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Review article

Response of high frequency floors: A literature review

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ABSTRACT

This article reviews the process of estimating the response of high frequency floors (HFFs) to footfalls. The article begins by describing the evolution of the various forcing models. Originally, analyses were conducted using the harmonic methods that use the Fourier components of a walking time history. After the fourth harmonic of a footfall (approximately 10 Hz) very little energy exists and the harmonic methods were found not to be suitable for design of these 'HFFs'. This was the reason for the development of some alternative force models. These models are discussed and their accuracy compared with real recorded footfall time histories. The article then continues to review the estimation of the floors dynamic properties, starting with hand calculations and evolving into using finite element analysis combined with modal superposition to estimate the floor's response. The mechanisms of damping and the reason for why it is not possible to estimate damping with respect to the material properties are discussed. The article ends with a review of response criteria, describing how criteria for sensitive occupancy, for which many HFFs are used for, were developed. It was found that there is much discussion about the cut-off frequency between high and low frequency floors. A solution would be to develop an universal forcing function that is suitable for both the methods. Even with an accurate forcing function, there is little guidance on how to model floors in general; some floors can have many bays, which can result in large number of modes proving costly in computing time using the present methodologies. The response of these floors is usually evaluated using Bolt Beranek and Newman's (BBN's) vibration criteria (VC) curves, which was developed as an extension of human vibration criteria using the signal analysers that were available at the time. This may not be the most efficient means of designing a floor, and criteria specific to the floors occupancy may be a better option in certain cases.

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1. Introduction

Construction methods for floors and their uses have changed over the last 100 years. Floors were traditionally designed to an Ultimate Limit State (ULS), where design for strength governed the size of the floor components. The concept of Serviceability Limit State (SLS) was to limit the maximum deflection of the floor and the SLS limit was not set to avoid damage of structural components, but to avoid cracking of finishes.

Now instead of deflection, vibration serviceability has become a major concern for several reasons:

1. Construction techniques have changed, allowing for longer span floors with much lighter construction.
2. Occupancy of 'normal' floors has changed. Historically, office spaces were cellular, filled with filing cabinets and bookcases. With moves towards open plan, paperless offices and increasing use of computer equipment, the mass of non-structural components supported has in general been reduced.
3. Huge technological advances have been made in medical, scientific and micro-manufacturing and as these disciplines move towards greater dimensional precision, the type of equipment used becomes extremely sensitive to vibration.

As a result, in order to ensure adequate performance and avoid vibration serviceability problems, in the last decade, there has been a significant increase in the volume of research on floor vibrations and vibration criteria (VC).

The original problem was limited to perception by humans, a problem not specific to floors and more commonly experienced (or at least made public) in footbridges. In this respect, reviews of human perception to vibration for floors and footbridges are given, respectively, by Pavic et al. [1] and Zivanovic et al. [2], with the relevant standards for human perceptibility of vibration being BS6472 [3] and ISO2631 [4].

These guidelines for human perception are not suitable as criteria for sensitive machinery and these have developed independently. During the 1970s, prompted by lack of guidance by machine manufacturers, Bolt Beranek & Newman Inc. (BBN) attempted to create a generic set of criteria specific to sensitive machinery [5]. These criteria are known as the VC curves and are currently widely used.

Having a well defined set of criteria is an excellent step, leaving the major problem of predicting floor response before construction. There are then four steps even before an analysis is done and a judgement is made:

1. The design force for the floor needs to be defined.
2. The floor stiffness distribution needs to be evaluated with adequate accuracy.
3. The floor mass distribution needs to be evaluated with adequate accuracy.
4. An appropriate level of damping needs to be associated with the floor.

For the first step, research into human walking forces has predated vibration serviceability problems, due to interest in the health sector [6] and for intruder detection [7]. As with acceptance criteria, the research on walking forces for floors has to some extent tracked research for bridges [1,2], and it is now commonly agreed that for most applications a footfall force is best represented in the frequency domain. It can be shown that a footfall contains most of its energy below 10 Hz, and this region can be assumed to be best represented by harmonic forcing functions. However, there is still energy present above 10 Hz and this is assumed to be best represented through an impulsive forcing function.

This notional boundary at 10 Hz was the origin of the term 'high frequency floor' (HFF) [8] since a HFF by definition does not exhibit a resonance response due to walking, but appears to respond as if to a sequence of impulses.

Given the forcing function, for steps 2–4, the technique of modal superposition is commonly used (and advocated in design codes) to predict the response. Stiffness and mass are linked through modal frequency, and design guides from the Steel Construction Institute (SCI) [9–12], American Institute of Steel Construction (AISC) [13], Canadian Standards Association (CSA) [14], the Concrete Society [15] and the Concrete Centre [16] all offer methods of predicting natural frequency and 'participating mass'. These methods have superficial differences but are based on similar theory.

Prediction of natural frequency is either by assuming the floor to act like a beam or a plate, and usually only the fundamental frequency is estimated, while the participating (or modal) mass estimation is based on a crude estimation of the mode shape. Such methods, designed to simplify management of floor vibration serviceability, become inaccurate when applied to complex floor arrangements. Given the inaccuracies due to simplifications and access to powerful computer software and hardware, detailed finite element analysis (FEA) is now often preferred and if applied correctly should be capable to estimate more accurately the modal frequencies and masses of a floor, not limited to the fundamental mode. On the other hand, damping ratios cannot be derived analytically and are usually selected from experience, or through suggested values in the design guides.

2. Types of high frequency floors

Although HFFs are generally constructed for sensitive occupancies, the range of sensitivities within the floor category varies considerably. Depending on the stringent criterion required for the specific sensitive occupancy, the construction type of a HFF will vary. Two main construction types exist: slab on grade, which is built directly on the ground, and suspended slabs supported by columns. Slab on grade floors perform very well in response to internal vibrations, however, they can only perform as well as the ambient conditions of the ground supporting them. When considering a suspended slab for a sensitive occupancy the design criteria shift from an ULS to SLS (i.e. design for vibration performance governs over strength).

For sensitive floors such as hospitals, stringent criteria can be met with a standard office style floor [5,9], but with larger member sizes. The SCI have recently been involved in the construction of many new hospital buildings using their SlimDek floors [17], shown in Fig. 1. Due to the office style construction, using lightweight, composite methods, there has been a public debate arguing whether steel-composite floors are suitable for sensitive occupancies [9,18–21]. Floors with sensitive occupancy were traditionally constructed using reinforced concrete, providing large mass but still enough stiffness for the fundamental frequency to be above 10 Hz. There was a concern that due to the reduction in mass of the steel-composite floor, even if the floor frequency is above 10 Hz, the floor would not meet the stringent criteria.