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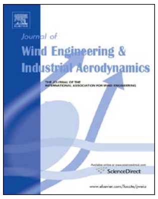

The fundamental human response to wind-induced building motion

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ABSTRACT

This paper identifies seven areas where an increase in our fundamental understanding of the human response to building motion will facilitate the design of next-generation serviceability criteria for wind-induced building motion. These advances in knowledge address: (1) understanding the effects of wind-induced building motion on occupants, (2) metrics for building performance assessment, (3) understanding of habituation to building motion, (4) potential and real benefits of education, (5) motion characteristics to predict adverse occupant effects, (6) differentiation between residential and office serviceability criteria, and (7) multidisciplinary research methods and measures used in occupant comfort research. Each is discussed with reference to engineering literature and incorporates a multidisciplinary perspective including psychological and physiological research. Finally, methodological issues in the occupant comfort literature are discussed and recommendations for future research are offered to facilitate the design of next-generation serviceability criteria for wind-induced building motion.

1. Introduction

A growing body of literature shows that wind-induced building motion can be perceptible (Goto, 1983; Hansen et al., 1979), induce motion sickness (Goto, 1983; Hansen et al., 1979; Lamb et al., 2013), provoke fear (Burton, 2006), cause sopite syndrome (sleepiness) (Lamb et al., 2014), and reduce work performance (Lamb et al., 2014). While these studies have advanced the understanding of the range of possible effects of motion on occupants, it is not currently possible to predict the motion conditions that cause adverse occupant effects. Consequently, there is insufficient research to form the basis of robust serviceability criteria to ensure that building occupants are minimally affected by building motion. Despite these incremental, but important advances, engineers and building designers have rapidly developed new design and construction techniques, allowing building designers and engineers to create increasingly tall skyscrapers that are inherently light and therefore wind sensitive.

The aim of this paper is to identify where an advancement of knowledge will inform the design of next-generation serviceability criteria for wind-induced building motion. The paper identifies areas that are potentially misunderstood, ignored, or under-researched. The following sections discuss each knowledge gap in the context of recent research and evidence from a broad range of disciplines, in order to propose a direction and method for future research. Finally, this paper discusses methodological deficiencies that exist in the occupant comfort literature, and suggests potential solutions.

2. Areas for knowledge advancement

2.1. Understanding the effects of wind-induced building motion on occupants

Effective and robust serviceability criteria must address all significant adverse effects of exposure to wind-induced building motion. Forty years of research identified a range of adverse effects including motion perception (Hansen et al., 1979; Lamb et al., 2013), motion sickness (Hansen et al., 1979; Lamb et al., 2013; Burton, 2006), and fear (Burton, 2006); see Kwok et al. (2009) for a comprehensive review. However, recent research identified two additional and significant adverse effects; sopite syndrome (mild motion sickness) and reduced work performance (Lamb et al., 2014).

Lamb et al. (2014) conducted the first study investigating the effect of wind-induced building motion on the work performance of office workers over a period of nine months. The study shows that building motion can cause sopite syndrome, thought to be a form of mild motion sickness. Sopite syndrome is characterised by sleepiness, low motivation, depressed mood and an aversion for work (Graybiel and Knepton, 1976). Sopite syndrome caused a large decrease in work performance (both self-reported and in a cognitive test). The reduction is inferred by comparison with a baseline measure during calm conditions (i.e. no

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building motion). The performance reduction is large, equivalent to nearly one standard deviation. While sopite syndrome can reduce cognitive performance (Matsangas and McCauley, 2013; Wright et al., 1995), the reduction in work performance observed in office workers may also be partly due to reduction in motivation.

The large reduction in work performance appears to occur at relatively low accelerations. While Lamb et al. (2014) was not able to obtain building accelerations for all participants, the likely acceleration range can be inferred. Sopite-syndrome-related symptoms accounted for 80% of adverse symptoms, motion sickness only accounted for 20% of symptoms. Sopite syndrome occurs in response to long duration exposure to gentle accelerations, while higher accelerations produce frank motion sickness, i.e. dizziness and nausea. Motion sickness usually occurs at around the 10 milli-g level (Goto, 1983; Burton et al., 2015), given the limited acceleration data reported in Lamb et al. (2014), it appears that these effects occurred in response to accelerations of less than 10-milli-g. Matsangas and McCauley (2013), support this estimate, as they observed sopite syndrome in participants at 5.7 milli-g (at 0.167 Hz), which is lower than accelerations allowed under current ISO serviceability criteria, ISO 10137 (International Organization for Standardization, 2007).

Developing criteria to minimise the incidence of sopite syndrome is complicated by the limited amount of research on the condition. Recent research shows that low-frequency motion causes sleep, but more importantly, that rocking produces a deeper than normal sleep (Bayer et al., 2011). Sopite syndrome may not simply initiate sleepiness, but may continuously suppress physiological and psychological arousal. The vestibular system is central to motion sickness, located in the inner ear, and is responsible for balance and the perception of motion. Physiological responses occur in response to imperceptible motion, and that individuals who report motion sickness, show a greater coupling of parasympathetic nerve activity and physiological responses (Hammam et al., 2014). Further, Wong et al. (2015) have shown that increasing acceleration causes increasingly large reductions in manual task performance undertaken by standing test subjects, peaking at 0.5 Hz. In addition to the effects of frequency and acceleration, participants affected by sopite syndrome show a larger reduction in performance than unaffected participants. These studies then show that building motion can potentially affect both physical and cognitive activity. This convergent evidence indicates that building motion can produce sopite syndrome which has significant implications for work performance and well-being in the workplace. A robust series of field and experimental studies is required to provide further evidence to identify the accelerations and duration of exposure required to produce sopite syndrome and to understand the full-range of effects on building occupants.

2.2. *Metrics for building performance assessment*

Formal occupant complaint has long been held as a reliable indicator of building performance (Hansen et al., 1973; Isyumov and Kilpatrick, 1996). Formal complaint is an attractive metric because the feedback is unprompted, meaning that there is no cost of effort associated with data collection and the complaint has validity as it is a direct metric of poor performance. However, several recent studies show that buildings may exhibit poor performance in the absence of formal complaint. In a sample of 1014 Central Business District (CBD) workers in Wellington, New Zealand, Lamb et al. (2013) shows that of those who experienced wind-induced building motion, less than 1% (N =2) complained to their landlord/property manager. None complained directly to the building owner. Only 4.8% of complaints reached the respondent's team leader. Yet, 45% informally complained to co-workers and family. Higher durations of exposure to motion, high susceptibility to motion sickness, and proximity to the top of the building all increased the likelihood of occupants informally complaining. In Hong Kong, Burton (2006) found a low-rate of complaint where only 2.3% of respondents who had felt wind-induced building motion made a formal complaint to their employer or the building owner.

Occupants may be reluctant to lodge a formal complaint for many reasons. Lamb et al. (2013) report that some occupants choose not to complain because of a concern that a complaint may affect their reputation and did not want to "cause trouble", while others assumed there was no simple solution to reduce building motion. Occupants in residential apartments may also be reluctant to formally complain as any official documentation of building motion issues would likely devalue their investments. Similarly, building owners may wish to avoid official documentation of reported issues. Any recorded issues that do exist are unlikely to be accessible to researchers, which may explain the low response rate reported by Isyumov and Kilpatrick (1996). Formal complaint is an unreliable metric of building performance. Rare instances of formal complaint obviously indicate poor performance, but the absence of formal complaints is not evidence of acceptable performance.

It is argued that occupant comfort research needs to move away from the assumption that low complaint rates legitimise building performance. Building performance measures must consult building users rather than rely on unreliable passive measures such as formal complaint. A Post Occupancy Evaluation (PoE) (Dykes and Baird, 2014) approach to create a standardised set of metrics assessing building performance may aid in benchmarking building performance and the development of a richer understanding of the effects of building motion.

2.3. *Understanding of habituation to building motion*

Habituation is the gradual reduction in a behavioural response as a result of sustained exposure to a given environmental stimulus (Rankin et al., 2010). Exposure to real or apparent motion can cause motion sickness in most healthy individuals; nausea is the primary symptom (Reason and Brand, 1975). Most individuals are capable of adapting to motion conditions, for example adaptation to motion at sea usually occurs within 2–3 days of prolonged exposure (Stoffregen, 2011). Individuals also require several days to re-adapt to dry land, called *mal debarquement* (Reason and Brand, 1975). The process of habituating to motion conditions is complex and not well understood. Individuals differ in susceptibility to motion sickness, also differing in their ability to develop and retain that adaptive response (Lackner, 2014). Women are more likely to suffer motion sickness at sea (Lawther and Griffin, 1988), report higher levels of susceptibility to motion sickness than men (Golding, 2006; Lamb and Kwok, 2015), and are more likely to report adverse responses to buildings motion (Lamb et al., 2013), likely due to higher levels of susceptibility to motion sickness. The gender-specific response to motion may inadvertently produce a discriminatory outcome where building design may, on average, result in reduced work-performance, comfort and employment opportunities for women compared with men. If quantifiable, such an effect could have legal consequences for building owners and designers. Presumably based on assumptions from general motion sickness research, in an outline of a performance modelling framework, Weigand and Kijewski-Correa, (2015) state that "it is assumed that tenants on residential and office floors will be habituated to building motion." (p.3). However, there is only weak evidence that occupants are able to habituate to building motion, and there are a number of complexities such that the general motion sickness literature cannot be generalised to wind-induced building motion, discussed in the following sections.

There is some evidence showing that some occupants may habituate to building motion. Denoon et al. (2000) found 21% of the Sydney airport control tower workers reported a greater acceptance of building motion over time. Lamb et al. (2013) report that 41% of those exposed to building motion reported that they became less affected over time. However, 48% reported no change over time and 11% reported being affected to a greater extent over time. Moreover, it is not possible to discern whether those who did report improvement over time were due