Understanding and Measuring Noise Sources in Vibration Isolation Systems

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Abstract:

TMC is a manufacturer of precision vibration isolation systems which are used to support a wide range of vibration sensitive equipment in both commercial and academic research environments. Though many people know that vibrational noise is a problem, few understand how it is measured and quantified. This is particularly true with *random* sources of vibration. Because of this, noise often is measured improperly. This can lead to incorrect or ambiguous 'floor vibration requirements' for commercial tools, misleading or inaccurate site surveys, and ultimately incorrect conclusions about system susceptibility and performance. This paper briefly introduces the key concepts in noise measurement, and how to interpret the results.

Introduction:

To measure vibrational noise (we will use simply *noise* here), three tools are typically used. These are a vibration sensor (*sensor*) which is usually a 'seismic grade' accelerometer[1], a storage oscilloscope (*scope*), and a two-channel spectrum analyzer with sub-Hertz capability (*analyzer*). The scope can be used to look at signal from the sensor in the *time domain,* and the analyzer can perform a *Fourier Analysis* on the sensor's signal to give a *frequency domain* picture of the same data.

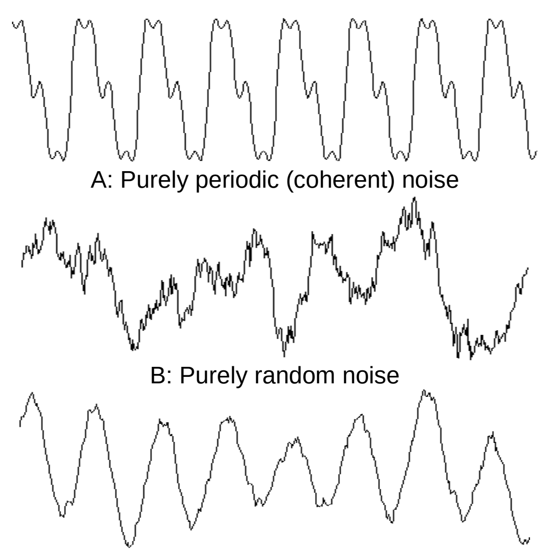
Sounds simple, but is it? A scope can tell you the peak level of noise, but it can't give you the 'frequency of the noise' or the RMS (Root-Mean-Squared) value of the noise. What is the meaning of a 'peak' value? Is it a sensible question to ask what the 'frequency' of noise is? What is the meaning of an RMS value? It turns out that it is *not* proper in most cases to ask what the 'frequency of noise' is, and an RMS value is meaningless without also specifying a frequency range over which it is calculated.

Likewise, an analyzer can calculate either an *amplitude spectrum* or an *amplitude spectral density.* One has the units of Volts and the other units of V/√Hz ("Volts per root Hertz"). Which should you use? Most analyzers default to the *amplitude spectrum*, which is the *incorrect* thing to use to characterize most noise sources. Not knowing better, most users end up taking meaningless data because the analyzer settings are incorrect.

To understand how to use these tools, it is important first to understand what you are trying to measure: *noise.* Noise can be characterized as either *random* or *coherent*[2]. As the next section shows, these can be further sub-classified as either *stationary* or *non-stationary.* These are *fundamentally* different sources of noise, and must be analyzed using different methods. It is up to you (the person doing the measurement or survey) to determine what type of noise you have, and to measure it appropriately.

Types of Noise - Random vs. Coherent:

Figure 1 shows several examples of what different types of noise might look like on a scope. These examples were chosen so that the different types are easily identified



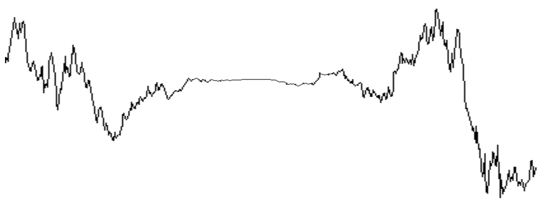
A: Purely periodic (coherent) noise

B: Purely random noise

C: Periodic and random noise together

D: Non-stationary periodic noise

E: Random plus non-stationary periodic noise



F: Non-stationary random noise.

Figure 1

Curves 1A and 1B represent what most people would recognize as noise – however they are also the least likely to be observed in the real world. Curve 1C represents the most common type of noise: a combination of A and B. In this case, the coherent noise source (periodic noise) dominates over the random component (for ease of illustration); however it is also very common to have random noise dominating. Most often an analyzer is required to 'see' the coherent noise components in a signal, as they are not generally evident from a scope trace.

In the real world, noise is almost never constant in amplitude, but changes with time. Such noise is called *non-stationary.* Curve 1D shows a periodic source being randomly turned on and off. Curve 1E shows what you might see in a building with an air compressor or HVAC system cycling on and off: there is a background of random noise, with a periodic component that comes and goes. Non-stationary does not always mean 'on' and 'off'', but can mean that noise gradually builds or wanes. Curve 1F shows non-stationary random noise. You might see noise like this holding a microphone near a highway, or in seismic noise data as a storm comes and goes.[3]

Measuring Noise:

Scopes are useful to get a quick indication of which type of noise dominates your measurement, and to determine the peak level of noise (something analyzers do *not* provide). These, however, are of limited use, and by far the most important tool for quantifying noise is the spectrum analyzer. Unfortunately, this is where things get tricky.

Stationary coherent noise sources are the simplest to measure and understand. In the case of Figure 1A, the signal is made up of a pure sine wave, plus some higher harmonics ($2f_o$, $3f_o$, $4f_o$ and so on). Each component of the signal has a definite frequency and amplitude. A spectrum analyzer can digitize this signal, perform a Fast Fourier Transform (FFT) on the digitized data, and give you an ***amplitude spectrum*** which plots the amplitude of the components (in volts or microns) vs frequency. This can be plotted, or the height and frequency of each peak simply tabulated. *Even in the presence of random noise, this is the correct method for measuring the strength of coherent noise sources.*

Random noise is fundamentally different, and requires an alternate approach. This is because, for random noise, there is no longer a certain level or amplitude of signal "at" a given frequency. In fact, the is *no noise* "at" any *single* frequency at all! Instead, random noise must be thought of in terms of *density.*

Consider a volume of air (say the room you are sitting in). There are clearly a lot of air molecules in the room, but there are no molecules of air *at any single point.* To define a number of air molecules, you have to define two things: the *density* of the air, and a *finite volume of air.* If you have no volume, you also have no air. It is perfectly legitimate to talk about the *average density* of air at a single point, and that density can even differ from point to point (for example, the air is slightly denser at your feet than at your head). The same is true with random noise.

For random noise, the equivalent density is called the ***amplitude spectral density*** (ASD) at a given frequency, and the equivalent volume is the ***frequency bandwidth***. The RMS level of the signal is analogous to the number of air molecules, which in the context of this paper is the RMS ground motion. The RMS amplitude is given by:

$$rms \;\; motion = \sqrt{\int_{f1}^{f2} \left[ASD(f) \frac{\mu m}{\sqrt{Hz}} \right]^2 df}$$

where the amplitude spectral density ASD(f) is a function of frequency, and has units[4] of microns/√Hz. The form of the integral makes it clear why the ASD is expressed "per-root-Hertz": this cancels the units of df, and gives the RMS result in the proper units (microns). An analyzer displays the ASD(f) when 1/√Hz or "per-root-Hz" units are selected.

Just as the number of air molecules is defined only for a fixed volume, the RMS motion is defined *only for a fixed frequency range,* in this case, from $f1$ to $f2$. It is very common to use the **1/3 octave plot** to express RMS motions. In these, the frequency spectrum is broken up into 1/3 octave[5] bins (from 1 to 1.23Hz, 1.23 to 1.59Hz, 1.59 to 2.0Hz and so on). This integral is performed over each of these frequency ranges, and the resulting RMS values (now in microns) are plotted as a bar graph vs. frequency. Many analyzers will do this as a built-in function. To calculate the RMS motion over a larger span in frequency, just take the quadrature sum[6] of all the bins in that range.

In a spectrum analyzer, *you must select amplitude spectral density units of [Volts or units]*/√Hz *for the vertical scale*[4]*.* Otherwise, you will not measure random noise properly. Likewise, if the analyzer is set up to measure a spectral density, it will not measure the correct amplitude for coherent noise sources (in either ASD or 1/3 octave formats). The analyzer must be told whether it is to measure an amplitude or a density.

What the Analyzer Does:

To further illustrate how random and coherent noise sources behave differently, consider the following figure:

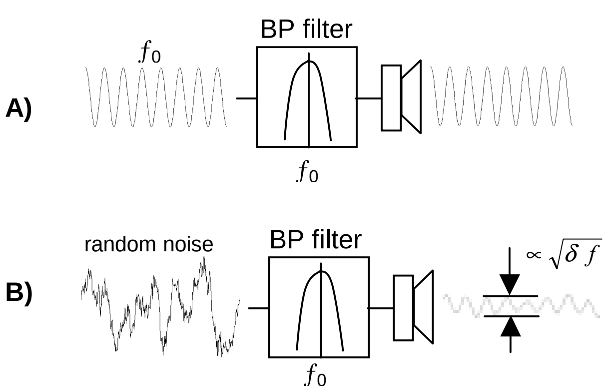


Figure 2

A simple band-pass filter centered on f_0 with a width δf is connected to a speaker. The filter has a band-pass (peak) gain of 1. In Figure 2A, a sine wave of frequency f_0 is applied to the input. The output of the speaker is the full amplitude of the input, *independent of the width of the filter* δf. This is because the filter only eliminates components of the input away from f_0 (and there are none). By contrast, Figure 2B shows that the effect on random noise is dramatic. The filter removes energy above the frequency $f_0 + ½\ \delta f$ and below $f_0 – ½\ \delta f$, leaving a signal which sounds closer and closer to a pure tone at f_0 as the width of the filter δf gets narrower. More importantly, as the filter becomes narrower, and it blocks more energy, *the amplitude of the output drops proportional to* $\sqrt{\delta f}$.

A spectrum analyzer is basically identical to a series of band-pass filters like that shown in Fig. 2, except instead of speakers, it measures the amplitude of the filter output(s), and displays those numerical results in graphical form. It can be shown that the width δf of the filters in Hz is approximately 1/T, where T is the duration of the analyzer's measurement in seconds. FFT analyzers space the 'filters' δf apart, which gives complete coverage of the frequency spectrum. For example, a 10 second measurement would give a 0.1Hz frequency resolution (filter widths), resulting in 100 data points between 1 and 10 Hz (for example).

Figure 2 illustrates what an analyzer setup to measure an *amplitude spectrum* would see: each filter faithfully passes the amplitude of any coherent noise at the filter's center frequency. The output amplitudes are measured, and plotted by the analyzer. The measurement time T changes the filter widths δf, but this does not affect the result (as in Figure 2A).

It is immediately evident from this discussion that the filters of Fig. 2 produce a nonsensical result for random noise: the amplitude of the noise spectrum would change as you change the measurement time T! The longer the measurement, the less noise you would appear to see. Clearly, the level of random noise is not a function of how long you choose to look at it. To correct for this effect, *when the analyzer is set to measure an* *__amplitude spectral density__,* it multiplies[7] the filter outputs by √T. Since T has units of 1/Hz, the resulting plot has units of Volts (or microns) *per-root-Hertz*. As you change the measurement time T, this factor corrects for the filter bandwidths, and presents a consistent spectral density level.

Conclusions:

Obviously, a factor of √T can be significant, but more importantly, *amplitudes* and *amplitude densities* are as fundamentally different from each other as a number of air molecules is from a gas density. They are in no way comparable. A comprehensive site survey should consist of the following steps:

1) Configure the analyzer for a 1-100 Hertz[8] measurement of the amplitude spectrum. Locate all sharp 'spikes' in the spectrum, and tabulate their frequencies and heights. These will correspond to single-frequency noise sources (building fans, compressors, transformer hum, etc.). Associate the peaks with specific noise sources whenever possible (by turning off the possible sources, and seeing which spikes change or disappear).

2) Change the vertical units to <units>/√Hz. Many analyzers will convert the amplitude spectrum to an ASD spectrum without recollecting data. Plot the results. Note that the height of the spikes from step 1) have changed their value. It is convenient to label the spikes on the ASD plot with their (Volt or micron) values you measured in 1). The 'background' noise floor around the spikes accurately reflects the noise density for random noise sources (people walking, seismic and wind noise). Now you have a single (annotated) plot which accurately represents the noise in your environment.

3) If your analyzer will calculate 1/3 octave plots from the ASD, this is a nice *additional* plot to have. Notice that the 1/3 octave 'bins' at the spike frequencies may look like 'spike bins'. You should note the values measured in step 1) on these bins, if you are confident the noise at those frequencies is dominated by coherent noise sources. Otherwise, the RMS values for those bins will be incorrect by a factor of √T.

4) Make note of any noise sources which might be non-stationary. Most of these sources will be coherent noise sources: compressors, fans, HVAC systems. Since the 'worst case' condition is usually of greatest interest, care should be taken to make the noise measurement when all noise sources are present. Random noise can change with the weather (literally), local road traffic, etc. It typically varies over longer time periods (hours to days) so thought should be given to conditions which might influence ASD measurements.

It is the responsibility of the person making the measurements to determine what types of noise sources are present, and to collect the appropriate data. Even following the simple steps above can be complicated by non-stationary sources. With the proper awareness, and by taking careful notes about possible noise sources, there will be much less confusion about what vibrational noise issues exist in your environment.

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[1] Any accelerometer with a sensitivity of 10 V/g or greater, such as the Wilcoxon 731A or PCB 393B12/31.

[2] There are also pnseudo-random noise sources, like a periodic source which is randomly turned on and off. These are beyond the scope of this paper.

[3] Wind and coastal waves are major contributors to seismic noise.

[4] Analyzers can be configured to convert your sensor's output (in Volts) to an 'engineering unit' like microns or 'g's. *Power Spectrums* can also be used to measure noise, but these have units of *[Volts or units]*^{2}/Hz

[5] An octave is a factor of 2 in frequency. 1/3 of an octave is a factor of 1.23.

[6] A "quadrature sum" is the square-root of the sum of the squares.

[7] Other correction factors apply due to *windowing* of the data (Hanning, Brickman, Flat Top, etc.). A discussion of windowing is beyond the context of this paper. See Hewlett Packard Application Note 243: "The Fundamentals of Signal Analysis".

[8] Common sensors (footnote 1) are poor at measuring noise below 1Hz, and noise above 100Hz is usually acoustic in origin – not seismic.