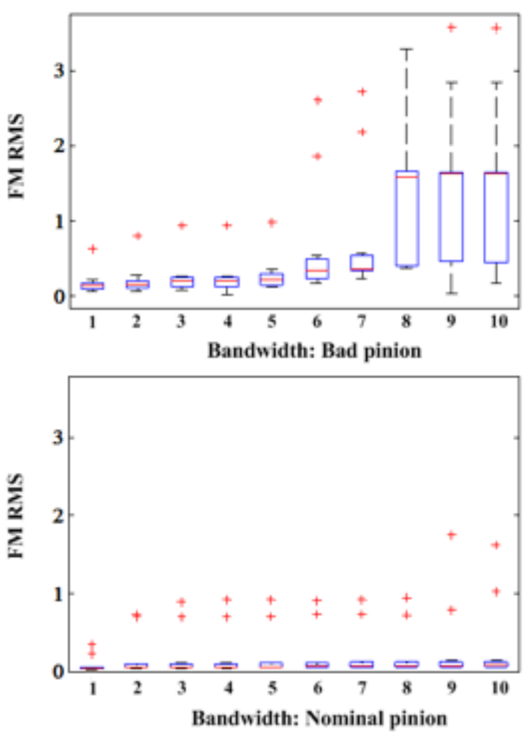

Figure 8. FM RMS for Bandwidth 1 to 10

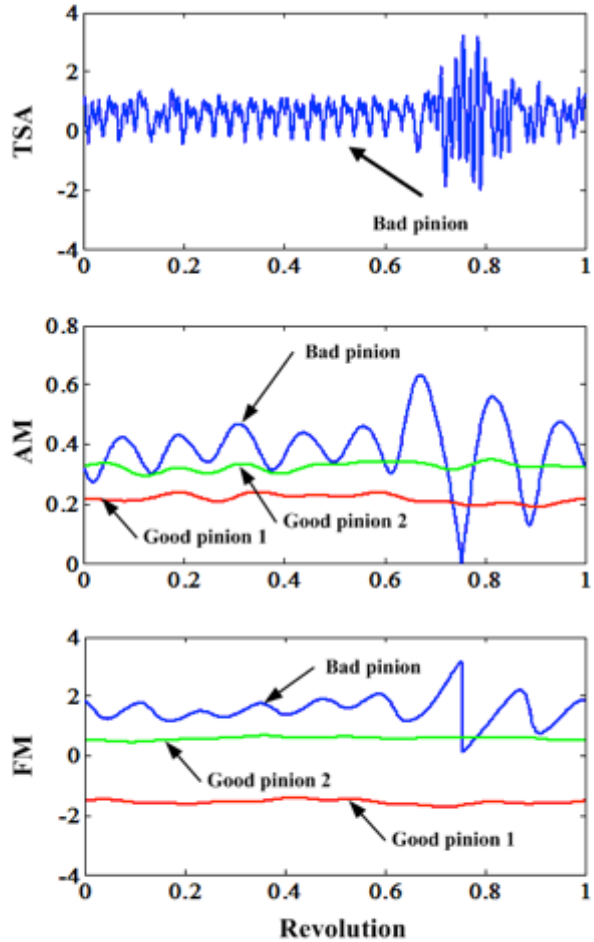

Figure 9. TSA, AM and FM analysis of damage pinion bandwidth 8

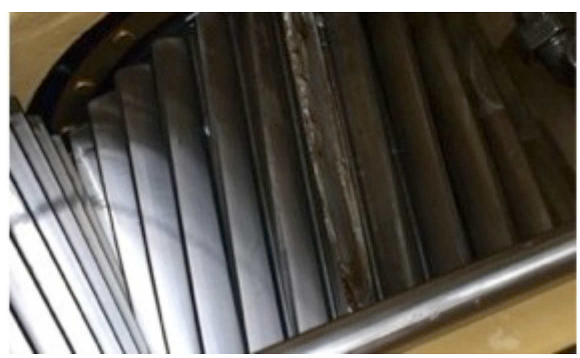

Figure 10. Damage High Speed Pinion

4. CONCLUSION

The control of bandwidth on synchronous analysis, such as the TSA, can greatly improve the ability to detect fault. Noise, and therefore signal to noise, is proportional to the square root of bandwidth. However, it must be noted that reducing bandwidth too much may in fact filter the fault signature out of the analysis (case in point bandwidth of 2 vs. 8 on the AM/FM analysis). For the TSA and associated analysis (energy operator, residual) the bandwidth of the TSA should not be less than 10 points per tooth. Thus, for a shaft with a 32 tooth pinion, the TSA bandwidth should not be reduced below 512 points. For ring gear, 111 tooth (for example) the TSA should not be less than 1024 points. For AM/FM analysis, the narrowband bandwidth should be approximately 25% the number of teeth. The bandwidth here should be great enough to capture the feature (change in tooth loading and phase) in order to maximize fault detectability

REFERENCES

Bechhoefer, E., &Fang, A., (2012) *Algorithms for Embedded PHM*, *IEEE Conference on Prognostics and Health Management*, June 18-21, Denver, Co.doi:10.1109/ICPHM.2012.6299539

Decker, H.J., & Zakrajsek, J.J., Comparison of interpolation methods as applied to time synchronous averaging. NASA/TM-1999-209086, 1999.

Lebold, M., McClintic, K., Campbell, R., Byington, C., & Maynard, K.,(2000) *Review of vibration analysis methods for gearbox diagnostics and prognostics*, Proceedings of the 54th Meeting of the Society for Machinery Failure Prevention Technology, May 1-4, Virginia Beach, VA.http://personal.psu.edu/staff/k/p/kpm128/pubs/FeatureTutorialBody18.PDF

McFadden, P., (1986). *Detecting fatigue cracks in gears by amplitude and phase demodulation of the meshing vibration.* American Society of Mechanical Engineering Transaction, Journal of Vibration, Acoustics, Stress and Design, 108, 165-170.

McFadden, P., (1987) A revised model for the extraction of periodic waveforms by time domain averaging. *Mechanical Systems and Signal Processing*, vol. 1(1), pp. 83-95

McInerny, S.A., Hardman, B., Keller, J.A. & Bednarczyk, R., (2003) *Detection of a cracked-planet Carrier*, Tenth International Congress on Sound and Vibration. July 2003, Stockholm, Sweden.

Press, W., Teukolsky, S., Vetterling, W., and Flannery, B., (1992) Numerical Recipes in C, Cambridge University Press

Samuel, P.D., & Pines, D.J.,(2005) A review of vibration-based techniques for helicopter transmission diagnostics. *Journal of Sound and Vibration*, vol. 282, pp. 475-508.

BIOGRAPHIES

Eric Bechhoefer is the president of GPMS, Inc., a company focused on the development of low cost condition monitoring systems. Dr. Bechhoefer is the author of over 100+ juried papers on condition monitoring and prognostics health management, and holds 23 patents in the field of CBM.

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