Maturation of the Vibration Environment in Advanced Technology Facilities

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Abstract

Semiconductor production and other advanced technology facilities are often designed in two states, the "base-build" state and the "hook-up" state. The base-build state, which after completion is termed "as-built" by the International Organization for Standardization (ISO)[1], includes the design and construction of the shell structure and all architectural, mechanical, electrical, and process systems needed for building operation. The hook-up state includes the installation of the production tools and their local support equipment (dry pumps, piping attachments, etc.). During the project design, cleanroom environment vibration and noise requirements are often assigned for compliance in the as-built state only (before tool hook up), since often a different design team or construction team or both is involved in the hook-up state and the base-build design team has little control of operational vibration and noise levels. This paper discusses typical changes, or maturation, in the production vibration environment after the as-built state. In these mature states, identified by ISO as "at rest" and "operational," there is usually an increase in environmental vibration and noise levels with the addition of tools and tool support equipment. This paper also discusses the role of maturation in building mechanical equipment as well as the means of controlling the increase in vibration.

KEYWORDS

Vibration, semiconductor, nanotechnology, facilities design and maintenance, maturation

INTRODUCTION AND DEFINITIONS

This paper discusses vibration conditions at the later stages in the operation of wafer fabrication facilities (or fabs). The general concepts apply to many types of advanced technology facilities, such as those used for nanotechnology, biotechnology, health care, physics research, etc.

In this paper, the term "mature" generally refers to facilities that have been in operation for several years. The term also identifies a state that represents an advanced age in the life of a research or production facility well after the building design team has turned the facility over to its users and permanent facility maintenance administration. This paper extends the process or concept of maturation from the completed "base-build" state, termed "as-built" by the International Organization for Standardization (ISO),[1] through the usable life of the facility. It is sometimes difficult to ascertain the as0built state because the construction of many facilities involves the start of tool installation before completion of the installation and balance of the base-build systems, such that the as-built state as strictly defined by ISO does not actually occur. It is immediately after this as-built state when the owners of the facility begin to modify the as-built environment with the addition of research, process tools, and support equipment (local dry pumps, chillers, power conditioning systems, etc.), that important and poorly-documented changes begin to occur in the vibration environment.

The as-built state is relatively early in the life of a facility, but in practice it is in this state that most vibration design criteria are applied to structures. Traditionally, this is because the design and operating teams may consist of different people or companies. The design team may have little control over the installation of equipment after they have completed and started the base building. From the standpoint of the design team, it is not practical to design the facility to resist any arbitrary mechanical load placed on it after start up of the facility, and more importantly, to monitor the installation process to verify compliance with requirements defined before the structure was in operation.

From a facility user standpoint, compliance with research and process equipment manufacturer vibration specifications is required in the as-built state as well as in the mature facility, since this is the environment in which the equipment will operate. The users will be largely responsible for maintenance base-building mechanical equipment and the addition of new building and research equipment that can affect the mature operating environment of the facility.

The coordination of processes and research equipment installation concepts during the design stage may be established to reduce the impact from changes that can occur in the mature facility. This coordination should include establishing general lab layout concepts, hook-up piping and support equipment isolation schemes, principles for selecting low vibration equipment, etc. It may be possible at this stage to identify exclusion zones for certain classes or power ratings for mechanical equipment to minimize impact.

The importance of base-building maintenance should also be emphasized. From a mechanical standpoint, establishment of dynamic balance requirements for mechanical equipment and vibration isolation for equipment and piping are typically necessary to meet the as-built vibration performance requirements. Out-of-balance forces may increase over time and vibration isolation may become partially or completely nonfunctional, especially with the use of poor quality isolators. These conditions may increase the vibration impact to the process areas. The use of vibration isolation hardware is generally a compromise solution for those cases where cost, thermodynamic, and other energy losses preclude separating the vibration source from the sensitive area. This compromise is detrimental from a vibration standpoint due to the increased maintenance implications of the use of isolation hardware. From a structural standpoint, end users must have an understanding of special vibration design features, such as structural isolation breaks and dynamic loading requirements, so these features are not accidentally compromised in later installations and retrofits.

CHARACTERIZING THE AS-BUILT STATE

In the as-built state, the structure of the building is complete and its mechanical equipment is operating. In this state, the relatively stiff floors that support sensitive processes or research should be performing in compliance with their as-built vibration design criteria. The vibration spectrum in this case tends to be essentially broadband in character (relatively synonymous with random vibration) due to the presence of turbulent sources such as fluid flow in piping and ductwork.[2,3] For suspended floors in particular, this broadband vibration tends to be highest at frequencies corresponding to modal frequencies in the composite and individual structural elements (floor membranes, columns, floor ribs, etc.).[3-5] Overlaid on this broadband spectrum may be some tonal (single-frequency) vibration components associated with rotating mechanical and electrical equipment.

The vibration environment may be characterized at the location of a tool using vibration data measured only at that location (or multiple locations within the footprint of that tool); however, the vibration environment may vary significantly over the extent of a large, vibration-sensitive space. The primary reasons behind this variation are the spatial relationships between sources and measurement locations, and the position of each measurement location within a bay. Generally, there may be a difference in spectral content from the middle of a bay to one of the supporting columns because of the relative location within the modeshape family of the floor. In order to represent a large area in its entirety, data must be utilized from a statistically significant number of measurement locations. There is no fixed definition of this quantity. In general, more locations may be required for floors with a large range in vibration amplitudes. The data population should be sufficient so that the average-plus-one-standard-deviation does not exceed the maximum measured value. Between 8 and 20 locations were typically selected for this study, depending upon engineering judgment and time available.

Using the average of this collection of data, approximately half of the space would exceed this value and there would be no representation of the scatter of data. Therefore, when evaluating a large space, measurements should be taken at a statistically significant number of randomly selected locations distributed over the space. Random selection is used to avoid a particular pattern that would introduce systematic variation due to modeshapes. There should not be a disproportionate number of mid-bay locations, near-column locations, or any other particular location within a bay, but there should be some mid-bay and near-column locations because at many frequencies the extreme may occur at these locations. The data should then be subjected to logarithmic statistical analysis (usually in terms of decibels regarding a reference, e.g., dB re 1 µm/s, however, other reference units are acceptable) and should characterize the space using the spectrum representing the log mean (or log average) plus the log standard deviation (also known as the average-plus-sigma or Average + St Dev case, dropping the log term but implying its use). Thus, the resulting spectrum represents the majority of the space although it will exclude extremes. A useful representation of the data shows the maximum, minimum, mean, and the mean-plus-one-standard-deviation spectra (Figure 1). An appropriate expression of the Average + St Dev spectrum is used to characterize a facility and compare it with its criterion. It is also used when making comparisons over time or between spaces.

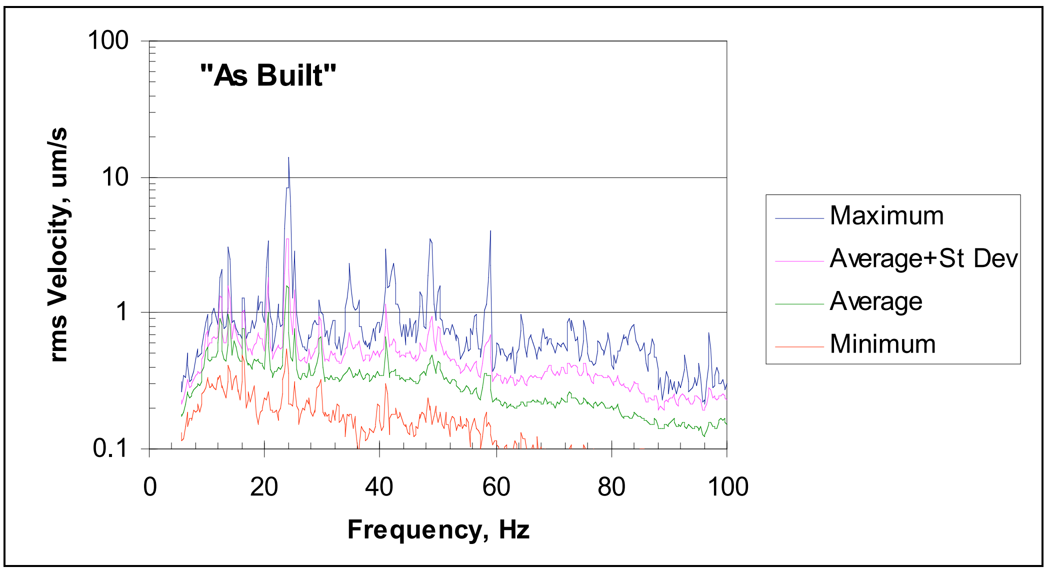

Figure 1. Statistical summary of vertical vibrations in typical fab production area during as-built state.

Figure 1 contains a statistical summary of vertical vibration spectra collected at numerous locations distributed over the area of a wafer fab process floor in the as-built operating state, illustrating the vrious components of the vibration previously discussed in the paper. Vertical statistics are presented separately from horizontal statistics. Two sets of horizontal statistics are usually presented, one for each primary orthogonal direction, usually the nominal north-south and east-west axes of the building. Vibration from any one of these axes would serve to illustrate the vibration phenomena discussed in this paper. The facility used for the data collected in Figure 1 is a large, state-of-the-art ISO Class 4 wafer fabrication cleanroom. The process floor is a waffle design suspended over two subfab levels. The data was collected with a portable fast Fourier transform (FFT) spectrum analyzer, seismic accelerometer (1 V/g), and an appropriate signal-conditioning amplifier. The data collected at each location represented in the figures in this paper is the result of 50 linear-averaged FFT data samples with an effective bandwidth of 0.375 Hz.[6] Note that the vertical vibration phenomena are common to any type of advance technology research or production facility and would be detectable using any suitable measurement methodology.

CHARACTERIZATION AFTER THE AS-BUILT STATE

In theory, process and research tool installation begins after the as-built state is reached. This activity generates primarily transient broadband or temporary deterministic vibrations similar to typical vibration due to construction activity. Deterministic vibrations are predictable as opposed to random vibrations. A steady-state sinusoidal (or tonal) vibration is deterministic. Sources of vibration include movement of equipment and materials (broadband transients), dropped loads or other impacts to the structure, and power tools (transient or short-term tonal or broadband impacts). This is a temporary state, however, and may recur when research or production equipment is installed or upgraded.

ISO[1] defines the subsequent states when these tools are installed but not operating as 'at-rest" and "operational" when they are operating. In the operational state, new continuous and transient vibration sources are operated in the facility. These vibration sources include the process and research tools and corresponding mechanical and electrical support equipment, such as electrical power conditioners, dry pumps, chillers, and environmental unit fans. The hook-up piping associated with these sources is also in place in this state. The vibration types are broadband (fluid flow in hook-up piping), tonal (rotating mechanical equipment such as pumps and fans), and transient (robotics, automatic materials handling systems, etc.). The vibration environment during this phase is relatively constant in processing facilities but may vary based on the equipment in use in research and analysis areas.

The next phases may be associated with the aging of the facility. Changes in the vibration environment at this stage may be subtle and are associated with the following phenomena or activities:

- The need for maintenance of building mechanical equipment (e.g., machine dynamic balance, adjustment of vibration isolators) tends to increase the vibration until adjustments are made.
- Curing of concrete (which increases with strength over time) tends to improve the vibration environment.
- Changes (additions, removals, maintenance, or replacement) in the operation of the equipment that powers the building or serves the tools can increase or reduce vibration.

COMPARISON OF AS-BUILT VERSUS OPERATING VIBRATION ENVIRONMENTS

Figure 2 is an update of Figure 1, showing a statistical summary of the data collected at the same building locations 20 months later and after the tools are in place and operating. This represents a continuous operating phase without any installation transients.

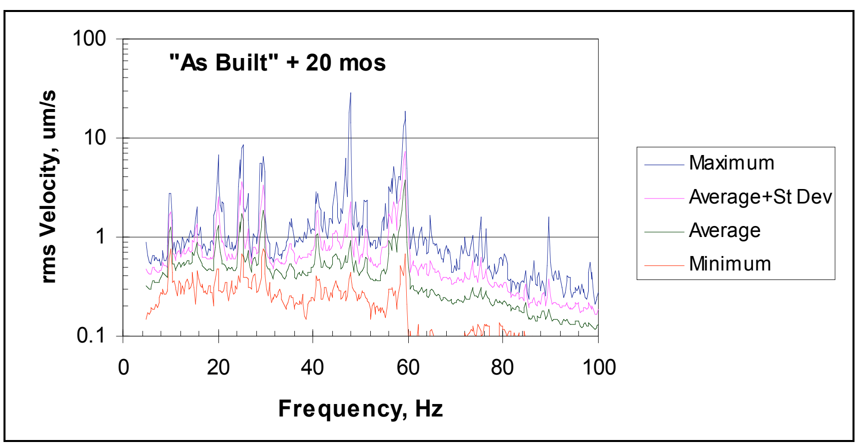

Figure 2. Statistical summary of vertical vibrations in typical fab production area 20 months after as-built state.

Figure 3 compares the average-plus-one-standard-deviation amplitude of the vibration environment in the as-built state to the environment 20 months later. There are several significant differences, and detailed evaluation of this facility shows with one exception that the changes in the vibration environment were due to the added tools and tool support equipment. Several tones between 12 Hz and 16 Hz and near 24 Hz are due to building mechanical pumps and fans that operate on variable frequency drives and have changed operation speed in the interval.

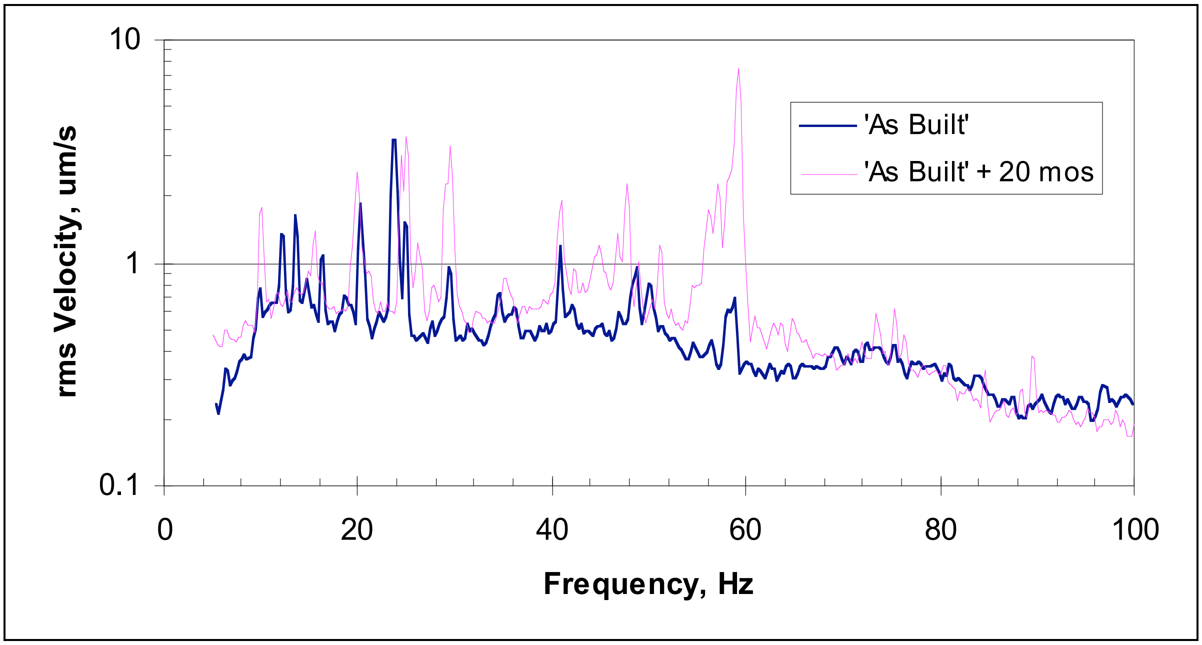

Figure 3. Statistical representation (in terms of mean-plus-sigma spectra) of vertical vibrations in typical fab production area at as-built state and 20 months after as-built state.

The most significant change occurs at frequencies just below 60 Hz. This vibration has been traced to the hundreds of dry pumps and local chillers located one level below (at subfab level). This is tonal vibration and varies slightly in frequency from model to model, but generally occurs between 56 Hz and 59.75 Hz (3360 rpm and 3585 rpm) in facilities operating with 60 Hz mains frequency. Some of this equipment, such as small scroll pumps, is also the source of the significant tonal vibration just below 30 Hz (1800 rpm). The increased broadband vibration between 3 Hz and 70 Hz is most likely associated with fluid flow in hook-up piping and exhaust ducts, as well as wafer handling systems. In some cases, the increased broadband vibration may be due to increased fluid flow velocities in the building main and secondary piping and duct systems,; however, in this case, an attempt was made to "false load" these systems during the as-built evaluation to capture the effects of design flow velocities. Capturing the effects of design flow velocities is critical because the vibration impact from these systems is proportional to the flow velocity.

Figure 4 shows a similar comparison of as-built versus operating vibration in another facility. In this case, the mains frequency is 50 Hz and the tool support equipment generates tonal vibration just below the mains frequency of 48 Hz to 49.75 Hz (2880 rpm to 2985 rpm). Vibrations have also increased at other discreet frequencies due to tools and hook-up equipment. In addition, there has been a small increase in the broadband vibration amplitude throughout the measured frequency range.

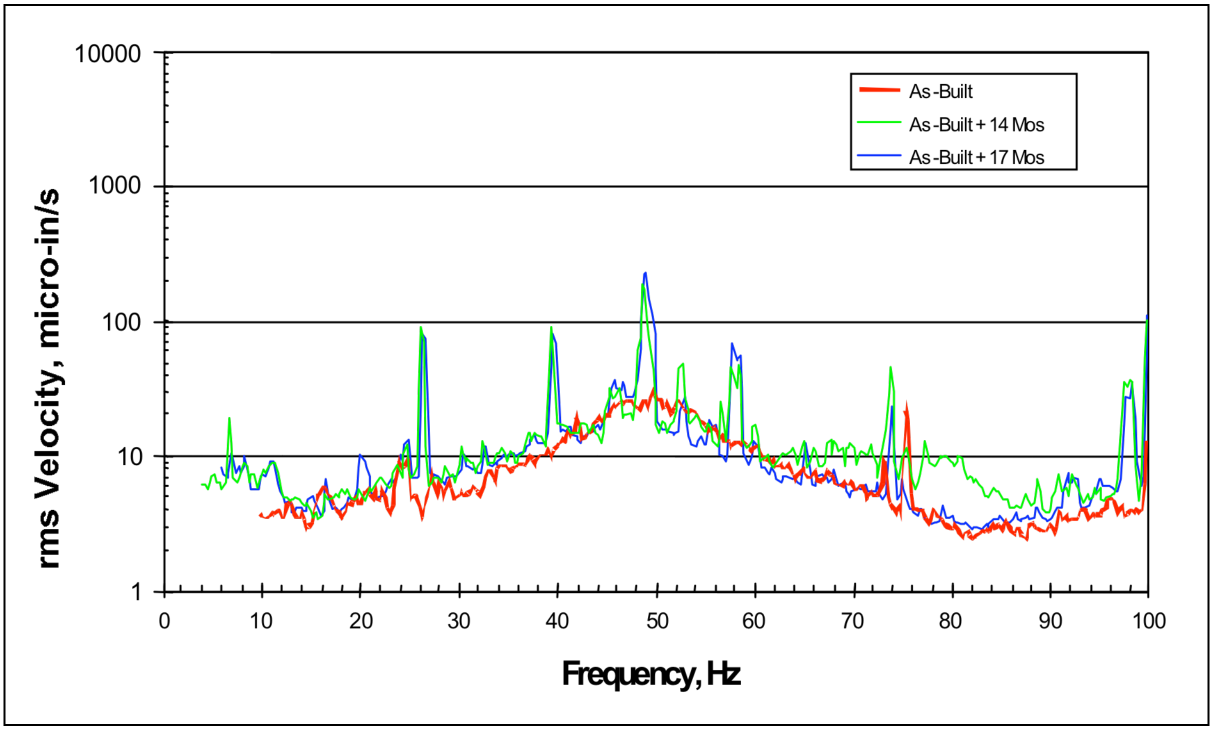

Figure 4. Statistical representation (in terms of mean-plus-sigma spectra) of vertical vibrations in a typical fab production area at as-built state and two times thereafter.

Figures 5 through 8 illustrate the characteristics of some of the vibration sources previously discussed in this paper. Figures 5 and 6 show measurements made on the casing of several dry pumps and several chillers placed in the subfab to support specific tools, respectively. The tonal signatures of this equipment are evident. Figure 7 contains statistical spectra from an operating process floor that is dominated by tonal vibration at 30 Hz due to an ion implanter process tool. (This plot also shows the characteristic hook-up equipment group tonal impact just below 60 Hz.) Other tools that generate vibration include chemical mechanical polishing (CMP) tools, spin rinse dry and other cleaning process tools, and various types of assembly tools (laser drills, bonders, die cutters, etc.). Figure 8 shows the vibration amplitude on a process floor in a wafer fab with a variation in the flow velocity in the cooling water system. The system change in Figure 8 is associated with the base-building design and is used only to illustrate broadband vibration impact. Improperly isolated hook-up piping not present in the as-built state might also cause this type of increase in vibration.

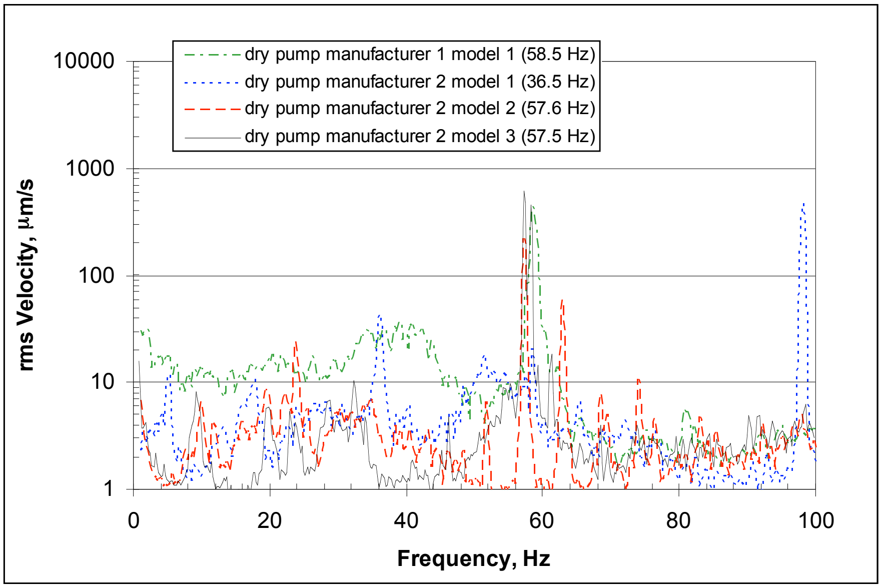

Figure 5. Vibrations measured on the casing of several representative dry pumps.

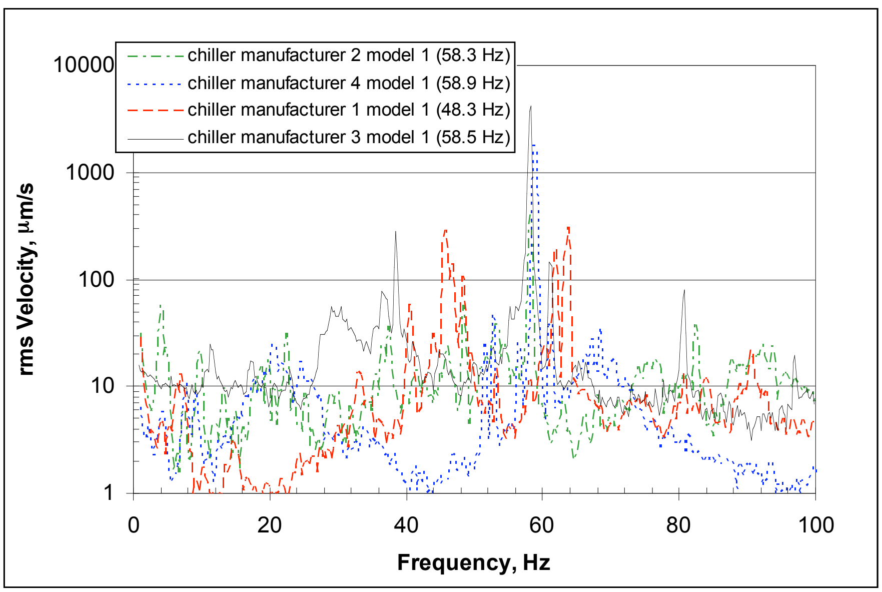

Figure 6. Vibrations measured on casing of several representative chillers.

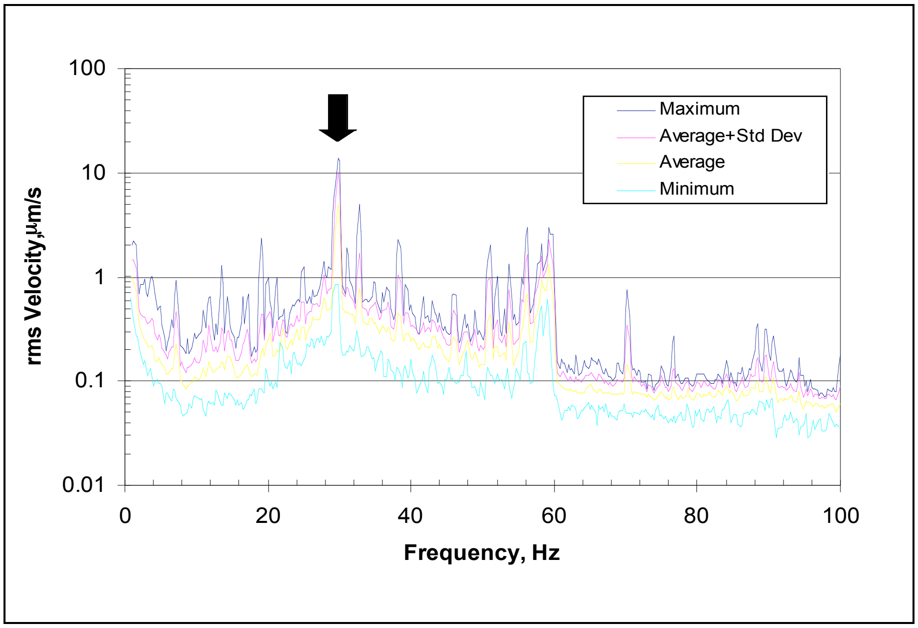

Figure 7. Statistical representation of vertical vibrations in a fab production area in which the vibration environment is dominated by tonal component at 30 Hz generated by an ion implanter.

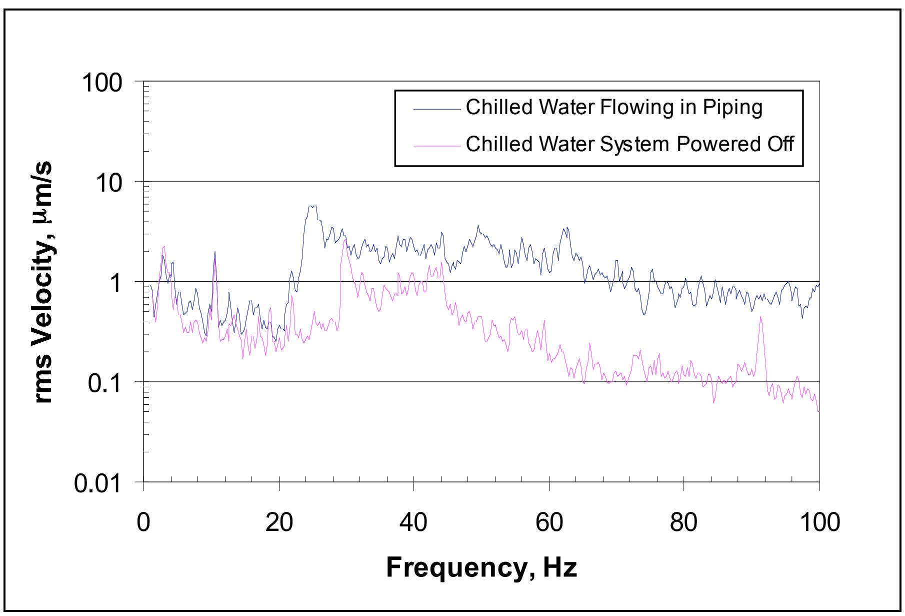

Figure 8. Change in vibration due to fluid flow in production facility subfab piping.

CHARACTERIZING MATURATION

From the data presented in Figures 1 through 3, an estimate can be provided of the "normal variation" (or generally, normal increase) in vibration due to the addition of the tools within a semiconductor production facility. The product of the average-plus-one-standard-deviation data at as-built + 20 months shown in Figure 2 divided by data at as-built shown in Figure 1 provides the results shown in Figure 9. These data are shown in terms of decibels (dB), as defined in equation 1.

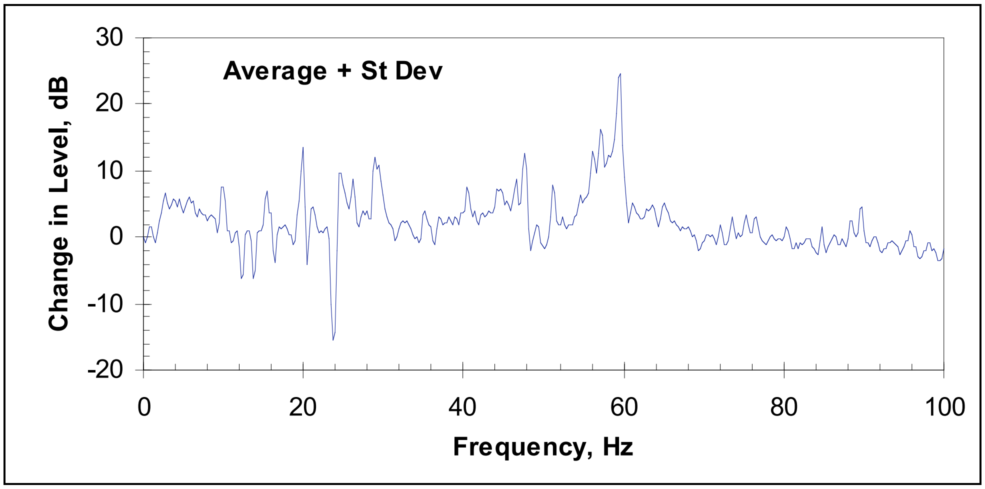

Figure 9. Change in vibration level from average-plus-one-standard-deviation as-built (Figure 1) to as-built plus 20 months (Figure 2) conditions.

$$Change_{dB} = 20 \times \log \left[\frac{As - Built + 20}{As - Built} \right] \tag{1}$$

We can assume that some range (e.g., ±6 dB) is normal variation. This range is arbitrary, but is consistent with data observations. Fabs have not yet been examined in sufficient numbers to produce a specific range representative of reality. In the example fab characterized in Figure 9, the mean change is an increase of 2.3 dB—essentially a log mean—and the standard deviation (σ) is 4.3 dB. Thus, the mean ± σ corresponds to the range −1.9 dB to +6.6 dB. Since the concept under discussion infers that "abnormal" maturation is that which is greater than the "normal" range, there is little practical difference from the arbitrary range of ±6 dB. The normal variation corresponds to the area between the dashed lines in Figure 10, which represents the change in terms of a factor defined by equation 2 rather than decibels. The spikes that extend above what might be defined as normal variation represent the frequency ranges in which the most significant changes in vibration are associated with maturation. The majority of this vibration due to user-supplied equipment is near 60 Hz, as shown in Figure 10, as previously discussed. The dip at 24 Hz is an artifact. (As noted previously, several tones between 12 Hz and 16 Hz and near 24 Hz are due to building mechanical pumps and fans that operate on variable frequency drives and have changed operation speeding the interval.)

$$Change = 10^{Change_{dB}/20} \tag{2}$$

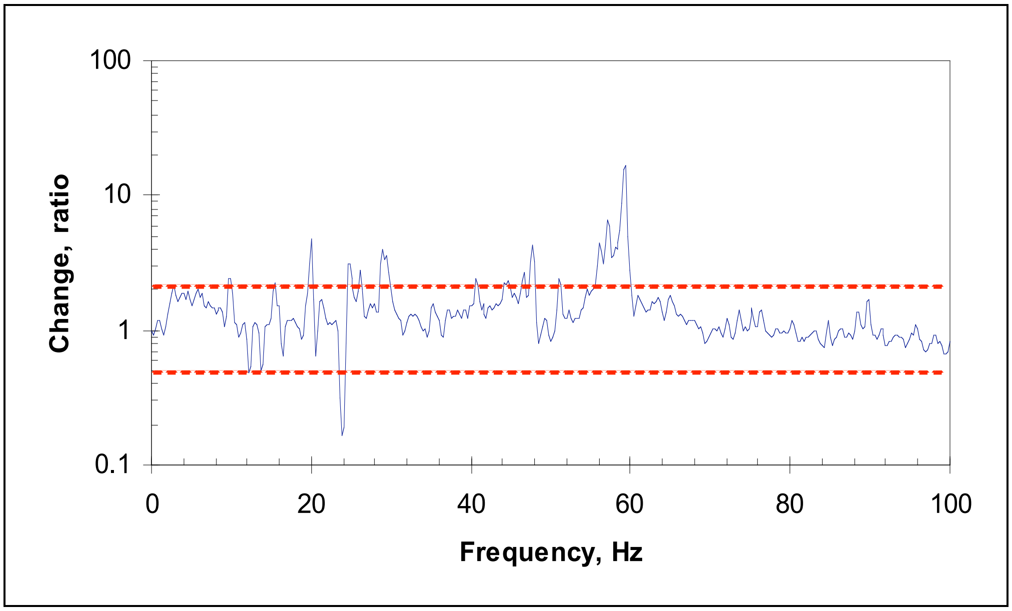

Figure 10. Normal versus exceptional variations in the vibration environment due to operating vibration sources.

CONCLUSIONS

The data shown illustrate that vibration in advanced technology facilities can increase significantly from as-built design amplitudes with the introduction of research and production equipment. The increases may also be due to other factors, such as aging and maintenance of the building mechanical equipment and structures. In order to control vibration increases to within acceptable limits, the following concepts should be considered:

- <u>Control of tool support equipment vibration.</u> The layout, design, and isolation of tools and tool support mechanical equipment and piping can significantly influence the eventual operating vibration environment. Therefore, it is incumbent upon the facility and tool owners to carry through with the same quality of design used in the installation of base-building equipment when installing new equipment. Failure to do so almost guarantees degradation of an otherwise good vibration environment. For example, locating dry pumps remotely from sensitive equipment can reduce the impact from this vibration and noise source. Alternately, improved isolation systems or isolation systems or isolation racking systems might be provided for this equipment. Isolation specifications for the associated hook-up piping should be considered if arbitrary rigid attachment of these pipes to the structure might prove to be detrimental. Tools that are significant sources of vibration should be effectively separated from the most sensitive tools. These are a few of the design and layout considerations commonly reviewed during the base-build state that might also be reviewed during the hook-up design state to control vibration from the associated systems.
- <u>Mechanical equipment maintenance.</u> Periodic maintenance and inspection of building mechanical equipment balance and isolation systems are critical in the preservation of design vibration conditions in the process environment. Due to cost constraints, conservative “over-design” and layout is rarely possible in the base-build design. Various strategies for machinery health monitoring typically include periodic or continuous monitoring of vibration amplitudes on the rotating equipment or inspection for bearing wear and other degradation or damage that can increase the transmitted vibration. Similarly, the efficiency of equipment and piping isolation systems may be reduced due to misalignment, short-circuiting, or failure, and these faults can be discovered and mitigated as a result of a program of periodic inspection and maintenance.

- Preventive design during the base-build state. The performance of the vibration-sensitive floors under mechanical load is a significant function of the stiffness of those structures.[5] Thus, a compensating structural design factor in structural stiffness to reduce impact from operating vibration might be considered. While it is not practical to provide enough stiffness to compensate for all of the excess vibration shown in Figure 10, improved tool support equipment isolation and compensating stiffness may be the best option if better performance is required.

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