THE DESIGN OF LOW-VIBRATION BUILDINGS FOR MICROELECTRONICS AND OTHER OCCUPANCIES

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Abstract

In this paper I present an overview of the factors and problems that must be considered in designing low-vibration buildings. Subjects covered include vibration criteria for different occupancies; sources of vibration and response predictions; major design factors for vibration control.

Introduction

This paper provides a general overview of a subject that is quite complex, many aspects of which are not properly understood at the present time. The major topics that I shall cover are, in order:

(a) Typical vibration spectra on building floors
(b) Vibration criteria for different uses
(c) Sources of building vibration--how these may be quantified
(d) Designing a building to achieve a design criterion

The author's experience in the area of building vibration design and control has derived largely from working with the microelectronics industry. In this industry vibration is considered as one of several "contaminants," that can affect the "yield" and therefore the profitability of the process in which integrated circuits of immense complexity are formed on chips of silicon. Many of the lessons learned in the microelectronics industry have application in other areas where vibration sensitive equipment and processes are used. These include medical and biological research facilities, university laboratories, and surgical facilities, especially those specializing in microsurgery.

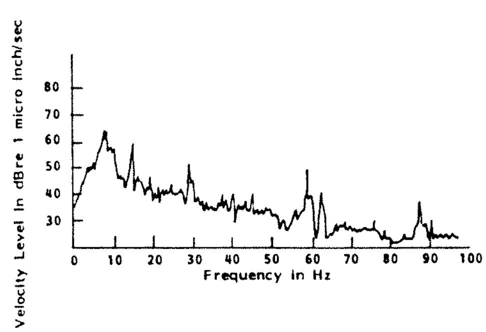

FIGURE 1. A TYPICAL NARROW-BAND VERTICAL VIBRATION SPECTRUM AT SECOND FLOOR LEVEL IN A STEEL FRAME AND CONCRETE BUILDING. (Bandwidth = 0.375 Hz)

A Typical Vibration Spectrum

A typical narrowband vibration spectrum is shown in Figure 1. The spectrum applies to vertical vibration measured at centerspan at second floor level on a building formed of steel columns and steel beams carrying a concrete floor. The building structure is quite typical in its design. The frequency range of analysis is 0 to 100 Hz. It is within this range that people and equipment exhibit the greatest sensitivity to vibration. The measurement bandwidth is 0.375 Hz.

The spectrum serves to illustrate the fact that most real vibration environments—be they measured on the ground or in a building—are dominated by broadband energy as opposed to tonal energy. The reason is that many of the sources of vibration have their origin in some form of random process—turbulence flowing through a duct, for instance, or traffic travelling along a road.

The spectrum of Figure 1 has a broadband peak centered at a frequency of about 8 Hz. This is the dominant flexural resonance frequency of the floor supported between the columns. Interestingly, we see no signs of significant higher-order resonant modes. Most of the other peaks are pure tones generated by unisolated or poorly isolated items of mechanical equipment supplying the building services.

It is in the context of this sort of spectrum that we must consider the matter of design criteria. How do we rate the spectrum shown in Figure 1? Does it represent a good environment for people, or even for high-powered microscopes?

Vibration Criteria for Different Uses

In our work with the microelectronics industry we have encountered a wide variety of vibration "goals" expressed by the potential users of a building. These have included such statements as: "The facility shall be vibration free," and "The vibration amplitude shall not exceed 1 micron within the frequency range 1 to 100 Hz."

The trouble is that neither of these specifications give us enough information to define a method of measurement. The first statement, of course, is meaningless--there is always vibration present even in the most perfect environment. The second statement is more specific but is still incomplete. It does not define whether the limit is applied to the peak-to-peak, zero-to-peak, or root-mean-square value of the vibration waveform. Nor does it define a measurement bandwidth--unless one is to assume that the limit applies to the total vibrational energy within the 1 to 100 Hz frequency range. The question of measurement bandwidth is of vital importance in measuring the spectrum of Figure 1 which is dominated by broadband energy.

The vibration specifications provided by manufacturers of equipment also are often incomplete, and a cause of considerable confusion. The problem here is that many manufacturers do not have the facilities to carry out orderly vibration threshold measurements on their equipment. The specifications they offer may be derived from very rudimentary measurements taken on the floor of their test/assembly shop. Sometimes they may even be "notional", on the basis that something is better than nothing.

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To illustrate something of the confusion that can occur, we show in Figure 2 a collection of specifications for five different E-Beam systems--used by the microelectronics industry for making the masks that are used in the photolithography process. To some extent these represent our interpretations of specifications which uniformly are incomplete. None of them makes mention of measurement bandwidth for instance.

The specifications for Systems A (above 10 Hz), C and D correspond to constant displacement. That for System E represents constant acceleration. The specification of System B could perhaps be approximated by a line of constant velocity.

Note the enormous range of vibration values covered by Figure 2. Admittedly, each of these machines is constructed differently; yet they serve approximately the same function. It is hard not to conclude that several, if not all, of these specifications are somewhat lacking in precision.

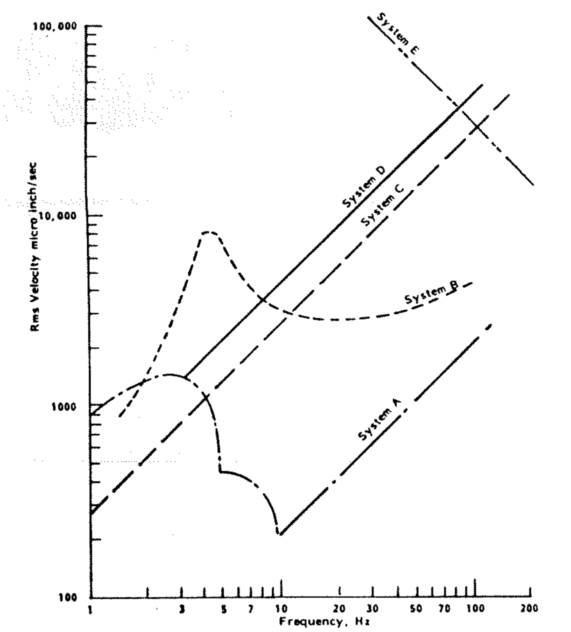

FIGURE 2. VIBRATION SENSITIVITY OF PRESENT-DAY E-BEAM SYSTEMS (SENSITIVITY THRESHOLDS QUOTED BY VARIOUS MANUFACTURERS AS INTERPRETTED BY BBN)

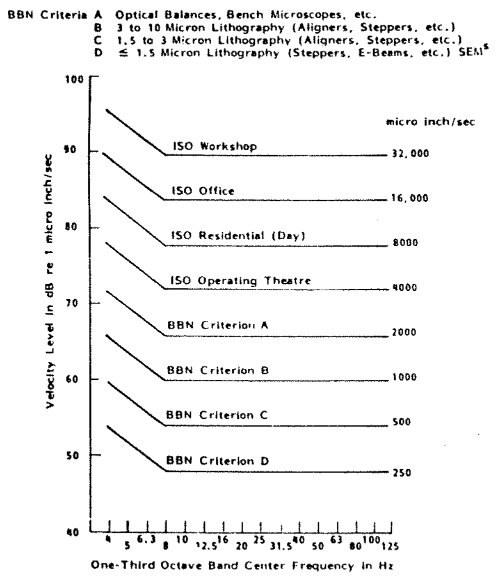

FIGURE 3. VIBRATION CRITERIA FOR SENSITIVE EQUIPMENT IN BUILDINGS (ALSO SHOWING ISO GUIDELINES FOR HUMAN OCCUPATION OF BUILDINGS)

Because of this confusion, and because we had a very pressing need to develop design criteria that would have general application in our design work, we developed the curves shown in Figure 3. These criterion curves are now quite widely used as a basis for facility design and as a means of performance evaluation. On Figure 3 we include levels taken from the ISO (International StandardsOrganization) Draft Proposal ISO 2631/DAD1, entitled "Guide for the Evaluation of Human Exposure to Whole Body Vibration."

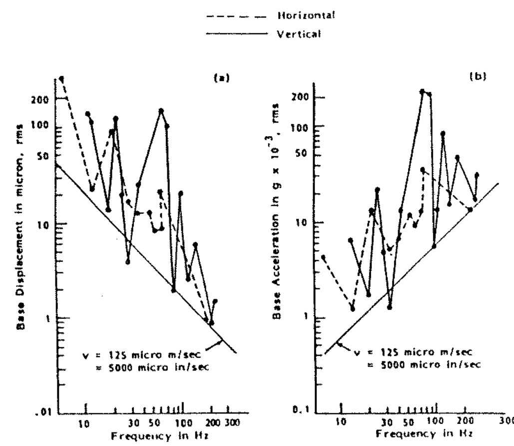

FIGURE 4. MAXIMUM ALLOWABLE BASE MOTION (IN TWO DIRECTIONS) FOR 0.1 MICRON IMAGE MOTION ON ONE PARTICULAR ITEM OF EQUIPMENT, IN TERMS OF
(a) Base displacement
(b) Base acceleration

The main elements of these criteria may be summarized, and rationalized, as follows:

(a) We use rms velocity (as opposed to displacement or acceleration) as the measure of vibration intensity. We have found in our studies that while different items of equipment may exhibit maximum sensitivities at different frequencies, often these points of maximum sensitivity lie on a curve of constant velocity.

This point is well illustrated by the vibration specification shown in Figure 4. In the case of this equipment the manufacturer--unlike those responsible for the curves in Figure 2--ran very careful tonal threshold tests at closely-spaced frequencies, over the frequency range 6 through 200 hz. The specification data are shown in terms of displacement and acceleration. In fact, as shown, the lower bounds of these threshold curves correspond closely to lines of constant vibration velocity. For this equipment the vibration limit could have been quoted simply in terms of a single value of velocity--applicable over a stated frequency range. We have drawn similar conclusions with other equipment also.

It is of interest to note that other vibration criteria are expressed in terms of velocity. The ISO guidelines for human occupation of buildings--included in Figure 3--are but one example. Another is the U.S. Bureau of Mines criteria for potential damage to building structures.

The criterion curves of Figure 3 permit greater motion for frequencies below 8 Hz. This reflects our belief that most equipment is relatively insensitive to vibration at frequencies below the fundamental resonance frequency of the structure which holds the equipment together. Problems, after all, generally require relative motion within the system and this, in turn, requires deformation of the structure.

(b)The second matter to note is that our criteria are expressed in terms of one-third octave bands of frequency, thus resolving the question of measurement bandwidth mentioned earlier. The selection of this bandwidth can be justified, we believe, on an assumption that for most equipment structures the damping might reasonably be about 10% of critical damping. On this assumption the response bandwidth of resonances would be about 20% of the band center frequency—very nearly equal to the 23% bandwidth of the standard one-third octave filter.

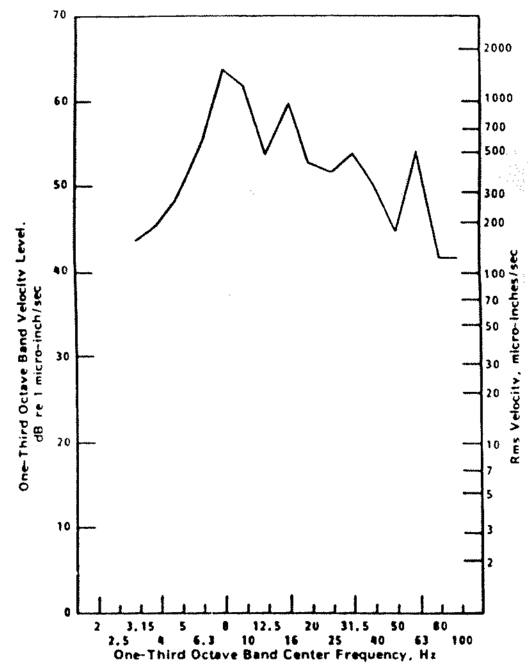

FIGURE 5. THE SPECTRUM OF FIGURE 1 MEASURED IN ONE-THIRD OCTAVE BANDS OF FREQUENCY

In Figure 5, we show the spectrum of Figure 1 as it would be (and was) measured using a one-third octave band analyzer. The effect of changing the measurement bandwidth when dealing with broadband energy is substantial—especially at the higher frequencies.

A further argument for using one-third octave hands is that they are conveniently available, having been used for many years by acousticians and others.

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The criteria of Figure 3 have been developed around the needs of the microelectronics industry. The line-width descriptors and the equipment types are those associated with the fabrication of integrated circuits. The criterion curves are based on the requirements of the most sensitive equipment known to us within each equipment category. It should not be too difficult to extend the use of these criteria to other environments also, and to include items of equipment from a wide variety of disciplines.

Sources of Building Vibration - How these may be Quantified

We now move into the realm of design: How can we design a building that will comply with a selected design goal? What are the sources of vibration? How can the effects of these sources on a particular design be predicted and controlled? The overall problem is illustrated in Figure 6.

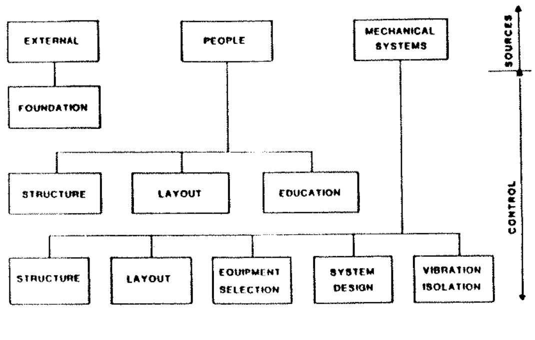


FIGURE 6. MAJOR SOURCES OF BUILDING VIBRATION AND ELEMENTS OF VIBRATION CONTROL

By external sources we mean those sources associated with the general environment which surrounds the building—the ambient. These sources include highways, local roads, railroads, industry and even natural sources such as ocean waves, and wind.

When we are surveying sites for a vibration critical building, we like to find one on which the ambient vibration levels lie substantially below (by 6 to 10 dB) the design goal that has been selected for the building. Because the building itself will introduce many new sources of vibration, the sum total of which must comply with the criterion. Over the past eight years or so, we have surveyed upwards of 75 sites throughout the world. The typical types and ranges of spectra are illustrated in Figure 7.

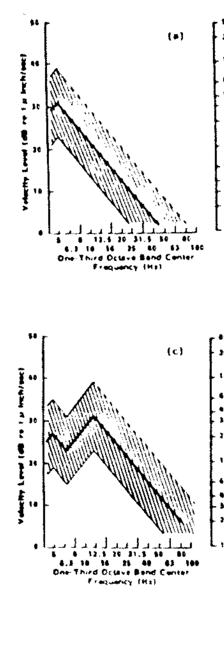


FIGURE 7. TYPICAL SPECTRUM SHAPES AND RANGES OF VERTICAL AMBIENT GROUND VIBRATION

The spectrum peaks in the vicinity of 5 Hz and 12.5 Hz appear, most commonly, to have in their origins in distant and nearby traffic flows, respectively. It is our experience that road traffic is the most commonly occurring source of ground vibration. This typically occurs in the frequency range 8 through 16 Hz. Heavy trucks on rough roads are clearly the major culprit. Trains also can be a source of substantial vibration—especially heavily loaded freight trains travelling at speed. Occasionally we have encountered significant vibration levels generated by heavy industrial processes; large forging hammers, automobile shredders, and large wind tunnels are three examples. To date, we have not encountered any significant site problems generated by natural phenomena—wind, waves, natural seismicity, or the like.

Clearly the soil conditions on a site can affect the ambient vibration levels. The efficiency of vibration propagation—the propagation velocity and the damping—is a function of soil type, water content, layering characteristics, and other parameters.

The second source category in Figure 6 derives from the people that occupy the building. Vibration is generated when people walk on the floors, slam doors, trundle hand-carts, etc. By far the most significant of these sources is the walker.

Ungar and White at BBN[1] and Thomas Murray at the University of Oklahoma[2] have studied and quantified the vibration effects of walkers. Using the work of Ungar and White, it can be shown that the peak velocity response, at resonance, of a lightly-damped floor to the individual steps of a walker can be expressed

$$V_w = C_1/kf_o \quad (1)$$

Where C_1 is a constant, whose value is set by the weight of the walker and upon the rate at which he walks; k is the static stiffness of the floor at centerspan and f_o is the predominant resonance frequency. This relationship does not apply to slab-on-grade floors which are highly damped. The relationship illustrates the importance of high stiffness, combined with high resonance frequency, in controlling the response of a floor to walkers.

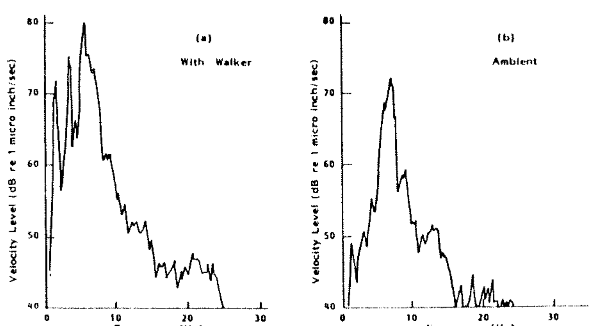


FIGURE 8. EXAMPLE OF WALKER-INDUCED FLOOR RESPONSE AND AMBIENT RESPONSE ON A LONG SPAN PRESTRESSED CONCRETE FLOOR (Narrow Band Analyses, 0.375 Hz Bandwidth)

An example of walker excitation of a floor is shown in Figure 8(a). The floor in this case was formed of deep double-T prestressed beams spanning a distance of 45 ft. The resonance frequency shown is about 7.5 Hz. The spectrum shows the major components generated by a 170-lb walker walking at a rate of about 110 paces per minute. The floor ambient, in the absence of the walker, is shown in Figure 8(b).

The presence of partitions, hung ceilings, ducts and pipes, etc., can affect the extent to which a floor responds to walkers. Murray attributes these effects to damping. They may also be the result of changes in mode shape and modal frequencies.

The final category of source lies in the mechanical systems that supply the building services—the pumps, fans, chillers, etc., and their associated pipework and ductwork. These sources can generate both tonal and broadband energy, as was illustrated earlier in Figure 1. The major sources of tonal energy are to be found in items of rotating equipment. Broadband energy tends to have its primary source in the flow of fluid turbulence through pipes and ducts.

The clean rooms employed by the microelectronics industry use enormous quantities of air: clean rooms typically involve 600 air changes per hour as compared with the 6 air changes per hour typical for normal office buildings. These buildings, therefore, are very subject to excitation by the huge quantities of air that must be ducted from the fans to the clean rooms.

Some years ago we carried out a detailed statistical analysis of the broadband vibration excitation on the floors of thirteen operating facilities. All of these facilities were supplied by centralized air distribution systems, and in all of them air flow velocities in ductwork had been carefully controlled. Generally, all these facilities were well-designed in terms of layout, equipment isolation, etc. We found good correlation and substantial uniformity of spectrum shape when the measured spectra (in one-third octave bands of frequency) were "normalized" against the floor stiffness at centerspan.

The type of "haystack" spectrum that we found was similar to that shown in Figure 5, around the 8 Hz floor resonance. We found that the maximum one-third octave band velocity was given by a relation of the form

$$V_m = C_2/k \qquad (2)$$

where C_2 is a constant and k is, again, the static stiffness at centerspan.

This relationship once again highlights the important role played by structural stiffness in determining the level of vibration in an operating clean room.

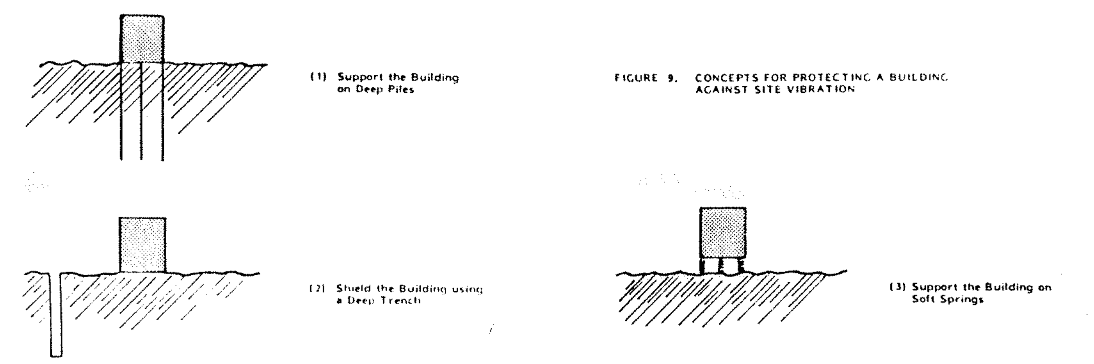


FIGURE 9. CONCEPTS FOR PROTECTING A BUILDING AGAINST SITE VIBRATION

Designing a Building to Achieve a Specific Criterion

The major elements of vibration control in building design are included in Figure 6. Let us discuss these briefly, one-by-one, in the context of our current thinking and past experience.

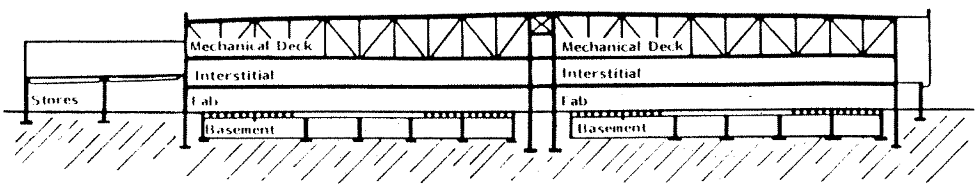
Foundation Design

Generally there is little that can be done to protect a building from high ambient site vibration. The one exception might be the case where bedrock lies fairly close to the ground surface. By supporting the building stiffly from bedrock it may be possible to effectively reduce the problem of excessive site vibration.

Three concepts which lie in the area of foundation design are illustrated in Figure 9. In two Case Histories which accompany this paper we have argued that concepts (1) and (3) have little practical value. Concept (2) is impractical for much the same reason as Concept (1): at the frequencies with which we are concerned, the characteristic length of the ground wave is too great to be affected by a trench of practical depth. The subject of vibration shielding by trenches is discussed by Richart, Hall and Woods.[3]

There is no doubt, however, that site preparation is an important factor to be considered when developing the construction documents for a vibration sensitive building. It is especially important in the design of slab-on-grade floors. Slab-on-grade floors can perform extremely well from the viewpoint of vibration so long as they are stiffly and uniformly supported by the underlying soil. But this support must remain stiff and uniform throughout the life of the building. We have many examples in our files of floors which have deteriorated over a number of years because of poor site preparation.

Certain benefits can be derived from the design of the foundation system. Thus, for instance, by separating footings we can make it harder for energy to travel from one location in a building to another. Separations can either be vertical or horizontal or a combination of both.



MAIN FEATURES:

CLEAR-SPAN DEEP-TRUSS ROOF

CIRCULATION AND MAKE-UP FANS ON MECHANICAL DECK

DUCTWORK IN INTERSTITIAL SPACE

PROCESS(FAB) FLOOR OF DEEP WAFFLE DESIGN WITH SELECTED COLUMN SEPARATION

ENERGY CENTER (Chillers etc.) REMOVED TO SIDE OF BUILDING

HEAVILY TRAVELLED CORRIDORS ON SLAB-ON-GRADE

SEPARATED FOOTINGS

FIGURE 10. AN EXAMPLE OF A WAFER FAB DESIGN

Examples of footing separations are shown in Figure 10. This figure illustrates many other features of a good wafer fab design. The benefits of footing separations, or for that matter "isolation breaks" in floor slabs, should not be overstated, however. In many instances the benefits to be gained are small—and are associated primarily with distance rather than with any inherent action of a structural break. In general, foundation design is not a critical element in vibration control,* but certain basic aspects of it must not be ignored.

* Foundation design can be a critical element in limiting the response of structures to seismic inputs. This, however, is a different problem than the steady-state low-amplitude vibration problem with which we are dealing in this paper.

Structural Design

The design of the structure is certainly the single most important element of a low vibration building. It is especially important to design a structure in which the floors are sufficiently stiff, and the dominant resonance frequencies sufficiently high, to keep the walker and mechanical response of critical floors within acceptable limits—according to Equations (1) and (2).

Modern long span floor structures will often have center span stiffnesses of the order of 2×10^5 lbs/in with resonance frequencies in the range of 5 to 8 Hz. "High tech" floors, of the sort currently being designed for the microelectronics industry, will typically have a stiffnesses in excess of 2×10^6 lbs/in with resonance frequencies of 30 Hz or even higher. Although these latter characteristics can be developed using steel-frame buildings, it is certainly easier to achieve them using cast-in-place concrete. The "waffle" floor is particularly attractive since it provides the benefits of two-way stiffness.

Other aspects of the structural design can be important also. Figure 10 shows an example of some of the features of a modern microelectronics facility in which the structural design plays a major role.

Layout

The layout of a building is important in determining its vibration performance. In a university facility, for example, it would clearly be inadvisable to locate heavily-travelled corridors immediately adjacent to an Electron Spectroscopy laboratory set on the same suspended floor slab. It is also generally undesirable to locate mechanical rooms directly below, or immediately adjacent to, critical spaces—there are limitations in the performance of even the most carefully executed vibration isolation!

Distance is a useful parameter in reducing the effects of vibration sources. In the design shown in Figure 10, for instance, we have maximized the distance between the fans that occupy the mechanical deck and the critical vibration areas that lie towards the center of the fab floor. More importantly, we have maximized the lengths of the structural transmisstion paths between the fab floor and the air supply ductwork and filter plena that are suspended within the interstitial space.

Education

Some of the worst aspects of "people" sources within and around buildings can be modified by education. This is not a really satisfactory method of control however, certainly not one that should be afforded any significant attention in designing a new facility.

Mechanical Source Control

The final three "boxes" in Figure 6—"equipment selection," "system design," and "vibration isolation"—all relate to the design and installation of the mechanical systems that supply the building services—conditioned air, electricity, elevators, etc.

The mechanical systems design lies second to the structural design in its importance in determining the vibration performance of a building.

Equipment selection is important because certain types of equipment have greater propensity to generate vibration than others. But more importantly, through the selection and purchase process, the quality of dynamic balance of the shafts and wheels of fans and other equipment can be improved, with consequent reduction in the vibrational forces generated. On the basis of our experience it is important to specify balance requirements for equipment that lies close to critical locations in vibration-critical buildings.

The design of the mechanical system is also important. The term "system design" here includes everything from the supports of the mechanical equipment to the design, routing and support of the ductwork and pipework.

In our experience, high velocity turbulent floor through major ducts and pipes is a major source of broadband vibration. Since turbulence cannot be eliminated from such systems, the major method of control lies in setting limits on the flow velocities.

It is bad policy, generally, to support equipment and major ductwork from the underside of a vibration-critical floor. Even with the best design and best intentions the practical isolation efficiency achieved by spring hangers, is limited.

Vibration isolation is the final control element to be considered here. The types of hardware that will be acceptable and details of the required performance must be very carefully spelled out in the construction documentation. Vibration isolation hardware includes spring supports for machines, spring hangers for ductwork, and flexible connectors for pipes and ducts.

References

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