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Vibration Data Representation for Advanced Technology Facilities

Hal Amick

Colin Gordon & Associates
San Mateo, California 94402

ABSTRACT

Vibration control in vibration-sensitive advanced technology facilities generally involves interaction between a vibration consultant and several other engineering disciplines. It is important that the other disciplines have a rudimentary understanding of the consultant's measurement methodologies and design approaches. Practitioners have developed a specialized analytical approach which shares some commonality with traditional civil engineering dynamics, but which also borrows techniques that evolved in other disciplines such as mechanical engineering, signal detection, and acoustics. Practitioners also use several forms of spectral representations of the low-vibration environment, but the spectrum form most familiar to civil engineers—the response spectrum—is not used. This paper presents some of the relevant fundamentals of signal processing and the manner in which they are applied to civil and structural engineering aspects of these projects.

INTRODUCTION

Vibration control engineering of vibration-sensitive advanced technology facilities (ATFs) generally involves some combination of measurement and analysis, for which data representation must be consistent:

1. "greenfield" site assessment,
2. design of structural and mechanical systems, including vibration isolation, and
3. measurements in operating facilities to verify compliance with facility or equipment requirements.

The differences between the data representation used in these applications and those used for "typical" civil engineering dynamics applications (such as seismic analysis or construction vibration assessment) often leads to confusion within a design team. In some cases, generic-sounding terminology may be associated with concepts different from those associated with civil applications.

A very fundamental difference between civil structural dynamics and ATF dynamic analysis lies with the reason for the analysis. With an ATF, we are generally concerned with avoiding the disruption of sensitive processes; the civil dynamicist is generally concerned in some way with structural integrity. In other terms, the ATF dynamicist is concerned with defining and quantifying a "mean" or "mean + σ" environment, where generally the civil dynamicist is generally concerned with "maxima."

The purpose of this paper is to present some of the relevant fundamentals of signal processing and the manner in which they are applied to civil and structural engineering aspects of ATFs. As an increasing number of civil engineers become involved with the design of these facilities, it is important that they become conversant in the analytical approaches used for them.

NATURE OF FACILITY VIBRATIONS

The vibration environment in an ATF is a more-or-less steady-state mixture of many single-frequency sinusoidal vibrations at a variety of frequencies superimposed upon random vibration and repeated-impact vibration.

In a well-designed and constructed ATF, the predominant vibrations are random, generated by interior sources such as flow-induced turbulence in large piping and ducting as well as exterior environmental sources such as traffic. The single-frequency sinusoidal vibrations are due to imbalance forces in rotating equipment. If all has gone well with equipment selection, balancing, installation, and vibration isolation, the amplitude of these vibrations will be quite small. The repeated-impact vibrations are generated by personnel activities—primarily footfall. In the most conservatively-designed ATFs—semiconductor facilities—footfall vibrations are of little significance because other factors usually govern. However, in less conservatively-designed facilities, such as biotechnology and pharmaceutical laboratories, footfall vibrations may govern a floor's design.

Any discussion of vibration criteria or vibration analysis must be clear on three aspects: (1) the analytical domain being used for data representation (time domain *vs.* frequency domain); (2) the metric being used (displacement *vs.* velocity *vs.* acceleration); and (3) the statistical form, generally a choice between instantaneous and energy-averaged amplitude. Most communications problems between civil dynamicists and ATF dynamicists (and some of those between ATF dynamicists themselves) arise because one or more of these aspects is inadequately defined or understood.

TIME *VS.* FREQUENCY DOMAIN

Vibration displacement, velocity or acceleration can be stated in either time or frequency domain. Time domain data are representations of physical motion, wherein motion is quantified as a set of amplitudes as a function of time. Frequency domain data may be defined in a similar manner, except as a set of amplitudes as a function of frequency. It is common to refer to time domain data as a "time history" and frequency data as a "spectrum."

In the time domain, one can work with either instantaneous amplitude or an average such as root-mean-square (rms). Use of instantaneous amplitude requires consideration of the algebraic sign of the amplitude with respect to the "at-rest" position. The severity of instantaneous amplitude can be characterized by a maximum value over some period of time, either as 0-to-peak (the maximum absolute value) or peak-to-peak (the absolute sum of positive and negative peak amplitudes).

In frequency-domain analysis, time-domain data are transformed in some manner to spectra. Practitioners use several forms of spectral representations of the low-vibration environment, some based upon Fourier transform (FFT) spectra and others based on digitally filtered signals, but response spectra are rarely used (if ever).

Spectra are defined by their frequency bandwidth and, in the context of vibration-sensitive facilities, are most commonly stated as (1) constant bandwidth (*a.k.a.* narrowband), (2) one-third-octave (*a.k.a.* proportional or percentage) bandwidth, or (3) spectral density. When working with measured vibrations, constant bandwidth and density spectra are typically obtained using FFT analysis, and one-third-octave band spectra are obtained by using either parallel filtering or a synthesis based on FFT analysis. All have evolved from the digital signal processing requirements of acoustics, physics, electrical engineering, and mechanical engineering. There is a large body of literature associated with spectral analysis of random and tonal vibrations.

TYPES OF DATA SIGNALS

Measured vibration data are commonly acquired as analog time history signals produced by acceleration or velocity transducers such as accelerometers or seismometers, respectively. From a data analysis viewpoint, Bendat and Piersol divide time history signals into two broad categories, each with two subcategories, as follows:

1. *Deterministic* data signals: (a) steady-state signals; (b) transient signals.
2. *Random* data signals: (a) stationary signals; (b) nonstationary signals.

Deterministic Data: Deterministic data signals are those for which one can, in theory, predict future time history values of the signal (within reasonable error) based upon a knowledge of the applicable physics or past observations of the signal. A periodic signal is one that repeats itself after a constant time interval. The time history of the vibrations generated by one rotary mechanical system can take the form of either a single frequency (a pure tone) corresponding to the shaft rotation rate or that of a series of harmonics, the frequencies of which are integer multiples of the shaft rate. In the presence of a collection of independent (unsynchronized) periodic sources (such as the mechanical plant in a "fab"—a microelectronics fabrication facility), the collective time history may not be rigorously periodic—in this case it is referred to as "almost periodic." "Transient" deterministic data signals are those that begin and end within a reasonable measurement time interval; these can include those from equipment startup and some types of well-controlled impacts.

Random Data: Random vibrations are broadly defined as those that are <u>not</u> deterministic, that is, where it is not theoretically feasible to predict future time history values based upon a knowledge of the applicable physics or past observations. In the time domain the amplitude—including the <u>peak</u> amplitude—is random. There is no periodicity.

INSTANTANEOUS *VS.* TIME AVERAGED REPRESENTATION

It is often convenient to represent an oscillating signal in a form that does not involve positive and negative amplitude. One cannot generally use a time-varying average, as commonly defined, because in many cases the average of an oscillating signal is zero. We use the average energy, or root-mean-square (rms), since it is based upon the *square* of the amplitude, which is always positive. Generally, this process is carried out electronically by an analyzer of some sort.

For most purposes, a sinusoid can be completely characterized by its amplitude and its frequency. Unfortunately, the situation regarding non-deterministic vibrations is not as straightforward. Random motion is typically characterized by an <u>average</u> amplitude, the most common of which is the rms value discussed above. In addition, there is no frequency directly associated with random vibration and a spectrum must be used to define the frequency content.

If the average properties of the signals are time invariant, such random data are said to be "stationary." If the average properties of random signals vary with time, the signals are said to be "nonstationary." (An example of nonstationary random ground vibrations would be those associated with the passage of a train.) The property of *ergodicity* dictates that for stationary vibrations the energy average (rms) amplitudes will be repeatable. This repeatability of the average amplitude—as opposed to the nonrepeatability of the peak amplitude—is a major reason that random vibrations are characterized by averages. It is convenient that the same repeatability can be found with the average rms spectrum of a collection of stead-state sinusoids, so that rms spectra can be used to quantify a wide variety of environments..

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