Reducing Tachometer Jitter to Improve Gear Fault Detection

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Abstract

Much research has been published on gear fault analysis techniques, almost all based on the time synchronous average (TSA). These include and are not limited to: residual analysis, energy operator, energy ratio, amplitude modulation, frequency modulation, sideband index, zero-order figure of merit, etc. Because the TSA is based on tachometer zero cross times for a key phasor, the performance of these analyses is dependent on the quality of the tachometer data. The tachometer signal always has jitter, due to electrical noise, magnetic noise, or manufacturing spacing error of the tachometer target (e.g. gear tooth spacing). By implementing a novel zero phase filter to reduce tachometer jitter, large improvements in the fault detection were observed. For a known gear fault, the separability, related to fault detection, increased from 10 to 25%.

1. Motivation for Vibration Health Monitoring

The *Review of helicopter airworthiness* (CAA, 1984) recognized that critical mechanisms, such as the rotor and rotor drive system, involve a single load path. It was shown that equipment utilized safe life design, and that often defect propagation would occur prior to failure. This lead the Helicopter Airworthiness Review Panel (HARP) to recommend that where full redundancy was not possible by design, then the use of a Vibration Health Monitoring (VHM) would warn of a likely failure in "a suitable time scale to provide an acceptable level of safety". This lead to acceptance of the CAP 693 (CAA, 1999) and later, the CAP 753 (CAA 2012), which provides guidance to operators utilizing VHM for rotorcraft.

The guidance (currently, CAP 753) loosely defines a design standard for VHM, and establishes a benchmark for minimum VHM performance. Specifically, VHM indicators for measurement and recording are:

- Shaft Order 1 and 2 (e.g. SO1, SO2),
- Bearing wear indicators and
- Gear tooth indicators

In general, the techniques used for determining shaft and bearing indicators are well established. It is felt that additional work on gear fault indicators are still an active area of research. Mush of the research for gear fault is based on algorithms that use the time synchronous average (TSA). Hence, reducing jitter is seen as a means to improve the TSA and those analysis based on the TSA.

1.1. The Time Synchronous Average

Many gear analysis algorithms are based on operations of the TSA (McFadden, 1987 and Zakrajsek 1993). TSA is a signal processing technique that extracts periodic waveforms from noisy data. The TSA is well suited for gearbox analysis, where it allows the vibration signature of the gear under analysis to be separated from other gears and noise sources in the gearbox that are not synchronous with that gear. Additionally, variations in shaft speed can be corrected, which would otherwise result in spreading of spectral energy into an adjacent gear mesh bins. In order to do this, a signal is phased-locked with the angular position of a shaft under analysis by using a key phasor.

This phase information can be provided through a *n* per revolution tachometer signal (such as a Hall sensor or optical encoder), where the time at which the tachometer signal crosses from low to high is called the zero crossing.

The model for vibration on a shaft in a gearbox was given in McFadden, 1987 as:

$$x(t) = \Sigma_{i=1}^{k} X_i\big(1 + a_i(t)\big)cos(2\pi i\, f_m(t) + \Phi_i) + b(t) \quad (1)$$

where:

- X_i is the amplitude of the kth mesh harmonic
- $f_m(t)$ is the average mesh frequency

- $a_i(t)$ is the amplitude modulation function of the kth mesh harmonic.
- Φ_i is the initial phase of harmonic i, and
- $b(t)$ 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. This vibration model assumes that f is constant. Because of the bandwidth limitation of the feedback control and time varying loads, there is some wander 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 theta, (θ), using a tachometer for the keyphasor signal:

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

The variable Φ is the period of the cycle of the shaft under analysis, and it referenced by the tachometer zero crossing time (keyphasor). If the tachometer signal is the true reference, the $m_x(\theta)$ is stationary and ergodic, Further, then non-synchronous noise is reduced by $1/\sqrt{rev}$, where rev is the number of cycles measured for the TSA.

The TSA resamples the vibration associated with a shaft or gear, in the spatial domain. Hence, vibration associated with each shaft order, in the Fourier domain, represent one frequency bin. For example, the gear mesh energy of a 37 tooth gear on a given shaft, is found in the Fourier domain to 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 uses 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 the shaft ratio from the shaft with the tachometer, to the shaft under analysis. The key phasor is then calculated by interpolating using the ratio between that tachometer signals and the shaft under analysis.

The tachometer signal is dependent on the sensor type. These sensors include, but are not limited to:

- Hall sensor, where there is a rising voltage associated with the passing of a ferrous target (such as a gear tooth) in front of the sensor,
- Inductive sensors, where there is a rising voltage associated with the passing of any metallic target (such as an aluminum shaft coupling),
- Optical sensor, where there is a rising voltage associated with the receiving of light from a reflective target on the shaft, or
- Generator or variable reluctance sensor, where the frequency and amplitude of a sinusoidal signal is proportional to target (usually a gear) RPM, and the time of the zero crossing is taken at the transition of the sinusoid from negative to positive voltage.

An incorrect tachometer signal will reduce the effectiveness of the TSA. From Eq 2, an error, such as jitter, causes an error in Φ. This phase error, especially for large N (e.g. gear mesh) causes the TSA to not be ergodic. This will negatively affect the ability of the analysis to detect component faults. This was stated in Priebe (2003), but no strategy to control or correct for jitter was presented. Other than Preibe (2003), there seems to be little in any discussion of the effect of jitter on the calculation of the TSA.

1.2. TSA Mechanization Issues

Consider that the output of tachometer is zero crossing time (ZCT), for each tooth/target. The shaft rate is the inverse derivative of this ZCT (dZCT). Assuming jitter is a zero mean Gaussian process with some standard deviation σ. Then the variance in shaft rate will be proportional to $\sqrt{2}\,\sigma$. This is because the shaft rate is a derivative, e.g. the difference in two ZCT.

$$shaft\ rate = {}^{1}/_{dZCT/PPR} \quad (3)$$

The variance in the jitter is added. For example, let one assume that there is an 8 pulse per revolution (PPR) target on a 30 Hz shaft. The ZCT time between each pulse is nominally 0.0042 seconds. The jitter, due to manufacturing error and electrical noise is 0.0001 seconds. This translates into standard deviation of shaft rate of 0.14 Hz. Thus, for one revolution, the phase jitter is: 2π x 0.14/30 Hz or 0.029 radians per revolution. For a 32 tooth gear, the phase error, per revolution is 0.94 radians!

To put example numbers to this problem, for a sample rate of 97656 samples per second, the length of the TSA is: $2^{ceil(97656/30)}$ = 4096 points. This means that for a soft/broken tooth, in which the impact should be in a given reference bin, the jitter effects that reference index by +/- 19 bins, 68% of the time. Hence, the TSA has become much less effective, and all subsequent analysis is compromised.

2. PROCESSING REQUIREMENTS TO REMOVE JITTER

In the application of VHM, a number of analyses are computed in real time. This requires that, for online analysis, the time required to remove jitter from the tachometer signal should have minimal impact on the time taken to do analysis. Traditional finite impulse response (FIR) filters have an order of operation of n^2, and a phase delay of $n/2$, where n is the number of filter coefficients.

A more efficient filter is the infinite impulse iesponse (IIR) filter. This class of filter requires far fewer coefficients to achieve a given bandwidth, than a FIR filter. For a filter with a normalized pass band of 0.05 and a stop band of 0.1, an FIR filter would have an order of 101, whereas an equivalent IIR filter would have an order of 15. For an application the FIR filter order of operations is 10201 vs. the IIR filter order of operation of 225 – in other words, the IIR is 45 times faster.

The phase of an IIR filter is non-linear, but by running the filter forward, then backward in time, the phase cancels (e.g. it's a zero phase filter), with the benefit of improving the noise rejection /jitter of the tachometer signal.

The IIR filter is described as a linear polynomial:

$$a[1]Y[i] + a[2]Y[i-1] + \cdots + a[n+1]Y[n] = b[1]X[i] + b[2]X[i-1] + \cdots + b[m+1]Y[m] \quad (3)$$

The frequency response of the transfer function is then defined as:

$$H(e)^{jw} = \frac{b[1]+b[2]e^{-jw}+\cdots b[m+1]e^{-jmw}}{a[1]+a[2]e^{-jw}+\cdots a[n+1]e^{-jnw}} \quad (5)$$

This gives a simple way in which to calculate the bandwidth of any proposed filter. In order to minimize the computation order, a single pole filter was designed.

For a single pole filter:

$$a[1]Y[i] + a[2]Y[i-1] = b[1]X[i] \quad (6)$$

Rearranging terms:

$$a[1]Y[i] = b[1]X[i] - a[2]Y[i-1] \quad (7)$$

By convention, $a[1] = 1$, then for the equation to be valid, $b[1] = 1- a[2]$. For a filter where the a coefficients are [1 .9], $b[1] = 1.0 - a[2] = 0.1$. Note that because the filter is run forwards and backwards in time, the transfer function is the conjugate square for any given set of filter coefficients and the phase is 0. The filter order is 2x, or now a two-pole filter. One can then calculated the effective transfer function as:

$$H(e)^{jw} = \frac{0.01}{1-1.8e^{-jw}+0.81e^{-j2w}} \quad (8)$$

The filter cannot be successfully applied to zero crossing times. For a low pass filter, the filter result will be dominated by DC (e.g. the mean value), of the signal. The zero crossing time increases over the length of the acquisitions. As such the DC value will be close to half the acquisition time. One strategy might be to take the numerical derivative of the signal. Because the time between zero crossing is noisy (e.g. jitter), taking the numerical derivative increases the variance by 2. Instead, it is proposed that the "pseudo" derivative be used.

In this process, it is assumed that the time between zero crossing is fixed (e.g. variance is zero) as:

$$dt = {ZCT_n - ZCT_1}/{n-1} \quad (9)$$

Where n is the total number of zero crossings. The pseudo derivative is then different measured zero cross time and the time if there was zero jitter (e.g. $dt * i$):

$$dZCT_i/dt = ZCT_i - dt * i \quad (10)$$

Note that $dZCT_i$ is not zero mean with some assumed Gaussian noise: subtracting a constant does not increase system noise. The signal $dZCT$ is then filtered, and filtered zeros crossing times is reconstructed by integration:

$$filtered\ ZCT_i = dZCT_i + dt * i \quad (11)$$

3. EXAMPLE 1: H-60 TAIL ROTOR DRIVESHAFT

This example shows jitter from both finite precision of the timer, and magnetic artifacts from a variable reluctance tachometer. The data is available from McInerny (2004), and was from a seeded fault test at the NAWCAD helicopter transmission test facility (HTTF) in Trenton, N.J., in 1997, involved the intermediate gearbox (IGB) of the SH-60 helicopter.

The shaft rate with jitter is approximately 68.5 Hz, with a standard deviation of 0.3725 Hz (Figure **1**). After removing the jitter, the shaft rate standard deviation has been reduced to 0.039 Hz, almost a 9x reduction in noise. Consider for a moment that the tachometer signal, 32% of the time (e.g. +/- 1 standard deviation is 68%), has an error larger than 0.37 Hz, or 0.5% error in the estimate of the shaft rate. As notied, the TSA model assumes that there is no error in the zero cross time.

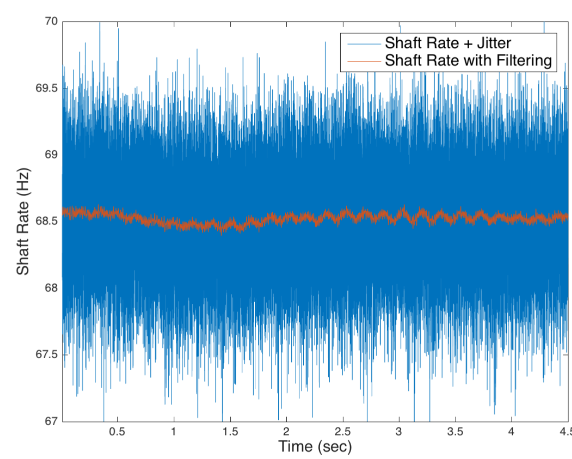

Figure 1. Jitter Resulting in Large Changes in Shaft Rate due to Noise

After removing the jitter, the shaft rate exhibits features that suggest there is a periodic change the shaft rate. There were 54117 zero crossing during the acquisition, which was 4.9152 seconds. The average time between samples was then 1/11,010.19. In order to perform spectral analysis on this, the time between "samples" must be constant, which can be done by interpolation. A higher sample rate of, say, 14000 samples per second will prevent aliasing. An estimate of the sample times is constructed by:

```
dt = 1/14000;
n = 4.9152 / dt = 68813
for (i = 0; i < n; i++)
    time[i] += dt;                                  (12)
```

which then allows a evenly space estimate of the shaft rate to be constructed:

```
zct: array of zero crossing times
fsr: filtered shaft rate
nsr: new shaft
     nsr = spline( zct, fsr, time);                 (13)
```

This allows the spectrum of the shaft rate can be taken (Figure **2**).

The spectrum shows three major features that effect the change in the shaft rate:

- 0.43 Hz that affects the shaft rate by 0.03 Hz. This may be related to the control response of the engine itself.
- A 6 Hz that affects that shaft rate at 0.02 Hz. This may be an signal conditioning artifact.
- The 20 Hz frequency at 0.005 Hz is associated with the tail takeoff main bevel gear (75 tooth).
- The 60 Hz frequency is likely due to electrical noise. The 6 Hz side bands suggest that the 6 Hz frequency could also be an electrical noise source.
- A 95.7 Hz that affects the shaft rate at 0.26 Hz. This is associated with the main spiral bevel pinion (21 tooth).
- The 196.5 Hz frequency is associated with either the accessory drive bevel pinion or the generator spur gear.

Without the removal of jitter, these features would not be visible. Further, it is just these features that the TSA was designed to correct for when resample.

4. EXAMPLE 2: HIGH SPEED INPUT SHAFT

In this example, the tachometer sensor is measuring a 3 per revolution coupling on the high-speed input shaft of a helicopter gearbox. The bracket is soft, such that the imbalance of the input shaft is causing the bracket to vibrate. The change in displacement of the tachometer sensor relative to the shaft coupling is source of jitter.

It is clearly seen in Figure **3** that there is an underlying 2 to 3 Hz control loop, causing a change in shaft rate of approximately 0.07 Hz. Because the shaft rate, and the resulting tachometer signal, is time varying, the tachometer signal can be resampled to accurately determine the cause of the jitter. Using a similar technique as in example 1 (Eq. 8 and Eq 9), the cubic spline interpolation is useful for this.

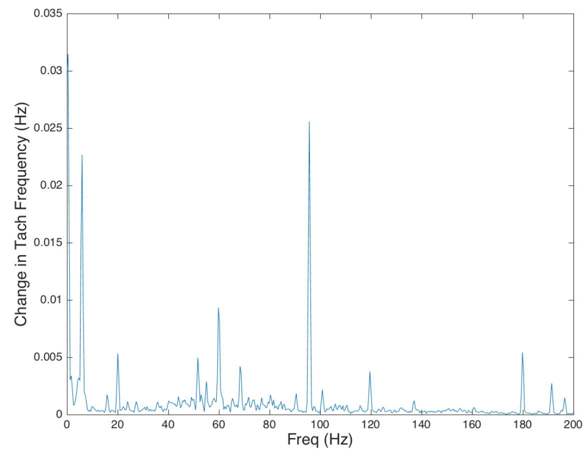

Figure 2. Spectrum Representing the Rate of Change in the Shaft Rate

In Figure **4**, a cubic spline is used to interpolate the tachometer time to an apparent delta time of 0.001 second (e.g. the interpolated sample rate is 1000 Hz). The predominant cause of the jitter is at 100 Hz (0.18 Hz change in shaft rate due to jitter), which is associated with the gearbox input shaft rate.

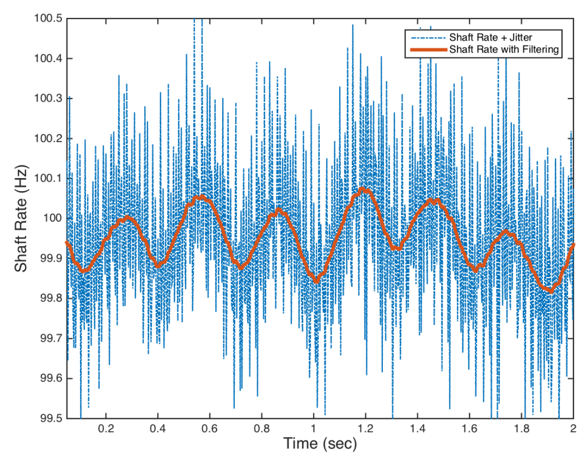

Figure 3. Jitter Due to Changes in Tach Sensor Displacement as a Result of Vibration

It is interesting to note that there is a 31.25 Hz sidebands (69.75 and 131.25 Hz, with a value of 0.06 Hz change in shaft rate), which is likely a result of the tachometer sensor bracket resonance. The control loop change in shaft rate (Figure **3**) can now be quantified as 2.93 Hz with a .075 Hz change in shaft rate, as seen in Figure **4**.

A concern, as noted, is that the filter should be zero phase, such that the resulting filtered tachometer signals features are maintained, and that the features below the bandwidth of the filter have similar phase. With the spline interpolated tachometer signal, it is possible to compare the effect of filtering on the 2.93 Hz control loop, which is a feature that should remain in the tachometer signal. The phase angle of the control loop is the arctangent of the ratio of the imaginary to real Fourier transform, evaluated at the frequency of interest.

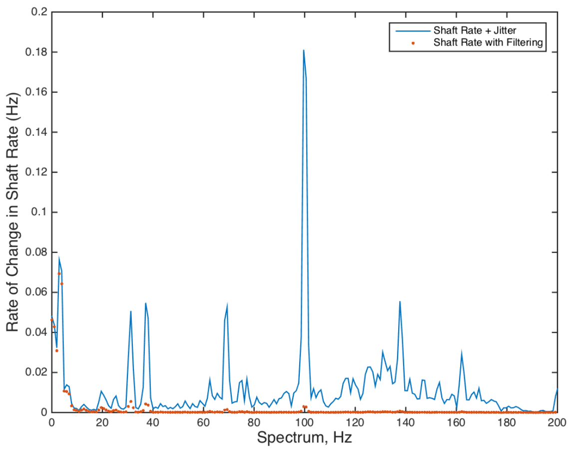

Figure 4. Change in Calculated Shaft Rate as a Result of Jitter

The phase for the unfiltered tachometer signal is 347.1535 degrees, while the phase of tachometer signal with the jitter removed is 347.192. The difference 0.3% can be attributed to the relatively short signal (2000 points) and noise, and will not affect the performance of the TSA. This validates that the zero phase filter is not effecting the phase of the tachometer zero cross times.

5. OPTIMAL SELECTION OF THE FILTER COEFFICIENT FOR JITTER REDUCTION

Every mechanical system has a bandwidth. For example, in Figure **3**, the control loop bandwidth is 2.93 Hz. This is a feature that should remain in the tachometer signal, as it is not associated with jitter. For this example, the bandwidth of the filter for jitter removal should be 3 Hz / 100 Hz, or greater than 3%. Bandwidth represents the frequency at which half (e.g. 3 dB) of the signal is removed.

The relationship between the filter coefficients *b* and *a* in Eq 3 is that $b = 1 - a$, such that Eq 4 can now be written as a function of a:

$$H(e)^{jw} = \frac{(1-a)^2}{a[1]+a[2]e^{-jw}+a[3]e^{-j2w}} \qquad (14)$$

The value of w in Eq 5 is the allowable percent change in shaft speed (say 5% for this example) * π, and j = sqrt(-1).

This allows for a simple Newton-Raphson optimization techniques to be used to solve for the filter coefficient a by setting the target value of -3dB, with the objective function being:

$$\text{Minimize ABS }(-3\text{dB} - \text{abs}(H(e)^{jw})^2) \qquad (14)$$

For Newton-Raphson to converge the objective function must be continuous and a derivative must exist. which this function does not supports. Instead, the alternative objective was used:

$$\text{Minimize }(-3\text{dB} - (H(e)^{jw})^2)^2 \qquad (15)$$

which is everywhere differentiable.

Using the optimization procedure, the coefficient value of a can be found for any given bandwidth (Figure **5**).

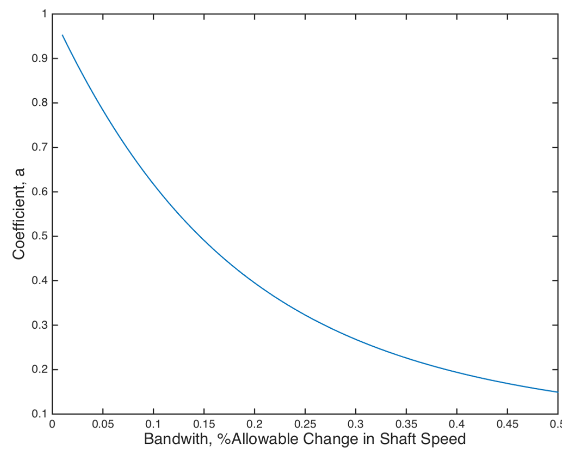

Figure 5. Filter Coefficient, *a*, based on %Change in Bandwidth

For a bandwidth of 0.05, the coefficient *a* is 0.7837.

6. IMPROVED DIAGNOSTICS EFFECTIVENESS FROM REDUCED JITTER

In order to quantify the effect of jitter on diagnostic algorithm, a real world fault with a 10 acquisitions was chosen (e.g. while a acquisition was taken every 10 minutes, 144 times a day, raw data, both vibration and tachometer, was collected only once per day over a 10 day period). The data set was taken from a 1.5 MW wind turbine.

The jitter is from both finite precision of the timer, and irregular spacing of the 8/revolution target on the shaft. Note that the shaft rate with jitter removed has low order, periodic change in shaft speed. This is due to the effect of tower shaft/wind shear. Typical, large wind turbines main rotor rate is 0.15 to 0.25 Hz, or one revolution ever 4 to 6 seconds. The main rotor has 3 blades. The period of the change of shaft rate is on the order of 1.3 to 2 seconds (e.g. the 3/Rev effect of tower shadow/wind shear), which is seen in the reduced jitter tachometer signal of Figure **6**.

The fault is a high-speed pinion, which drives the generator, with an approximate shaft rate or 30 Hz. The pinion has a soft tooth. A comparison of the gear component analysis with jitter and without jitter shows that removing jitter improves the analysis. This can be quantified by using the population statics of gear analysis condition indicators (CIs) from a nominal machine vs. the gear defect by measuring the populations' separability.

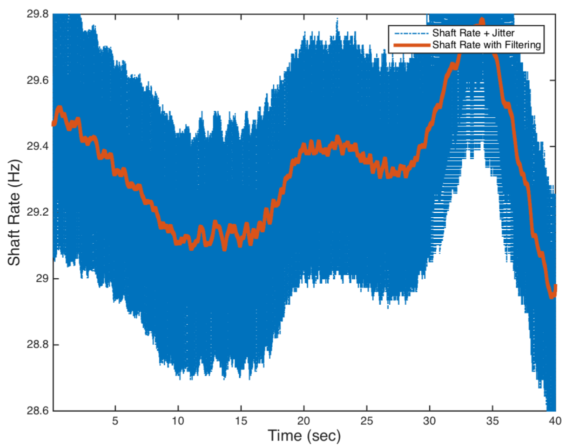

Figure 6. Shaft Rate and Jitter from a machine with a bad gear

The measure of seperatbility was calculated using the pooled sample standard deviation. The sample size was 20 acquisitions per sample set, where the populations for the null set came from the nominal gear (no damage) and the alternative set came from the damage gear population.

The test statistics is then:

$$T = E[Y_1] - E[Y_2]/S_p\sqrt{2/n} \tag{16}$$

where:

$$S_p = \sqrt{(n-1)S_1^2 + (n-1)S_2^2/2n-2} \tag{17}$$

Separability is the statistical distance between two populations: nominal vs. faulted. It is the normalized distance based on the measurement variance and is a good measure of the ability of a condition indicator (CI) to detect a fault. A separability of 3.58 is approximately a probability of false alarm (PFA) of 10^-3 (ref 8).

6.1. Condition Indicators for Gear Fault Detection

There are at least six failure modes for gears (Motion System Design, 2001): surface disturbances, scuffing, deformations, surface fatigue, fissures/cracks and tooth breakage. Each type of failure mode, potentially, can generate a different fault signature. Additionally, relative to the energy associated with gear mesh frequencies and other noise sources, the fault signatures are typically small. A number of researchers have proposed analysis techniques to identify these different faults (Zakrajsek, 1993). These analyses are based on the operation of the TSA. In this example the fault is a broken tooth, and the following analysis where conducted (note the gear mesh frequency is found by: take the FFT of the TSA, take the absolute value of the number teeth + 1 bin):

- Figure of Merit 0: the TSA peak-to-peak divided by the sum of the 1st and 2nd gear mesh frequencies;
- Residual Analysis: where shaft order 1, 2, and 3 frequencies, and the gear mesh harmonics, of the TSA are removed. Faults such as a soft/broken tooth generate a 1 per rev impacts in the TSA. In the frequency domain of the TSA, these impacts are expressed as multiple harmonic of the 1 per rev. The shaft order 1, 2 and 3 frequencies and gear mesh harmonics in the frequency domain, and then the inverse FFT is performed. This allows the impact signature to become prominent in the time domain. CIs are statistics of this waveform (RMS, Peak 2 Peak, Crest Factor, Kurtosis).
- Energy Operator (EO): which is a type of residual of the autocorrelation function. For a nominal gear, the predominant vibration is gear mesh. Surface disturbances, scuffing, etc, generate small higher frequency values which are not removed by autocorrelation. Formally, the EO is: TSA2:n-1 x TSA2:n-1 x – TSA1:n-2 x TSA3:n . The bold indicates a vector of TSA values. The CIs of the EO are the standard statistics of the EO vector
- Narrowband Analysis (NB): operates on the TSA by filtering out all frequencies except that of the gear mesh and with a given bandwidth. It is calculated by zeroing bins in of the Fourier transform of the TSA, except the gear mesh. The bandwidth is typically 10% of the number of teeth on the gear under analysis. For example, a 23 tooth gear analysis would retain bins 21, 22, 23, 24, and 25, and there conjugates in frequency domain. Then the inverse FFT is taken, and statistics of waveform are taken. Narrowband analysis can capture sideband modulation of the gear mesh frequency due to misalignment, or a cracked/broken tooth.
- Amplitude Modulation (AM) analysis is the absolute value of the Hilbert transform of the Narrowband signal. For a gear with minimum transmission error, the AM analysis feature should be a constant value. Faults will greatly increase the kurtosis of the signal
- Frequency Modulation (FM) analysis is the derivative of the angle of the Hilbert transform of the Narrowband signal. It's is a powerful tool capable of detecting changes of phase due to

uneven tooth loading, characteristic of a number of fault types.

For a more complete description of these analyses, see Bechhoefer and He, 2014). Table **1** gives the separability for each CI.

Table 1. Effect of Jitter on Condition Indicator Separability.

Analysis	*With Jitter*	*Jitter Removed*	*Improvement*
Residual RMS	9.65	9.83	2%
Residual Kurtosis	17.4	19.3	9.9%
Residual P2P	14.82	16.2	9.2%
Residual Crest Factor	6.11	7.91	26%
Energy Operator Kurtosis	8.32	10.1	22%
Figure of Merit 0	8.67	9.05	5%
Narrowband Crest Factor	2.51	3.08	22%
Amplitude Mod. RMS	31.24	34.9	10%
Frequency Mod. RMS	5.58	5.65	1%
Frequency Mod. Kurtosis	15.4	16.0	4%

In general, there is a 10 to 25% increase in separability. The separability was calculated as the normalized statistical difference between the faulted gear (10 raw data samples) and two machines with nominal gears (9 and 10 raw data sample respectively) using the pooled standard deviation.

For condition monitoring systems based on CI thresholds, this will have an immediate improvement in fault detection. For other condition monitoring system where the CIs are transformed into a Health Indicator (HI), this will result in a potentially larger improvement in performance. The HI, being a function of CI distribution (where a whitening linear transform is used to map the CIs and to the HI) would be more sensitivity when there is consensus (e.g. all of the CIs are "moving" in the same direction).

7. CONCLUSION

Jitter, as a result of electrical noise, magnetic noise, target spacing manufacturing error, etc., affects the performance of the TSA. Because most gear analyses are based on the TSA, improving the data quality of the TSA should improve the performance of gear condition indicators. This papers develops a zero phase filter to remove tachometer jitter, then test performance of condition indicators based on the improve data quality of the TSA.

Using a zero phase filter to remove jitter, it was possible to better identify features that represent changes in the shaft rate. The change in shaft rate is due to bandwidth limitations of the control system, gear tooth cogging or shaft torsional resonance. These features are periodic. By using interpolation, the spectrum of the shaft rate calculated from the tachometer signal, and was used to identify the magnitude of shaft rate change by frequency for a specific gearbox component.

The bandwidth of the zero phase filters can be notionally set based on system knowledge. For example, if the feedback control of the engine is no greater than 3 Hz, and the 1/Rev is taken from a 100 Hz input shaft, the nominalized bandwidth of the filter should be 2 * 3 / 100 or 0.06. This then allows the optimal filter coefficients to be calculated using Newton-Raphson method. It was demonstrated with real world data that the filter was zero phase for a known feature.

Using data from a known fault, population statistics were calculated using the raw tachometer data, and zero phase filtered tachometer data. For the ten gear condition indicators tested, for 10 samples, there was a 2 to 26% improvement in the separability between the faulted gear and two machines with nominal gears.

NOMENCLATURE

CAA	Civil Aviation Authority
CI	condition indicator
dZCT	derivative of the zero crossing time
FIR	finite impulse response
FM0	figure of merit, 0
HI	health indicator
IIR	infinite impulse response
IGB	intermediate gearbox
PPR	pulses per revolution
TSA	time synchronous average
ZCT	zero crossing time

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BIOGRAPHIES

Eric Bechhoefer received his B.S. in Biology from the University of Michigan, his M.S. in Operations Research from the Naval Postgraduate School, and a Ph.D. in General Engineering from Kennedy Western University. His is a former Naval Aviator who has worked extensively on condition based maintenance, rotor track and balance, vibration analysis of rotating machinery and fault detection in electronic systems. Dr. Bechhoefer is a board member of the Prognostics Health Management Society, and a member of the IEEE Reliability Society.

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