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Wind-induced motion on tall buildings: A comfort criteria overview

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ABSTRACT

Comfort performance during wind-induced motions is an important building design issue. Several criteria concerning comfort evaluation are not agreed between different authors and different normative codes such as use of peak instead of root-mean-square (rms) acceleration; influence of waveform on comfort evaluation; and comfort evaluation based on users' perception and level of complaint. The discussion presented in this paper analyses comfort evaluation aligned with the hypothesis that, in the future, users must be aware of the building motions and educated to cope with it. Provided the building motion does not affect structural integrity and safety, an alternative approach for human comfort assessment to wind-induced motion might take place. Assessment of sustained vibration for nausea, task performance reduction and other compensatory behaviors might lead to less conservative structural design.

1. Introduction

Serviceability limit state (SLS) of a tall building during wind-induced motion can be a critical design issue. Once the strength criteria are satisfied, users' comfort must be assessed in order to validate the structural design.

A building's SLS for wind-induced motion is usually verified by calculation of the lateral drift between two consecutive stories or by the overall lateral displacement of the building, where these displacements are calculated using equivalent static wind loads from the local wind code (NBR6118, 2014; Griffis, 1993). These lateral displacements are verified to ensure that non-structural elements such as cladding and partitions will not be damaged during windstorms (Griffis, 1993). Other criteria such as creaking noises and feeling of self-movement were documented by Hansen et al. (1973), nonetheless no comfort criteria were made later on based on these documented motion cues.

Users' comfort to motion is evaluated by the acceleration at the floor of interest. Since tall building might present mixed uses (Residential, Hotel and Offices) and the comfort threshold is different for each one of these uses (as it will be discussed later in this paper), the comfort verification might take place on the highest occupied floor (Sarkisian, 2012) or on some residential/hotel floor at a lower story.

Current criteria to evaluate comfort are based on users' perception to motion, which is assessed through acceleration curves (ISO 6897, 1984; ISO 10137, 2007; Sarkisian, 2012; Tamura, 2007). A precise explanation about the reason to use acceleration to evaluate comfort shall subsequently take place in the next section of this paper. Fig. 1.1 illustrates the situation considered in the design phase for the user at the target floor of a tall building.

According to Burton et al. (2006), motion can be perceived through several forms such as vestibular organs, proprioceptive sensations, auditory cues and visual cues. The interaction of these mechanisms of perception composes the sensing system, determining a person's sensitivity to a building's motion.

In the 1950s and 1960s, the aerospace industry performed several experiments to predict human response to vibration. However, it was questionable to apply these results on tall buildings, since most of these experiences were made for frequencies higher than 1 Hz (Chang, 1973), while the first few natural frequencies of a tall building vary within a range of a small fraction of 1 Hz to 1 Hz.

During the subsequent decades, a large number of experiments were carried out using motion simulators for tall building applications. These tests concentrated efforts on the relationship among a wide selection of variables and the perception, comfort and task-performance thresholds, like maximum peak acceleration, frequency, wave form (sinusoidal, random), movement direction (lateral, fore-aft), damping rate and biodynamic response (Kwok et al., 2009).

1.1. Objectives

This paper addresses important issues of comfort criteria in buildings subjected to wind loading. The characteristics of the motion (kinematic, physiological, statistical and psychological) are

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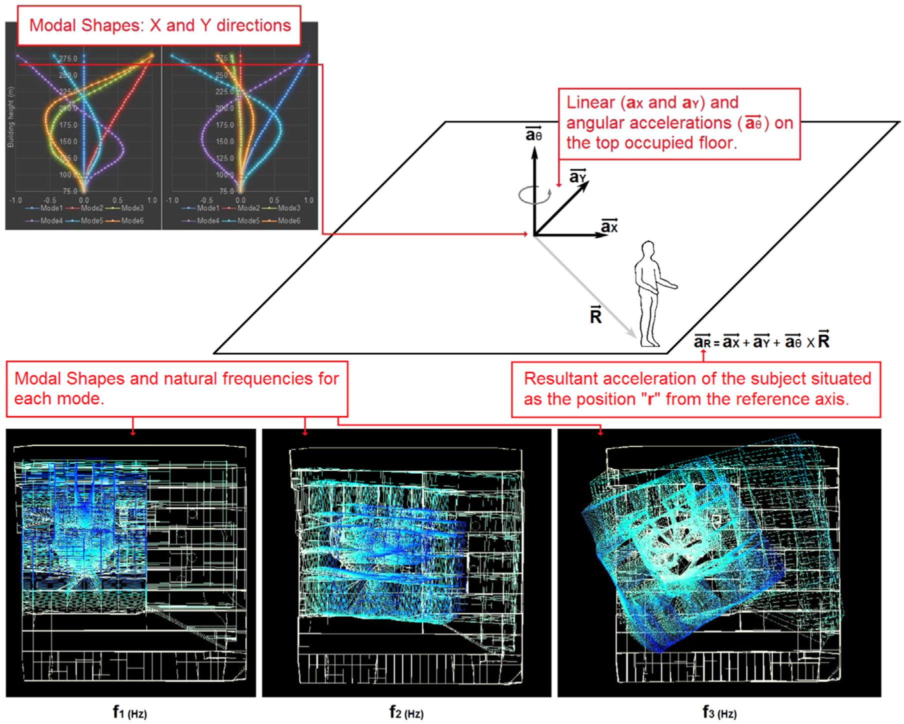

Fig. 1.1. Acceleration assessment overview.

initially discussed. Section 2 (*Properties of the motion*) addresses the reasons for using the acceleration for comfort assessment, frequency dependency of comfort thresholds, return period, etc.

Then, Section 3 explains the current approach for human comfort assessment during wind-induced motion in tall buildings. This explanation covers historical backgrounds, compares different National codes/International standards and leads to an ample understanding of them.

Finally, Section 4 discusses the main issues proposed in this paper, especially the two approaches for comfort assessment:

1) The current approach: based on perception levels (introduced later on this paper);
2) A new approach: based on nausea and reduction task performance (also, introduced later).

2. Properties of the motion

2.1. Kinematic properties of the motion

According to Taranath (2012), users' comfort during wind-induced motion on tall buildings can be assessed through several indicators such as displacement, velocity, acceleration and the derivative of acceleration. Acceleration, however, became the standard measure of comfort due to its easy field measurements and analytical verification.

Chang (1973) explored each of these indicators in his work. In this chapter, each of these kinematic properties will be presented.

2.1.1. Amplitude of motion

Chang (1973) used the amplitude of motion and the first natural frequency of the building to estimate the acceleration assuming a sinusoidal vibration. Afterwards, Chang made a comparison with a set of comfort curves to categorize the building motion in regions of comfort/perception such as "non-perceptible", "perceptible", "annoying", "very annoying" and "unbearable".

Amplitude of motion might give to the subject apparent visual cues of the building movement, such as visual parallax. It also might trigger noise cues such as the creaking noises documented by Hansen et al. (1973). These visual and sound cues might confirm and/or increase the feeling of the motion by other mechanisms of perception (Kwok et al., 2009).

Chang (1973) also stated that previous investigations identified that human discomfort is a function of the amplitude above certain frequencies only. Apparently, for the frequency range of wind-induced vibrations (from a fraction of Hertz to 1 Hz), amplitude of motion does not trigger other than visual and noise cues of the motion.

2.1.2. Velocity

2.1.2.1. Linear velocity. Chang (1973) stated that individuals cannot feel velocity directly they can only feel the indirect effects of it, such as the wind pressure on the body. Naturally, people free from atmosphere effects, vibrations, sounds and visual cues cannot tell if they are moving at a constant speed or standing still.

Chang cited researchers telling that the threshold depends on velocity for vibrations between 20 Hz and 60 Hz (frequencies far above the range of wind-induced vibrations in studies of comfort in tall buildings).

2.1.2.2. Angular velocity. Sarkisian (2012) presented Council of Tall Buildings and Urban Habitat (CTBUH) criteria for torsional velocity: 1.5 milli-radians/s for one-year return period windstorms; 3.0 milli-radians/s for 10-year return period windstorms. In many cases, torsional velocities and accelerations can be more important than linear accelerations.

2.1.3. Acceleration

2.1.3.1. Linear acceleration. The otolith organs, in the vestibular system, are deeply responsible for the detection of accelerations (Burton et al., 2006; Chang, 1973). In the ISO 6897 Standard (1984), the main motion perceiving cues are assumed to be those from the proprioceptive sensations and from the vestibular organs and, therefore, linear acceleration is the chosen property to evaluate comfort and perception to motion in that document and also the parameter of comfort evaluation for several other normative documents. Chen and