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Human-Induced Vibrations in Buildings

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Abstract

Occupant footfalls are often the most critical source of floor vibration on upper floors of buildings. Floor motions can degrade the performance of imaging equipment, disrupt sensitive research equipment, and cause discomfort for the occupants. It is essential that low-vibration environments be provided for functionality of sensitive spaces on floors above grade. This requires a sufficiently stiff and massive floor structure that effectively resists the forces exerted from user traffic.

Over the past 25 years, generic vibration limits have been developed, which provide frequency dependent sensitivities for wide classes of equipment, and are used extensively in lab design for healthcare and research facilities. The same basis for these curves can be used to quantify acceptable limits of vibration for human comfort, depending on the intended occupancy of the space. When available, manufacturer's vibration criteria for sensitive equipment are expressed in units of acceleration, velocity or displacement and can be specified as zero-to-peak, peak-to-peak, or root-mean-square (rms) with varying frequency ranges and resolutions.

Several approaches to prediction of floor vibrations are currently applied in practice. Each method is traceable to fundamental structural dynamics, differing only in the level of complexity assumed for the system response, and the required information for use as model inputs. Three commonly used models are described, as well as key features they possess that make them attractive to use for various applications.

A case study is presented of a tall building which has fitness areas on two of the upper floors. The analysis predicted that the motions experienced would be within the given criteria, but showed that if the floor had been more flexible, the potential exists for a locked-in resonance response which could have been felt over large portions of the building.

Keywords: Human-induced vibrations, Sensitive equipment, Occupant comfort, Building performance, Vibration criteria

1. Introduction

The study of vibration in floors has become more of a necessity in recent years due to the optimization of materials in building design creating lighter structures, combined with improvements in research and imaging technology that demand a more stable operating environment. Research and healthcare facilities are a prime example of spaces where a variety of uses and space optimization places vibration sources closer to vibration sensitive equipment and processes.

The primary source of vibration in most facilities is human activity. As people walk, the impact from each footfall induces floor motions that may easily transmit to nearby spaces. Quantifying vibration from walking, whether through measurement of existing spaces or numerical predictions for guiding the design of a new facility, is a complex task. This task is complicated in part by the availability of a number of vibration measurement and prediction methodologies, each associated with both similar and unique assumptions. The difficulties in measurement and prediction are further complicated by the fact that the engineering community has not agreed to a standard method for quantifying vibration and processing methods for assessment of spaces of concern.

In this paper we discuss the impact of unwanted vibrations both from a human perceptibility and sensitive equipment standpoint. Generic and specific vibration criteria that are commonly used in international practice are presented. Several predictive models are discussed that apply to both steel and concrete construction. Finally, a case study involving aerobic activity will be presented, showing the magnitude of vibration that can be induced by human activity.

2. Impact of Unwanted Vibration

Floor vibration from footfalls and mechanical equipment may be transmitted to the floor structure that supports vibration sensitive healthcare/laboratory spaces. Vibration affects sensitive instrumentation by causing relative motion of its key internal components, or relative motion between the instrument and the specimen or target being studied. Figure 1 shows the impact of baseline ambient vibration conditions on the image of an *E. coli* bacterium taken with a Scanning Electron Microscope at approximately 65,000X magnification.

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In healthcare/laboratory spaces housing vibration-sensitive equipment, floor vibration can:

- Cause exceedances of manufacturer-specified vibration criteria for equipment within the space;
- Cause substantial “noise” or errors in measurement, which interferes with the accuracy of measurement results (e.g., imaging);
- Cause the reliability or performance of the equipment to deteriorate; and/or,
- In extreme cases, cause damage or result in loss of equipment calibration.

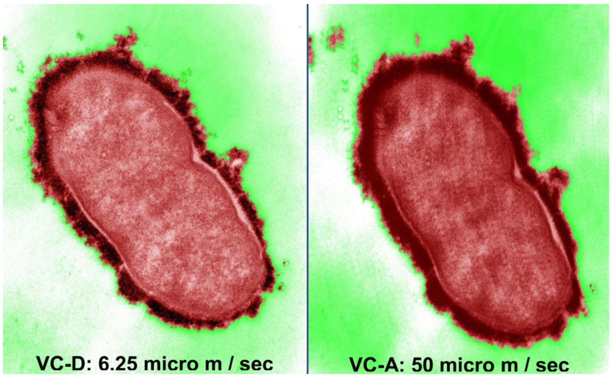

Figure 1. Coloured scanning electron microscope images of *E. coli* bacterium at approximately 65,000X magnification under two levels of ambient vibration.

In addition to their effects on instrumentation, persistent floor vibrations may also cause fatigue and discomfort to building occupants, whether the usage of the building is commercial or residential. High levels of floor vibration can render a space unusable by its occupants, and the impacts can be costly.

3. Vibration Criteria

Over the past 25 years, generic vibration limits have been developed, which provide frequency dependent sensitivities for wide classes of equipment, and are used

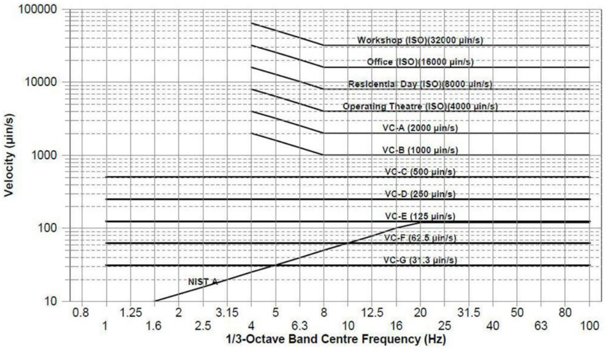

Figure 2. Vibration criteria curves.

Table 1. Generic vibration criteria for healthcare spaces (adapted from Amick et al., 2005)

Vibration criteria curve	Velocity max level[1] μm/s (μin/s)	Description of Use
Workshop (ISO)	800 (32,000)	Distinctly perceptible vibration. Appropriate to workshops and non-sensitive areas.
Office (ISO)	400 (16,000)	Perceptible vibration. Appropriate to offices and non-sensitive areas.
Residential day (ISO)	200 (8,000)	Barely perceptible vibration. Maximum recommended for general sleep areas. Usually adequate for computer equipment and microscopes with less than 40X magnification.
Residential night (ISO)	140 (5,600)	Appropriate for most sleep areas such as hospital recovery rooms.
Op. Theatre (ISO)	100 (4,000)	Threshold of perceptible vibration. Suitable in most instances for surgical suites, catheterization procedures and microscopes to 100X magnifications and for other equipment of low sensitivity. Suitable for very sensitive sleep areas.
VC-A	50 (2,000)	Adequate in most instances for optical microscopes to 400X, micro-balances, and optical balances.
VC-B	25 (1,000)	Micro-surgery, eye surgery and neurosurgery, CT, CAT, PET, fMRI, SPECT, DOT, EROS.
VC-C	12.5 (500)	Appropriate for MRIs, NMRs, standard optical microscopes to 1000X magnification, and moderately sensitive electron microscopes to 1 μm detail size.
VC-D	6.25 (250)	Suitable in most instances for demanding equipment, including may electron microscopes (SEMs and TEMs) at more than 30,000X magnification and up to 0.3 micron geometries, and E-beam systems.
VC-E	3.12 (125)	A challenging criterion to achieve. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, systems working at nanometer scales and other systems requiring extraordinary dynamic stability.
VC-F	1.56 (62.5)	Appropriate for extremely quiet research spaces. Generally difficult to achieve in most instances. Not recommended for use as a design criterion, only for evaluation.
VC-G	0.78 (31.3)	Appropriate for extremely quiet research spaces. Generally difficult to achieve in most instances. Not recommended for use as a design sriterion, only for evaluation.

Notes: [1] As measured in one-third actave bands of frequency over the frequency range 8 to 80 Hz (ISO, VC-A and VC-B) or 1 to 80 Hz (VC-C through VC-G).

extensively in lab design for healthcare and research facilities. The vibration criterion (VC) curves that have been developed are internationally accepted as a basis for designing and evaluating the performance of vibration sensitive equipment and the structures that support them. Figure 2 shows the vibration criterion curves, which range between Workshop (least stringent) through VC-G (most stringent).

These curves were originally based on the ISO 2631-2 (1989) base curve for human response to whole body vibration, which is the threshold of human perception, but have since evolved somewhat. The ISO base curve is often referred to as the ISO-Operating Room criteria, and is less stringent than the VC-A curve. See Table 1 and Figure 2 for descriptions and plots of the commonly referred to ISO curves.

The above noted criteria are specified as velocities in 1/3rd octave bands. The generic vibration curves -existent, or incomplete, or where specific equipment has not yet been selected.

When available, manufacturer’s vibration criteria for sensitive equipment are expressed in units of acceleration, velocity or displacement and can be specified as zero-to-peak, peak-to-peak, or root-mean-square (rms) with varying frequency ranges and resolutions. This inconsistency between manufacturers makes it difficult to compare criteria. An example of criteria for a Transmission Electron Microscope is shown in Figure 3, where the criterion is given in peak-to-peak displacement. In this case, the predicted/measured vibration must be compared to the criteria by using Fast Fourier Transforms (FFT) of the floor motions, with a frequency resolution of 0.125 Hz. This can be challenging when predicting floor motions using simplified models that do not employ time history responses.

The American Institute of Steel Construction (AISC, 1997) has recommended acceleration criteria for various occupancies of residential and commercial buildings (Figure 4). These criteria are based on peak acceleration values, and are dependent on the fundamental frequency of response of the floor. The recommended acceleration levels for rhythmic activities are ten times greater than those for residential and office occupancies, as people engaged in those activities are more likely to accept greater vibrations due to the nature of their activities. A greater allowance is also made for shopping malls and spaces intended for dining and dancing. As with the VC criteria described above, these curves are based on the ISO 2631-2 (1989) base curve for human response (also shown in this figure). The National Building Code of Canada (NBCC 2005) provides similar guidelines.

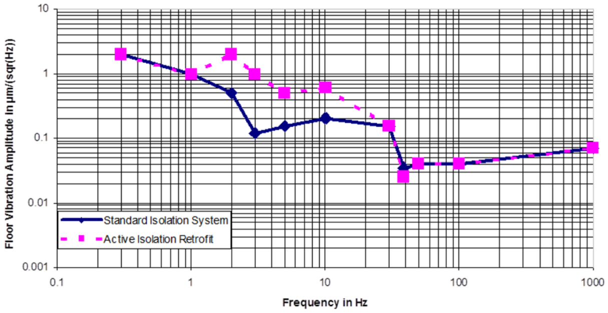

Figure 3. Allowable vertical floor amplitudes for JEOL JEM-2100/2200 with standard and active retrofit isolation system.

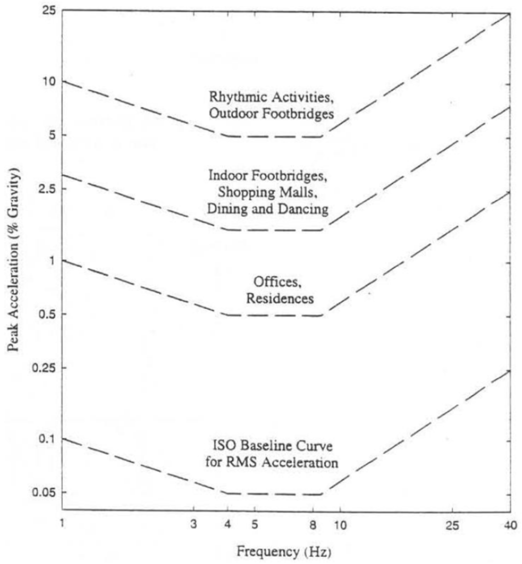

Figure 4. Recommended peak acceleration for human comfort for vibrations due to human activities (AISC 1997).

4. Predicting Floor Vibrations

Several approaches to prediction of floor vibrations are currently applied in practice. Each method is traceable to fundamental structural dynamics, differing only in the level of complexity assumed for the system response (i.e., SDOF versus MDOF), and the required information for use as model inputs (i.e., modal mass, modal damping and stiffness characteristics). Although more complex models are often touted as being more accurate for use in design, they are not without fault, as a certain level of expertise is required to without the possibility of correlation with measurements of the structure. As a result, assumptions must be made throughout the modeling process that can affect predicted vibration levels and design recommendations. Less complex design methods do not suffer from many of these problems; however, they are limited in their range of applicability, since they are often based on empirical data gathered under specific conditions. Nevertheless, a benefit of these less complex design methods is that fewer inputs are required, making them less susceptible to user error and accessible to a wide range of practitioners.

The modeling technique outlined by the American

Institute of Steel Construction (AISC, 1997) has been used in North America for the past 10~15 years by structural designers and vibration engineers to estimate the response of composite steel and concrete floors to footfall vibrations. The method is popular because it is accessible to a number of practitioners and can be easily applied to regular framing configurations common to many buildings in North America. Commercial software implementations of the technique are also available and are currently used by a number of structural engineers.

The point deflection of the floor is computed based on beam deflection formulas and a numerical estimate of the number of effective composite tee beams. These parameters can be estimated using other techniques such as finite element modeling. The remaining parameters are based on the weight and speed of the walker, which define an idealized footfall pulse forcing function. The magnitude of the footfall pulse is defined based on measurement data. At its core, the AISC response estimate is simply the response of an SDOF oscillator with a calculated stiffness, frequency, and zero (or near zero) damping, subjected to a single idealized foot pulse having characteristics defined based on empirical relationships.

The Steel Construction Institute (SCI P354, 2007) provides a detailed procedure to predict the time history response of a floor in a steel framed building. It has been in use primarily in the United Kingdom and portions of Europe for several years, and has only recently started to be used in North America. It is a more complex approach compared to the AISC procedure, but is more versatile, in that it is able to more accurately represent the dynamic response of a complicated floor arrangement. The SCI method requires the development of a Finite Element Model (FEM), and provides several recommendations regarding modeling techniques for such a dynamic model. Further, since it produces multi-modal time history predictions, further spectral analysis is possible. This feature is useful when comparing predicted responses to more complicated criteria that require narrow-band frequency analysis (such as that shown in Figure 3). Finally, the SCI method makes a distinction between, and has separate analysis procedures for, ‘low-’ and ‘high-frequency’ floors. The former (< 10 Hz) typically show a resonant response to human activity, while the latter typically show a transient impact response.

The Concrete Centre (CCIP-016, 2006) provides a detailed procedure to predict the time history response of a floor in a concrete framed building. It has also been in use primarily in the United Kingdom and portions of Europe. The approach is similar to that of the SCI, where the primary difference is in the dynamic load factors that have been observed in buildings with concrete construction. CCIP-016 also requires the development of a FEM, as well as different methods for ‘low-’ and ‘high-frequency’ floors. Its accuracy has been validated and independently peer reviewed.

5. Case Study - Rhythmic (Aerobic) Activity

Rhythmic activities such as dancing and aerobics can cause excessive vibration levels due to the possibility of synchronization of the participants in response to a musical beat. Music during aerobic activities typically falls within a range of 120 to 180 beats/min, resulting in correlated footfall impacts occurring at a rate of 2~3 Hz.

Forces are also affecting the floor at multiples of the fundamental stepping frequency (i.e., 4 Hz, 6 Hz, 8 Hz etc., for a fundamental step frequency of 2 Hz), and it is therefore possible to excite the floor at frequencies higher than the fundamental stepping rate. In general, it is desirable to design the floor to have a fundamental frequency above approximately 10 Hz.

An assessment of vibration due to rhythmic activity was completed on two upper levels of a high rise concrete/steel building. The vibration levels were compared against recommended comfort criteria for the fitness rooms. The floor system consisted of a 180 mm concrete slab supported by a steel truss framework. The floor was supported at the centre by the building core, and at the perimeter by large columns.

A structural FEM of the fitness levels was developed using SAP2000 Nonlinear analysis software, and was used to estimate the dynamic properties of the floor. The methodology prescribed by the Steel Construction Institute (SCI P354) was used to predict the response of the floor to several aerobic loading scenarios, ranging from 12 to 80 people jumping at various points on the floor at rates between 120 and 180 steps/minute. The synchronization between individuals was modeled using a scaling factor that is based on the number of individuals engaged in the rhythmic activity (as prescribed in SCI P354).

Figure 5 shows the predicted responses for the worst-

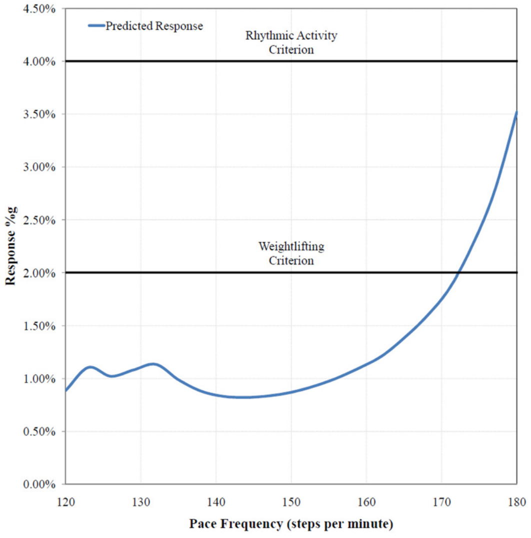

Figure 5. Predicted acceleration response for 35 people performing rhythmic activities in the North portion of the fitness room.

case loading scenario under consideration, compared to the criteria requested by the client, which in this case was the NBCC (2005). The NBCC provides separate criteria for weightlifting and rhythmic activities, which are more stringent than those provided by the AISC. It can be seen from this figure that the criteria are expected to be met for the expected worst case, but will be very perceptible to people standing in the aerobics area (perceptibility for most people in this frequency response range is generally above 0.5%*g*). The upwards tail at higher jumping frequency is due to the input frequency approaching the fundamental frequency of the floor. Had the floor been less stiff, it is possible that the rhythmic activity would have led to a locked-in resonance response, which has the potential to be felt in a widespread area of the building.

6. Conclusion

This paper presented an overview of human-induced vibration in concrete and steel buildings. The impact of these vibrations can have a detrimental effect on the performance of sensitive equipment and impact the occupants through annoying and potentially alarming motions. There are several established and evolving criteria for determining acceptable levels of vibration which range from far below perceptibility to motions that are very noticeable. The degree of allowable perceptibility depends primarily on the usage of the space, with stricter criteria for residential and office occupancies, and more lenient levels for areas expecting aerobic and dancing activities.

Several methods for predicting the levels of human-induced vibrations are in widespread use internationally, with three of the more common methods being the AISC Design Guide 11, SCI P354 and CCIP-016. The AISC method is based on empirical factors, and is most useful for quickly predicting motions on floors that have simple and repeated layouts across all bays, while the SCI and CCIP methods depend on the development of a Finite Element Model in order to capture the more complicated behaviour of complex structures. The latter two methods are also capable of producing time history predictions that can be processed into forms that are comparable with complex criteria.

A case study was presented of a tall building which had fitness areas on two of the upper floors. The analysis predicted that the motions experienced would be within the given criteria, but showed that if the floor had been more flexible, the potential ex-over large portions of the building.

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