Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

DETRIMENTAL EFFECTS OF WIND-INDUCED BUILDING MOTION ON OCCUPANT WORK AND TASK PERFORMANCE

K. C. S. KWOK, S. LAMB, and K. S. WONG

Institute for Infrastructure Engineering, Western Sydney University, Penrith, Australia

We present recent multidisciplinary research conducted by psychologists, engineers and physiologists investigating the effects of wind-induced building motion on wellbeing, manual task performance and cognitive performance. In a sample of actual office workers, we show that sopite syndrome is the main consequence of exposure to wind-induced building motion. Sopite syndrome, a form of mild motion sickness characterized by drowsiness and low motivation, is the main cause of reductions in work performance. Experimental research shows that biomechanical properties of the human body are influenced by the frequency of motion, which amplifies body sway and interferes with task performance at 0.5 Hz, and to a greater extent with increases in acceleration. Exposure to motion induced sopite syndrome in some participants, who performed significantly worse than unaffected individuals. A new generation of serviceability criteria should aim to minimize sopite syndrome, motion sickness, motion induced body sway, and other psychological and physiological factors, rather than only address perception thresholds, which will likely allow engineers and designers to create a new generation of buildings that will ensure an improved level of comfort and performance for building occupants.

Keywords: Building vibration, Motion sickness, Sopite syndrome, Occupant comfort, Productivity.

1 INTRODUCTION

Wind-induced building motion poses a design challenge for structural engineers who must balance building costs against performance. Allowing higher building accelerations reduces costs but may cause motion sickness, occupant discomfort and reduce work performance. Previous research attempted to understand the occupant response to motion (Chen and Robertson 1972, Burton *et al.* 2011, Tamura *et al.* 2006). They however used task performance measures that may be too simple to detect true performance differences, expose participants to unrealistic short durations of motion, and do not allow participants to display adaptive behaviors (e.g., taking breaks, using medication). Consequently, past and present building design criteria may be inadequate to ensure a healthy and productive work environment, as they are based on an incomplete understanding of the human response to building motion and focus primarily on motion perception thresholds and occupant complaint (Architectural Institute of Japan 2004, ISO 10137 2007). A balanced and comprehensive research program requires the use of carefully designed experimental studies supported by field research examining actual building occupants during episodes of wind-induced building motion.

Motion sickness can occur in response to tall building motion and is characterized by nausea, and sometimes vomiting. Sopite syndrome, a form of mild motion sickness, is a less known consequence of long duration exposure to low-acceleration, low-frequency motion, conditions that occur during building motion. Sopite syndrome has a sedative effect on individuals, causing symptoms of sleepiness, difficulty concentrating, low mood, and decreased motivation, which may never develop into nausea (Graybiel and Knepton 1976).

This paper outlines recent multidisciplinary research conducted to investigate the effect of wind-induced building motion on occupant work performance and wellbeing. The research includes contributions from psychologists, engineers and physiologists.

2 RECENT MULTIDISIPLINARY RESEARCH ON OCCUPANT RESPONSE TO WIND-INDUCED BUILDING MOTION

2.1 A Ground-Level Survey of the General Public in a Wind-Prone City

1014 office workers in Wellington, New Zealand, one of the windiest cities in the world, completed a survey investigating experiences of wind-induced building motion (Lamb *et al.* 2013). 42.0% of the sample reported that they had experienced wind-induced building motion, and 41.6% of that group reported they experience building motion at least once a month. A quarter of participants reported classic symptoms of motion sickness, nausea and dizziness, during building motion. Predictably, individuals highly susceptible to motion sickness reported higher rates of motion sickness. Participants also reported symptoms of sopite syndrome, most notably, 42% reported difficulty concentrating. Overall, participants reported habituation to motion over time, though sensitive participants reported that the effects became worse over time. Half of participants reported some behavior change in response to building motion, taking more breaks and standing up and walking around.

Formal complaint to the occupant's CEO or the building owner/manager was very low, at 1.8%. Only 4.8% of occupants complained to their team leader. However, nearly half of occupants (45%) complained informally to their co-workers and family. Asked why they did not complain, participants indicated they did not want to "cause trouble", or risk the perception of being a "complainer". In a work environment, there are clear reasons why occupants may be unable to voice objection to building motion. Two participants reported that their organizations moved office buildings because of frequent episodes of building motion, indicating that management judged building motion a significant cost to performance and/or staff wellbeing. Given the low rate of formal complaint building, and despite clear objection to building motion, complaint rates are likely to be a misleading metric of building performance.

2.2 A Longitudinal Survey of Office Workers in Wind-Sensitive Buildings

Again in Wellington, we recruited 47 office workers located on high floors, spread across 22 wind-sensitive buildings, and 53 office workers on or near the ground floor (a control or comparison condition) (Lamb *et al.* 2014). Participants completed a total of 1909 short online surveys across a period of 8 months, during conditions ranging from calm (1.2 m/s) to near gale (29.0 m/s). The analysis used objectively measured wind speeds and predicted accelerations to support participant reports of building motion. The large number of study buildings and building owner permissions limited us from measuring accelerations in all buildings.

On allocated survey days, participants indicated if they could ‘possibly’ feel building motion (barely perceptible), ‘definitely’ feel motion (clearly perceptible), or reported no instances of motion. Shown in Figure 1, the lowest wind speeds corresponded to no reported motion perception. Wind speeds and predicted building accelerations were significantly higher during ‘possible’ motion and significantly higher again during ‘definite’ motion.

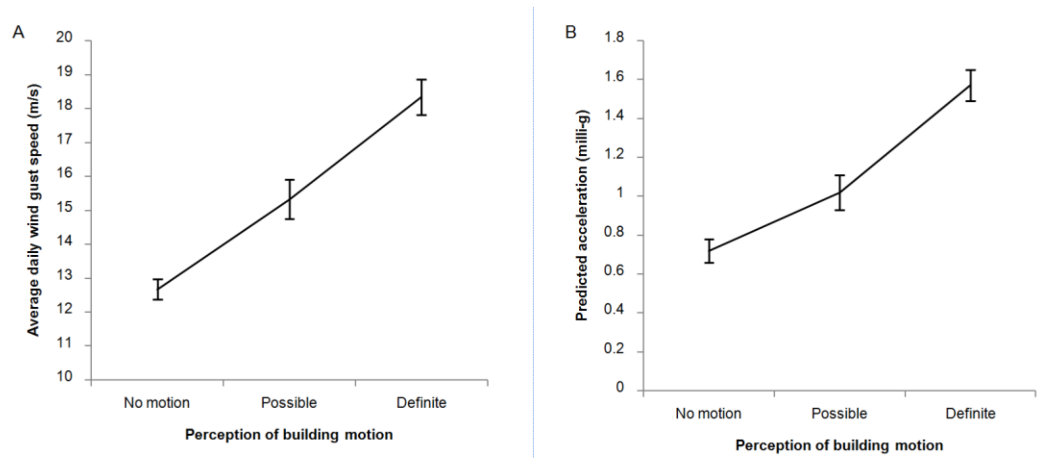

Figure 1. (A) Average daily gust speeds by reported building motion, and (B) Predicted peak building accelerations by perception of motion.

Participants were significantly more likely to report nausea, dizziness and feeling “off"” (slightly unwell), distraction and sleepiness during perceptible building motion. Aggregating these symptoms, the ‘Combined Motion Sickness Scale’ (CMSS) includes both classic symptoms of motion sickness and sopite syndrome. Motion sickness/sopite syndrome is 2-3 times more likely to occur during building motion than during baseline (no-motion). Sopite syndrome accounts for 80% of the reported symptoms. Sopite syndrome-like symptoms occur with a baseline incidence of about 12%, because these symptoms can occur during static conditions, for example, people can report tiredness for a variety of reasons such as work stress, or feel distracted because of personal/family stress.

Self-reported work performance significantly decreases as participants report higher levels of sopite syndrome/motion sickness. Performance is above average at baseline and drops below average with moderate to high level sopite syndrome/motion sickness, a large decrease equivalent to nearly 1 standard deviation (effect size 0.91). However, performance does not decrease solely due to reported building motion, only when participants report sopite syndrome/motion sickness. Performance on the Stroop Test, a word/color matching task shows the same decreasing trend, see Figure 2. Sopite syndrome/motion sickness likely causes stress, decreasing mental resources available for work performance.

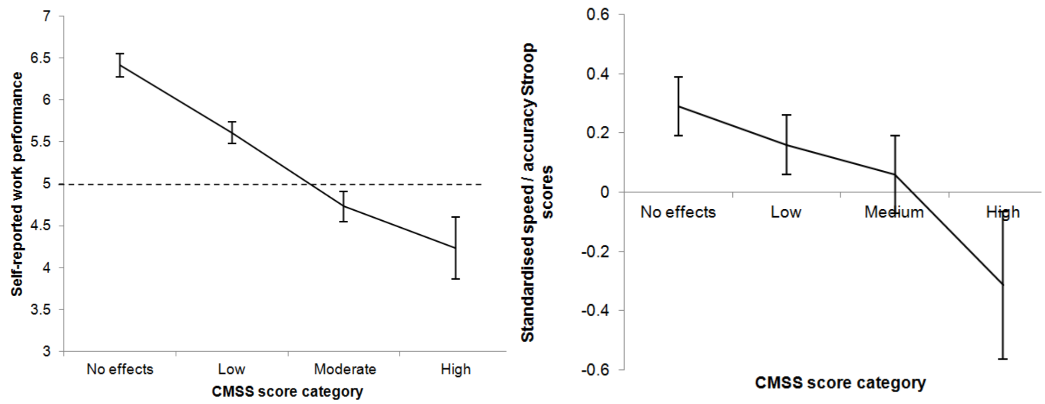

Figure 2. Left, self-reported work performance by CMSS scores. The scale mid-point of 5 reflects 'average' work performance, with higher scores indicating above average performance. Right, standardized speed / accuracy scores on the Stroop Test across CMSS score category. Error bars represent standard error.

In an effort to improve their comfort, participants reporting sopite syndrome/motion sickness spent 46% longer (21 minutes) outside their building during the work day than those suffering no ill effects. Further, participants reported a 28% increase in the use of analgesic medication (painkillers) when experiencing sopite syndrome/motion sickness. Lamb *et al.* (2014) estimate that 5.4% of office workers in the top third of wind-sensitive buildings in Wellington will experience moderate to high symptoms, that have a large impact of work performance, approximately 53 work days a year. During the study, wind speeds only reached 75% of the one-year return period, so observed effects are likely to be conservative.

2.3 Effects of Low Frequency, Low Acceleration Motions on Manual Task Performance

We conducted a motion simulator study to understand how wind-induced building motion affects building occupants' manual task performance (Wong *et al.* 2013), using the motion simulator, as shown in Figure 3 (Left), at the Hong Kong University of Science and Technology (HKUST) (Kwok and Wong 2012). The study used 12 horizontal fore-aft sinusoidal motions, covering a wide range of motion frequency (0.125 to 1 Hz) and acceleration (8 to 30 milli-g) that would be experienced by a broad range of buildings (~ 50 to 500 meters in height) under various wind intensities, compared with a static control condition. Effects of wind-induced building motion provoked symptoms of sopite syndrome on manual task performance were also investigated.

We used a manual tracking task to assess task performance. The tracking task required participants to stand and direct a laser pointer towards the center of a target mounted on the wall of the motion simulator. An internal setup of the motion simulator, and target are shown in Figure 3 (Middle) and (Right) respectively. We used digital video cameras to record, at 50 Hz, the loci of laser dot shone on the targets and analyzed the recorded videos using an image processing program to determine the distance between the laser dot and the target center for each frame of the video. In addition, participants reported any symptoms of sopite syndrome and motion sickness before and after exposure to motion using the Motion Sickness Assessment Questionnaire (MASQ, Gianaros *et al.* 2001).

Figure 3. Left, external view of the HKUST motion simulator; Middle, internal setup of the motions simulator; and Right, a target used in a tracking task experiment.

Standard deviations x (σ_x) and y (σ_y) components of a laser dot from the target center determine the degrees of variation of the laser dot movement and/or aiming accuracy respectively in the horizontal and vertical directions. They were used to measure tracking task performance. Averages of σ_x and σ_y measured under static conditions for all participants were about 4 mm. Larger σ_x and σ_y were generally measured under motion conditions, compared with static conditions, particularly in the vertical direction, (i.e., σ_y), as shown in Figure 4 (Left). This suggests that low-frequency, low acceleration horizontal fore-aft sinusoidal motions clearly degraded participants' aiming accuracy.

Fore-aft sinusoidal motions induced greater biomechanical human body vibrations in the fore-aft direction than in the lateral direction, which amplified the variability of the laser pointer movement in the vertical direction. This may be due, at least in part, to stance width. A wide stance may have provided better postural stability in the lateral than in the fore-aft direction. As a result, the effects of fore-aft sinusoidal motions on the variation of vertical component are greater than horizontal (lateral) component.

Laser pointer variability (σ_y), as shown in Figure 4, increased with acceleration. This is expected because under high acceleration motion conditions it becomes more difficult to maintain balance and the imposed motion interferes with motor control, resulting in greater tracking task performance degradation.

Task performance has a non-linear relationship with motion frequency. Task performance variability (σ_y) increased from 0.125 Hz, peaked at 0.5 Hz, and dropped at 1 Hz. This trend supports the results reported by Burton *et al.* (2006) who determined frequency dependent acceleration magnifications of body sway, which is dependent on the biomechanical characteristics of the human body: a standing human resonates at approximately 0.5 Hz. Evidently, the 0.5 Hz motions resonated test participants and amplified their body sway, causing performance degradation. The results suggest that occupants' tracking task performance is likely to be the most affected by wind-induced building motions at a fundamental frequency of about 0.5 Hz, which is representative of tall buildings at around 100-meter tall.

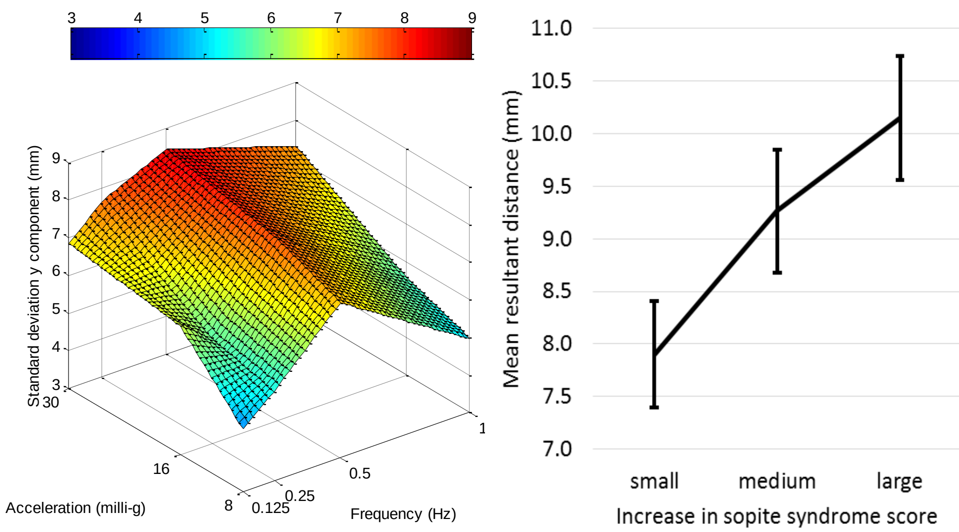

Figure 4. Left: Standard deviations y-coordinate (σ_y) of laser dot measured under motion conditions. Right: Mean resultant distance (mm) between a laser dot and target centre of test participants who have small, medium and large increases in sopite syndrome score.

MSAQ scores increased after exposure to motion, particularly for participants with symptoms of sopite syndrome. This suggests that motion duration, frequency and magnitude were sufficient to induce sopite syndrome in some participants, but not strong enough to provoke severe motion sickness symptoms such as nausea, vomiting, and dizziness. These results support Lamb *et al.* (2014) where wind-induced building motion provoked a greater frequency of sopite related symptoms than nausea.

Participants were divided into three groups (large, medium, and small) according to the magnitude of the increase in sopite syndrome scores. Figure 4 (Right) shows that task performance accuracy decreases with increases in the magnitude of the increase in sopite syndrome scores. This shows that test participants who suffered more severe symptoms of sopite syndrome performed worse under motion conditions than test participants with no symptoms, or a lower magnitude of sopite syndrome provoked by low frequency low acceleration motions. This suggests that sopite syndrome, often mild compared with nausea, is provoked by relatively short durations of exposure to motion, which causes task performance degradation. Hence motion sickness prone occupants in wind-excited buildings are likely to suffer symptoms of sopite syndrome that affect performance of manual tasks, particularly those requiring fine motor control.

3 FUTURE RESEARCH AND NEXT GENERATION SERVICABILITY CRITERIA

3.1 Future Research

Despite the significant implications for real-world work environments, few studies have sought to develop a fundamental understanding of sopite syndrome. While we know the condition has real and significant adverse effects on those exposed to low-frequency motion, we do not understand: (1) the development of symptoms with exposure to motion, (2) the motion dose required to produce these symptoms (the frequency, acceleration, motion type, individual susceptibility), (3) how and why sopite syndrome affects performance, and (4) whether sopite syndrome is low-severity motion sickness or an independent condition caused by similar environmental conditions. Our limited understanding of why sopite syndrome and motion sickness occur complicates the task of creating building standards designed to reduce or prevent these conditions. Developing a comprehensive understanding of sopite syndrome will facilitate the creation of a new generation of serviceability criteria, requiring contributions from psychologists, physiologists and engineers.

3.2 Serviceability Criteria

Occupant comfort serviceability criteria currently in use are based on the outcome of research on the psychological and physiological effects of motion on human. These effects include tactile, vestibular, proprioceptive, kinesthetic, visual and auditory cues, and visual-vestibular interaction, on human response to building vibration. Other factors such as prior experience, motion expectation, habituation, personality, culture and even job satisfaction may also play an important role. This complex mix of diverse factors presents a difficult challenge for researchers attempting to develop comprehensive serviceability criteria. Hence it is not surprising that there are significant differences and uncertainties amongst the few occupant comfort serviceability criteria commonly in use by wind tunnel laboratories and design professionals, which generally reflect country/regional building code requirements, building design professionals' interpretation and preference, and market forces. Kwok *et al.* (2009) summarized the characteristics and compared the suggested acceptable acceleration levels of commonly adopted criteria, as shown in Figure 5, including ISO 6897 (1984), Melbourne and Cheung (1988), Isyumov (1993), AIJ-GEH (2004), ISO 10137 (2007) and Burton *et al.* (2007).

Recently, ASCE published a monograph: Wind-Induced Motion of Tall Buildings - Designing for Habitability (Kwok *et al.* 2015) prepared by a subcommittee comprised of researchers, wind engineers and practitioners with an interest on wind effects on tall buildings, occupant response to wind-induced building motion and vibration mitigation. In addition to providing a summary of current knowledge on human response to wind-induced building motion, the monograph suggests the following general guidelines based on peak acceleration thresholds to assess building habitability and the need for mitigation against unacceptable/excessive building motion.

- 5 milli-g is a perception threshold, which is perceptible to many occupants, but is unlikely to cause significant adverse occupant response or alarm.
- 10 milli-g is a comfort and well-being threshold which is perceptible to the vast majority of occupants. In practice, buildings that frequently exhibit such wind-induced motion and/or for an extended period of time may not be acceptable to some occupants, particularly those who are prone to motion-sickness.
- 35-40 milli-g is a fear and safety threshold sufficiently severe to cause some occupants to lose balance. Such building motion is unlikely to occur in modern tall buildings except during extreme wind events. Nevertheless, such building motion should be avoided where possible.

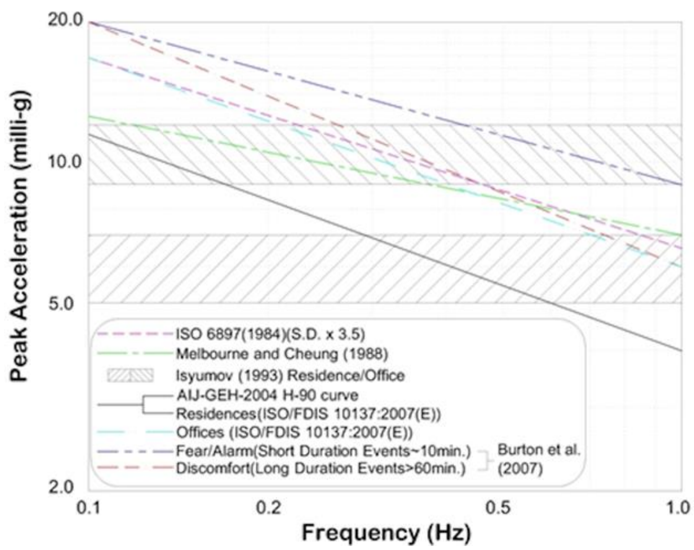

Figure 5. Comparison of occupant comfort serviceability criteria for a one year return period wind storm (Kwok *et al*. 2009).

It is noteworthy that occupant complaint against wind-induced building motion played a significant role in the formulation of some of the acceptance criteria. However, there is strong evidence based on large sample population surveys that occupant complaint rate is a far more complex behavior than previously thought, influenced by the nature of the stimulant (motion frequency, acceleration and exposure duration) and the occupants' motion sickness susceptibility (Lamb *et al.* 2013, Lamb *et al.* 2014). In fact the data suggest that despite occupants frequently perceived wind-induced building motions and these motions significantly affected occupants' general well-being and work performance, particularly for motion sickness-prone individuals, building occupants in general almost never make formal complaints about building motion. This is in direct contrast to the widely held assumption that complaint is an effective index of building performance. Instead, some building occupants actively compensated for the adverse effects of building motion by taking more breaks and self-medicated in a significant proportion of cases. These compensatory strategies not only degrade the work performance which directly affect productivity, frequent encounters with or prolonged exposure to wind-induced building motions presents a genuine health hazard that requires an appropriate intervention.

We propose that serviceability criteria abandon the concept of motion tolerance and complaint rate, as evidently occupants will tolerate high levels of building motion, but with large adverse effects for them and their organizations. Criteria should instead try to establish the maximum allowable accelerations that have a minimal disruption to building occupants. Sopite syndrome is the main cause of work performance reductions and occupant discomfort, shown by both field and simulator studies. Rather than address perception thresholds, future serviceability should determine the minimum 'dose' of motion, which is a complex combination of acceleration, frequency, motion type, and duration of exposure to motion, that causes sopite syndrome and associated adverse effects. Future studies could perform a cost-benefit analysis to determine the optimal investment into the reduction of building accelerations taking into account the costs of lost productivity, turnover and risk of adverse building reputation, comparable to that undertaken in regard to thermal comfort.

4 CONCLUSIONS

Recent research shows that sopite syndrome is the main consequence of exposure to wind-induced building motion, and is the primary cause of reduction in performance, shown in both field and simulator studies. These effects may occur at accelerations previously thought to be benign. Building motion can cause occupant complaint, but occupants complain informally to family and colleagues, not senior staff in their organization or building owners. Research shows that biomechanical properties of the human body are influenced by the frequency of motion, which amplifies body sway and interferes with task performance at 0.5 Hz. Task performance accuracy also reduces with increases in acceleration, and interact with frequency. Exposure to motion induced sopite syndrome in some participants, who performance significantly worse than unaffected individuals. A new generation of serviceability should aim to minimize sopite syndrome and motion sickness, rather than address perception thresholds, which will likely allow engineers and designers to create a new generation of buildings that will ensure an improved level of comfort and performance for building occupants.

Acknowledgements

The authors acknowledge the invaluable contributions to research on human perception and tolerance of wind-induced building motion over the past 20 years by the team at University of Sydney, HKUST and Western Sydney University. This research is supported by the Australian Research Council Discovery Projects: DP1096179 and DP150102652.

References

Architectural Institute of Japan, Guidelines for the Evaluation of Habitability to Building Vibration, Tokyo, Japan: Architectural Institute of Japan, 2004.

Burton, M. D., Kwok, K. C. S., and Abdelrazaq, A., Wind-Induced Motion of Tall Buildings : Designing for Occupant Comfort, *International J. of High-Rise Buildings*, 4(1), 1–8 2015.

Burton, M.D., Kwok, K.C.S., and Hitchcock, P.A., Occupant comfort criteria for wind-excited buildings: based on motion duration. *Proc. of 12th International Conference on Wind Engineering*, Cairns, Australia, 2007.

Burton, M.D., Kwok, K.C.S., and Hitchcock, P.A., Effect of Low Frequency Motion on the Performance of a Dynamic Manual Tracking Task, *Wind and Structures An International Journal*, 14(6): 517–536, 2011. doi:10.12989/was.2011.14.6.517.

Burton, M.D., Kwok, K.C.S., Hitchcock, P.A., and Denoon, R.O., Frequency Dependence of Human Response to Wind-Induced Building Motion, *Journal of Structural Engineering, ASCE*, 132(2): 296-303, 2006.

Chen, P.W., and Robertson, L.E., Human Perception Thresholds of Horizontal Motion, *Journal of the Structural Division ASCE*, 92(8): 1681–1695, 1972.

Denoon, R.O., and Kwok, K.C.S., Implications of Full-Scale Building Motion Experience for Serviceability Design, *Wind and Structures An International Journal*, 14 (6): 537–557, 2011. doi:10.12989/was.2011.14.6.537.

Gianaros, P.J., Muth, E.R., Mordkoff, J.T., Levine, M.E., and Stern, R.M., A questionnaire for the assessment of the multiple dimensions of motion sickness, *Aviation, Space, and Environmental Medicine*, 72(2), 115–119, 2001.

Goto, T., Studies on Wind-Induced Motion of Tall Buildings Based on Occupants Reactions, *Journal of Wind Engineering and Industrial Aerodynamics*, 13: 241–252, 1983.

Graybiel, A., and Knepton, J., Sopite Syndrome: A Sometimes Sole Manifestation of Motion Sickness, *Aviation, Space, and Environmental Medicine*, 47(8): 873–882, 1976.

Hansen, R.J., Reed, J.W., and Vanmarcke, E.H., Human Response to Wind-Induced Motion of Buildings, *Journal of Structural Division, ASCE*, 99(ST7): 1589-1605, 1973.

ISO 6897:1984, Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion (0.063 to 1.0 Hz), *International Organization for Standardization*, Geneva, Switzerland, 1984.

ISO 10137, Bases for Design of Structures - Serviceability of Buildings and Walkways against Vibration, *International Organization for Standardization*, Geneva, Switzerland, 2007.

Isyumov, N., Criteria for Acceptable Wind-Induced Motions of Tall Buildings, *Intnl. Conf. on Tall Buildings*, Council on Tall Buildings and Urban Habitat, Rio de Janeiro,1993.

Isyumov, N., and Kilpatrick, J., Full-Scale Experience with Wind-Induced Motions of Tall Buildings, *Proc. of 67th Regional Conference Council on Tall Buildings and Urban Habitat*, Chicago, USA, 1996.

Kwok, K.C.S., Hitchcock, P.A., and Burton, M.D., Perception of vibration and occupant comfort in wind-excited tall buildings, *Journal of Wind Engineering and Industrial Aerodynamics*, 97, 368–380, 2009.

Kwok, K.C.S., and Wong, K.S., A Dual-Axis Tall Building Motion Simulator to Investigate Effects of Wind-Induced Building Motions on Human, *Proc. of 15th Australasian Wind Engineering Society Workshop*, 2012, 23-24 February, Sydney, 2012.

Lamb, S., Kwok, K.C.S., and Walton, D., Occupant Comfort in Wind-Excited Tall Buildings: Motion Sickness, Compensatory Behaviours and Complaint, *Journal of Wind Engineering and Industrial Aerodynamics*, 119: 1–12, 2013.

Lamb, S., Kwok, K.C.S., and Walton, D., A Longitudinal Field Study of the Effects of Wind-Induced Building Motion on Occupant Wellbeing and Work Performance, *Journal of Wind Engineering and Industrial Aerodynamics*, 133 (October): 39–51, 2014. doi:10.1016/j.jweia.2014.07.008.

Melbourne, W. H., and Cheung, J., Designing for serviceable accelerations in tall buildings, *Proc. of 4th International Conference on Tall Buildings*, Hong Kong and Shanghai, 1988.

Tamura, Y., Kawana, S., Nakamura, O., Kanda, J., and Nakata, S., Evaluation Perception of Wind-Induced Vibration in Buildings, *Proc. of the ICE - Structures and Buildings*, 159(5): 283–293, 2006. doi:10.1680/stbu.2006.159.5.283.

Wong, K.S., Hau, C.L.V., and Kwok, K.C.S., Effects of Wind-Induced Tall Building Vibrations on a Tracking Task, *Proc. of 12th Americas Conf. on Wind Engineering*, Seattle, USA, 2013.