1 Introduction

Advances in materials, construction, and design technology have led to the construction of lighter floor systems, which are more susceptible to footfall-induced vibration. Meanwhile, improvements to imaging technology, including magnetic resonance imaging (MRIs) and electron microscopes, have led to devices which have increasingly stringent vibration requirements to ensure optimal performance. As a result, it is becoming more common for floor vibrations to be the governing factor in the design of the structural system.

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.

In this paper we discuss generic and specific vibration criteria that are commonly used in international practice for sensitive spaces. Several predictive models for footfall-induced vibrations are discussed that apply to both steel and concrete construction.

2 Vibration Criteria

For human comfort, vibration criterion is normally expressed as the root mean square (RMS) response of each one-third octave band from 1 Hz to 80 Hz [1]. For sensitive equipment, the criteria may be expressed in one-third octave bands, or other formats, including power spectral densities, peak-to-peak levels, etc. 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 design of healthcare and research facilities [2]. These vibration criterion (VC) curves are internationally accepted as a basis for designing and evaluating the performance of vibration sensitive equipment and the structures that support them. The VC curves range between Workshop (least stringent) through VC-G (most stringent). See Table 1 for a list of descriptions of use for spaces meeting these criteria levels.

These curves were originally based on the ISO 2631-2 (1989) [3] base curve for human response to whole body vibration, which is the threshold of human perception, but have since evolved. The ISO base curve is often referred to as the ISO-Operating Theatre criteria. The VC curves should not be used to replace manufacturers’ specifications for vibration requirements, but are beneficial where manufacturers’ specifications are non-existent, incomplete, or where specific equipment has not yet been selected.

<table>
<thead>
<tr>
<th>Vibration Criteria</th>
<th>Description of Use</th>
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<tbody>
<tr>
<td>Workshop (800 μm/s)</td>
<td>Distinctly perceptible vibration. Appropriate to workshops and non-sensitive areas.</td>
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<tr>
<td>Office (400 μm/s)</td>
<td>Perceptible vibration. Appropriate to offices and non-sensitive areas.</td>
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<tr>
<td>Residential Day (ISO) (200 μm/s)</td>
<td>Barely perceptible vibration. Maximum recommended for general sleep areas. Usually adequate for computer equipment.</td>
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<tr>
<td>Residential Night (140 μm/s)</td>
<td>Appropriate for most sleep areas such as hospital recovery rooms.</td>
</tr>
<tr>
<td>Operating Theatre (100 μm/s)</td>
<td>Threshold of perceptible vibration. Suitable in most instances for surgical suites, catheterization procedures and microscopes to 100 X magnifications.</td>
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<tr>
<td>VC- A (50 μm/s)</td>
<td>Adequate in most instances for optical microscopes to 400X, micro-balances, and optical balances.</td>
</tr>
<tr>
<td>VC- B (25 μm/s)</td>
<td>Micro-surgery, eye surgery and neurosurgery, CT, CAT, PET, iMRI, SPECT, DOT, EROS.</td>
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<td>VC- C (12.5 μm/s)</td>
<td>Appropriate for MRIs, NMRs, standard optical microscopes to 1000X magnification, and moderately sensitive electron microscopes to 1μm detail size.</td>
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<tr>
<td>VC- D (6.25 μm/s)</td>
<td>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.</td>
</tr>
<tr>
<td>VC- E (3.12 μm/s)</td>
<td>Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, and systems working at nanometer scales.</td>
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Table 1: Vibration criteria descriptions of use.

The Guidelines for Design and Construction of Hospitals and Outpatient Facilities (FGI 2014) [4] provides limits for floor vibration in several types of areas in healthcare facilities caused by footfalls, which are consistent with those found in Table 1. The CSA Standard Z8000-11 (Canadian Health Care Facilities) [5] also refers to these vibration criteria levels. These two documents require the use of the American/Canadian Institute of Steel Construction (AISC/CISC) Design Guide 11 (DG11) [6] to provide footfall-induced vibration predictions.
3 Predicting Footfalls

3.1 American/Canadian Institute of Steel Construction Design Guide 11

The modeling technique outlined by the American Institute of Steel Construction (AISC) Design Guide 11 has been extensively used in North America for the past 15 years. For human comfort, the AISC method assumes the floor behavior is governed by the resonant response of the fundamental floor mode. A steady-state floor response is calculated assuming the walker and vibration-sensitive receptor are both located at the position of the maximum modal displacement (center of the bay) to produce a worst-case response. The natural frequency of the floor is estimated from the maximum static deflection of the bay under consideration due to the acting dead and live loads. Such a simplistic method cannot easily predict the natural frequency when the floor layout is irregular, such as would occur around shafts and/or in non-rectangular buildings.

For areas with sensitive equipment, the AISC considers three walking speeds: 50, 75, and 100 steps per minute. An empirical force coefficient is estimated as a function of the walking pace, and the weight of the walker. Simple beam theory is employed to calculate the floor deflection, and the natural frequency. The floor response velocity is then calculated as a function of the force coefficient, floor natural frequency, and floor deflection.

3.2 Steel Construction Institute and Concrete Centre

The methodologies proposed by The Steel Construction Institute (SCI P354) [7] and The Concrete Centre (CCIP-016) [8] for calculating footfall-induced floor vibrations are similarly derived. The methods recommend utilizing a Finite Element (FE) model to predict the mode shapes and natural frequencies of the floor. FE modeling is advantageous since it allows the calculation of many mode shapes, any of which can contribute significantly to the vibration of a specified floor region. Moreover, irregular floor features (including non-rectangular bays, shafts, and different beams or slab thicknesses from bay-to-bay) can easily be accommodated by the FE model.

The response of each mode is assumed to be either resonant or impulsive, depending on the associated floor frequency. Empirically determined frequency-dependent dynamic load factors are used to excite the floor along probable walking paths as determined from the architectural drawings. The loading conditions are then used to develop a time series response for each mode. The time series responses for each mode are then linearly superimposed to produce a total floor response at any receptor point on the floor. A range of realistic walking frequencies and walking paths are considered to determine the governing floor response. Spectral analysis can be performed on the predicted time-series responses to express the floor behavior in a format appropriate for comparison with the relevant criteria.

Refer to [9] for a comparative study on the accuracy of these methods.

4 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.

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.

References