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A review of vibration serviceability criteria for floor structures

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Abstract

This paper is a survey of the historical developments in modeling human dynamic loads, perception criteria used in structural floor vibrations, and the techniques used to mitigate the human-induced vibrations. Two of the techniques are explained in more detail, namely: semi-active control and passive control using advanced materials.

Keywords: Dynamic loads; Vibrations; Floor systems; Perception criteria; Vibration control

1. Introduction

Sports stadiums, discotheques, gymnasiums, aerobic dance studios, shopping malls, and airport terminal corridors are all subjected to significant dynamic loads produced by occupants either while remaining in one location or traversing the structure. Coherent crowd harmonic movements can produce resonant or near-resonant structural vibrations that are uncomfortable and intolerable for some occupants. Some structural failures, such as the Hyatt Regency Hotel in Kansas City [1], indicate that there can be many lives at stake when human loading is imposed. In addition, there have been serviceability problems that required costly remodeling or revision of building regulations.

At the present, US codes and standards are primarily concerned with avoiding structural failure (i.e., a strength requirement), and deal with excessive vibrations (i.e., a serviceability requirement) only to a limited degree [2,3]. Empirical serviceability requirements usually do not involve the frequency of the loading or the natural frequency of the structure. Many researchers believe these requirements are inadequate for controlling the human-induced vibrations. This paper provides a survey of the historical developments in modeling human dynamic loads, perception criteria used in structural vibrations, and various techniques that are used to mitigate the human-induced vibrations.

2. Human-induced dynamic loads

Live loads are produced by the use and occupancy of a structure. Human loads comprise the large portion of the live loads in floors of offices and residential

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buildings. In assembly structures such as ballrooms, grandstands, health clubs, as well as pedestrian bridges, human-induced dynamic loads are the principal source of live loads. In general, the human live loads are classified into two broad categories: in situ and moving. Periodic jumping to music, sudden standing of a crowd, and random in-place movements are examples of in situ activities. Walking, marching, and running are examples of moving activities.

Tilden [4] and Fuller [5] were among the first researchers to experimentally quantify the dynamic load effects of individuals and groups, respectively. Tilden considered both in situ and moving loads. Fuller attempted to experimentally quantify the crowd dynamic effect due to a group of people on a gymnasium balcony. Greimann and Klaiber [6] predicted the spectator dynamic loads on the Iowa Sate University stadium during a football game. Structural vibrations have been recorded as a result of spectator movements in rock concert in Canada [7]. Tuan and Saul [8] defined various types of in situ movements by measuring the load-time histories for individual subjects on a small piezoelectric force platform. Ebrahimpour and Sack [9] used a large instrumented force platform to measure in situ loads by individuals and groups of two and four people. In a subsequent study, Ebrahimpour and Sack [10] constructed a 3.7 m by 4.6 m floor system and measured forces of up to forty people performing in situ harmonic movements. They also recommended simple design values for coherent crowd harmonic movements.

Only a very few studies of human moving loads have been reported. Canadian researchers measured dynamic forces of individuals and small groups of people [11]. Ebrahimpour et al. [12] measured the input forces imposed by moving groups of people using a set of instrumented platforms, mathematically modeled the loads, performed simulations, and suggested simple design loads for serviceability criteria.

3. Human perception of structural vibrations

The most frequently cited reference for human perception of vibration is by Reiher and Meister [13]. The Reiher–Meister scale is based on a displacement range of 0.01–10 mm and frequency range of 1–100 Hz. The modified Reiher–Meister scale was proposed by Lenzen [14] for vibrations due to walking impact. For floors with less than 5% critical damping, Lenzen suggested the original scale be applied if the displacement is increased by a factor of ten. Wiss and Parmelee [15] suggested that a constant product of frequency and displacement existed for a given combination of human response and damping. Allen and Rainer [16] developed vibration criteria in terms of acceleration and damping intended for quiet human occupancies such as residential buildings and offices. As damping increases, the steady-state response due to walking becomes a series of transient responses; resulting in a less significant response. Murray [17] suggested a human perception scale for required damping as a function of the product of initial displacement and frequency, which are the same parameters used in the Wiss–Parmelee scale. Allen et al. [18] suggested a design procedure for assembly floors subjected to rhythmic activities such as dancing and exercises. The International Standards Organization (ISO) [19] recommends vibration limits in terms of acceleration root-mean-squared (rms) and frequency. As shown in Fig. 1, a baseline curve is used by ISO and different multipliers are used for different occupancies.

The vibration serviceability criteria for floors have been categorized into two broad categories. These are: criteria for steel beam and concrete slab construction, and wood/lightweight construction. The following sections describe the research in each category.

3.1. Criteria in steel beam and concrete slab construction

Allen and Rainer [16] developed a vibration criterion for floors due to footstep loading which were based on tests on 42 long span floor systems. Ellingwood and Tallin [20] recommended a criterion for commercial floors. It is based upon a specified maximum deflection with a prescribed point load placed anywhere on the structure (i.e., a stiffness requirement). Updated guidelines for preventing annoying vibrations in steel framed floor systems are presented in a guide jointly published by the

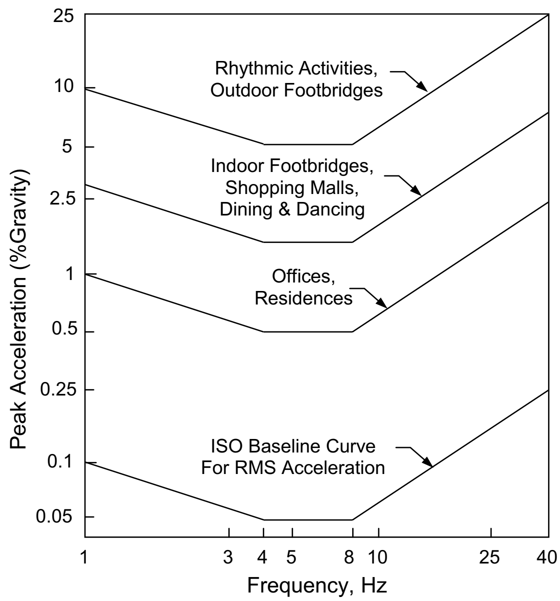

Fig. 1. Peak accelerations for human comfort for vibrations due to human activities [19].