MANAGEMENT UPDATE

SPECIFYING AND INTERPRETING A SITE VIBRATION EVALUATION

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Many pieces of semiconductor production and test equipment are highly sensitive to vibration. Equipment manufacturers often provide environmental vibration limits and recommend, even require, a site vibration evaluation prior to installation of a system. Suppose a company is planning to install one of these systems. What does the manufacturer's vibration specification really mean? What should a vibration consultant do for the company in the site evaluation? How does the company make maximum use of the consultant's report?

Acoustics, the parent discipline of vibration engineering, has its own language, as does any applied science. Unfortunately, many vibration specialists fail to realize that their jargon—precise and well-defined within the acoustics community—creates confusion for those who must specify their services or read their reports. This article will discuss how a vibration survey may be specified and interpreted. Since we are discussing specifications, precise jargon will occasionally be necessary, with explanations of the jargon included when needed.

BASICS OF VIBRATION

Units of Vibration. Vibration severity is expressed in terms of amplitude. Vibration amplitude, in turn, may be discussed in terms of acceleration (a), velocity (v), or displacement (d) amplitudes. These amplitudes, at a frequency (f), are related by the following equation:

$$a = 2\pi f v = (2\pi f)^2 d$$

In general, the choice of velocity, displacement, or acceleration is largely one of convenience. Acceleration amplitudes are usually stated as a multiple or fraction of gravitational acceleration (9.8 m/sec^2)—denoted g—but occasionally in terms of Gal (cm/sec^2) or conventional engineering units. Displacement and velocity amplitudes are generally stated in easily recognized English or metric engineering units.

Figure 1 illustrates several ways that sinusoidal vibration amplitude is commonly stated: peak-to-peak (p–p), zero-to-peak (peak), and root-mean-square (rms). The rms amplitude represents the average energy of the vibration over a fixed period of time.

Measurement of Vibrations. The most common vibration sensor is the accelerometer, although velocity sensors are also available. The signal from an accelerometer can be electronically integrated to convert it to a displacement or velocity signal. As with sound, commonly occurring vibration amplitudes cover a wide dynamic range, from 0.00001 in./sec to more than 0.100 in./sec rms. As acousticians did with sound, vibration engineers

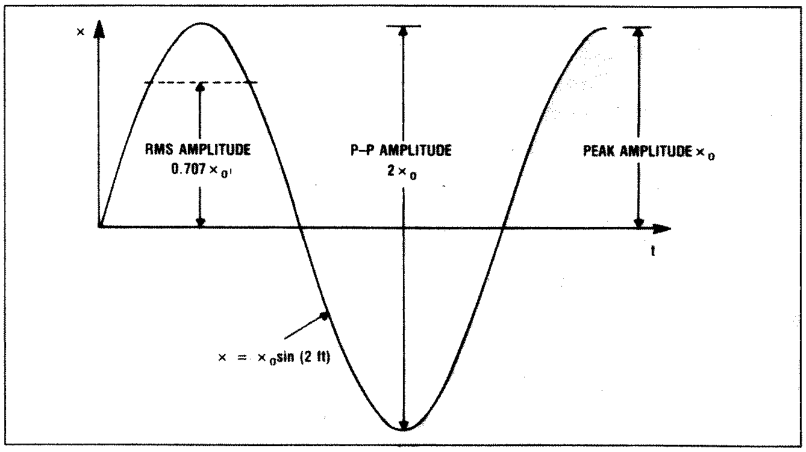


Figure 1: Common ways of stating simple sinusoidal vibration amplitude.

have found it convenient to make this dynamic range more manageable by using a logarithmic scale of measurement called the decibel (dB). The vibration unit is defined as:

$$\text{Vibration level in dB} = 20 \log_{10} \left(\frac{\text{measured amplitude}}{\text{reference amplitude}} \right)$$

Unlike the sound decibel, the reference amplitude for the vibration decibel is not standardized, so one may see decibels with reference to 1 g, 1 mg, 1 μg, 1 μm, 1 μin./sec, and so forth. Negative decibels mean that the measured amplitude is less than the reference amplitude (thus, the ratio in the above equation is less than 1).

A graph or spectrum can be produced that shows the frequency content of vibrations. Amplitude is shown on the vertical axis and frequency on the horizontal axis. Spectra can be produced using several types of analog or digital electronic equipment.

Spectra may be specified and measured with many different widths and progressions of frequency bands. Spectra are commonly measured in bands of either constant width (a fixed number of hertz in each band) or in proportional bands, in which the bandwidth is proportional to frequency. Full octave and one-third octave bands are the most popular proportional bandwidths. Power spectrum density defines a spectrum in which the bandwidth is defined as 1 Hz.

Constant bandwidth or narrowband spectra are usually produced using fast Fourier transform (FFT) analysis; proportional band spectra may be created using either FFT-based methods or real-time analysis using filters.

Figure 2 shows measured one-third octave band vibration spectra in three orthogonal directions on the floor of a recently constructed Class 1 submicron facility with a basement. Figure 3 shows the same vertical data expressed as a narrowband spectrum. The individual spikes or pure tones are generated by rotating equipment. These tonal spikes show up less prominently in the one-third octave band spectrum. The latter spectrum gives greater weight to random (nontonal) vibrations, which is similar to the way in which sensitive equipment responds.

Equipment sensitivity to vibrations stems from internal resonances of the equipment. These resonances cause relative motion among the parts of the equipment structure. Vibrations at frequencies much lower than the lowest resonance frequency generally do not cause significant relative motions; at low frequencies the system is effectively rigid. Likewise, vibrations at high frequencies are less significant because internal isolation and damping within the structure are quite efficient at frequencies significantly above the fundamental. Our studies have shown that the frequency range of concern for most sensitive equipment lies between 8 and 100 Hz. Most pieces of sensitive equipment have their major internal resonance frequencies in the 15–40 Hz range.

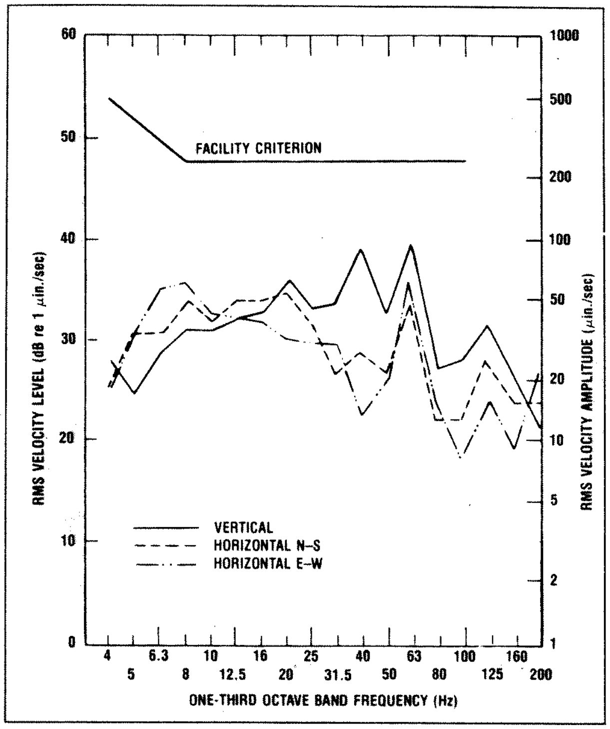


Figure 2: Representative floor vibration data measured in operating facility with basement.

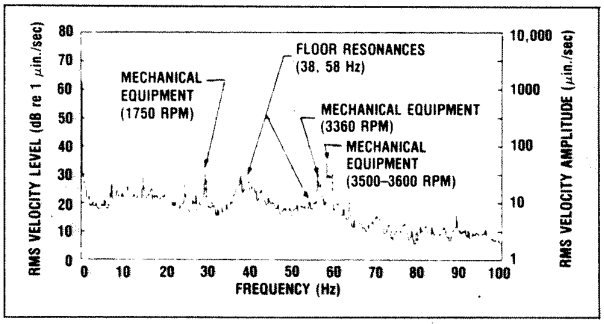


Figure 3: Representative vertical vibrations in bands of 0.375 Hz bandwidth.

GUIDELINES FOR GOOD EVALUATION PROGRAM

A good evaluation program can be viewed in three parts: the criterion, the measurements, and the report. When preparing for a vibration survey, a company should aim for completeness of these three ingredients. The criterion should be stated without ambiguity. The measurement program must provide results appropriate for comparison with the criterion and information necessary for diagnosing any problems of the study location. In addition to documenting the data, the report must be complete and clear enough that another vibration engineer can understand what measurements were taken.

Complete Criteria. A criterion defines the scope of the survey, so vagueness or ambiguity may lead to useless data. A fully stated equipment or facility criterion has the following minimum requirements:

- It should be stated in terms of a vibration amplitude with clearly defined units (displacement, velocity, or acceleration).
- It should state the measure of amplitude to be used (p–p, peak, or rms—see Figure 1).
- It should define the frequency range over which it applies. Both the amplitudes and frequency ranges should be realistic and not overly conservative.
- It should state the frequency bandwidth in which vibrations should be measured. Ideally, the measurement bandwidth should be related to the internal damping of the equipment and reflect how the equipment actually responds to random and tonal vibrations.
- It should state the measurement statistic that is to be used. Vibrations in a building or on a building site fluctuate with time. The vibration analyst must know whether the criterion applies to the maximum amplitudes measured over some period of time, to the energy average levels, or to some percentile of the statistical variation over time (such as the 10% level, i.e., the level that is exceeded for 10% of the sample time). It is generally inappropriate to use maxima since these are statistically unreliable measures.

As an example of the above requirements, the BBN criterion curves for vibration-sensitive equipment are shown in Figure 4. These criteria specify use of one-third octave bands, since this bandwidth corresponds approximately to the response bandwidth of a resonator having 10% damping. The criteria are stated in terms of rms velocity at frequencies between 4 and 100 Hz. The curves are generally applied at the energy average level, although in new or green field site studies they are generally applied at the 10% (L10) level. When used to assess a site prior to construction, values somewhat more stringent than the facility criterion are used to allow for contribution by sources within and around the proposed building when it is operational.

BBN CRITERION

A–PROBE TEST EQUIPMENT; 100× MICROSCOPES

B–500× MICROSCOPES; ALIGNERS, STEPPERS TO 5-μm GEOMETRIES

C–1000× MICROSCOPES; ALIGNERS, STEPPERS TO 1.5-μm GEOMETRIES

D–STEPPERS, E-BEAMS TO 0.3-μm GEOMETRIES; CD INSPECTION EQUIPMENT; MOST SEM TO 50,000×

E–ANTICIPATED TO BE ADEQUATE FOR FUTURE FABRICATION AND TEST EQUIPMENT FOR LOW SUBMICRON GEOMETRIES

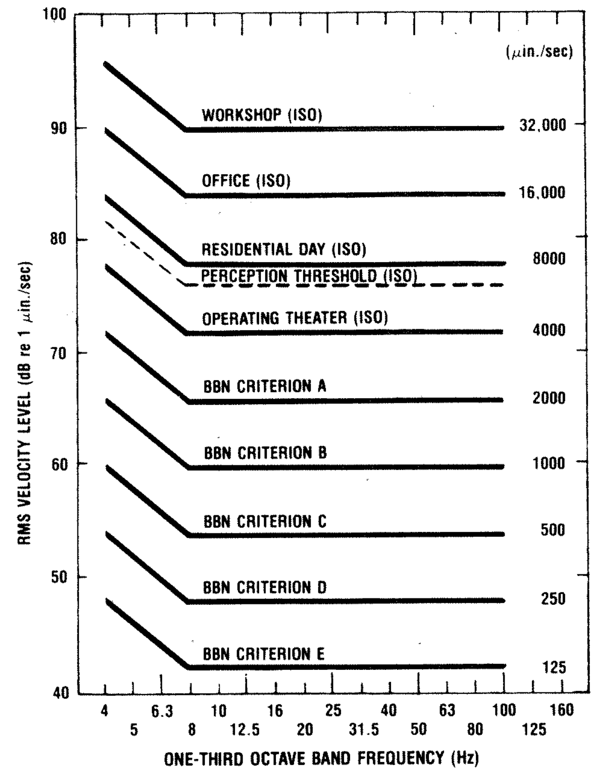


Figure 4: Floor vibration criterion for equipment used in production of ICs, including criteria recommended by International Standards Organization.

One should recognize the obvious flaws in a specification stated along the lines of: "The floor shall not have any vibrations." *There is no such condition.* Not many specifications are this vague, although many criteria, including some from equipment manufacturers, still neglect a few of the realities of vibration theory or field measurement. One should be aware of some of the following common but subtle shortcomings and resolve them before performing a survey:

- Failing to specify whether limits apply to p–p, to peak, or to rms amplitude.
- Failing to mention the measurement bandwidth that is required.
- Specifying a criterion amplitude at a single frequency without mention of other frequencies. (For example: "Vibration amplitude shall not exceed 1 μm p–p displacement at 10 Hz." What is unacceptable at 20 Hz?)
- Limiting vibrations, particularly displacements, at very low frequencies (<4 Hz). Few items of equipment experience relative internal movement at very low frequencies and this restriction may be unrealistically stringent; it is also difficult to measure low-amplitude vibrations in this range.
- Limiting vibrations at 0 Hz: this limit is meaningless because 0 Hz represents static conditions.
- Specifying vibration limits at *all* frequencies.

The least ambiguous criterion includes a spectrum graph to augment the verbal description. If the graph is shown with a logarithmic or proportional bandwidth frequency scale, the problem of a 0 Hz specification is eliminated.

Complete Measurement Program. Many aspects of the measure-

ment program itself are best left in the hands of an engineer experienced in measurements for sensitive equipment. A less-experienced engineer may need some guidance in order to ensure useful results.

The vibration sensor that is used *must* have a high enough sensitivity to produce a usable signal. Typically, accelerometer sensitivity in the range of 1 to 10 V/g is required. The sensor should be able to measure vibration amplitudes at least 10 dB below the criterion before reaching its noise floor.

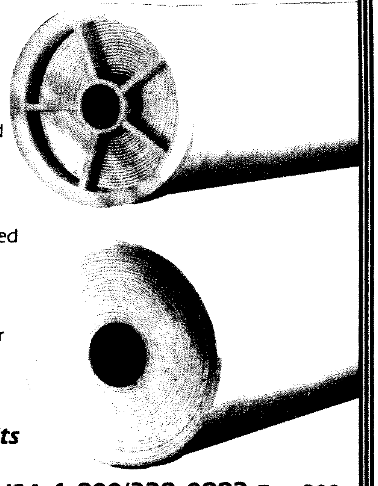
The vibrations should be measured at enough locations to adequately characterize the site over a period of time that is long enough to establish the statistical characteristics of amplitude variation with time. Reliable measurements of vibrations from steady-state mechanical sources can usually be made with samples lasting only a few minutes. However, a survey assessing vibrations due to such variables as traffic or construction should measure for at least 20–30 minutes per location. If conditions vary significantly through the day, several such periods should be evaluated.

The vibration signals may be analyzed as they are taken in real time or tape-recorded for later laboratory analysis. They should be analyzed to determine frequency content in a manner compatible with the criterion. If proportional bandwidth methods are used and the criterion is exceeded on a site that is influenced by such fixed mechanical sources as fans, pumps, and the like, the vibrations should be analyzed in narrow bands to identify the predominant frequencies of the offending sources. In many instances these sources may be identified by comparing the tonal frequencies with the shaft speeds of equipment, which can be measured accurately using a tachometer or stroboscope.

The site measurement period should be chosen to include whatever conditions will exist when the facility is operational, such as trains or heavy traffic, and to exclude conditions that may not exist during operation, such as construction on the site. The worst traffic vibrations may not occur at rush hour, particularly if the traffic is stop-and-go. The most severe vibrations often occur at off-peak hours when trucks, buses, or other heavy vehicles are able to travel at or over the speed limit.

Complete Data and Presentation. A comprehensive vibration report should provide complete documentation of the vibration environment at the time of the measurements. Someone familiar with vibration analysis should be able to read the report and know how the data were measured and processed *with little or no ambiguity.* The results should be compared with the criterion so that someone with a technical background but little knowledge of vibrations should be able to see how "good" or "bad" the vibrations are. The engineer should assess whether or not the vibrations meet the criterion. If troublesome sources are evident, the report should discuss the nature of the sources.

The report should provide a list of the equipment used in the survey, including manufacturer and model number. It should indicate the dates and times of the measurements as well as the names of the personnel involved in the measurements. If the measurements are done outdoors,



the report should describe the significant weather conditions. For example, wind can affect ground vibration measurements. If the measurements were made on the ground, the report should describe how the sensor was attached to the ground and any abnormalities of the ground surface.

The sample duration should be documented along with a brief description of how the signal was processed. It should include such things as whether data were tape-recorded or processed live, if FFT or real-time analysis was used, the statistics involved, and the band type and bandwidth employed.

The report should include some representative data, which might take the form of single, range-of-measurement, or upper-bound spectra. A company may request presentation of *all* data in its report, but this will probably increase the cost of the report. Analyzers usually do not produce report-ready spectrum graphs. The engineer will have to annotate any spectra used in the report. This will take up more of his time and cost more.

Each spectrum in the report should have annotation defining the frequency axis in hertz and the amplitude axis in the appropriate engineering measurement units. The amplitude must be shown using a logarithmic axis, either in engineering units labeled in powers of 10, or decibels labeled in increments of 5 or 10 decibels. If decibels are used, the reference amplitude should be given, either on the graphs or in the text.

Finally, some thought should be given to what the company actually wants from the report. The cost of a vibration study might be reduced by providing only enough data to address the immediate problems. However, the inexpensive report may be useless when addressing long-term needs. From our experience, a vibration report can be used more than once; therefore, it should provide enough data to be useful more than once.

CONCLUSION

A vibration study can be a valuable investment. With careful communication of requirements and results among equipment manufacturers, facility management, and the vibration engineer, the study's report can provide great insights into the quality of a facility's environment.

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