GENERATION OF TACHOMETER SIGNAL FROM A SMART VIBRATION SENSOR

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Abstract: The tachometer plays an important role in the quality of a vibration-based diagnostic. Because of the bandwidth limits of the machine controller, most machines have a slight change in speed over time. This change in speed necessitate the resampling of the data, based on a tachometer signal, to facilitate shaft, gear and bearing analysis of the machine. This is because a change in shaft rate changes the spectral content of the signal, upon which vibration analysis is dependent.

Unfortunately, there may be cases, such as glandless pumps, where due to heat and pressure it is impractical or infeasible to install a tachometer sensor. In other situation, such as monitoring gas turbine engine, interfacing with the existing tachometer for the power turbine or compressor turbine, may change certification requirements (adding cost) or increase system cost and weight. These issues may make adding a tachometer impractical.

Using a novel, two step process, we were able to generate a high quality tachometer signal from the vibration data. The first step uses an idealized bandpass filter to remove extraneous vibration signal such that the cyclic rate of the shaft can be constructed. The second step then removes any extraneous jitter in the tachometer signal. The resulting tachometer signal is usually of higher quality than that achievable from a traditional tachometer sensor. The tachometer signal is then used for the time synchronous average or time synchronous resampling algorithms, which are the basis for modern shaft, gear and bearing analysis. We demonstrate the efficacy of the technique on two data sets, showing that the resulting condition indicators are indistinguishable from a system using a traditional tachometer signal as an input.

Key words: CBM; TSA, Demodulation, Fourier Transform;

Introduction: R.M. Stewart (Ref. 1) introduced the time synchronous average (TSA) into gearbox analysis, and revolutionized condition based maintenance on helicopters and other rotating equipment. His analysis, such as FM0/1/2/3/4, the “difference signal”, the envelope analysis, etc., are used by most, if not all, Health and Usage Monitoring Systems (HUMS) currently available. Stewart’s design is heavily dependent on a tachometer input to allow resampling of vibration data for the analysis. Further, Stewart recognized the importance of tachometer jitter, noting that there was a limit to the number of revolutions to take on the TSA (e.g. at some point, the TSA was not consistent).

The need to interface with a tachometer adds cost and complexity for every application. Additionally, there may be cases, such as glandless pumps (Boiler Circulator Pumps), where due to heat and pressure it is impractical or infeasible to install a tachometer sensor. In other situation, such as monitoring a rotorcraft turbine engine, interfacing with the existing tachometer for the power turbine or compressor turbine, may change certification requirements (adding cost) and again increasing system cost and weight. These are just a few examples where adding a tachometer is impractical. Hence, the ability to derive a tachometer signal from vibration can reduce both cost and weight of a system, facilitating new applications.

For helicopter applications, weight and cost of HUMS integration can be reduced through the use of a bused, smart system (Ref 2). The use of a data bus greatly reduces interconnects, while smart sensor makes for a more scalable system. The smart vibration sensor also allows a path to locally processing vibration data to reconstruct a tachometer signal on the sensor, so that the TSA and other tachometer dependent analysis can be performed in situ.

Tachometer Signal From Vibration: This ability for a smart sensor to acquire vibration data, extract the shaft speed from the vibration data, and then process the data allows vibration based fault detection capability at a lower cost and weight than current systems. This also results in reduced installation complexity over traditional tachometer based system. Reducing cost, weight and installation complexity will expand the business case for condition monitoring, improving safety and reliability in many systems.

Cost is an important driver in the decision for operators to implement a condition monitoring system (CMS) such as HUMS. While it is well recognized that condition monitoring systems improves operational availability and reduces maintenance cost, the decision to install a CMS or HUMS for many operators is driven by cost. Removing a tachometer sensor and interface by adding this function to a smart sensor improves the value proposition of a system to a customer.

Spectral content of vibration is measured using the Fast Fourier Transform (FFT). The FFT is used in vibration-based diagnostics to: determine the magnitude and phase of component's vibration (such as shafts, gears or bearings), which can be indicative or wear and failure. Additionally, many common vibration analyses (Residual or Difference Analysis, Narrowband analysis (Ref 3, 4, 5)) use the FFT for ideal filtering of the signal, or to perform a Hilbert transform of the signal (Amplitude and Frequency Analysis).

The Fourier transform (and FFT) assumes that the signal under analysis is infinite in time. This assumption fails for real signals, but can be mitigated by the use of a window function (such as a Hamming or Hanning window). The other assumption is that the signal is stationary. Stationarity implies that the conditions of the signal do not change, e.g. the shaft rate is constant. This assumption in practice is violated: rotating machines have variation in the their shaft rate. This change in rotational rate is due to changing load and the limits of the feedback control bandwidth.

The failure of stationarity results in “spectral smearing” of energy associated with a shaft. This in turn results in not accurately measuring the energy associated with a particular fault frequency. In order to improve the performance of analysis using the FFT, Time Synchronous Averaging (the TSA, for shaft/gear analysis) and Time Synchronous Resampling (TSR) have been developed (Figure 1).

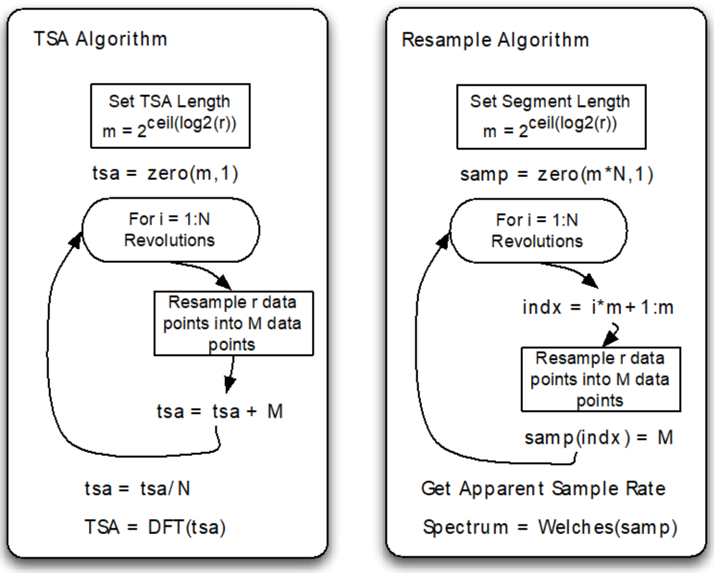

Figure 1: Resampling Algorithms for Vibration Based Diagnostics.

Resampling Algorithms: The TSA resamples the vibration associated with a shaft or gear, in the spatial domain, such that vibration associated with each shaft order, in the Fourier domain, represent one frequency bin. For example, consider a system in which the shaft rate is such that for a given vibration sample rate, the acquisition system on average collects 800 samples per revolution. The TSA would resample the 800 samples to the 1024 data points. The value 1024 is the next highest radix 2 value. Radix 2 values are used because the simplest implementation of the FFT is based on powers or 2, e.g radix 2 values. Consider that if the load on the shaft reduces, the shaft rate increases: the measured vibration data points decrease to 780 samples. It takes less time for the shaft to make one revolution, hence fewer samples. The 780 samples are resampled to 1024 points. At some future time, say that the load on the shaft may increase, slowing the shaft, resulting in measuring 820 samples, again the data is resample to 1024 points. For every revolution, the resampled data is summed point by point. After *n* revolutions, each of the 1024 points of is divided by *n*, essentially averaging the vibration data for that point in the TSA vector.

Assume in this case that there is a gear with 37-tooth gear on the shaft. The gear mesh energy of the gear would be a frequency of 37 x the shaft rate. In the Fourier domain, energy associated with the shaft rate would be in bin 2, and the gear mesh energy would be bin 38, and the second harmonic of that gear would be in bin 75 (37 x 2 + 1, bin 1 is the DC energy). The TSA also reduces non-synchronous vibration by 1/sqrt(*n*), where *n* is the total number of shaft revolutions which where used to construct the TSA. In this way, the TSA corrects for variation in the shaft rate and improves signal to noise.

The TSR similarly resamples (e.g. up samples) the vibration to correct variation in shaft speed. The apparent sample rate is the ratio of the total resampled time domain, vibration data set length divided by original data set length, multiplied by the original sample rate. Both the TSA and TSR use a tachometer signal to calculate the time over which a shaft completes one revolution. The time taken for any shaft to complete a rotation can be calculated even if the tachometer is not associated with a given shaft. This is done by taking into account the shaft ratio from the shaft with the tachometer, to the shaft under analysis, then interpolating based on that tachometer signal.

The Tachometer Signal: In implementation, the tachometer signal is the rising edge of a voltage trigger from the passing of a shaft key phasor (e.g. a stationary point of the shaft). The tachometer signal is then converted to time. This time is accrued for each pass of the key phasor. In an architecture where the tachometer signal is measured using an analog to digital converter (ADC), the resolution in time of the rising edge is 1 over the sample rate of the ADC. For condition monitoring purposes, the sample rate for a high-speed shaft could be 96,000 samples per second. In another architecture, the tachometer signal inputs into a voltage comparator. When the tachometer signal crosses zero (or some low voltage offset), the comparator goes high. The output of the comparator is monitored by the microcontroller using a general-purpose input/output (GPIO) pin. When the microcontroller senses the GPIO pin going high, it records the time. The resolution of time on the microcontroller is typically much higher than an ADC. For example, in a system using a 12 MHz clock, the microcontroller might run at 96 MHz, but the counter for time in the microcontroller would run at 48 MHz. The tachometer resolution in time would then be 2.0822e-8 seconds, or 500 x greater resolution than the ADC architecture.

Vibration signals from rotating equipment are sinusoidal and, by definition, synchronous with the shaft. However, the nature of vibration makes it impossible to use the vibration signal without significant signal processing. Measured vibration is the superposition (e.g. addition) of many signals in time domain. For example, consider a simple gearbox with an input shaft, and output shaft and a gear pair. The input shaft turns at 30 Hz, and has a 32 tooth gear, the output shaft has a 82 tooth gear with a speed of 11.707 Hz. The gear mesh frequency is 30 * 32 = 960 Hz. It is likely that the gear mesh frequency will have side bands as a result of any shaft imbalance being modulated onto the gear mesh. This can be proved using the trigonometric identity (Eq 1):

$$cos(a) * cos(b) = 1/2\,[cos(a+b) + \, cos(a-b)] \tag{1}$$

Where in this example, cos(a) is 960 Hz, and cos (b) is 30 and/or 11.707 Hz shaft. Additionally, if the shaft is bent or bowed, there will be a 2x shaft vibration component. Other manufacturing defects such as the gear not being mounted perpendicular to the shaft, or not centering the shaft on the gear (e.g. eccentricity) adds additional tones.

Tachometer From Vibration: Bonnardot (6) in 2005 describes a method of using an acceleration signal of a gearbox to perform the TSA. This was further developed by Combet (7) in 2007. These methods call for band pass filtering of the signal around a gear mesh, then in (6) taking the Hilbert transform to estimate phase, and using phase to estimate zero crossing time. In (7), the signal was band pass filtered then demodulated, with the resulting time domain signal used for the zero crossing.

Both solutions are sub optimal, due to the nature of using the FIR (Finite Impulse Response) band pass filter. Additionally, because modeling errors are present even after band pass filtering, the tachometer signal is corrupted by jitter. In this paper, we present a two-step method to reconstruct a tachometer signal from vibration. Step one is to construct an ideal band pass filter and create an analytic signal in one functional procedure. Step two uses a jitter reduction model to remove noise (jitter) from the reconstructed tachometer signal not associated with changes in the shaft rate. While this system could be implement on any computer, it is ideally suited for implementation in a smart sensor, which distributes the processing cost and power within the condition monitoring system, reducing the overall cost of the system.

The pseudo code to recover a tachometer signal from vibration is:

Define the Sample rate = *sr*. The number of data points of vibration data, n = *sr* x acquisition length in seconds, then:

1. Calculate the next larger radix-2 length for the FFT. nRadix = 2^ceil($\log_2(n)$)
2. Calculate the low and high bandwidth index (*bwlow, bwhigh),* which are centered are a know gear mesh
3. Take the zero padded FFT of the vibration data
4. Zero the FFT from zero to *bwlow*, and from *bwhigh* to nRadix
5. Take the inverse FFT
6. Calculate the unwrapped argument of the signal from 1 to n time series
7. Normalize the time series of radians by the number of teeth of the gear (assuming 1st harmonics)
8. Interpolate the number of indexes for every 2π radians
9. Normalized to tachometer zero crossing times by *sr*.

A band pass filter is the convolution of a low pass filter with a high pass filter. These filters are implemented as Finite Impulse Response (FIR) filters to improve their stability. Unfortunately, even rather large tap filters have poor filter response. Consider a case of a wind turbine gearbox, with an aforementioned approximately 29 Hz shaft and a 32 tooth gear, giving 928 Hz. The bandwidth of the filter is set from 910 Hz to 950 Hz, to exclude the 30 Hz of the high-speed shaft (e.g. 29 * 32 -29 = 899 Hz and e.g. 29 * 32 + 29 = 957Hz). The filter response for this case, using a 120 tap FIR filter is seen in Figure 2.

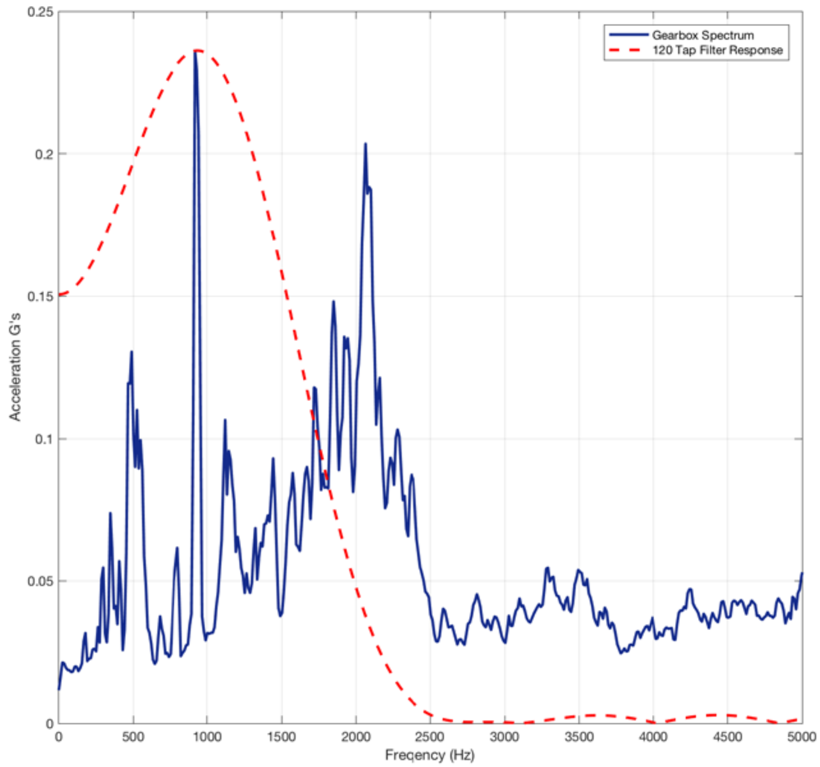

Figure 2 Spectrum from a wind turbine high-speed shaft, and a 120 tap FIR band pass filter

Note that the bandwidth (50% power, 3dB) of this filter is 1670 Hz. The filter does not reject the spectral content at 500 Hz, or at 1121 Hz. These additional tones distort the desired analytic signal, reducing the quality of the resulting tachometer signal.

Consider a process in which the developed analytic signal uses an ideal filter. The analytic signal is defined for real valued signal *s(t)* as Eq 2.

$$S(f) = F\{s(t)\} \tag{2}$$

Where *F* is the Fast Fourier Transform, then:

$$S_a(f) = S(f),\;\; f = 0$$
$$S_a(f) = 2S(f),\;\; f > 0$$
$$S_a(f) = 0,\;\; f < 0$$
$$s_a(t) = F^{-1}\big(S_a(f)\big)$$

where *S(f)* is as noted the Fourier transform of *s(t)*.

For a signal which is sampled at 97,656 samples per second, for six seconds, the total length of *s(t)* is *n*, 585,936 data points. As noted, there are advantages to using radix 2 lengths for the Fast Fourier Transform (FFT). By zero padding the FFT to next larger radix two value, 2^20 or 1,048,576, the index representing the cutoff frequency for the band pass frequencies are: *bwlow* = 910 Hz / 97,656 x 1,048,576 = 9771, and *bwhigh* = 960 / 97,656 * 1,048,576 = 10,308. Then one can define the band pass analytic signal in Eq 3 as:

$$S_a(f) = 2S(f), \;\; bwlow \leq \; f \leq bwhigh \qquad (3)$$
$$S_a(f) = 0, \;\; f < bwlow, f > bwhigh$$
$$s_a(t) = F^{-1}\big(S_a(f)\big)$$

There is no need to multiply by 2, as the argument (e.g. angle) which is of interest, is the arctangent ratio of the imaginary parts of $s_a(t)$ and the real parts of of $s_a(t)$. The idealized band pass function reject all signals not associated with the desired pass band. Figure 3 is a zoomed view of the spectrum in Figure 2., comparing the pass band of the idealized filtered realized using Eq 3.

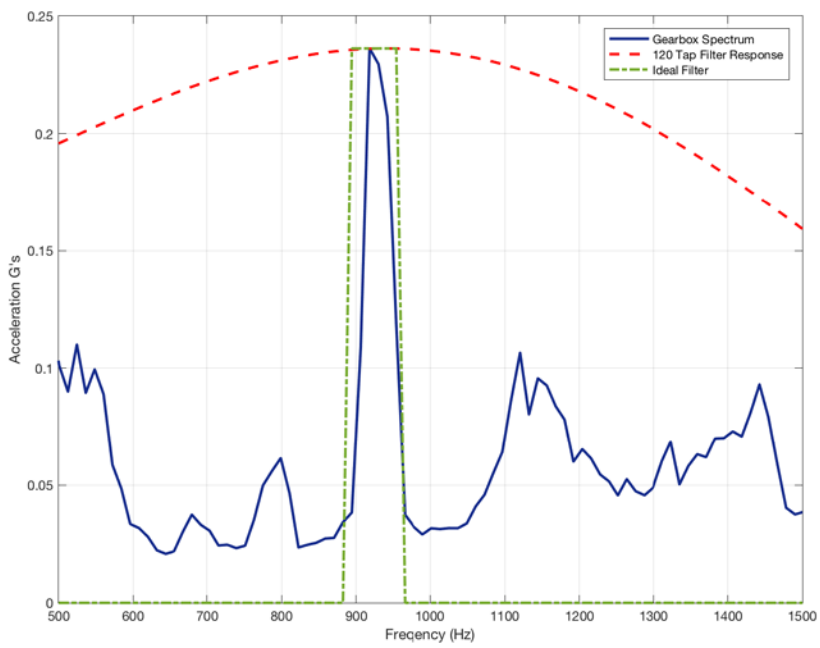

Figure 3. FIR band pass filter vs. the idealized filtered realized using Eq 3

The FIR filter does not reject the 500 Hz and 1150 Hz tone. The idealized filter captures only the signal associated with the desired gear mesh tone. This allows for higher signal to noise ratio and improved reconstruction of the tachometer signal from vibration. This tachometer signal is recovered from the arctangent of the analytic signal.

It is important to note that the arctangent function returns radians between 0 to π and -π to 0. But the evolution of the angle represents the incremental increase in phase for each sample in time. For example, the phase of the analytic signal for three cycles is: 2π x 3 or 6π. The arctangent of that signal will be -π to π for 3 cycles. The result of the arctangent must be unwrapped to capture these increases in phase vs. time. Unwrapping of the phase angle requires keeping track of the previous angle and current angle. The current angle is added to the previous angle, except when the returned arctangent goes from π to -π. In this case, π is added to the returned value to correct for the case when the returned value is between -π to 0.

After unwrapping the phase angle, the units are in radians per sample. While the FFT and inverse FFT operated on the radix 2 length (in this case 1,048,576), the argument and phase angle computation are performed only on the original sample length, *n*. Note that this time series of radians is for the gear mesh. To converts to radians per revolution of the shaft, the time series is divided by the number of teeth in the gear: in this example, 32.

However, it may be that the strongest gear mesh tone is the 2nd or 3rd harmonic, in which case the pass band is adjusted accordingly, and the time series of radian angle is divided by 2 x number of teeth for the 2nd harmonic, etc. The resulting time series represents the radian angle of the shaft, were each index advances the angle in time by *dt*, or 1/sample rate. Every 2π radians represents one shaft revolution. Because one is interested in the time, exactly every 2π, a form of interpolation is needed. For example, consider that the index just prior to 2π is 6.282780795474 (or 0.0004 less than 2π) at array index 3395, while at index 3396, the radian value is 6.284629142378, or 0.0014 greater than 2π. It is then a simple matter to interpolate between the index 3395 and 3396 for a radian value of 2π. In this case, the interpolated value is: 3395.21885053316.

This interpolation gives the number of index for each revolution. Note that this estimate of the tachometer zero cross signal is corrupted by noise. Combert (7) reports that the phase error standard deviation is related to the local signal to noise at the mesh harmonic *k* as:

$$\sigma[\delta] = {}^{1}\!/_{\sqrt{2}}\, 10^{-SNR/20} \quad (4)$$

Typical measured SNR are 6 to 8 dB. This suggests that the standard deviation of the phase error would be 6 to 10 degrees. This phase is zero mean, but as it is non-zero, it will add jitter to the reconstructed tachometer signal.

Controlling Jitter: In "*Improving Gear Fault Detection by Reducing Tachometer Jitter*" (8), it was shown that tachometer jitter contained a low a low frequency component associated with the engine control unit, and random, higher frequency components. Bechhoefer et. al. improved gear fault detection by using a zero phase, low order IIR, backward/forward filtering. As noted previously, both FIR and IIR filters bandwidth is defined by the 3dB reduction in signal energy. The filter does not remove all signals above the bandwidth, and in fact reduces some signal energy below cutoff (up to 50%).

The idealized filter using the FFT processing is zero phase as well. The improve analysis would proceed similar to the forward/backward process:

1. Take the pseudo derivative of the tachometer signal
2. Calculate the the radix-2 length of the pseudo derivative signal of length n
3. Zero pad the array from n to the radix-2 length
4. Calculate the bandwidth index of the FFT
5. Idx = floor(bandwidth * radix-2 length / 2);
6. Bandwidth is a normalized value, typically 0.12
7. Take the real FFT of the zero padded derivative signal
8. Set the real and imaginary parts of the FFT from Idx to the radix-2 length
9. Take the inverse real FFT.
10. Reconstruct the tachometer signal by taking the pseudo integral of the signal

Figure 4 demonstrates the effectiveness of the ideal low pass filter in removing jitter from the tachometer signal. The tachometer was from a wind turbine with 8 targets per revolution. The tachometer signal was resampled and the spectrum taken.

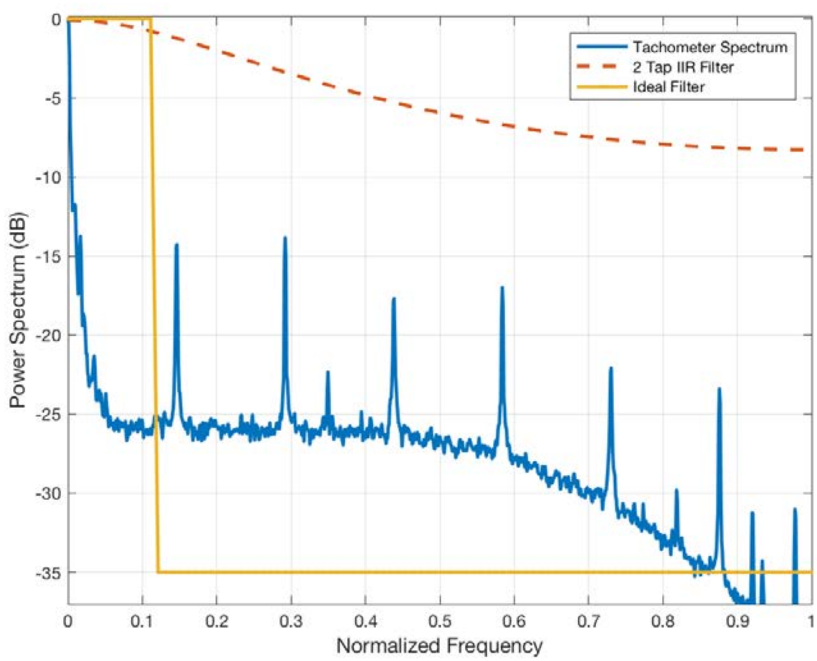

Figure 4: Tachometer pseudo derivative spectrum compared to the IIR and ideal low pass filter.

Note that the tachometer spectrum is primarily DC, with peaks associated with the unequal spacing of the targets. The idealized filter retains more low frequency response than the IIR filter, and effectively removes all spectral power (jitter) above the cutoff frequency.

Case 1: High Speed Pinion on a Wind Turbine: This machine was found, through vibration based diagnostics, to have a cracked tooth on the high-speed pinion. The acquisition length was six seconds, sampled at 97,656 samples per second. The high-speed shaft is approximately 30 Hz. This system was equipped with a tachometer, which is used as a reference to compare against the vibration based tachometer signal. The installed tachometer was a Hall sensor, using the GPIO architecture to capture zero crossing time. The tachometer target had eight pulses per revolution, but time was calculated using each 8th timing mark (e.g. one revolution). Figure 5 compares shaft speed derived from the Hall sensor base tachometer signal, vs. the vibration based tachometer signal, vs. the final processing use the new jitter reduction technique. Wind turbine analysis is particularly difficult in that there is a high degree of variability in the torque.

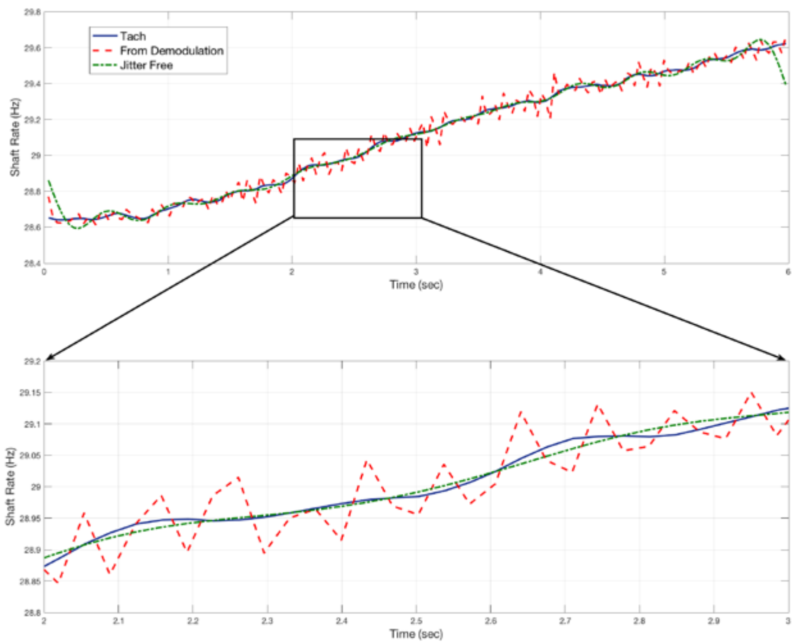

Figure 5. Shaft Rate from Tachometer signal in comparison with jitter free tachometer from vibration. Note that after reducing jitter, the two tachometer signals are virtually the same.

The bottom graph is a zoomed from the 2nd to 3rd second on the acquisition. In general, after removing jitter using the new process, the vibration based tachometer signal is not significantly different from the tachometer derived from the Hall sensor. Figure 6 depicts the TSA and the spectrum of the analysis. The difference between the TSA is effectively only phase angle. From the spectrum, we can calculate the signal to noise ratio to be approximately 6dB. Statistics derived from the TSA are given in table 1.

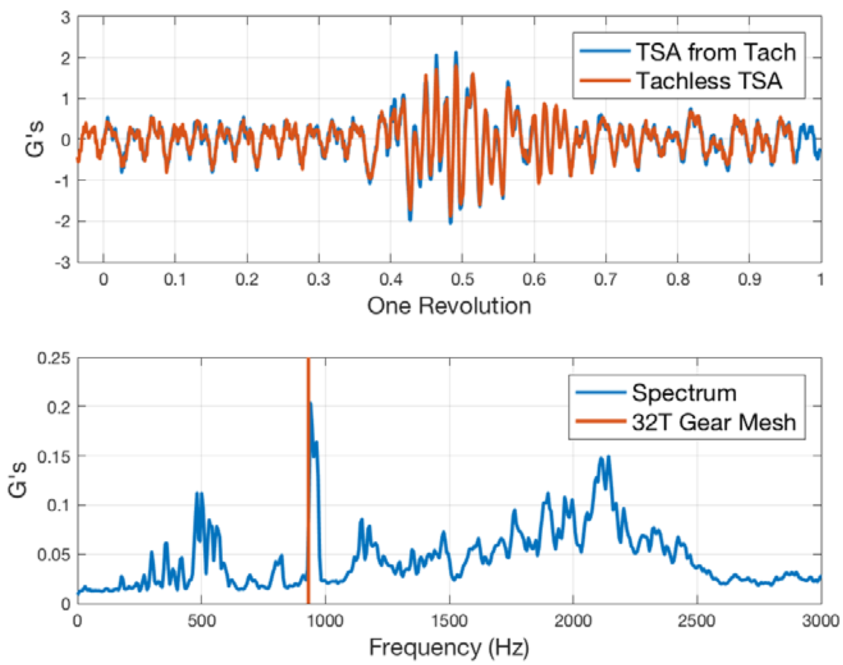

Figure 6: Comparison of the TSA derived from a tachometer and vibration sensor

Table 1 Tach vs. Tachless for Standard Vibe Statistics

Analysis	Tach	Tach from Vibe
SO1	0.0100 g	0.0104 g
SO2	0.0013 g	0.0016 g
SO3	0.0019 g	0.0018 g
TSA RMS	0.5091 g	0.4828 g
TSA P2P	2.0887 g	1.8430 g
FM0	4.278	4.00
AM RMS	0.100 g	0.099 g
AM Kurtosis	4.242	4.217
FM RMS	0.428 radians	0.426 radians
FM Kurtosis	4.995	4.844

Clearly, the gear fault was detectable with either a tachometer, or via vibration method.

Case 2: Tail Rotor Intermediate Gearbox: This was taken from public domain data set, donated by NAVAIR AIR 4.4.2 (Ref 9.). The sample rate was 100,000 samples per second, using the ADC architecture for recording zero crossing data. The tachometer sensor was a variable reluctance speed sensor, using a 22-tooth gear as a target. The shaft rate for the target gear was approximately 3000 rpm (e.g. 500 Hz), with a ratio from this shaft to the tail rotor drive shaft of 7.3:1. As seen in Figure 8, the tachometer signal is noisy (high jitter), with a mean shaft rate of 68.5 Hz.

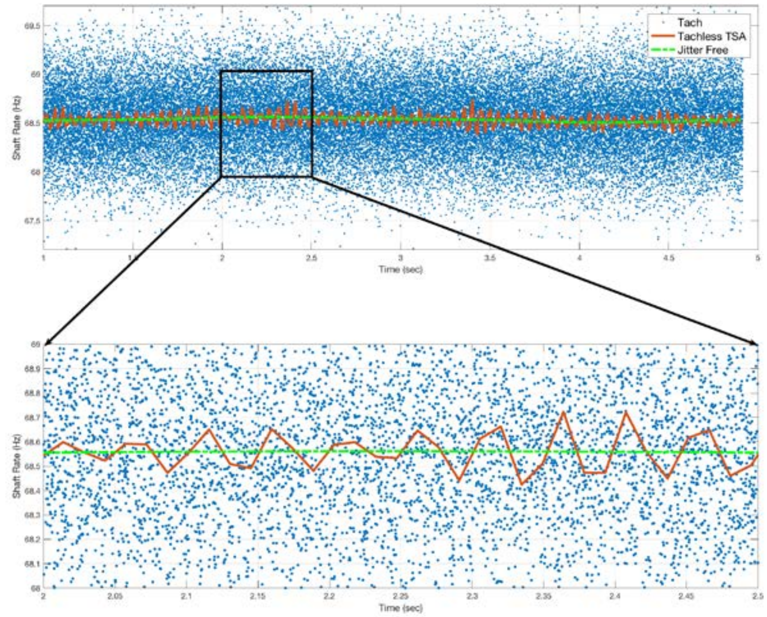

Figure 7: VR Tachometer vs. jitter free tach from vibration

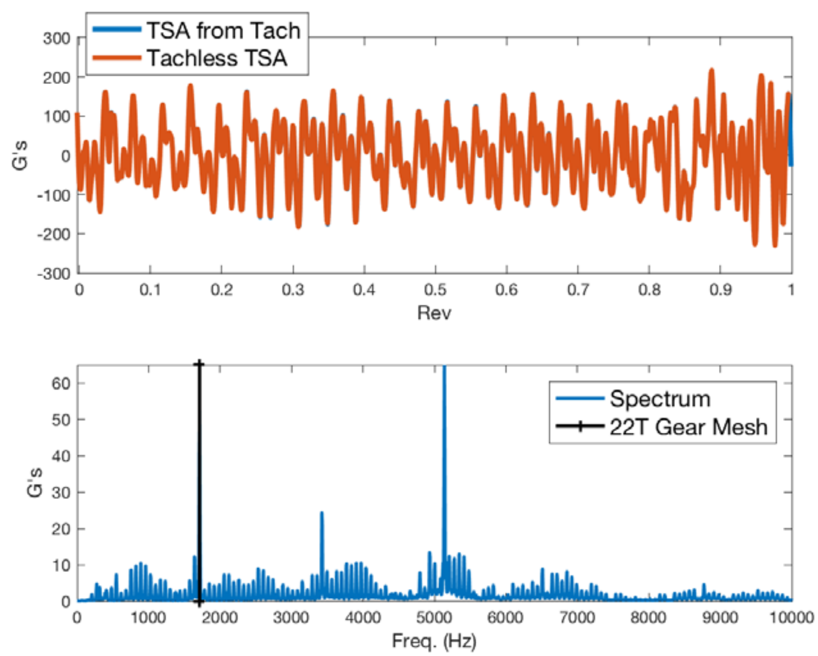

Figure 8: Comparison of the TSA derived from a tachometer vs. vibration sensor

The zoomed view shows the tachometer from vibration and with less jitter than the VR sensor tachometer signal, while the jitter free tachometer signal is smooth, capturing a slowly evolving change in shaft rate. The SNR for this example is approximately 12 dB, due to the 65g mesh frequency (Figure 8). The resulting TSA, aside from a difference is phase, is indistinguishable from the TSA using a tachometer from the VR sensor.

Statistics derived from the TSA for the tail rotor input gear are given in table 2:

Table 2 Tach vs. Tach-less for Standard Vibe Statistics

Analysis	Tach	Tach from Vibe
SO1	0.043g	0.043g
SO2	0.283 g	0.282 g
SO3	1.855 g	1.85g
TSA RMS	81.646 g	81.591g
TSA P2P	222.77g	223.02g
FM0	16.94	15.38
AM RMS	17.06g	17.06g
AM Kurtosis	4.126	4.126
FM RMS	3.037 radians	3.048 radians
FM Kurtosis	2.46	2.45

Conclusions: A method to reconstruct the tachometer signal from vibration was demonstrated using a two-step process. The first step uses an idealized band pass filter implemented with a complex FFT to create an analytic signal, which is needed to derive the tachometer signal for the shaft under analysis. The second step uses another idealized low pass filter on the pseudo derivative of the reconstructed tachometer signal to remove jitter. This processing is run on a smart vibration sensor, which facilitates improved vibration analysis on rotating equipment where in the past the addition of a tachometer would be prohibitive due to cost, weight, certification requirements or being physically impractical.

The quality of the resulting analysis compares favorably with traditional tachometers on real world fault data. In fact, the tachometer from vibration signal may have less noise, resulting in improved fault detection, than traditional tachometer sensor based system

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