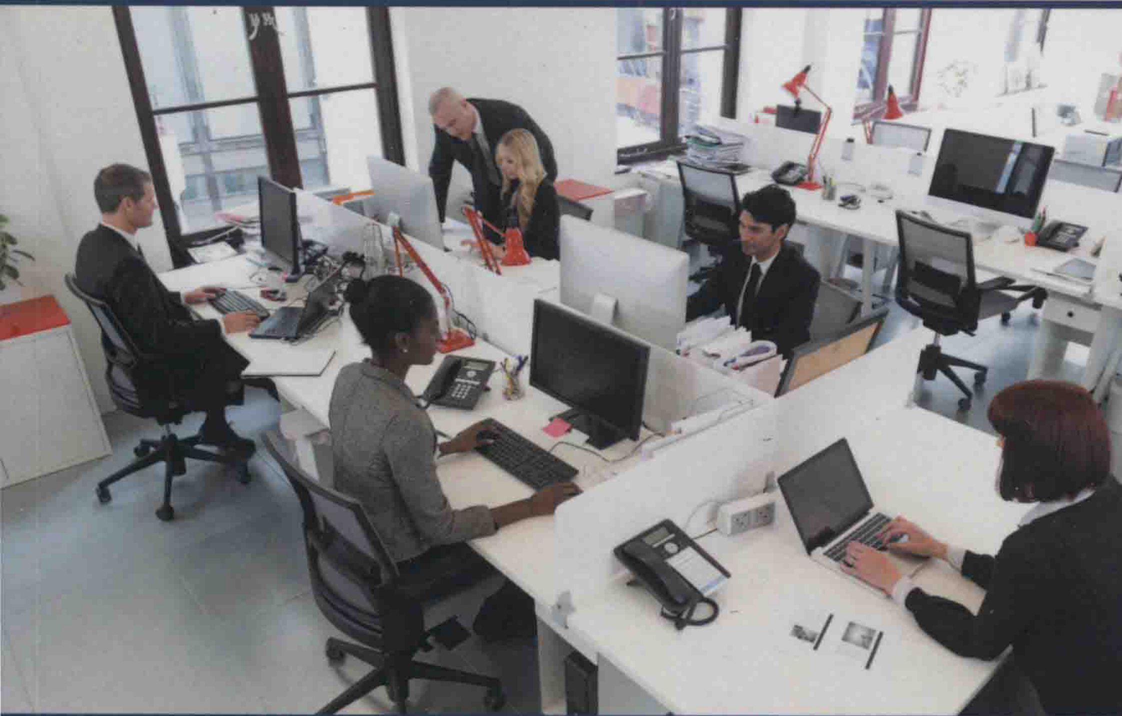
Wind-Induced Motion



# of Tall Buildings

DESIGNING FOR HABITABILITY

Kenny C. S. Kwok, Ph.D., C.P.Eng.; Melissa D. Burton, Ph.D., C.Eng.; and Ahmad K. Abdelrazaq, S.E.

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Designing for Habitability

by
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Preface

The past few decades have witnessed a tremendous growth of tall and super-tall buildings all over the world, particularly in east and south Asia, the Pacific Rim and the Middle East. Although advances in engineering materials, structural design and knowledge of wind-structure interaction ensure that these buildings meet strength and safety requirements under wind actions, occupant response to wind-induced building motion of new buildings of ever increasing height and complex shape remains a major challenge for property developers, building owners and tall buildings design professionals.

A team of researchers and practitioners were assembled to prepare this monograph on "Wind-Induced Motion of Tall Buildings: Designing for Habitability". This monograph presents a state-of-the-art report of occupant response to wind-induced building motion and acceptability criteria for wind-excited tall buildings. It provides background information on a range of pertinent subjects, including:

- Physiological, psychological and behavioural traits of occupant response to wind-induced building motion;
- A summary of investigations and findings of human response to real and simulated building motions based on field studies and motion simulator experiments;
- A review of serviceability criteria to assess the acceptability of wind-induced building motion adopted by international and country-based standards organizations;
- General acceptance guidelines of occupant response to wind-induced building motion based on peak acceleration thresholds; and
- Mitigation strategies to reduce wind-induced building motion through structural optimization, aerodynamic treatment and vibration dissipation/absorption.

This monograph equips building owners and tall building design professionals with a better understanding of the complex nature of occupant response to and acceptability of wind-induced building motion. Equally important, this monograph recommends a set of general acceptance guidelines of wind-induced building motion based on peak acceleration thresholds, which property developers, building owners and tall building design professionals can use to assess building habitability and the need for mitigation.

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Acknowledgments

The completion of this monograph has been undertaken collaboratively by a team of contributors each equipped with the necessary expertise and/or practical experience to ensure the content represents state-of-the-art information on human perception of and response to motion. The efforts of these experts and contributors are gratefully acknowledged in bringing the document to final fruition and its present final format. We hope that this monograph will be continuously updated to reflect the best practices and latest advances in wind-induced motion principles.

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Foreword

The design of tall buildings for wind effects is often constrained by concerns for habitability rather than strength alone. In such situations it becomes necessary to take measures to limit wind-induced motions in order to assure the comfort of occupants and to maintain their confidence in the structural integrity of the building. Of concern are the oscillatory motions that can occur due to wind-induced resonance at and near the natural frequencies of the building. Such motions can become noticeable and potentially annoying if they persist at significant amplitudes and occur relatively often.

Occupant perception and tolerance of wind-induced motions are subjective and have a high degree of variability. Not unlike passengers on a ship, some building occupants may feel the motion and become alarmed and in severe cases even nauseated; others may feel the motion but do not become particularly concerned; and others may be unaware of the motion all together. Human perception of building motion primarily depends on the magnitude of the horizontal acceleration, which causes lateral body forces and affects various sensors of the human body that control balance and physical well-being. Such audio cues as the creaking and groaning due to an unintended interaction of structural and non-structural systems or the clashing of elevator cables can prompt and accentuate motion awareness. Motion awareness can also be prompted by visual cues caused by the time-rate-of-change of building displacements and rotations. For example, in the presence of a significant torsional velocity, prompts of the building motion can be provided by an apparent sensation of a "swinging" horizon.

The ingredients of a design that avoids motion related problems are the selection of an external shape that minimizes the time-varying aerodynamic forces and a structural system that does not unduly amplify the wind-induced response at resonance. In short, the development of a successful design requires a good marriage of architecture and structural engineering. Special studies may be necessary in order to predict the expected wind-induced motions of a particular building. For most tall buildings, wind tunnel model testing is the method of choice. Such studies are not discussed in this Monograph, however, ample information can be found in the literature and in ASCE publications such as: the ASCE Manual of Practice No. 67-1999 on "Wind Tunnel Studies of Buildings and Structures" and ASCE Standard 49-2012, entitled "Wind Tunnel Testing for Buildings and Other Structures".

Some codes and standards of practice include specific requirements or recommendations on acceptable wind-induced building motions; however, the design of tall buildings has largely relied on conformance with accepted practice, which emerged from past studies, full-scale experience and good judgment.

Committee No. 36 of the Council on Tall Buildings and Urban Habitat (CTBUH), in concert with the ASCE Wind Effects Committee, has previously attempted to gather information that would assist designers in the evaluation of acceptable motions. A draft of a monograph on "Motion Perception, Tolerance and Mitigation" was assembled in 1998; however, it remained unpublished. Those earlier efforts were recently re-started by the ASCE with a new vigor, with new contributors and with the benefit of new data on occupant motion perception and tolerance determined from studies in motion simulators and the growing feedback from full-scale monitoring programs of existing buildings. This ASCE Monograph on the "Wind-Induced Motion of Tall Buildings: Designing for Habitability" is the end product of this noteworthy effort. I highly commend all participants in this important activity.

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CHAPTER 1
Introduction

Tall building structures, like all structures, move due to the action of wind. From a structural standpoint building motion is expected and is not an indication of inferior design, unless the motion is excessive and cannot be tolerated by occupants.

The building motion due to wind consists of two components: a static or sustained action, which is not apparent to occupants but is included in the estimation of the building drift, and oscillatory or resonant vibration, which is due to the dynamic and varying action of wind. It is this resonant motion that becomes perceptible to occupants, and if excessive can cause possible "discomfort" or even "fear". The focus of this monograph is to present the state-of-the-art and best practices on the effect that resonant wind-induced motions have on the habitability of tall buildings.

The dynamic response of a tall building to wind excitation is significantly influenced by many factors; such as the site conditions (which may change over the life of the building), shape and height, and dynamic characteristics (which include vibration periods, mode shapes, mass distribution, lateral stiffness distribution, and damping). Engineers continue to find elegant wind engineering solutions to control the resonant and dynamic wind-induced motions. Overcoming the dynamic wind effects can only be solved effectively at its root through collaborative efforts between the architect and engineers at the conceptual design stage by shaping structures to inhibit the vortex shedding formation and reduce its correlation along the height and by tuning the dynamic characteristics of the building to keep them out of range of resonance for most wind directions, events and return periods.

Nowadays, buildings are being designed taller, more slender, and lighter. When such buildings frequently experience wind events it is critical for the designers to understand the full spectrum of the building behavior and to mitigate against adverse motions by establishing acceptable design performance criteria that fit both the owner and occupant needs. Consideration of a change to the building structural system or supplemental damping to guard against occupant "fear" may be required to mitigate these motions.

While, significant works can be found in the literature regarding the "effects of wind-induced motion of tall buildings", the subject matter has never been summarized into a single and concise document that can be used by tall building designers, owners, developers, and researchers as a reference to establish suitable and acceptable performance for their project.

This monograph takes the stakeholders (designers, developers, owners, wind engineering experts, researchers, occupants, etc.) into the journey of understanding 1) the underlying principles of human sensitivity to perceiving motion and their tolerance to it, 2) the reliability of acceleration predictions, 3) the human threshold of perceiving and tolerating motion experimentally, 4) the human perception and tolerance of building motion under real conditions, including post-event review of motion in buildings, 5) best international practices and international design criteria and guidelines 6) design strategies for mitigating the oscillatory motions through aerodynamic modification, and damping devices, and 7) the significance of using motion simulators to familiarize the stakeholders with the expected building motions before the completion of the design.

This monograph provides state-of-art information and best practices for evaluating the acceptability of wind-induced motions on existing and new buildings. It does not provide information for predicting the magnitude and frequency of occurrence of such motions. This must be done with the reliance of existing databases and specific wind tunnel model studies.

As a final note, historically tall building design and construction relied solely on minimum building code requirements, fundamental mechanics, scaled models, research, and experience. While many research and several monitoring programs have been carried out for tall buildings, these programs have been limited in scope and are yet to be systematically validated and/or holistically integrated.

Considering the latest technological advances in IT, advances in fiber optic sensors, nanotechnologies, dynamic monitoring devices, new GPS system technologies, and wireless monitoring techniques, designers, owners, and building authorities should seriously consider the complete and comprehensive Structural Health Monitoring Programs (SHMP) as an integral part of the Intelligent Building Management System. This allows the building authorities, owners, and designers to obtain feedback on the real building behaviour and on the validity of the design assumptions. The adoption of such a program importantly contributes to the overall sustainability of future cities and environments and will no doubt lead in delivering a more cost effective structural solution that is performance based.

The adoption of a SHMP should not be limited to understanding the resonant wind-induced motions of the buildings, but should, for most gain include the entire structural behavior during construction and over the building's lifetime.

CHAPTER 2
Physiology and Psychology of Human Perception of Motion

2.1 HUMAN SENSITIVITY TO MOTION

Vibration of the whole or a part of the human body is one of the oldest and chronic environmental stresses to which we are subjected from early riders of chariots in 60 A.D., to the present day concern of swaying motion of tall buildings during windstorms (Figure 2-1).

The human body is a close, integrated network of interacting subsystems: structural, hydraulic, electrical, chemical and thermodynamic. The human brain is the central control unit over all these subsystems, and it is supplemented by optical and acoustic systems. Overall biodynamical response of the human body varies in a random fashion from person to person. Therefore, the external manifestations of human response to swaying motion are varied and will differ from person to person. Concern, anxiety, fear, and even symptoms of vertigo express human psychological response to the observed motion; whereas, dizziness, headaches, and nausea are the common symptoms of motion sickness.

The mechanisms for perceiving and responding to motion can be classified as tactile, vestibular, proprioception, kinesthesis, visual and audio cues, and visual-vestibular interaction. These mechanisms cause the sensing, transmitting, and integrating of the motion cues.

How humans perceive and respond to changes in their physical environments is among the most technically challenging and conceptually sophisticated areas of modern psychology. Human sensation is not necessarily a primitive process simply because it appears to function similarly and with similar apparatus in animals or even less advanced organisms. In the study of physiology and perception, psychologists no longer consider human beings as passive receptors of environmental inputs. The person's role in perceptions might be better thought of as an agent in responding to and exchanging information received from the environment. Certain dominant ideas tend, however, to linger on outside the disciplines that have developed and refined them and so there is some advantage in reviewing and understanding core ideas surrounding the perception of motion, it being one of the least understood and most controversial areas of investigation.

Human beings are not limited to five senses as they were expressed in the Aristotelian Tradition: vision, audition, smell, taste and touch. These five senses are commonly referred to as the *exteroceptors*. We are sensitive to and respond to information from additional sources, and these additional sources are particularly important in the perception of motion. In addition to the traditional five senses

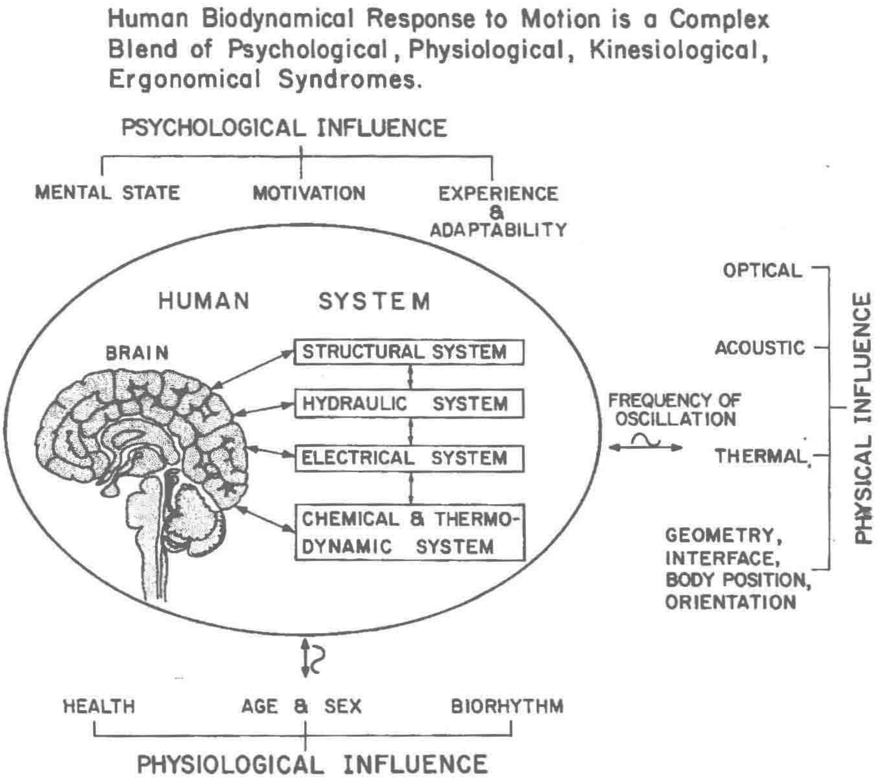

Figure 2-1. Human system and environments
SOURCE: Courtesy of Ahsan Kareem.

other senses include temperature (thermoception), kinesthetic sense (proprioception), pain (nociception), balance (equilibrioception) and acceleration.

There is some evidence to support other types of senses, such as a sense of time and a sense of direction.

One important consequence of the complexities of human perception is that what is revealed in behavior can sometimes be further explained in physiology and psychology. Human beings do not always accurately report what they perceive and the consequences of our perceptions are not always immediately apparent to us. To say some processes are 'unconscious' is to undermine the idea that we actively monitor our own behavior and so the concept of 'perception' is much broader and more sophisticated than the everyday examples of sight, smell, touch, taste and hearing provide for us.

2.2 MECHANISMS OF MOTION PERCEPTION

The term 'proprioception' derives from the Latin 'proprius,' which means 'one's own'. This highly sophisticated sense allows human being to know where they are in space and where their limbs are relative to each other. The ability derives from the fact that within the muscles and tendons are receptors called *proprioceptors*. Within the joints there is a special class of receptor called *kinaesthetic receptors*. These receptors provide feedback on the location of our limbs in relation to movement. These systems are integrated with the vestibular system, which in turn is linked to the cerebellum and the visual pathways.

The vestibular system is located in the inner ear of humans and has three main functions: (1) to help regulate posture and muscle tone, (2) to control compensatory eye movements, and (3) to provide input to the autonomic nervous system (Strandring 2008).

The vestibular system does not generate a conscious sensation (like vision or audition) but plays a critical role in a wide-range of actions from navigation and spatial orientation. The integration of information via the vestibular systems allows us to distinguish between actively generated head movements from those that are passive (Angelaki and Cullen 2008), detects inertia, co-ordinates movement and critically, for our concerns, detects actual motion. The vestibular system is integrated with the cerebellum immediately at the first synapse and is highly dependent on inputs from the body making it multisensory and multifunctional (Angelaki and Cullen 2008).

The two relevant parts of the vestibular system to motion sickness are the Semi-Circular Canals and the Otolith Organs. The Semi-Circular Canals are three almost circular protrusions, positioned roughly orthogonal to each other, which detect angular acceleration of any pitch, yaw or roll of the head. In a standing position gravity provides a constant force on the Endolymph fluid contained in the canals, and movement of the head causes the fluid to move through the canals, which is detected by tiny hairs, called Cilia, which transmit the signal to the brain (Strandring 2008).

The Otoliths (literally 'ear rocks') are comprised of the Saccule and the Utricle, which function much like a builder's plumb bob, and detect linear acceleration as well as the force of gravity. The Saccule is orientated vertically, to perceive motion like in an elevator, whereas the Utricle is arranged horizontally, to enable perception of acceleration, such as a vehicle travelling in a straight line. Both the Saccule and the Utricle are comprised of tiny crystals, called Otoconia, which are embedded in gelatinous matter over a fixed supportive base. Linear accelerations place force on the relatively heavy crystals, which move with respect to the supporting cells, pulling on tiny hairs called Stereocilia, which again send signals to the brain indicating the strength of the linear motion (Strandring 2008).

A *sensory threshold* (also known as a *limen*) is a theoretical concept used in *psychophysics*, the branch of psychology that investigates the relationship between the perception of stimuli and the measurable quality and quantity of those stimuli. This division of psychology has a relatively long history with much of the early work requiring the development of behavioral measure to assess individual subjects' subjective experiences. However, owing to the fact that there is wide individual variation in the experience of different stimuli and numerous influences on their presentation and experience, there are still vast areas where the experimental work concerning the basic nature of human ability is still poorly developed. Among these areas is the perception of 'movement' – more accurately 'self-motion,' as human perception of moving objects is much better understood.

The basic systems required for perceiving motion are integrated with other systems, especially the eyes. Tilted room experiments first demonstrated the dominance of visual input in displaying an accurate assessment of angular rotation by the simple process of requiring subjects to estimate displacement from horizontal with their eyes closed. Subjects were found to be more accurate without the visual reference distorting their perception (Witkin 1959).

There are significant inter-individual variations in sensitivity to motion in real-world contexts. These can be measured using a straightforward questionnaire when concerning high dosage and the common symptoms of long-duration exposure (Golding 1998, 2006).

Importantly, Golding's work in developing and validating the MSSQ (Motion Sickness Sensitivity Questionnaire) reveals that people know they are more or less prone to the effects of motion and simple questions such as 'Do you regard yourself as susceptible to motion sickness?' reveal such. Less clear answers emerge from questions that examine motion exposure; those contexts that might create the conditions of motion sickness (e.g. carnival rides, channel ferries and the like) might be avoided by an individual who acknowledges their susceptibility to motion.

In the theory of structural dynamics, a linear transfer function relates the response of a structure to the loading function. Similarly, in the case of biodynamical response of the human body to motion, the stimulus is related to perception by a nonlinear transfer function, which is an n^{th} power law:

$$R = KS^n \tag{1}$$

where S is the stimulus, R is the sensory greatness, and K is a constant (Kareem 1988). The physical parameters of stimulus are products of amplitude and a power of frequency. Therefore, the stimulus parameters must be controlled to improve the human comfort in tall buildings. Generally the power n is taken to be 2, which represents acceleration.

2.3 SUMMARY

Structures in the inner ear called the vestibular systems are integrated with sensors in the body and are connected to the central nervous system in such a way as to build an 'internal model' of orientation and movement.

Human responses are complex physiologically and behaviorally and are likely to be masked by the way in which we interpret and report them. There is a wide variation in individual ability to detect motion and this is recorded in surveys that reliably record individual sensitivity and susceptibility to motion sickness.