Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Vibration effects in healthcare facilities

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In the USA, the principal rating system for "green" buildings is named, *Leadership in Energy and Environmental Design* (LEED®). There is now a proposed LEED rating system for healthcare facilities as described in a "pilot draft" document that was released for public comment in November 2007. This document, in turn, cites the 2006 *AIA/AHA Draft Interim Sound and Vibration Design Guidelines*. These AIA/AHA Guidelines focus on both the human perceptual effects of vibration as well as the control of structure-borne noise. This paper addresses another aspect of vibration in healthcare facilities — the effects of vibration upon sensitive diagnostic equipment installed on floors above grade. Such equipment may include magnetic resonance imagers, surgical microscopes, and computed tomography (CT) scanners, some of which do not have specific vibration limits provided by the manufacturer. The obvious need for attaining low-level building vibration may conflict with other design constraints imposed on modern healthcare facilities as architects and engineers strive for lightweight floor bays having widely-spaced support columns. This paper reviews the generic vibration design criteria found in the AIA/AHA Guidelines and discusses them in light of several case studies.

1 Introduction

Modern healthcare facilities employ a variety of sophisticated imaging devices for both diagnostics and therapeutic purposes. Several of these devices can be rather sensitive to imaging errors caused by low-frequency building vibration. The vibration levels that can affect sensitive imaging devices are often below the human perception threshold — that is, a vibration amplitude that could disturb sensitive equipment may not be sensed by an individual standing or sitting in the same environment. Since the frequency range of such low-level vibration is typically less than 50 hertz, an occupant might not even perceive secondary manifestations from vibrating building surfaces such as rattling of light fixtures, structure-borne noise, etc.

1.1 Vibration Criteria for People in Healthcare Facilities

In 2006, a set of *AIA/AHA Draft Interim Sound and Vibration Design Guidelines* were prepared by the American Institute of Architects (AIA) in conjunction with the American Hospital Association (AHA). The goal of this document was to help healthcare administrators and design professionals address noise and vibration in new facilities. These guidelines generally address both the human perceptual effects of vibration as well as the control of structure-borne noise. The main focus is to protect patients and staff from being annoyed by perceptible vibration and/or excessive structure-borne noise generated by mechanical equipment.

The received vibration is presumed to affect the entire body of an individual standing or sitting on the floor in question; thus, the cited criteria are collectively referred to as *whole body* vibration and are expressed as a constant vibration velocity in 1/3-octave bands from eight to 80 hertz. Below eight hertz, the criteria contain a sloped segment representing a region of constant vibration *acceleration* (see Figure 1 on the following page). The human threshold of perception corresponds to the contour labeled "100 micrometers per second" (or 4000 micro-inches per second in conventional U.S. units).

1.2 Performance Vibration Criteria for Equipment

These same guidelines also mention the sensitive nature of "Medical and laboratory instrumentation" and cite generic building vibration criteria found in the *ASHRAE Applications Handbook*.[1] These ASHRAE criteria also pertain to vertical vibration found on the building floor. The ASHRAE criteria are a family of contours that mimic the shape of the human perceptual frequency response. Applying a human frequency characteristic to the response of machines is based on the assumption that both people and machines have comparable distributions of stiffness and mass; therefore, the resonant behaviors of a human body and a machine generically have similar amplitude-versus-frequency characteristics.

Referring to Figure 1, the ASHRAE criteria are sorted into classes and assigned letter grades ranging from "A" to "F". The letter grade "A" represents the human perception threshold (100 micrometers per second).

The letter grade "F" is the most stringent classification and is intended for specialized facilities such as semiconductor wafer fabrication plants. Each successive letter grade represents a halving of vibration velocity with respect to the preceding letter grade; thus, "F" is assigned to a vibration velocity of 3.125 micrometers per second (125 micro-inches per second).

The having (or doubling) of vibration velocity is thought by some researchers to be a halving (or doubling) of sensed vibration intensity. That is, an unbiased individual would judge a doubling of vibration velocity to be a doubling of perceived sensation. This subjective scale for perceiving vibration is different than in acoustics where an approximate doubling of perceived sensation is equivalent to a 10-decibel increase in sound pressure within the center of the speech frequency range.

1 **ASHRAE** — An acronym for the American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE has developed many guidelines for noise generated by mechanical equipment in buildings. Beginning in 1995, these guidelines have incorporated classes of floor vibration criteria for various space usages within a building.

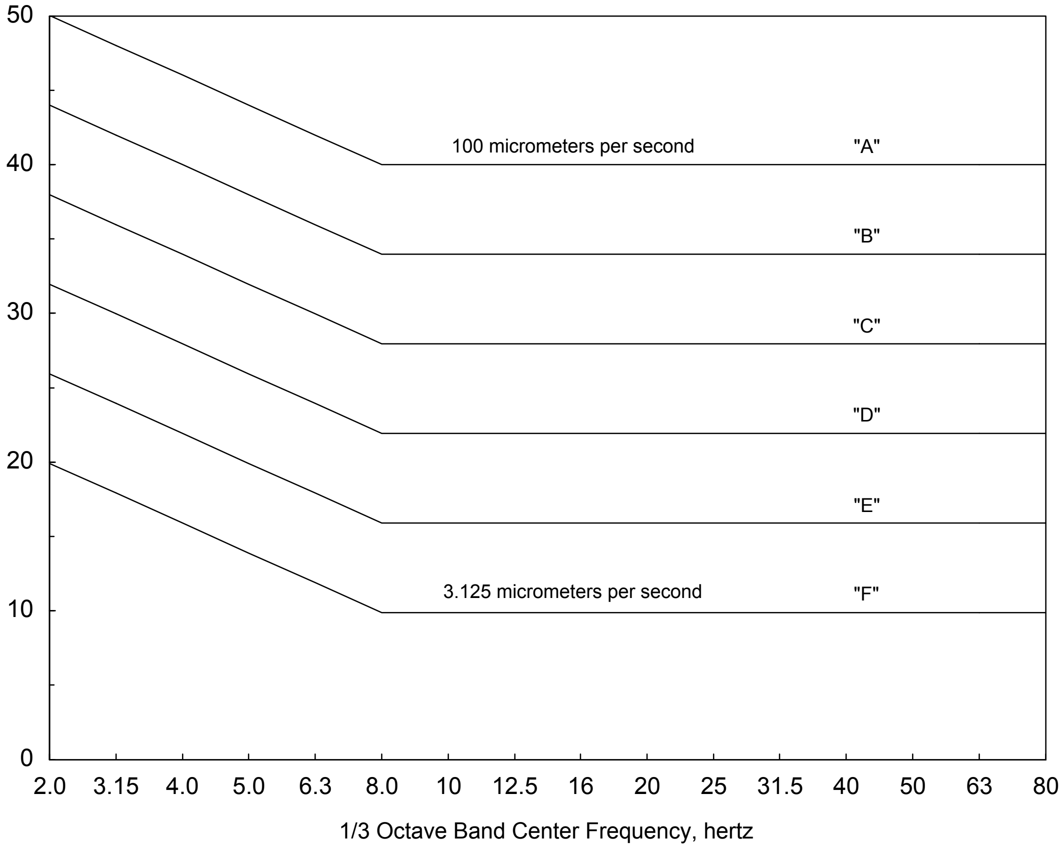

Fig.1 Floor vibration criteria from the *ASHRAE Applications Handbook*. Each of the six categories represents a specific vibration velocity contour whose shape mimics the human perception threshold for whole-body vibration (i.e., the human perception threshold is equivalent to the uppermost "A" category).

1.3 Predictive Vibration Criteria

The *AIA/AHA Draft Guidelines* also refer to a complementary set of design criteria from a document published by the *American Institute for Steel Construction*. The document is called *AISC Design Guide 11 — Floor Vibration due to Human Activity*. This document addresses vibration effects in buildings using an entirely different perspective — predicting the dynamic response of heavy steel-frame floor systems to forces generated by human footfalls (i.e., people walking).

The prediction of floor vibration due to a walking person requires a considerable amount of information about the dynamic behaviour of a complex structure involving a network of girders, beams, plates, and columns. Typically, such structures would be sensitive to the location of the footfall impact as well as the rate and intensity of the applied dynamic load. A precise assessment of footfall vibration implies that a finite-element model of the floor structure would be available in combination with a dynamic force signal that is accurately defined in the time domain. In short, a thorough analysis of floor vibration from human footfalls involves many factors, both known and unknown.

In *Design Guide* 11, a number of simplified mathematical models are included, enabling a structural engineer to calculate the expected response of a simple steel/concrete floor when excited by an idealized force pulse generated by a human footfall. The calculated result from this model is then expressed as a peak floor velocity at the first natural frequency of the floor system.[2] Recommended limits for the peak velocities from footfalls are found in Table 6.3.2-1 of the *AIA/AHA Draft Guidelines* (reproduced on the following page).

Verifying the peak vibration velocities predicted by *Design Guide 11* is possible only if the floor system reasonably corresponds to the simplified structural model. That is, the floor should be both stiff and quite massive with a first natural frequency above 15 hertz. Other types of floors (e.g., light-frame wood or metal) may behave quite differently than the heavy steel frame and concrete model described in *Design Guide 11*.

[2] As used here, the "natural frequency" of a floor system is an abbreviated form of engineering terminology in the field of modal analysis. The formal definition of "natural frequency" is the first lateral bending mode of a floor system having specific boundary conditions. In technical terms, it is the frequency where the distributed mass and stiffness of the floor system lead to a resonant condition whenever the floor panel undergoes "free" vibration (i.e., after the initial forcing stimulus has terminated). Such a resonant condition would exhibit a maximum relative motion at the center of the freely-vibrating floor panel. The "natural frequency" of a floor is significantly affected by its boundary conditions (i.e., its perimeter supports). In most buildings, floor systems are considered as simply supported (i.e., the floor panel is not restrained by bending forces developed across its perimeter supports). A simply supported floor can be modelled as a plate resting upon a series of pivoting supports such as the apex of a triangular wedge. The converse of a simply supported boundary condition is a "clamped" boundary condition. In practical terms, a true "clamped" boundary condition is not attainable in conventional building structures.

Space Category	Footfall Vibration Peak Velocity	
	micro-inches per second	micrometers per second
Patient Rooms and other Patient Areas	4000	100
Operating and other Treatment Rooms	4000	100
Administrative Areas	8000	200
Public Circulation	8000	200

Table I Predictive vibration criteria from *AIA/AHA Draft Guidelines* (Table 6.3.2-1). The calculated vibration velocity values shown in this table pertain to a floor system that responds freely at its first natural frequency after excitation from a transient force generated by an [idealized] human footfall. The human perception threshold (i.e., 100 micrometers per second) is assigned to spaces where the potential recipient of vibration tends to be stationary — the floor vibration criteria are relaxed for spaces where the recipient tends to be more active.

2 Field Experiences

For most equipment used in the healthcare industry, manufacturer's floor vibration criteria are not available. The lack of criteria is partly due to the vibration insensitivity of the equipment relative to the human threshold of perception; i.e., occupants of the facility would tend to complain about "feelable" vibration well before a degradation of the equipment's performance was noticed. An example of such a situation might be image blurring experienced by a person viewing a computer monitor. Building vibration sufficient to cause image blurring would also be noticeably "felt" in one's body. When equipment vibration criteria fall below the human perception threshold, however, the situation changes. For more sensitive medical equipment, the manufacturer usually specifies a maximum level of environmental vibration specific to the device.

A typical example of a sensitive machine is the magnetic resonance imager (MRI). Since the MRI is one of the most common vibration-sensitive devices encountered in healthcare facilities, it will be discussed further in this section.

In the medical field, computed imaging processes are known generically as *computer-aided tomography* (CAT). Several imaging principles are used in CAT "scanning" machines — the particular advantage of a MRI is that it can generate images of the body's soft tissues much more clearly than an ordinary X-ray machine.

Figure 2 illustrates a modern MRI as used in a clinical setting. The general operating principle of the MRI involves material properties at the molecular level in which protons have a characteristic alignment of their magnetic moment or "spin".[3] The proton's "spin" can be momentarily disrupted by a brief radio-frequency pulse received in the presence of an intense static magnetic field. After the pulse disrupts the "spin" alignment of the proton, it will slowly relax back to its original alignment. This process is repeated about once per second, thus generating the repeated "bangs" a patient hears during a MRI scan.

Protons in various molecules of the body's soft tissues relax to their characteristic "spin" alignments at various rates. Assuming the re-alignment rate of the "spin" varies with the type of molecule, a computer could be programmed to analyze the relaxation rates and later display them as a grayscale pattern ranging from light to dark. In a modern MRI, the computer receives signals from internal magnetic sensing coils that detect the rates of the "spin" re-alignment after termination of the pulse.

Since the MRI utilizes a sequential scanning process to image portions of the body, it is important that the bore and the sensing coils not be subjected to excessive vibration, otherwise the image will be slightly blurred.

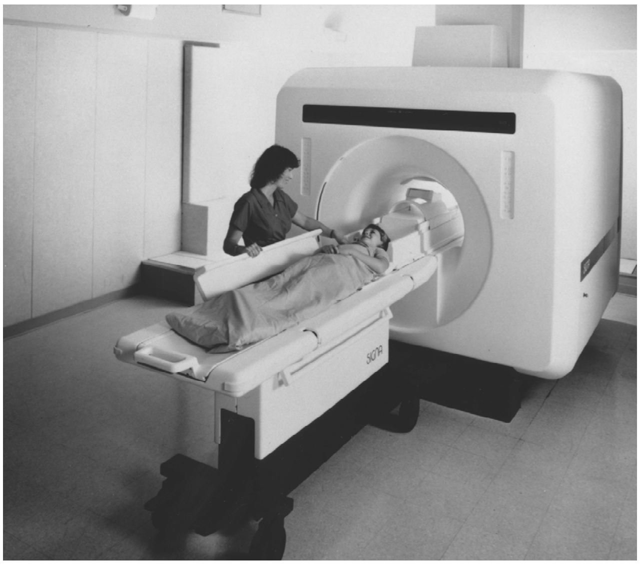

Fig.2 Photograph of an MRI with a patient being prepared for a scanning session. The MRI is the large device with the cylindrical bore. The patient is lying on a movable sled that will later be moved into the bore. The MRI is installed in a room surrounded by heavy magnetic and radio frequency shielding. An intense static magnetic field is continuously generated by superconducting coils located around the bore.

[3] In this paper, the description of the MRI operation is greatly simplified. Refer to Stoller for a more rigorous explanation of MRI principles.

The MRI manufacturer typically divides the machine's floor vibration specification into two parts — one for continuous and one for transient vibration. The transient criterion can be quite difficult to attain in medical facilities where people routinely walk past the MRI location.

The reason for the [apparently] excessive vibration level is that it is specified using *acceleration* rather than *vibration velocity*. The outcome is that high-frequency vibration from people walking by in hard-heeled shoes can exceed the acceleration criterion while the vibration velocity remains relatively small. That is, the mathematical integration of an acceleration signal to obtain velocity results in significant attenuation of high-frequency spectral components.

High-frequency ("banging") noise generated by the MRI can also be transmitted into adjacent sensitive spaces by means of "structure-borne" floor vibration. One manufacturer offers a noise-control accessory in the form of a foamed urethane mat covered with a thick steel plate. The MRI is then fastened to the steel plate using isolated restraint bolts. This vibration isolation arrangement offers about 10 decibels of acoustical improvement and is the only vibration control system pre-approved for use with the MRI.

3 Closing Remarks

In the absence of other specific criteria, the 2006 *AIA/AHA Draft Interim Sound and Vibration Design Guidelines* suggest using generic categories of floor vibration from the *ASHRAE Applications Handbook*. These categories of vibration velocity are based on the shape of the human perception threshold for *whole body* vibration.

The document, *AISC Design Guide 11 — Floor Vibration due to Human Activity*, contains generic methods for predicting the degree of floor vibration due to human footfalls. These simplified methods are limited to predicting the peak vibration velocity caused by impacts from an idealized footfall occurring in heavy steel-frame and concrete floor structures.

Modern healthcare facilities are expected to accommodate a range of sensitive imaging equipment and other diagnostic instruments. Some of this equipment can be particularly sensitive to vibration levels well below the human perception threshold.

A common example is the magnetic resonance imager. The MRI manufacturer typically provides specifications for the maximum continuous *and* transient vibration levels — the latter can often be quite difficult to satisfy, especially if it is expressed in terms of acceleration rather than vibration velocity. High-frequency acceleration from people walking in hard heels can easily exceed the transient criterion even though the vibration velocity remains relatively small.

References

[1] E. E. Ungar, "Designing Sensitive Equipment and Facilities", *Mechanical Engineering*, pp. 47-51 (1985)

[2] D. W. Stoller, "Magnetic Resonance Imaging in Orthopaedics & Sports Medicine", J. B. Lippincott Company, Philadelphia, ISBN 0-397-51144-2 (1993)

[3] J. H. Newhouse, J. I. Wiener, "Understanding MRI", Little, Brown and Company, ISBN 0-316-60474-7 (1991)

[4] A. L. Horowitz, "MRI Physics for Radiologists – A Visual Approach", Springer-Verlag, ISBN 0-387-97717-1 (1992)

[5] A. Nash, "Vibration criteria for a magnetic resonance imager", *The International Society for Optical Engineering*, Vol. 2264, pp. 135-46 (1994)