Spectrum Averaging vs. More Spectrum Lines --- A Comparative Study of Enhancement Effects on Spectrum

Summary

This application note documents a comparative study that investigates the effects of spectrum enhancement achieved by two different approaches: 1) spectrum averaging; and 2) more spectrum lines but no averaging. The major part of the study was done by simulation using signals generated by a DSP software package. Different signals, i.e. broadband white noise and repetitive impulse train, were used in order to reveal the differences of the two spectrum enhancement techniques. Statistic parameters computed on spectral line amplitudes were used to give a quantitative description of the differences and noise reduction performance. Finally, vibration data from an electric motor driving a screw compressor is presented, further confirming the observation in the simulation study.

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1. Introduction

In the vibration signal analysis field, spectrum averaging has long been recognized as a spectrum enhancement technique to reduce the level of noise in a spectrum. Another technique that is also very effective in reducing spectrum noise level is constructing a spectrum with a higher number of lines.

This raises the question, which technique is a better approach? This application note is aimed at addressing this question by documenting a comparative study that quantifies the performance of the two techniques with simulated signals as well as real vibration data collected from an electric motor driving a screw compressor.

2. Simulation Investigation

The simulation was done using two types of signals:

- Broadband white noise signal
- Repetitive impulse train with added broadband white noise signal

The white noise signal simulation is quite fundamental in answering the question of which technique is more effective in reducing the spectrum noise level: spectrum averaging or a higher number of spectrum lines. This is because spectrum averaging or higher spectrum lines should have no effect on periodic signals with discrete frequencies. Only random signals like noise can be affected by using averaging or higher spectrum lines.

Thus the simulation is done first using broadband white noise signals to reveal the noise reduction properties of the two techniques. This is followed by comparing signal to noise ratios using repetitive impulse train with added broadband white noise signals.

The spectral line for the spectrum with averaging is chosen to be 800 since it is believed to be the most popular measurement setup. To ensure the comparison is done without any bias, the size of the data block used in averaging mode and non-averaging mode is kept the same, as shown in figure 1. Note that there is a 50% overlap in averaging mode. Three groups of simulation results are presented in this application note.

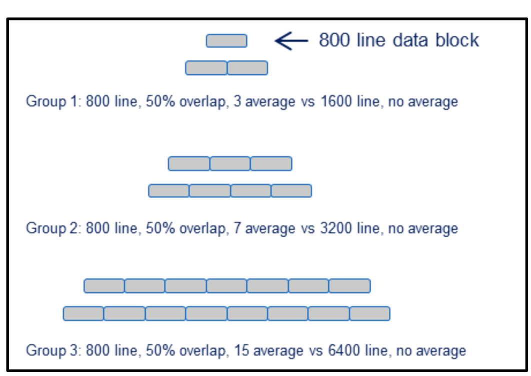
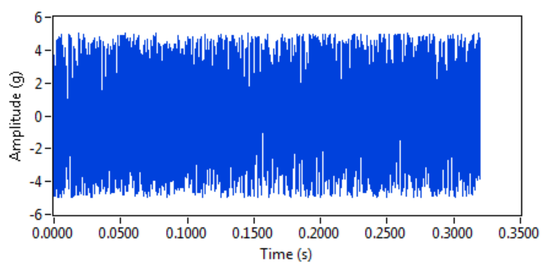


Figure 1 Data block size employed in the simulation

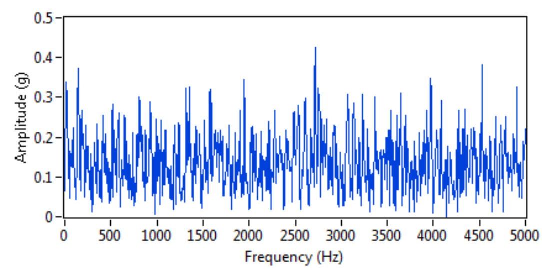
2.1. White Noise Signal

Three blocks of broadband white noise (12.8 kHz sample rate with frequency content up to 5 kHz) signals were generated to support an 800 line spectrum using 3, 7, 15 averages with 50% overlap. The first 2048 data points are used to calculate an 800 line spectrum, which is the baseline spectrum with the highest noise ceiling. In addition, a 1600, 3200, and 6400 line spectrum without averaging are also calculated. Figure 2 gives the time waveform plot (figure 2.a), an 800 line spectrum without averaging (figure 2.b), an 800 line spectrum with 3, 7, 15 averages (figure 2.c, 2.e, 2.g), and a 1600, 3200, 6400 line spectrum without averaging (figure 2.d, 2.f, 2.h).

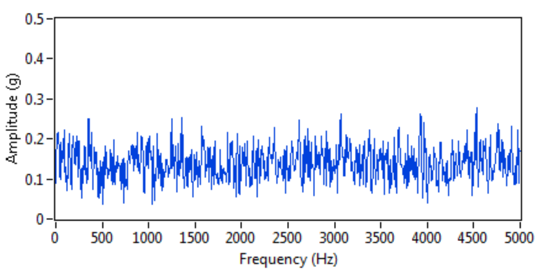
Please note that all spectra are calculated with a Hanning window.



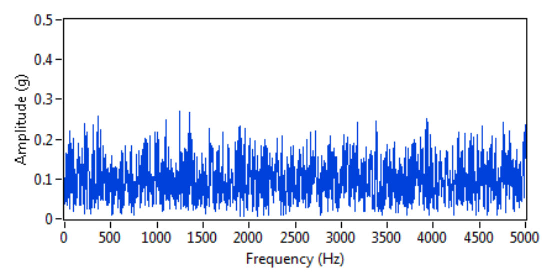
a) White noise waveform



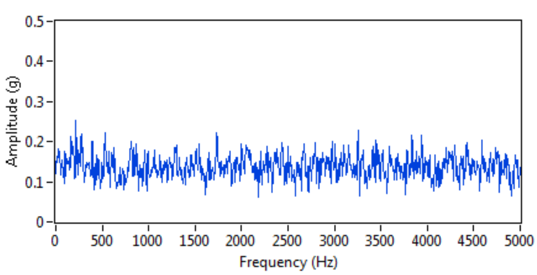
b) 800 line, no average spectrum



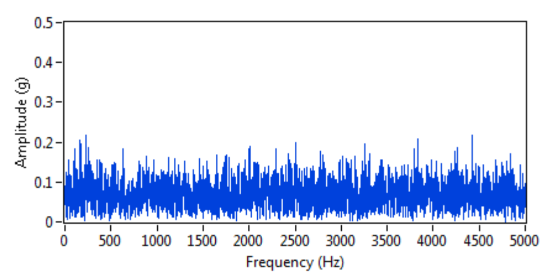
c) 800 line, 50% overlap, 3 average spectrum



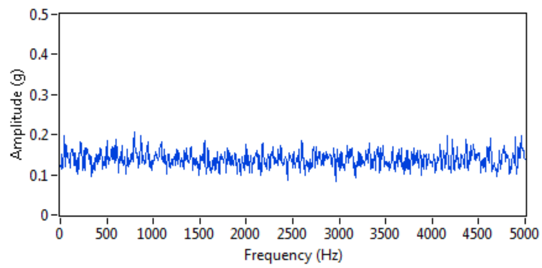
d) 1600 line, no average spec



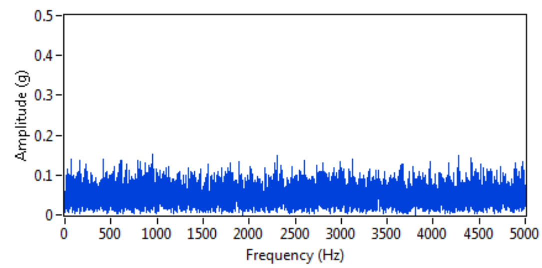
e) 800 line, 50% overlap, 7 average spectrum



f) 3200 line, no average spectrum



g) 800 line, 50% overlap, 15 average spectrum



h) 6400 line, no average spectrum

Figure 2 Time waveform of white noise and spectra with different averaging mode and number of spectral lines

It is quite obvious that between the two spectra with the same 800 lines, 15 averaging results in a much less “noisy” spectrum than a non-averaging spectrum (see figure 1.g and 1.b). The observation, even though categorically correct, does not describe the difference quantitatively. In order to describe the difference in a quantitative way, the “MEAN” and the “STANDARD DEVIATION” of the line amplitudes of the spectrum are used.

For the purpose of calculating the noise reduction performance of the different methods, “mean + 2* standard deviation” is used as the spectral noise ceiling. The logic behind this noise ceiling definition is that only 2.275% of the spectral line amplitudes are higher than the level represented by spectral mean plus 2 times the standard deviation, assuming the noise distribution is a normal distribution. Relative noise ceiling expressed as percentage using the 800 line, non-averaging spectrum as the base line, are computed to show noise reduction performance of each simulation case. The results are given in table 1.

Averaging Mode	Mean	Standard deviation	Mean + 2*Std	Relative noise ceiling level
800 line, No Averaging	0.1385	0.0729	0.2843	100%
800 line, 50% overlap, 3 Ave	0.1395	0.0414	0.2223	78.2%
1600 line, No Averaging	0.0993	0.0504	0.2001	70.4%
800 line, No Averaging	0.1387	0.0720	0.2827	100%
800 line, 50% overlap, 7 Ave	0.1380	0.0293	0.1966	69.5%
3200 line, No Averaging	0.0693	0.0360	0.1413	50.0%
800 line, No Averaging	0.1381	0.0700	0.2781	100%
800 line, 50% overlap, 15 Ave	0.1386	0.0194	0.1774	63.8%
6400 line, No Averaging	0.0490	0.0253	0.0996	35.8%

Table 1 Mean, standard deviation and noise ceiling comparison

The noise ceiling reduction performance achieved by various averaging modes and spectral line numbers is presented in figure 3 as the percentage of noise ceiling level of the base line spectrum in each group.

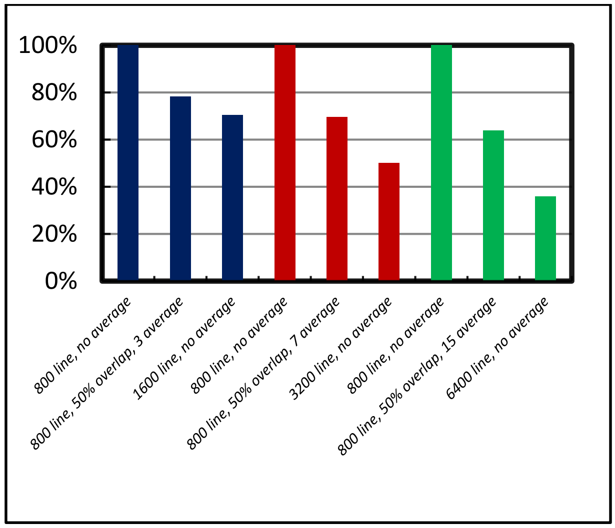


Figure 3 Relative noise ceiling comparison

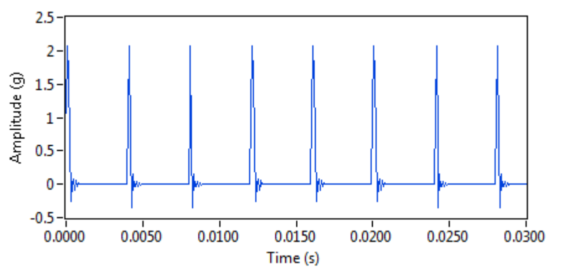
From table 1 and figure 3, the following observations are made:

1. Spectrum averaging does not reduce the mean of line amplitudes, while increasing spectral lines results in a reduction of the mean of line amplitudes, assuming the signal is a white noise.
2. If the ratio between the number of lines between two spectra is R, the mean of line amplitude of the spectrum with more spectral lines is lower than the other spectrum by a scale of $\sqrt{R}$ (this will be mathematically proved later in this application note). This means taking more spectral averages makes the larger spectrum with no averaging a more attractive approach to reduce spectral noise. For example, the ratio of the number of lines between a 3200 and 800 spectra is 4. Therefore the mean of line amplitude of the noise ceiling of a 3200 line spectrum is lower than the 800 line spectrum by $\sqrt{4}$ = 2.
3. The standard deviation calculation results in table 1 indicated that the averaging process gives a slightly smaller standard deviation than more spectral lines. This gives a more smooth spectrum using averaging process than the spectrum using more spectral lines. Note that when comparing the noise ceiling using mean plus 2 times standard deviation, more spectral lines still performs better.
4. More than a 40% noise reduction can be achieved comparing a 6400 line non-averaged spectrum and an 800 line 15 averaged spectrum, while near 30% noise reduction is observed comparing 3200 line non- averaged spectrum and an 800 line 7 averaged spectrum.

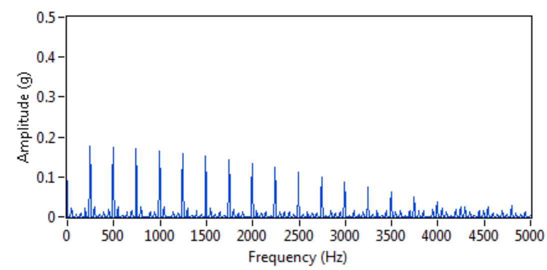
2.2. Repetitive Impulse Train Signal with Added White Noise Signal

Repetitive impulse train signal is another common type of signal encountered in vibration analysis. A defective bearing outer race will result in such a waveform after the enveloping process. It is recommended in many SKF technical documents that no averaging be used when taking enveloping measurements. Instead, a higher number of lines can generally give a better spectrum in terms of identifying the bearing defect.

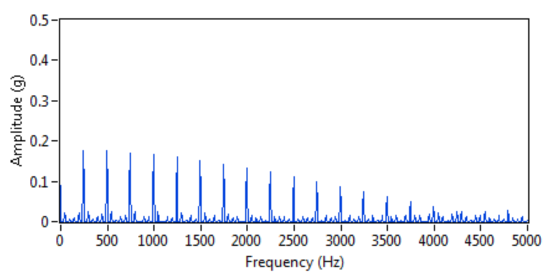
In figure 4 and 5, time waveform and spectra using different average modes and spectral lines of a repetitive impulse train signal with and without added broadband white noise are plotted. It is expected that spectral averaging or higher spectral lines do not affect the quality of the spectrum of the repetitive impulse train signal when there is no broadband white noise present (figure 4). Please note that all spectra are calculated with a Hanning window.



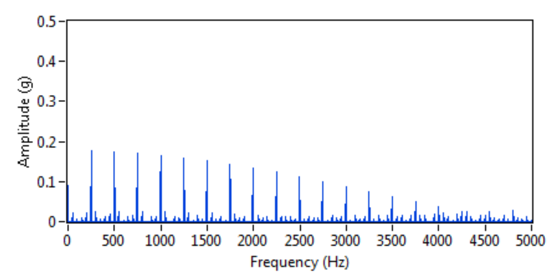
a) Time waveform of an impulse train with 250Hz rep rate



b) 800 line, no average spectrum

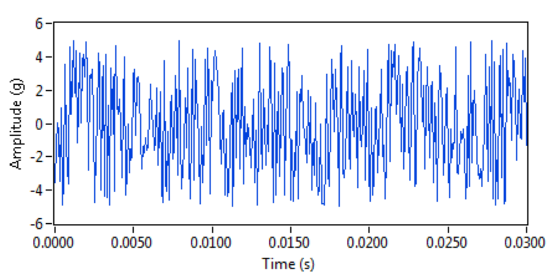


c) 800 line, 3 average spectrum

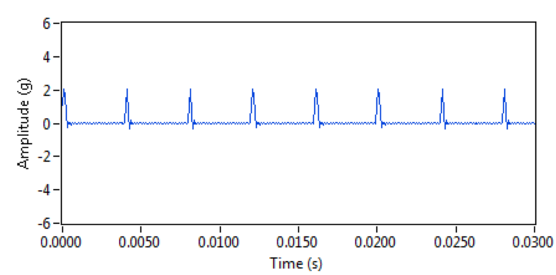


d) 1600 line, no average spectrum

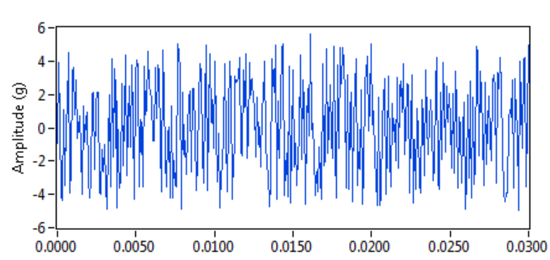
Figure 4 Waveform of repetitive impulse train and spectra with different averaging modes and number of spectral lines



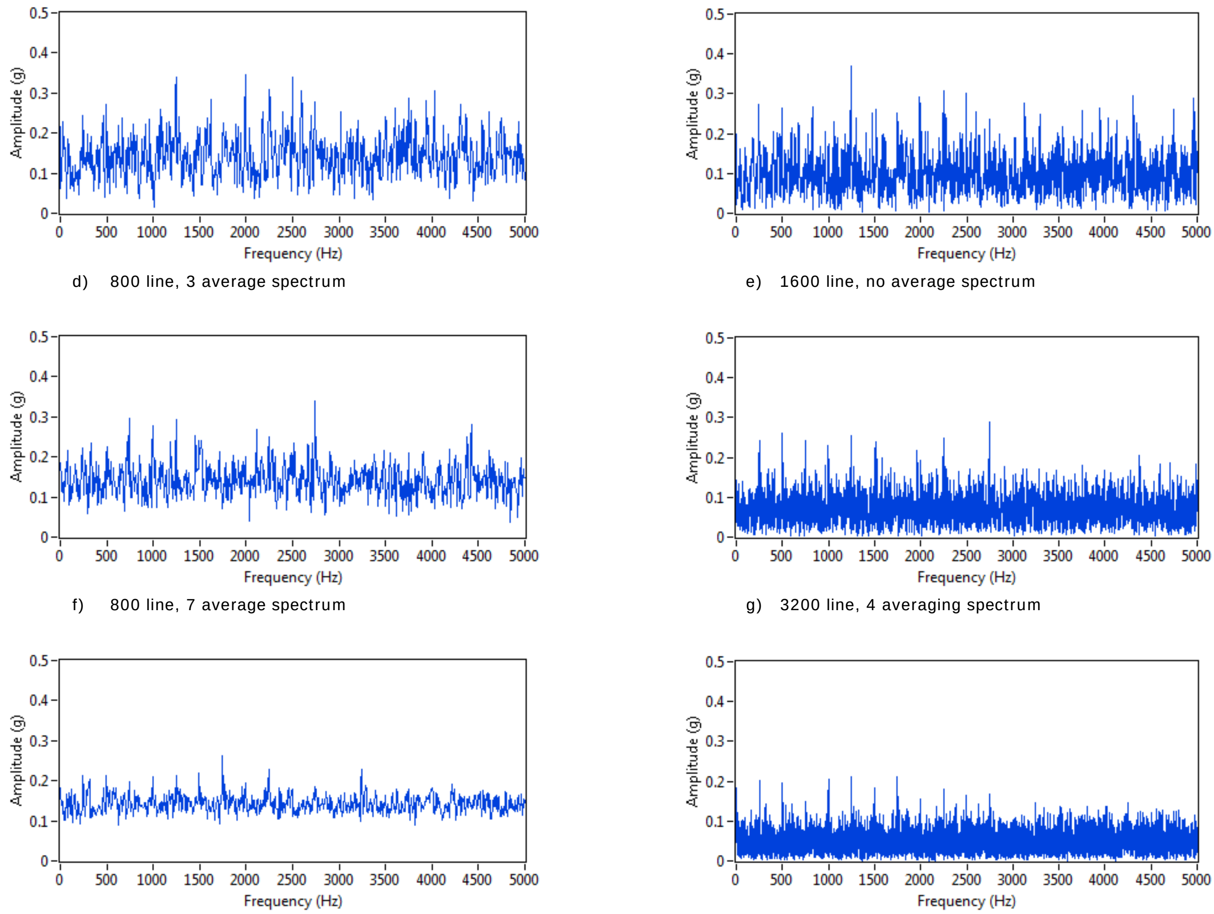
a) Random noise waveform



b) Impulse train waveform



c) Waveform of random noise summed with impulse train



d) 800 line, 3 average spectrum

e) 1600 line, no average spectrum

f) 800 line, 7 average spectrum

g) 3200 line, 4 averaging spectrum

h) 800 line, 15 average spectrum

i) 6400 line, no average spectrum

Figure 5 Waveform of repetitive impulse train with added broadband white noise and spectra with different averaging modes and number of spectral lines

In figure 5 above, a better spectrum for identifying a repetitive impulse signal achieved by the larger spectrum over the smaller spectrum with averaging can be observed. This is largely due to the better noise reduction performance of the larger spectrum without averaging than smaller spectrum with averaging.

3. Field Data

The data presented in this section was collected on an electric motor driving a screw compressor. The electric motor has known outer race bearing damage at the non-drive end side.

The relevant technical information about the electric motor is provided below.
Speed: ~ 1520 RPM
Bearing: 6315

Below the results of 2 enveloping measurements are presented to illustrate the differences caused by spectral averaging and higher line resolution (more spectrum lines) on the spectrum.

Note that the size of data blocks for the two measurements are the same, making a valid comparison.

Measurement 1 – Envelope Filter 3 point measurement attributes
Fmax: 1260Hz
Lines: 800
Averages: **4 (Average from FFT, data block size is 8192 samples)**
Low Freq cut-off = 0

The spectrum below (figure 7) shows a clear peak at 1X BPFO however its harmonics cannot be seen as they are suppressed by the noise ceiling level.

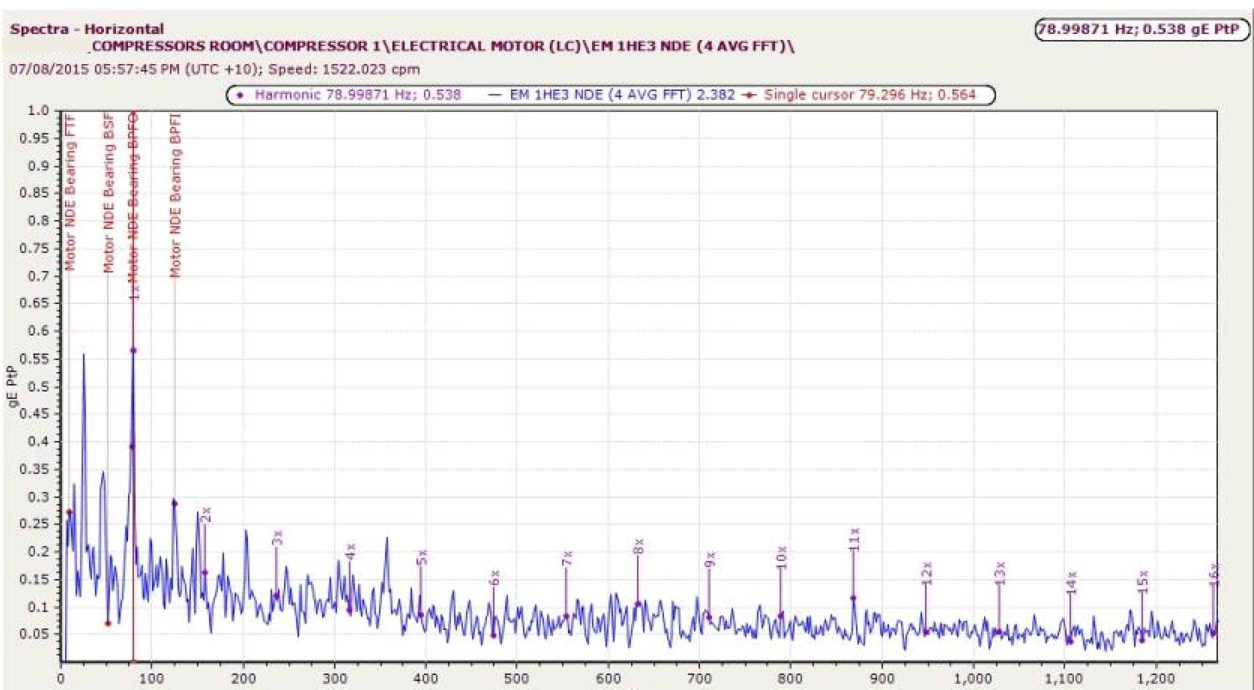


Figure 7 - Env 3 FFT, 4 Averages, 800 Lines

Measurement 2 – Envelope Filter 3 point measurement attributes
Fmax: 1260Hz
Lines: 3200
Averages: **OFF (data block size is 8192 samples)**
Low Freq cut-off = 0

The spectrum below (figure 8) shows a clear peak at 1X BPFO along with a few harmonics such as 2X and others, thanks to the higher spectrum line resolution.

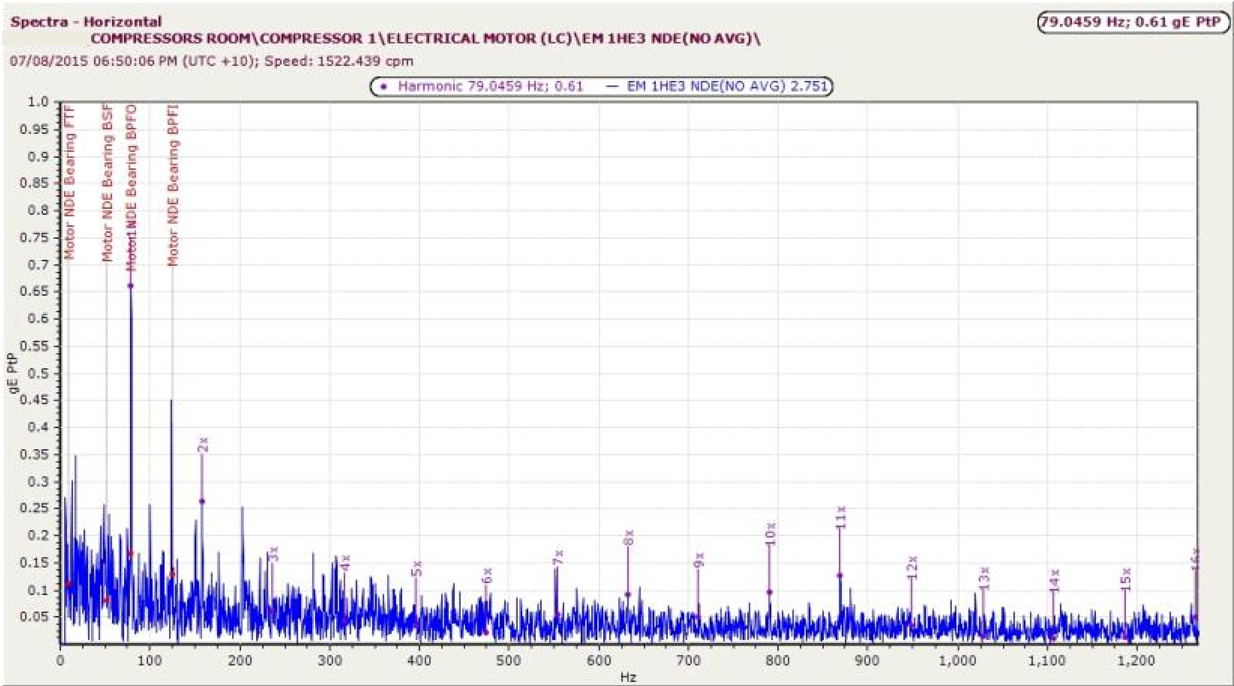


Figure 8 - Env 3 FFT, No Averages, 3200 Lines

4. Observation from a Mathematical and Historical Perspective

4.1. What does math say about this?

Let’s consider the white noise signal, since the same data block is used in computing the smaller, averaged spectrum and the larger, non-averaged spectrum is the same. The total energy, or the RMS overall value, should be the same for the two spectra. For the purpose of discussion, assume the ratio of spectral line is R, then for each spectral bin of the averaged spectrum, there should be R bins for the non- averaged, larger spectrum for the same frequency range. Hence the following should hold true:

$$\sqrt{A^2} = \sqrt{\sum_{i=1}^{R} B_i^2} \qquad (1)$$

Where A is the line amplitude of the averaged spectrum and B_i is the line amplitude of the larger, non-averaged spectrum. Let B to be the averaged line amplitude of the non-averaged spectrum, the total summation of energy in the corresponding frequency band can be simplified as:

$$\sum_{i=1}^{R} B_i^2 = RB^2 \qquad (2)$$

Therefore, the following relationship exists:

$$A = \sqrt{A^2} = \sqrt{\sum_{i=1}^{R} B_i^2} = \sqrt{RB^2} = \sqrt{R} * \sqrt{B^2} = \sqrt{R} * B \qquad (3)$$

So we can say, from statistical view point, if the signal is a white noise, the mean of line amplitude of an averaged spectrum is a factor of $\sqrt{R}$ higher than the mean of line amplitude of larger, non-averaged spectrum computed from the same data block, if the ratio of spectral line is R. This conclusion is confirmed by table 1, first column.

Note that the discussion above in this section only applies to random noise signal. For discrete, sinusoidal or repetitive impact signal, averaging or non-averaging have no effect on the line amplitude of the signal. Now it is clear why larger, non-averaged spectrum results in a better signal to noise ratio than spectrum with averaging.

4.2. Historical reason for spectrum averaging

Vibration data collection/analyzing started to emerge in the 1970's. The limited resources available to the onboard microprocessor, i.e. memory space, and processing power, forced the engineers to use a smaller FFT block size. Spectrum averaging was recognized as an effective technique to increase signal to noise ratio which resulted in a better spectral presentation for vibration data. Modern day microprocessors used in vibration data collectors are much more powerful and memory space limitation is a thing of the past. A much larger size FFT can be computed very easily. So using more spectrum lines to increase signal to noise level is a preferred method. However, without knowing this background information, there is still a belief in the machine vibration analysis community that spectrum averaging is the way to go.

4.3. Windowing effect and spectrum line resolution perspective

It is quite obvious that an N average spectrum has 1/N of line resolution compared to a spectrum computed with the same data block without averaging. An immediate benefit is better frequency identification in the larger, non-averaged spectrum. Any vibration analyst can relate to that when needing to identify a bearing defect frequency in a spectrum. In addition, the use of a window function, typically a Hanning window, will cause a signal to have a skirt which will overshadow a line above and below with half of its amplitude. So if the signal source has a strong and weak sinusoidal signal with frequencies close to each other, the larger, non- averaged spectrum will have a better chance to separate the two signals in the spectrum.

4.4. Variable speed vs constant speed machines

Using the higher number of lines for the noise reduction, the better view of the data is only possible if the machine has a constant speed during the collection of the data. However, for very long measurement times, the data of the peak of the vibration can be smeared if the speed of machine varies.

Therefore it is advised that data collected with very long measurement times on a variable speed machine should use order tracking (not only for the noise reduction purpose). Note that in this particular case with a variable speed machine, the smaller the data block produced less smearing in the spectrum. So a 400 line spectrum with a 50% overlap and 7 averages, if order tracking is not used, will have the same amount of smearing as the 1600 line non-averaged spectrum, while a 400 line spectrum without averaging will probably have less smearing than both a 400 line, a 7 averaged spectrum and a 1600 line non-averaged spectrum, but the noise ceiling will be higher.

5. Conclusions

The simulation investigation as well as field vibration data from a motor driving compressor illustrated that higher line resolution is a more effective technique than spectral averaging in reducing spectrum noise ceiling and increasing signal to noise ratio. The result is a better defect signal identification in a noisy spectrum. More specifically, the following conclusions/observations were made:

1. For discrete deterministic signals, averaging or increased spectrum lines have no effect on the spectral amplitude of the signals.
2. Spectrum averaging does not reduce the median level of the spectrum noise ceiling while more spectrum lines result in a significant reduction of the median level of the spectrum noise ceiling.
3. Both spectrum averaging and increased spectrum lines can reduce the standard deviation, or degree of spreading of line amplitudes around the median level of the spectrum noise ceiling. Averaging process tends to have a slightly better performance and produces smaller standard deviation. This is the reason why averaging process gives a smoother spectrum than more spectral lines.
4. If the size of the time domain data block used in spectral averaging is the same as when no averaging is used, but with more spectrum lines, the reduction of spectrum noise ceiling can be as much as over 40% with 6400 lines in a non- averaged spectrum.

All of the above factors acting together makes using more spectrum lines a better choice if reduced spectrum noise ceiling is needed On the other hand, if a smoother spectrum is desired, spectrum average is a better choice. This is the choice one makes on the basis of preference, the data producing the spectrum is still the same.

The final remark on the business of average is that for enveloping measurement, since the overall value is the true peak to peak from time domain, average is not a good choice. This is because the severity of defect is better reflected by the worst impact incident during the measurement period. Average hides the actual severity by averaging out the worst impact event. Someone may argue that without average, there is more variation in the overall trending. However, the variation could actually indicate whether or not the defect is rapidly expanding. More variation could be caused by the edge of defect being smoothed and sharpened from impact to impact.