TSA Methods for Bearing and Gearbox Signature Enhancements in Wind Turbines

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Time Synchronous Averaging

• Definition
• Time chunking (constant speed machine)
• Spectral Averaging
• Angle domain averaging
• Tale of 3 signals
Objectives / Disclaimer

• The following is a set of signal processing analysis results and discussion, it is not intended to have an authoritative result.

• Feedback, questions, comments are highly encouraged. Your feedback and ideas will be considered for future work.
Sources

• H. Lou and H. Qui (2009). Synthesized Synchronous Sampling Technique for Damage Detection
Blade Pass Pulsations Computer Fan

- 10 Time Synchronous Averages
- Slightly Varying Speed (2300RPM)
- Resampling based
- Integer # blade events per revolution

7 Blades, one is missing
Time synchronous averaging is equivalent to vector averaging where an explicit channel is used to trigger the analysis block. Here we see a tachometer channel with one pulse per revolution. Any pulse can be used to trigger an acquisition block. For a tachometer signal with multiple pulses per revolution, the pulse corresponding to a known angular position should be used consistently for each analysis block.

Whichever pulse is used, the triggering used for time-synchronous averaging forces correlation between the analysis block and signal components related to the constant running speed.
Again, the spectra are intentionally plotted on the same magnitude scales so that changes in noise floor are more evident. The max is 0 dB and the min is -50 dB for the y scale. It can be seen that correlated signal components average to the expected value, and uncorrelated noise is “averaged out”. That is the noise floor actually drops with increasing vector averaging. We see a 6 dB drop for 4 averages and a 20 dB drop for 100 averages. Vector averaging drops the noise floor by the square root of the number of averages.

Note, that uncorrelated components occur with random phase with respect to the analysis block. Therefore, vector averaging (which averages complex quantities) effectively removes these random components.

One must be careful though that the signals of interest are correlated to the block. For frequency analysis of sinusoidal components, this is equivalent to requiring that the signal components are at constant phase relative to the start of every analysis block. This can happen automatically when analyzing signals that are periodic within continuous analysis blocks. Otherwise, triggering should be used to correlate the analysis block with the acquired data.
This review of time synchronous averaging leverages three signal sources.

The first is a simulated signal, with known frequency, phase, amplitude, and noise components.

The second is an impact of the second hand ticking in a stopwatch as measured by a Swantech Stresswave sensor.

The third is the number 6 accelerometer used in the gearbox round robin.
Our simulated signal is shown in the upper left. We added white noise to the signal, resulting in the lower left signal.

Using the tachometer trigger as a guide to the rotational frequency of the shaft, we can cut the time waveform into cycles of the frequency component we want to average.

This works when the speed of the shaft is stable.

Time synchronous averaging works here to recover the impact signal at 0.85 Hz.
Yet, what if we did not know the exact frequency? We expect the signal to be at 0.85X, yet due to manufacturing error, etc. There is some variation in the frequency.

By using a zoom FFT function, it is possible to track the frequency and use the tracked frequency as an input to the time synchronous averager.

However, in order for the “time waveform slice” method to work, we need to be very accurate in the calculation or choice of the frequency component to track.

The top right graph shows TSA with a small error in frequency. Amplitude is reduced and the signal is smeared, caused by incorrect alignment of the record from record to record.

The right FFT is the zoom FFT with a cursor on the peak, as well as peak detection calculating the peak frequency of the measurement.
The next signal is the stopwatch signal. The signal has limited energy in the frequency domain, and a clear “haystack” at the resonant frequency of the Stresswave sensor.
After several guesses at the exact frequency, using a Zoom FFT, the exact frequency is still unknown and TSA with time waveform record slicing is not accurate.

- Guess order at 5.0016X

Actual Amplitude is 0.15, averaged to 0.015
Close in shape, but not in magnitude
Using an envelope demodulation filter, and rectifying plus squaring the result, we see a clear time domain instance. If we use an exponential RMS average analysis of the demodulated time waveform, we get a saw tooth wave at the frequency of the stopwatch tick. Can we use this saw tooth as a tachometer to align the stopwatch impacts with an equal number of voltage samples per tick?
When resampling to the saw tooth intervals (using the saw tooth wave as a tachometer reference), the resulting shape of the tick improves in clarity, however the magnitudes are still different.

The Stresswave sensor is excellent for measuring the effect of impacts on a specific resonant frequency of the sensor, yet it may not represent the 5Hz impulse waveform accurately. This may be a source of error in the input data.
We now turn to the AN6 accelerometer time waveform from the gearbox reliability round robin.

We will try time slice TSA, resample Time Slice TSA, and Spectral Averaging TSA.
Using a time slice averaging at 73.0225 Hz, we see an oscillation with apparent higher frequency content.

The observed frequency of the original signal is different from the 73.695 frequency calculated from the Bearing data sheet.

Was the 73Hz from some other mechanical component?
As an aside, let's review the peak search function.

Like Power in Band, Peak search in the spectrum can provide valuable metrics to assess vibration severity. Unlike power in band, peak search looks to quantify spectral components at discrete frequencies rather than summing the energy across a broad band.

We spent a lot of time talking about frequency resolution when discussing fundamentals of the FFT. Peak search enables us to identify tonal components even when the frequency is between bins. As the diagram indicates, this is accomplished by fitting the spectrum of the window shape to the three highest-amplitude bins at every local maximum in the spectrum. Whether it be for a frequency spectrum or an order spectrum, fitting the window shape ‘interpolates’ spectral peak values and effectively overcomes two of the biggest limitations in FFT peak detection: namely scallop loss and frequency resolution.
In order to try a resampling to a specific number of measurements per revolution, we first need to identify a tachometer signal. In the top graph, we have smoothed the speed signal and removed the DC offset of the speed signal. The result is a predictable tachometer signal.
For completeness, we first use a zoom FFT and peak search to identify an exact peak frequency, and then use the exact frequency to drive the even angle waveform slicing TSA.

The zoom FFT and Re-sampled or even-angle waveform slicing TSA results are shown on these graphics.
Comparing the time domain waveform slicing TSA to the even-angle domain TSA shows differences. Did the wavelet de-noising process in the even-angle domain analysis remove the oscillation shown in the top graph?
When using wavelet de-noising and envelope demodulation, we get a more interesting result. The even-angle resampling TSA shows a stronger repetitive magnitude, perhaps showing some scuffing in the inner-race. Also, the Zoom FFT after demodulation shows the peak to be at 75Hz as compared to 73Hz.
Here is a comparison of all three. The results are different, indicating further study is required.
There exist several possible errors in these results. These are listed here, and methods will be checked and improved in future analysis efforts.

Future Ideas?

- Review De-noise and envelope demodulation
  - Time slice
  - Resampling
- Continue to use Zoom FFT and peak detection to detect actual fault frequency
- Double check the fault frequencies (FAG or SKF)
- Remove gear frequencies before working with bearing frequencies
- Include possible speed oscillations in the speed profile during a single revolution of the high speed shaft.
Summary

- LabVIEW Signal Processing (sandbox)
- Simulation tools
- Graphical System Design
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ADDITIONAL BACKGROUND SLIDES
Spectral Leakage

What happens when you are processing signals between bins of resolution on the DFT?

For example, when sampling a sine wave, it is almost impossible to acquire exactly an integer number of cycles. One of the fundamental assumptions of the DFT is that the acquired signal is periodic.

If you take just the red region of the waveform and assume that it is periodic, it looks like there are artificial discontinuities inserted in the signal based on the assumption the DFT makes.

This is how it looks in the time domain. How does it look in the frequency domain?
Spectral leakage in the frequency domain

From what we know about the frequency domain. A single frequency component in the time domain should transform (via the DFT) into a single spike in the frequency domain.

As seen in the middle row of graphs, if you sample a non-integer number of cycles, the sine frequency is between the DFT bins of resolution, and the maximum amplitude of the DFT decreases and the energy bleeds or leaks into adjacent lines of resolution. The DFT reports frequency content that does not exist on your input signal. Remember that this leaked energy is due to the artificial discontinuity at the edges of the block as seen in the middle.

In the bottom time-domain graph, we see the effect of applying a Hann window in the time domain. The discontinuities at the edge of the time-domain block are attenuated. The windowing, therefore, also has the effect of reshaping the energy in the frequency domain.

Even after the energy is reshaped, you still have only a partial view of the spectrum. This was previously termed the “Picket Fence Effect”. This partial view does not capture the true frequency, and the observability of the true frequency is very much limited by the frequency resolution of the FFT spectrum.
Averaging Terms

- Time Averaging
- Linear
- Exponential
- Modes
- RMS
- Vector
- Peak Hold
- Time Synchronous

\[
\text{Average} = \frac{1}{\sum_{i=1}^{n} w_i} \sum_{i=1}^{n} x_i w_i
\]

\[
\text{Average} = \frac{1}{n} \sum_{i=1}^{n} x_i
\]
The spectra are all plotted on the same magnitude and frequency scales.

It can be seen that increasing the number of averages reduces the variance in the noise. In fact, the variation in the noise is reduced by the square root of the number of averages.

While the variation in the noise is reduced, the noise level is not affected by RMS averaging.
Again, the spectra are intentionally plotted on the same magnitude scales so that changes in noise floor are more evident. The max is 0 dB and the min is -50 dB for the y scale. It can be seen that correlated signal components average to the expected value, and uncorrelated noise is “averaged out”. That is the noise floor actually drops with increasing vector averaging. We see a 6 dB drop for 4 averages and a 20 dB drop for 100 averages. Vector averaging drops the noise floor by the square root of the number of averages.

Note, that uncorrelated components occur with random phase with respect to the analysis block. Therefore, vector averaging (which averages complex quantities) effectively removes these random components.

One must be careful though that the signals of interest are correlated to the block. For frequency analysis of sinusoidal components, this is equivalent to requiring that the signal components are at constant phase relative to the start of every analysis block. This can happen automatically when analyzing signals that are periodic within continuous analysis blocks. Otherwise, triggering should be used to correlate the analysis block with the acquired data.
Here on the bottom graphs, you can see how vector averaging can make signal components ‘disappear’ if they are uncorrelated to the analysis blocks. Increasing the number of averages further underestimates the energy present at each uncorrelated frequency component and can make high-energy components indistinguishable from the noise despite the fact that the noise floor has been reduced.

Because vector averaging can inadvertently underestimate signal components, it is important to trigger the analysis blocks. For impact testing, it is sufficient to trigger off a force channel or a reference accelerometer. For constant-speed equipment with rotating or reciprocating components, a tachometer signal can be used to align, or synchronize, the analysis block to the dynamic vibration.
Here we can see two different use cases that would prompt the use of different weighting modes.

Linear averaging was performed to compute the spectra on the left and exponential averaging was performed to compute the spectra on the right. The spectra are graphed such that the y-axis is in dB and the frequency axis is a linear scale from 0 to 2000 Hz (Fs/2.56).

The top row of graphs shows linear and exponential averaged spectra for 4s of time data with a stationary sine component and significant noise. The time data was processed in 100 blocks (each block = 2048 samples or 40 ms). Linear averaging clearly shows the stationary spur at 120 Hz because the variance of the noise in the spectrum has been reduced.

The bottom row of graphs shows the linear and exponential averaged spectra for time data with an increasing sine component and significant noise. Again the time data was processed in blocks of 2048 samples, but the analysis was stopped when the spectrum exceeded a predefined upper limit. In a real vibration monitoring application, depending on the severity of the vibration, the code we could perform some additional action such as logging vibration data, notifying plant personnel, or even shutting down the machine. For this example though, exponential averaging demonstrates greater sensitivity to the changing levels of non-stationary components.
Due to the nature of peak-hold averaging, this spectrum is useful for limit testing for alarms, but the peak-hold spectrum is not very useful for diagnostics because there is not adequate separation between noise and low-amplitude vibration components.
This slide shows a comparison of the averaged spectrum returned after 100 averages with each averaging mode.

A quick review on averaging:

RMS averaging returns the average energy at each bin and reduces the variation in the noise.

Peak hold returns the maximum value of each bin and is good for limit test.

Vector averaging can lower the noise floor, but can also underestimate frequency components that are not correlated to the analysis blocks.

Triggered vector averaging and time-synchronous averaging are completely equivalent. Averaging the complex spectra produces the same result as averaging blocks of time data!

I want to take a moment to pause to see if there are any questions on spectral averaging...
Here a peak search is conducted on an averaged spectrum (100 RMS averages). Hann(ing) window was applied to each block of acquired data prior to the FFT. Overlap = zero. The green spectrum shows the measured power spectrum with frequency resolution of 100 Hz (block duration = 10 ms). The blue spectrum is the interpolated spectrum assuming only one spectral peak in the displayed frequency range. Again, the spectrum of the window is used for the interpolation function. The orange dashed line shows the threshold for peak detection, and the orange crosshairs mark the peak as determined by bin picking and peak search, respectively.

Cursors can be used to locate local maxima in the spectrum, but it is clear from this example where the frequency is not periodic within the block duration, that simple bin picking is not sufficient to accurately measure the actual frequency nor amplitude of vibration. The simple measurement finds the closest bin in the coarse spectrum and underestimates the power by almost 20%.

Peak search, on the other hand, accurately measures the frequency to within .01 Hz which is .01% (100% * .01Hz/100Hz) of the frequency resolution and the amplitude of the spectrum to three full significant digits.