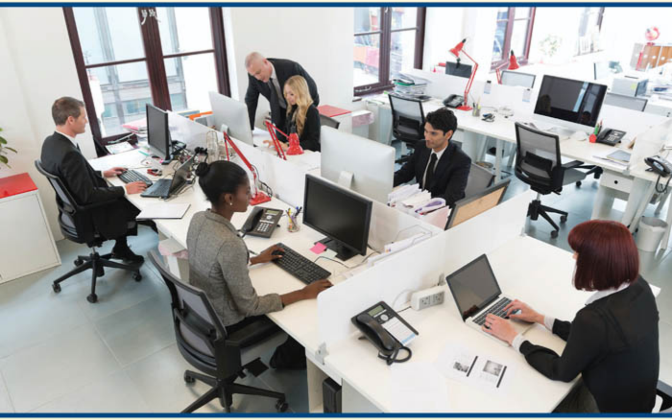
Wind-Induced Motion



# 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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Contents

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.

Kenny Kwok
University of Western Sydney

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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

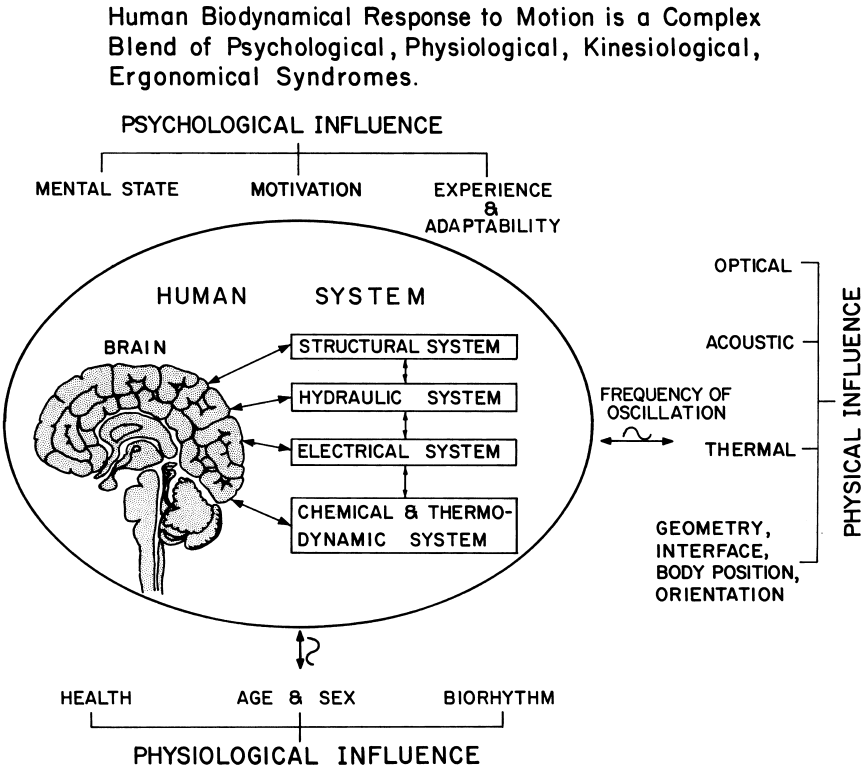


Figure 2-1. Human system and environments

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.

CHAPTER 3

Important Considerations

3.1 RELIABILITY OF ACCELERATION PREDICTIONS

3.1.1 Using a Code Based Approach

There are numerous approaches suggested in wind codes and standards to predict accelerations from which building motion acceptability is primarily based. The key goal is to determine the resonant component of building response for appropriate mean recurrence intervals, usually in the range of 1-10 years, which are considered relevant in the assessment of occupant response to wind-induced building motion.

Many wind codes do not provide wind speeds for short mean recurrence intervals or return periods only containing wind speeds suitable for strength design. In these cases, simplified assumptions may be required in determining the estimated wind speed. For example, ASCE 7 gives guidance of the 10-year return period wind pressure being approximately 70% of the 50-year return period wind pressure. Clearly, this ratio may vary significantly depending on the wind climate and the dominant storm types. This variation increases with shorter return periods, such as 1-year where the storm types may be completely different from the storm types resulting in the 50-year design wind speeds.

Accelerations tend to be directionally sensitive. There are only a few building codes in the world that provide directional wind speed characteristics, and these are generally regional in nature. It is possible to improve code-based acceleration predictions by using these techniques with site-specific wind climate analyses.

The methods of predicting accelerations from building codes are variable depending on the code. The component of response that results in perceptible acceleration is the resonant component of the dynamic response. This may result from alongwind, crosswind, or torsional vibration. Most codes have well developed approaches for alongwind response, but the calculation of the resonant component may not be explicit in the equations. For tall slender buildings, it is more commonly the crosswind component of response that results in the largest accelerations. There are relatively few codes that contain predictions for crosswind response. Some, such as the Australia/New Zealand standards, have a method based on some tall buildings of simple form without surroundings and are derived from wind tunnel testing of this type of building; as these buildings are uniform in shape, and do not benefit from any shielding from surrounding buildings (or conversely, additional excitation by the wakes of nearby isolated buildings), estimates of acceleration tend to be conservative (but in rare cases un-conservative) when applied to real buildings. While this may be acceptable for the prediction of life-safety issues such as loads, it is not as useful when dealing with serviceability issues such as accelerations. Other codes, such as the Canadian code, have a more empirical approach, which may result in more realistic estimates for most buildings, but may result in underestimates for many buildings. Torsional response is not covered well by any wind codes.

Overall, code-based approaches to the prediction of wind-induced building accelerations are always going to be approximate in comparison with wind tunnel predictions and are best used as an early check that accelerations are going to be of a reasonable magnitude, or at least to indicate where further investigation may be required.

3.1.2 Using a Wind Tunnel Analysis

The principal advantages of wind tunnel testing versus a code-based approach for the prediction of building accelerations are the same as the advantages in the predictions of loads: the effects of the surroundings can be fully accounted for, as can the unique architecture of the building under investigation and the directional characteristics of the local wind climate.

While the wind tunnel has clear advantages over a code-based approach to predicting the acceleration response, there are still a number of uncertainties in the reliability of the predictions. The key uncertainties result from the wind climate analysis and the assumed structural properties of the building. Wind climate data is never perfect and rarely fits the theoretical distribution curves perfectly. The goodness-of-fit of these curves has a considerable effect on the predicted accelerations, and it is necessary to check that the fit is good for the return periods of interest in acceleration predictions, rather than those of interest for the extreme events of interest in the prediction of loads. This is particularly the case in regions where there is a significantly mixed wind climate. The prediction of structural properties is also something of an art, rather than a science. Generally, the natural frequencies and other modal properties are derived from a finite-element model of the structure. The accuracy of this is dependent on the simplifications and assumptions that have been employed. Numerous field studies have been conducted on completed buildings that have shown natural frequencies significantly higher than predicted design values at low amplitudes of vibration (Kwok et al. 2011). While it might be argued that the natural frequencies at higher amplitudes of vibration could be expected to be lower, some of the differences that have been measured are far greater than would be expected from this effect. As well as any differences between the design and prototype modal characteristics, there is also the question of the level of inherent structural damping that has been assumed in the design compared with that which will be experienced in the field over the lifespan of the building. There are relatively few reliable measurements of inherent structural damping in tall buildings, and even fewer at perceptible levels of motion, and thus the damping values that are input to the acceleration predictions are generally fairly crude and simplified estimates.

3.2 PEAK ACCELERATION VERSUS RMS

Two different measures of acceleration are most often used: the peak value, which occurs during a period of time—say 10 to 60 minutes—or the rms value over this same period. These distinctions have arisen because of the different waveforms, or acceleration signatures, corresponding to different wind excitation mechanisms (e.g., Melbourne 1977) that must be addressed. A few representative signatures illustrating a wide range of waveforms are shown in Figure 3-1. All of these signatures can be characterized as narrow-band vibration at the same frequency, with differences in the envelope uniformity.

The first signature of Figure 3-1 is harmonic (sinusoidal) vibration. Harmonic acceleration of this nature does not occur in real buildings, but it has been widely used in laboratory "moving room" experiments aimed at determining human thresholds of perception of small vibrations, or tolerance of larger vibrations, under controlled conditions. The uniformity of this signature can be characterized, on a first-order basis, by the ratio of peak value to rms value (standard deviation). This ratio, commonly referred to as the *peak factor* and designated g_f, is $\sqrt{2}$ for sinusoidal signatures.

The second signature was recorded from an accelerometer in a wind-tunnel model of a tall building, measuring the crosswind vibration while "locked-in" to

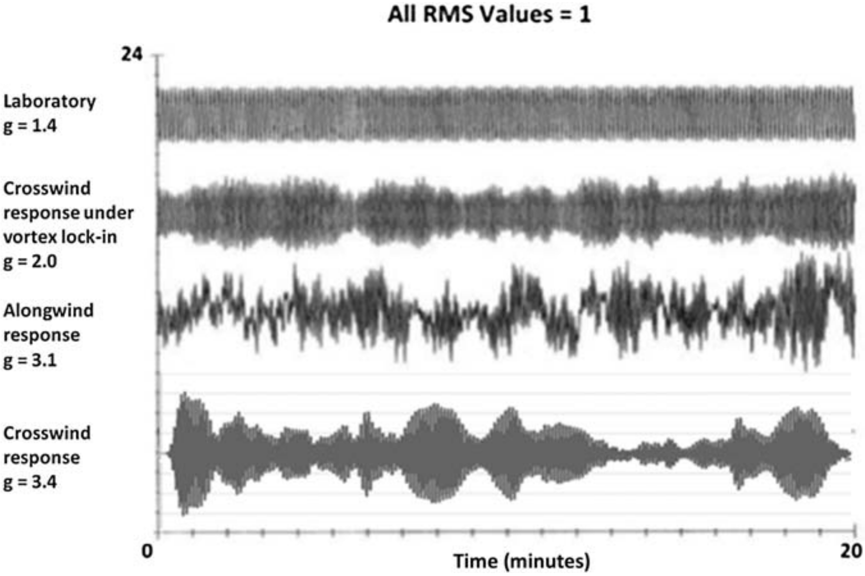


Figure 3-1. Characteristic acceleration signals, scaled to have equal rms values

vortex shedding forces. The signature is nearly harmonic but slightly random, with a correspondingly higher peak factor ($g_f = 2.0$). Acceleration of this type is rare in typical buildings, but could occur in special structures such as relatively lightweight and slender towers.

The third signature was obtained from an accelerometer in the same model under the same conditions, but it was oriented parallel to the wind direction. This motion is characteristic of tall building motion in the alongwind direction. It is more random than the above and has an even higher peak factor ($g_f = 3.1$).

The fourth signature is an example of a crosswind response and shows a random response to vortex shedding-induced forces. Its signature is random narrow-band with an envelope which shows distinct beats or "bursts" containing several cycles of relatively similar amplitude. The duration of these bursts and hence the number of cycles per burst increases with reduced damping. Most wind-induced motion problems for tall buildings are due to this type of crosswind response.

Both the along- and crosswind responses of wind-sensitive tall buildings tend to remain narrow-band random with peak factors of $3 < g_f < 3.5$. Lock-in may well be possible for tall slender chimneys but is seldom an issue for tall buildings at serviceability and working load levels.

Historically, most acceptance criteria for human response to vibration of various natures have been based on the rms index. This includes the ISO6897 (International Organization for Standardization 1984), ISO2631 Part 1 and 2 (International Organization for Standardization 1989) in which the "effective acceleration" is defined as the rms value, ANSI S3.29 (Acoustical Society of America 1983), and Irwin (1978).

Floor vibrations due to walking have been studied quite extensively (Reiher and Meister 1931; Lenzen 1966; Wiss and Parmelee 1974; Chang 1973), and it now seems to be well established that transient effects are less significant than steady state effects.

This following observation was stated succinctly by Alexander et al. (1945) in connection with studies of nausea induced by vertical motions: "Common observation suggests the conclusion that the time character of stimulation and not its intensity is the critical consideration". The large magnitude of peak accelerations is not the cause of nausea. There are several arguments also from a technical standpoint that favor the use of the rms index. These center on the fact that the rms index is more straightforward to measure and/or predict, in either analytical or wind-tunnel studies, and is therefore more likely to result in uniformity among predicting methods or agencies. This is most important when understanding how to add together multi-modal responses. The equations for combining rms and predicted peaks are quite different.

The effect of acceleration on humans cannot simply be described as "acceleration" as was done so often in early research. The waveform is of great importance, and peak values as well as rms values provide valuable information to characterize its effect.

3.3 RECURRENCE INTERVAL

People will tolerate discomfort felt infrequently and/or for short periods of time, but not as routine occurrences. That is, a larger vibration will be tolerated if there is a longer period between occurrences. It is believed that acceptability of maximum vibrations experienced will increase if the time between events is increased, that is for a longer recurrence interval (Hansen et al. 1973).

Synoptic gales, monsoons, typhoons, hurricanes and thunderstorm winds are all extreme wind events that need to be considered when evaluating the vibration in tall-buildings. Wind events dominating the climate depend on geographical location and the parent wind climate specific to that locale. In areas where synoptic gales are dominant, there is a strong causal relationship between regularly occurring vibrations in tall buildings and higher levels of vibration occurring during extreme wind events. In locations where typhoons (or hurricanes) and thunderstorm activity dominates the wind climate, a simple relationship between large vibrations and regularly occurring vibrations does not exist.

Synoptic and monsoonal winds are long duration events lasting for a couple of hours or a couple of days. Tropical-cyclones (variously called hurricanes, typhoons or cyclones) have similar timescales but thunderstorms pass through areas relatively quickly; about 10-minutes of high winds in a thunderstorm. Although the duration of strong synoptic, monsoonal and tropical-cyclone winds is similar, the way in which the strength of the winds varies with the recurrence interval is much different. Strong tropical-cyclone winds may occur only once a year or may be decades between events whereas strong yearly synoptic winds are probable. In areas affected by tropical cyclones, the one-year wind speed can be around 35-45% of the design wind speed; this is in contrast to a synoptic climate where a wind speed of around 75% of design strength has a yearly recurrence interval.

In the assessment of occupant comfort, 5 and 10-year recurrence intervals have been justified by users who suggest that perceptible motions occurring on average at this rate will not affect the functioning or commercial viability of a structure. Although this longer recurrence interval may adequately mitigate fear for safety resulting from extreme motions (and extreme events), it does not appropriately address the discomfort associated with regularly occurring wind events. A more recent trend has seen the evaluation of vibrations in windstorms with a one-year recurrence interval become more common. This shorter recurrence interval is more relevant to occupants' daily lives and deals more readily with the discomfort induced by motions.

Nonetheless movement noticed during rare events may still be alarming unless occupants are aware that this is expected behavior. The reaction to short-term thunderstorm events is generally more accepting than to longer term buffeting by a 6-12 hour duration extra-tropical storm. The different nature of these events points towards need for a variety of criteria rather than single value as in current standards.

When the wind climate is mixed; perhaps with both synoptic gales and tropical-cyclones, synoptic gales will likely dominate occupant comfort and well-being in the shorter recurrence intervals, but acceptability of vibrations at the longer recurrence intervals may be controlled by tropical cyclone events. In this case it is reasonable to evaluate motions against both a shorter return period that is more relevant to an occupant's daily life (either a one-year recurrence interval or less) and a longer return period (a 5- or 10-year recurrence interval) that limits accelerations during rare storms events to values that will not cause fear and alarm among occupants.

In some cases, significant building movements (such as those starting to make walking difficult) in buildings affected by rare tropical-cyclone events have been accepted by building owners, rather than incurring the cost of installing dampers. Such buildings were shown to perform well on a day to day basis and occupants were forewarned about the motions that may be noticed when strong winds were occurring.

Most problems in practice have come from movements which are felt much more regularly than the 10-year return period. It is likely that the original choice of 10-year return period was partly dictated by the desire to use a return period for which wind speed values were readily available, and in Canada where the 10-year return period originated, 10-year reference wind pressures were already available at that time for other purposes such as calculation of cladding loads. In parts of the world where extra tropical cyclone winds dominate, the choice of return period is perhaps not critical as long as the criteria are scaled to be appropriate for the return period selected.

In recent years, a number of extremely tall and slender buildings have been proposed that have periods as long as 10 to 20 seconds. Depending on their width, this can result in resonant excitation due to vortex shedding occurring at common wind speeds, e.g., once per month. In these cases, the existing criteria set at the 1- or 10-year recurrence intervals are not adequate in themselves. For events as frequent as one per month the emerging practice appears to be that the motions simply be kept below the human perception threshold, although data on human perception at such long building periods are scarce.

3.4 FREQUENCY DEPENDENCE

Thresholds of motion perception and the judged severity of vibration vary widely from person to person. The human body is not a passive system which responds monotonically to a physical stimulus (such as low levels of vibration). The body responds to vibration in an environment by damping, or in some cases magnifying it to different levels depending on the frequency of oscillation (Burton et al. 2006a). The level of magnification is dependent upon posture, body mass, flexibility, and other factors.

At extremely high levels of vibration, the awareness of motion stems from ‘somatic’ sensations arising in the skin, but as vibrations decrease in magnitude, the somatic sensations reduce and finally disappear, leaving the individual with a sense of motion not associated with somatic cues (Walsh 1961). In the absence of somatic sensations the body depends upon information received by the vestibular apparatus in the inner ear to qualify levels of vibration. It is this dependence on motion cues from the inner ear that dictates the frequency dependence of motion.

This dependence has been demonstrated for the extensive frequency range of 0.063 Hz to 10 Hz in motion simulators globally for lateral, fore-aft and bi-directional motion for both sinusoidal and random vibrations (Chen and Robertson 1972; Irwin 1981; Kanda et al. 1988; Denoon 2000; Burton 2006).

A stand-alone investigation, which has led to researchers suggesting non-frequency dependent comfort criteria, examined perception thresholds of elliptical and circular motions. The study demonstrated a near lack of any frequency dependence over the range of motions investigated (Shioya et al. 1992); however, this research was based on only a small range of frequencies (0.125 Hz – 0.315 Hz) and the findings were in conflict with those of related research teams (Kanda et al. 1988).

3.5 OCCUPANCY TYPE

Three of the recognized occupant comfort criteria (National Research Council of Canada 1995), AIJ-GEH-2004 (Architectural Institute of Japan 2004), and ISO10137 (International Organization for Standardization 2007) suggest different magnitudes of acceleration for residential and commercial occupancy.

Typical office buildings are occupied for eight hours a day, while residential buildings are inhabited continuously. In areas around the world with established weather warning systems in place, commercial buildings are typically vacated prior to severe windstorms. Individuals vacating these office environments will usually seek refuge in their residence. It is impractical and undesirable to evacuate hotels and residences in periods of strong winds.

Applying more stringent criteria on wind-induced vibrations in residencies ensures that individuals seeking refuge in extreme events are not discomforted by the levels of vibration nor do they fear for their safety. It is considered unacceptable and a risk to life safety to have occupants of a residential complex fleeing their homes in times of high winds.

Given that under extreme wind events workplace environments are typically vacated, the limits on acceptable vibrations may be less onerous. The expectation of residential occupants is such that there would be no need to vacate their home in high winds and that the residence is a comfortable and safe place into which to retreat. There is also the opposing viewpoint, which states that because employees are able to leave work (at least more easily than to leave home), that poor environments encourage absenteeism in the workplace. At home, in contrast, a resident is more likely to stay, and eventually become accustomed to the motion. This viewpoint actually argues for more stringent motion criteria in office buildings.

For more frequently occurring wind storms when it would not be expected to vacate the workplace, and where discomfort is induced in occupants, it is sensible that similar limiting accelerations for the residence and workplace be applied.

3.6 INFLUENCE OF TORSION

Motions of tall buildings are generally composed of three components: sway in two orthogonal directions and torsion. All three components can be resolved into translational motion at any point on a building floor. While there have been laboratory experiments to show that humans are sensitive to torsional motion, the kinaesthetic perception is not relevant to buildings where, away from the center of torsion, any torsional motion will be kinaesthetically perceived as a translational motion.

It has been postulated that torsional motion needs to be considered from a viewpoint of introducing an external visual cue due to the rotation of the building relative to external visual references and hence a translational motion can be visually detected. However, it has equally been postulated that at the amplitudes at which this would occur, there are already internal visual cues, including those caused by parallax as a result of occupants swaying in reaction to the motion.

Naturally, where torsion is present it means that translational motions will be different at different locations on the floor-plate of a building. It is common to assess the motion at either an extremity of a floor, at a radius of gyration (or central point between the center of rotation and the floor extremity), or the center of the floor or a combination of these three. While it is important to consider the effects of torsion, whether the net accelerations are assessed at a radius of gyration or at a floor extremity is a matter of choice and may be dependent on the intended occupancy of the building.

Other studies have proposed that the relative motion of distant objects becomes visually apparent due to the time rate of change of the building rotation or the torsional velocity and that this optical magnification, typically present for occupants in perimeter zones of actual buildings, creates the visual sensation of a “swinging horizon” and accentuates motion perception (Isyumov and Kilpatrick 1996). [N.B. In a group of tall buildings, adjacent buildings are perhaps more relevant references for visual cues than the ‘horizon’, unfortunately this study did not detail this information.]

Suggested limits on the peak torsional velocity were introduced in 1993 (Isyumov 1993); however, these limits are still tentative as they are based on limited research and there are practical indications they are too restrictive. Limits on the torsional velocity are suggested as a separate requirement to be considered in addition to assuring acceptable peak values of the resultant or "total" horizontal acceleration.

3.7 PEAK RESULTANT ACCELERATION

Most guidelines for acceptable accelerations do not specifically state what measure of the peak acceleration should be considered. The interpretation of the guidelines is to use the peak value of the resultant or the total horizontal acceleration. Typically, this includes the combined motions in both sway modes and the additional torsion-induced translational acceleration at some selected radius from the center of rotation. There are two questions which arise in the use of this approach: first, how does one form the peak resultant or total acceleration; second what frequency does one use when comparing this value with criteria that are frequency dependent?

When working in the time domain, the maximum value of the resultant at any moment can be determined exactly. Working in the frequency domain, the peak resultant or total acceleration can be estimated from the square root of the sum of squares (SRSS) of the peak values of the component accelerations. Alternatively, one may utilize the complete quadratic combination (CQC) rule, which accounts for the correlation between components when frequencies are close; SRSS becomes a special case of CQC for uncorrelated cases (Chen and Kareem 2005).

When the peak values of the component accelerations are not coincident and when the forcing on different modes is uncorrelated, the use of the SRSS/CQC method results in a conservative estimate. An empirical approach to reduce this overestimate is to use a joint action factor. [N.B. If rms responses are most important then the joint action factor rules for peaks given in (2) is not suitable and CQC rules would still apply].

It has been proposed (Isyumov et al. 1992) that the effective peak value of the resultant of two or more independent component accelerations can be calculated using a coincident action approach as follows:

$$\hat{a}_{res} = \left(\hat{a}_1^{\,2} + \beta_{2,3}^{\,2}\left(\hat{a}_2^{\,2} + \hat{a}_3^{\,2}\right)\right)^{1/2} \tag{2}$$

where $\hat{a}_{res}$ = peak resultant

$\hat{a}_1$ = peak acceleration of the largest component

$\hat{a}_2$, $\hat{a}_3$ = predicted peak accelerations of the other two components

$\beta_{2,3}$ = coincident action factor that defines the magnitudes of the companion accelerations $\hat{a}_2$ and $\hat{a}_3$, which are expected to be present or "coincident" at the instant of time when the largest component acceleration $\hat{a}_1$ reaches its maximum or peak value

Based on work presented in their study the magnitude of the coincident action factor is typically taken as $\beta_{2,3} = 0.5$. This means that the magnitudes of the numerically smaller components of the acceleration, which are taken to be coincident with the peak value of the largest component, correspond to peak values formed with a peak factor taken as ½ of that used in forming the individual component acceleration peaks.

Typically, the peak or maximum value of a time-varying wind-induced response of a tall building, denoted as x(t), attained during a time interval of T is expressed as:

$$\hat{x} = g_x x_{RMS} \tag{3}$$

where g_x = is the peak factor and x_{RMS} is the rms or the root-mean-square value of x(t). For wind-induced vibrations of typical tall buildings during a time interval of T = 1 hour this peak factor is typically in the range 3.5 to 4.0.

Thus, using a coincident action factor of $\beta_{2,3} = 0.5$, means that the coincident acting values of $\hat{a}_2$ and $\hat{a}_3$ are peak values calculated with peak factor of ½ of typical values, i.e., 3.5/2 to 4.0/2 = 1.75 to 2.0. In other words, the coincident acting values are typically 1.75 to 2.0 standard deviations above the mean. For a linear structure, the wind-induced accelerations typically follow a Gaussian distribution with a mean of zero. The probability of getting a coincident value with a magnitude greater than +/– 1.75 to +/– 2.0 standard deviations is in the range of 5 to 8 %.

Using (2) with a coincident action factor of $\beta_{2,3} = 0.5$ means that the maximum effective resultant acceleration represents a resultant formed using the maximum value of the largest component of the acceleration, with coincident values of the lesser components that are not typical in magnitude but which are themselves relatively rarely exceeded.

The use of this algorithm simplifies the question of what frequency to use when building performance is compared with frequency-dependent acceleration criteria. Since in this approach the peak total acceleration is dominated by the largest component acceleration, the acceptability of the total acceleration would be judged using the frequency of the mode of vibration that generates the largest component peak acceleration. Using the frequency of the largest component acceleration is also expected to provide a good estimate in situations where the peak resultant acceleration is determined from a time domain analysis.

Wind tunnel laboratories can process test data using a time domain approach and thus determine the actual values of the resultant acceleration and the peak factor; however, this is not commonly done.

CHAPTER 4

Human Perception and Tolerance under Experimental Conditions

4.1 INTRODUCTION

There is a vast amount of data in the published literature dealing with high frequency industrial and machine vibrations and vibrations associated with flight, maritime and ground (motor vehicles and trains) transportation. There are relatively few studies conducted at frequencies relevant to wind-induced tall building vibrations, typically in the range 0.1 to 1.0 Hz. The new generation of tall and very tall buildings is characterized by natural frequencies well below 0.1 Hz where even fewer studies have been conducted. Kwok et al. (2009) have reviewed past motion simulator studies on human perception of vibration and tolerance thresholds of wind-induced building vibration in these lower frequency ranges.

4.2 MOTION SIMULATORS

Motion simulator and shake table experiments have been conducted on human test subjects by Khan and Parmelee (1971), Chen and Robertson (1972), Goto (1975), Irwin (1981), Kanda et al. (1988), Goto et al. (1990), Shioya et al. (1992), Shioya and Kanda (1993), Noguchi et al. (1993), Denoon et al (2000a), Burton et al. (2003, 2004a, b, 2005, 2006a), Michaels et al. (2009, 2013) and others, under carefully controlled experimental conditions to overcome the uncertainties posed by field experiments and building occupant surveys. In these motion simulator experiments, uni-directional, bi-directional, and/or yaw (torsion) vibrations were typically simulated by varying frequencies, amplitudes and durations, and with human subjects tested in different postures or engaged in different activities to assess their perception of motion, cognitive performance or task performance. Although the vast majority of the earlier experiments were based on sinusoidal vibrations, more recent experiments conducted by Denoon et al (2000a) and Burton et al. (2003, 2004a, b, 2005, 2006a) focused on random vibrations and included task distractions to reproduce an environment normally encountered in wind-excited buildings. Figure 4-1 is an example of a purpose-built 3 m by 3 m dual axis motion simulator, which is capable of simulating sinusoidal vibrations

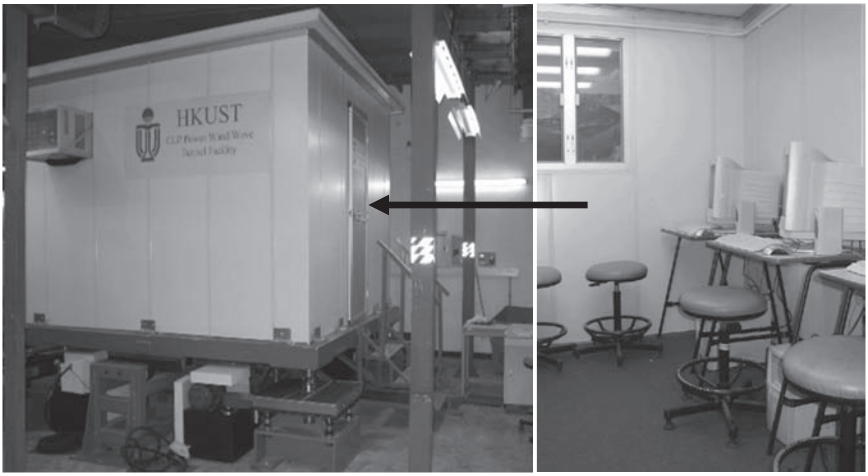


Figure 4-1. A dual axis motion simulator showing the test room and configuration inside the test room

and two degree-of-freedom tall building random vibrations with dominant frequencies between 0.1 to 1.2 Hz.

Despite the potential of biased results due to pre-conditioning, in which the test subjects expect to experience vibration, and the reliance on a simulated instead of an actual building environment, motion simulators remain the most practical tool to study human response to wind-induced tall building vibration.

4.3 PERCEPTION THRESHOLD

4.3.1 Body Posture/Orientation/Movement

There have been a number of experiments to investigate the effects of orientation relative to motion on the perception threshold of whole body vibration. The majority of these experiments have focused on higher amplitudes and higher frequencies of vibration than might commonly be experienced in tall buildings. Differences in perception threshold based on body posture have also been demonstrated, although these differences are smaller than the intra-subject differences. Effects of subject movement on perception threshold have not been fully investigated at the frequencies and amplitudes relevant to tall building motion, but it can be concluded that occupants moving in buildings will reduce their sensitivity to building motion as their own motion dominates perception. Whether any of the factors of body posture, orientation, and movement are relevant to setting motion criteria for buildings is debatable given the small effects these are likely to have relative to other motion cues in buildings, and the range of postures and orientations adopted by building occupants over the period of a typical wind storm.

4.3.2 Effect of Combined Motions and Frequency

Perception of motion is caused by perception of an instantaneous acceleration or a change in acceleration (referred to as jerk). Acceleration can be much more accurately measured than jerk, and so it is acceleration that is used as the basis for discussing perception thresholds.

The majority of work that has been conducted on motion perception has used uni–axial motion with a single frequency of motion. This may not, however, reflect the real response of buildings where motion may be bi-axial at a range of frequencies. A typical situation would be where a building was exhibiting crosswind behavior leading to the maximum accelerations. At the same time, it may be being buffeted in an alongwind direction. The natural frequencies in the orthogonal directions could be quite different. The resultant motion could be relatively complex. This combination of motions could lead to higher rates of change of acceleration and could, theoretically, lead to perception of motion at lower acceleration amplitudes for a given primary frequency.

Benson et al. (1986) investigated the perception of linear motion in absence of visual and auditory cues. This research attempted to answer two questions, the first, whether the detection of motion differed between body axes, and the second, whether the threshold of perception was dependent on the frequency of oscillation. A seat was mounted on a linear slide; it was controlled by a servo motor and had the ability to rotate in three directions. The test subject was strapped to the seat. The results of the investigation showed that individuals had a greater sensitivity to oscillation in the fore-aft and lateral direction of motion, when compared with vertical vibration and that there was a dependence of the perception of motion on frequency.

4.3.3 Visual and Acoustic Cues

While kinaesthetic perception has been the focus of most research into human perception of wind-induced building motion, there are a number of other cues that may trigger perception of motion by building occupants. The most common of these are visual and acoustic cues.

Examples of visual cues include swinging lights, moving blinds, swaying plants, sloshing liquids, etc. These are all internal visual cues. Other internal visual cues can arise from occupants swaying in response to the motion and observing motion as a result of parallax effects. There have been suggestions that torsional motions of buildings can be visually perceived from motion of external objects relative to internal objects such as window frames. At the amplitudes of motion that are being experienced, it is far more likely that what is being observed is the swaying motion of the occupants relative to close and far reference points, rather than the true motion of the building (Burton et al. 2006b). There are, however, other external visual cues that may trigger perception in occupants who are accustomed to motion in a given building and have a degree of expectation of such motion on windy days. Cues could include swaying trees, extended flags, and other indications that there are high wind speeds.

Like visual cues, there are a number of possible sources of acoustic cues. Some of the audible motion cues may provide information about the frequency of the motion and others may not. The most common acoustic cue that would provide an occupant with information about the natural frequency of the motion, which would supplement and be consistent with kinaesthetic cues, is structural noise, such as creaking resulting from the building sway. Other cues that have been experienced are venetian blinds impacting window frames as they sway back and forth. Wind noise can also be strong cue, for building occupants.

Another type of cue, which is not strictly an acoustic cue, is being prompted about building motion by other occupants of the building. This type of cue increases in likelihood where there are large numbers of people congregated.

4.4 BODY RESPONSE

4.4.1 Cognitive Task Performance

Much of the previous research that has been conducted on task performance has been for the aerospace and vehicular industries and, therefore, at both higher frequencies (>1.0 Hz) and accelerations (>50 milli-g) than those typically experienced in tall building vibration. A comprehensive review of vehicle related studies is given in a paper by McLeod and Griffin (1989). Although it has been suggested that vibration could interfere with cognitive processes, there is currently little experimental evidence of any deleterious effects.

It has been postulated that vibration may act directly on the central nervous system by providing surplus information and altering levels of arousal, thereby affecting cognitive skills such as memory and concentration (Jeary et al. 1988). Sherwood and Griffin (1990, 1992) studied cognitive effects, with tasks designed upon an understanding of experimental psychology, due to vertical sinusoidal vibration with accelerations at levels typically observed in vehicles. It was found that motion did not disrupt long-term memory processes but did negatively affect working memory.

Previous motion simulator investigations (Denoon 2000), focusing on the effects of motion on cognitive efficiency and cognitive fatigue, investigated some major psychological constructs and demonstrated that single degree-of-freedom narrow band random motion did not have significant effects on cognitive performance for a range of tasks investigated. Morris et al. (1979), for various levels of acceleration at the frequency of 1.6 Hz, also determined that the level of vibration had no effect on task performance. Commenting on their own work, the investigators noted that the simulated tasks were likely over simplified and a selection of more realistic tasks was imperative to convincingly explore the possible effects of vibration on task performance. This is a problem of many previous investigations, where the majority of the involved participants had little difficulty in completing the presented tasks, therefore resulting in a non-Gaussian distribution of scores, i.e., ceiling effects (Morris et al. 1979; Jeary et al. 1988; Denoon 2000). However, the opposite effect is also possible, where a task is so difficult that any additional difficulty caused by the vibration is insignificant, i.e., floor effects (Griffin 1997). More subtle effects on complex cognitive processes may be hindered by vibration but current information is too limited to formulate confident statements regarding these specific effects.

It has become known that multiple frequency vibration causes a greater disruption to performance than does the presentation of any single frequency, and similarly, the effects of multiple axis vibration are thought to be more detrimental than the effects of a single axis (Griffin 1997; Griffin and Brett 1997). Motion simulator investigations carried out by Burton (2006) were conducted using narrow-band bi-directional motion. Again with this study no statistically significant relationship was observed between cognitive performance on the tasks presented and the various levels of motion simulated. The results of these studies indicated that the cognitive task performance was more greatly dependent on the individual's perceptions of the vibration rather than directly related to the levels of simulated motion.

It was Webb et al. (1981) that initially proposed that the differences in cognitive performance under certain stressors was more a function of an individual's personality, rather than performance being directly linked to the stressor level. They defined two different types of subjects: "internal" subjects that perceive effort as an instrument of personal achievement and "external" subjects that believe success and failure are outside their own influence. In their studies it was observed that "internal" subjects performed significantly better than "external" subjects, leading to the belief that much of the inter-subject variability could be related to an individual's personality.

4.4.2 Manual Task Performance

Manual tasks include any activity in which an individual is required to grasp, manipulate, or restrain an object, and it is well known that whole body vibration may interfere with such activities (Griffin 1997). An understanding of the effects of vibration on task performance may be of significant importance for individuals who are often exposed to extremely adverse vibration conditions, such as helicopter pilots or construction workers. However, it is possible that even lower levels of vibration, such as the low frequency, low acceleration motion of a tall building in a wind storm, although not typically resulting in injury or damage to one's health, may have adverse effects on task performance. These lower levels of vibration may affect the body's senses used in the collection of information and create difficulties for the individual performing the task. Although whole body vibration may affect more complex and specific mental processes, it is thought that the mechanisms affecting performance are more greatly dependent upon levels of fatigue and arousal (Griffin 1997). A general effect of motion on performance may occur when the motion reduces motivation due to motion sickness or if the motion requires increased effort or energy output by someone subjected to the motion in order for them to perform a task.

Individuals suffering from motion sickness may experience a wide variety of sensations including headache, nausea, fatigue and disorientation (Yamada and Goto 1977). Often an individual may not be able to pinpoint a specific symptom, but simply have an overall uncomfortable feeling. It has also been postulated that even at levels of vibration below the threshold of perception, after exposures of several hours duration, an individual may find himself/herself unconsciously uncomfortable (Reed et al. 1973).

To determine whether task performance was impaired at levels of vibration below conscious perception, Jeary et al. (1988) conducted investigations using simulated motion in an actual tall building. Although significant performance degradation was not observed in the tests that could be carried out, it was hypothesized that vibration could act directly on the central nervous system by providing surplus information and disrupting skills such as memory and concentration.

Some of the previous research that has been conducted on manual task performance has been for the shipping industry; focusing on low frequency vertical sinusoidal vibration (Wertheim 1998). Other researchers have investigated the effects that high acceleration motions could have on physical activities, including the ability to walk a straight line or up and down a set of stairs (Goto 1975).

In a series of advanced studies in the 1980's, Irwin and Goto conducted manual dexterity tests in the frequency range of 0.02 Hz–10.0 Hz for five motion combinations: yaw and lateral vibration, yaw and fore-aft vibration, yaw, fore-aft and lateral vibration, and fore-aft vibration. Participants in the study performed tasks that closely represent typical tasks that skilled workers may need to carry out on a regular basis (threading a needle and tracing various shapes and patterns) before the vibration commenced, during the vibration, and following the conclusion of the vibration. The time taken to complete the needle threading, and the deviations from the tracing patterns were used as markers for task degradation. Overall, the time taken to complete a task was shorter at frequencies greater than 1.0 Hz, and the trace lines showed greatest deviation in the frequency range 0.2–1.0 Hz. No differences were reported for the task performance between the five types of motion combination.

More recently, Wong et al. (2013a) conducted experiments in a motion simulator to investigate the effects of sinusoidal motion, at a range of frequencies and amplitudes, on the performance of a tracking task. Tests subjects were required to aim a laser light at the centre of a concentric target in a standing position and subjected to either fore-aft or lateral motion. The test results clearly demonstrated the effects of motion on tracking task performance due to postural instability caused by the simulated motion. Wong et al. (2013b) also conducted experiments based on the Fitts' Law task (Fitts 1954) in which test subjects responded by moving and clicking a computer mouse. The test results show that increase in frequency and particularly acceleration level led to measureable performance degradation in terms of mean movement time in the Fitts' Law task.

In some extreme cases, the stress of vibration has been shown to motivate participants to improve performance above that achieved under static control conditions (Sherwood and Griffin 1990).

4.4.3 Frequency Dependence

The mechanisms for perceiving motion can be classified as tactile, vestibular, proprioceptive, anaesthetic, visual and auditory cues, and visual-vestibular interaction. The interaction of these mechanisms forms the sensing system that determines an individual's sensitivity to motion. Lacking visual and audio cues, motion can be assumed to be sensed through proprioceptive, (i.e. joint or muscle) cues or through the inner ear.

Griffin (1997) highlighted that individuals cannot detect translational movements of the body at constant velocity, but that perceptible motions are those composed of a change in the velocity, causing the acceleration or deceleration of the body [N.B. A fundamental characteristic of physics: there is no way to detect constant velocity in a sealed environment]. It is the vestibular organs of the inner ear, some of the body's primary motion sensors (Walsh 1961; Israel and Berthoz 1989; Vibert et al. 2003), which detect this linear acceleration. The principle of this comes from early experiments conducted by Walsh (1961) on individuals with defective ear canals/labyrinths and others without otolith function. Further research (e.g., Guignard 1972) confirmed that oscillatory motion below 1.00 Hz causes sensations of inner ear only, whereas oscillation within the bandwidth 1.00–10 Hz causes resonances in the body that trigger both inner ear and physical sensory cues.

When the body moves in a long period sway, motion information can be gathered from the proprioceptive systems of the neck and body, but these sensory mechanisms have lengthy response times and tend to be inconvenient measurement systems (Goldberg and Hudspath 2000). The vestibular organs are able to sense motion directly and quickly enough to activate appropriate response mechanisms. The vestibulocollic reflex, a neural reflex that activates neck muscles when head motion is sensed by the vestibular organs, dominates the compensatory head movement from 0–1.00 Hz (Peng et al. 1996).

Burton et al. (2006a) demonstrated that the response of the human body could be described by a frequency-dependent amplification. For a person's back this peaks at 0.5 Hz for both fore and aft and lateral directions. The head amplification by contrast continued to rise with frequency over the range from 0.15–1.0 Hz.

Lin and Rymer (2000) indicated that the neuromuscular system exerts a larger damping force for larger velocity amplitudes, and a smaller damping force for smaller velocity amplitudes. The characteristically larger damping provides greater postural stability against large perturbations, yet allows the less disruptive smaller amplitudes to persist. At low frequencies the time to displace the trunk may be too long to activate the para-spinal muscle stretch reflex, whereas at high frequencies, the stretch reflex is activated and the para-spinal muscles become stiffer, damping the level of acceleration.

Lee and Svensson (1993) investigated spinal deformation at loading rates of 1.00 Hz, 0.50 Hz and a "quasi-static" rate and demonstrated a significant reduction in displacement of the spinal vertebrae as the frequency was increased to 1.00 Hz.

Most of previous investigators researching whole body vibration have found large variability amongst the collected data. Whitham and Griffin (1977) propose that the difference could stem from the differences in the body itself or the adoption of a specific posture.

4.5 PHYSIOLOGICAL AND PSYCHOLOGICAL EFFECTS OF VIBRATION

Motion sickness is best known for the characteristic effect of producing nausea and vomiting in its victims. In all but the most severe conditions, nausea and vomiting are preceded by prodromal (early onset) symptoms. These early onset features include drowsiness (e.g., Graybiel and Knepton 1976) and impaired hand-eye coordination.

The progression of symptoms is mediated by a combination of at least three factors: individual susceptibility, severity or 'dose' of motion, and duration of exposure (Reason and Brand 1975). Exposure to a long duration of a low-dose motion will induce prodromal symptoms, which may progress to primary symptoms in moderately susceptible individuals, or may not progress in less susceptible individuals. In contrast, even short exposure to severe motion will result in primary symptoms quickly; prodromal symptoms will be less salient if present at all (Reason and Brand 1975).

Graybiel and Knepton (1976) observed a phenomenon where long duration exposure to low-dose motion induced an increased frequency of yawning, drowsiness, lack of motivation for work (physical or mental), reluctance to participate in group activities, daydreaming and low-level depression in participants. [N.B. This is termed Sopite Syndrome, whose effect is leveraged by parents when rocking their young children to sleep. The term sopite derives from the Latin term 'sopor', meaning a deep sleep.] Graybiel and Knepton (1976) state that "The onset was insidious, and the unsophisticated might attribute the yawning and drowsiness to boredom and relaxation. More distinctive symptoms, however, included a disinclination to be active physically or mentally".

Research typically focuses on the high-level symptoms of motion sickness and the types of motion that induce nausea and vomiting, and under what conditions. Low-dose environments, and consequently low-level responses, like Sopite Syndrome, receive less attention, perhaps neglected because the symptoms are perceived to be relatively less severe or less important. Kennedy et al. (2010) states the detrimental effects on performance and safety can be larger than higher-level symptoms such as sweating and nausea.

Tall buildings are an example of a low-dose environment as they rarely, if ever, induce vomiting. However, under certain conditions there are reports of building occupants taking motion sickness tablets to counteract symptoms of nausea (Melbourne and Cheung 1988), and of employees asking to be dismissed for the day due to discomfort. There are other examples of hotels, e.g., one in Chicago which offers a motion sickness pill, while the Hyatt in San Francisco alerts its guests of the potential motion of the building under winds through a printed note, assuring their guests that this is the normal behavior of the building. Accordingly, the building occupants should be conditioned to the performance of buildings under winds to avoid unnecessary apprehension and cause for discomfort at much lower levels of motion (Kareem 1988).

4.6 TOLERANCE OF MOTION

With the heights and slenderness of buildings and towers now being built, it is no longer practical to ensure that the level of motion these tall buildings undergo in wind storms will remain below occupants' perception threshold. It has become necessary that occupant comfort criteria, employed the world over, be based more validly on occupant's tolerance thresholds.

There have been very few motion simulator investigations that have focused primarily on the tolerance threshold of motion, as distinct from the perception threshold. There have however been full-scale investigations, including the polling of occupants following significant motion events, in attempts to ascertain their reaction to comfort and "acceptability" in addition to perception. The first of these was probably the landmark study of Hansen et al. (1973), in which the occupants of two buildings/events were asked "how many times a year would a similar experience occur before it became objectionable?" Thus they obtained a relationship between motion intensity (for two different values of rms acceleration at the top of the building) and the percentage of people that can be expected to object.

In a more recent study presented in Isyumov and Kilpatrick (1996), full scale survey results, shown in Figure 4-2, demonstrate the distinct difference between the perception and tolerance threshold of motion. The results of the twenty-seven cited tall building surveys suggest that although motion was perceived in many of the buildings, the motion was tolerated and no expression of occupant fear or concern was documented. Unfortunately, the apparent random scatter in these results is so great that no conclusions can be made.

Of the previous experiments that have been conducted using motion simulators to investigate the effects of low frequency motion on individuals, significant difficulties have been encountered in translating tolerance of motion derived from simulator investigations into tolerance of motion in tall buildings. The environmental conditions in the motion simulator are such that space and fear are not accurately represented (Reed et al. 1973), and since difficulty exists in replicating these environmental factors in the simulator, and the variability amongst participant responses is great, it is problematic to extract information

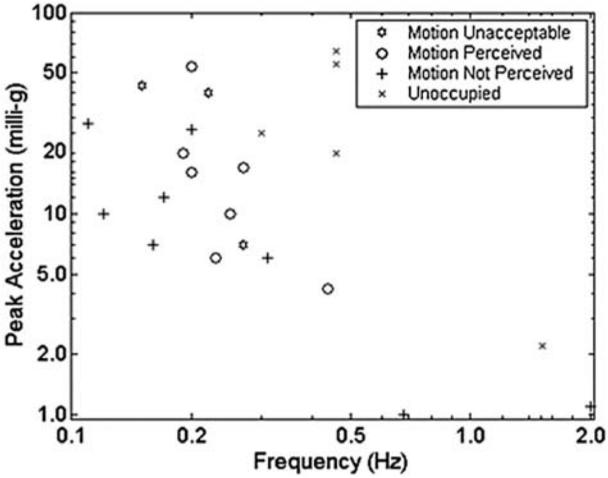


Figure 4-2. Measured wind-induced accelerations of tall buildings and occupant response

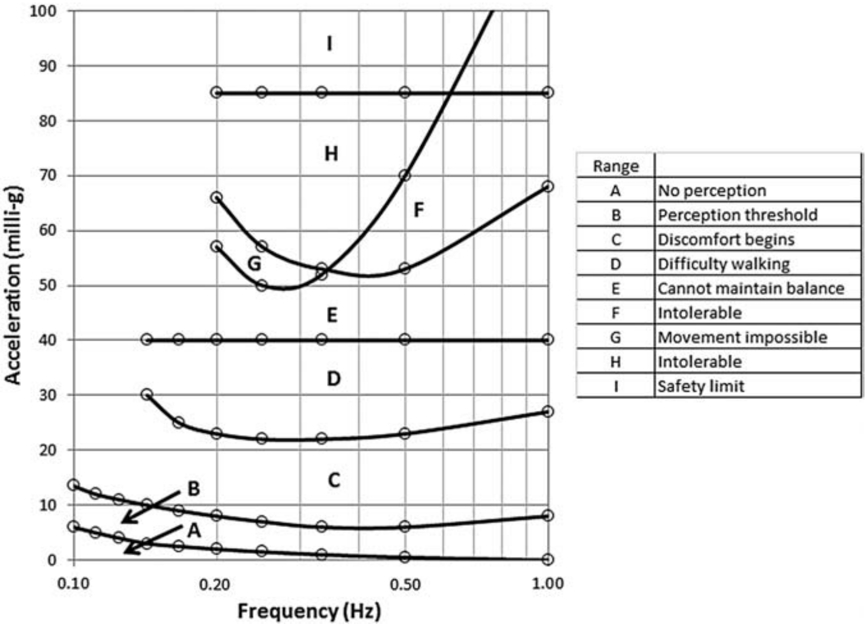
SOURCE: Isyumov and Kilpatrick (1996); reproduced with permission from the Council on Tall Buildings and Urban Habitat.

regarding motion acceptability directly from an individual's tolerance of the simulator's motion.

By synthesizing laboratory motion simulator investigations from Khan and Parmelee (1971) and Chen and Robertson (1972), and full-scale research from Hansen et al. (1973), Irwin (1978) proposed the design recommendations, which led to the development of the ISO6897 (International Organization for Standardization 1984) guideline for evaluating the acceptability of low-frequency horizontal motion of buildings subjected to wind forces. Irwin set the limits of acceptable motion based on a tolerance threshold as opposed to a perception threshold.

Denoon (2000) completed both field and motion simulator experiments and focused not only on the perception of motion, but also the tolerance of motion. At the completion of the testing program, Denoon surveyed all of the participants and determined that factors affecting the tolerance of motion were: the magnitude of motion which leads to fear and alarm, and the frequency of occurrence of perceptible motion. The study concluded that both education and habituation increased the tolerance of occupants to wind-induced vibration.

Goto (1975) realized the necessity of understanding not only the perception threshold of motion for tall building vibration, but also the effects that a high level of motion could have on other activities. He presented results from a series of investigations which examined: motion inducing feelings of nausea associated with motion sickness, the ability to perform manual tasks, and the ability to walk both a straight line and up and down a set of stairs, as shown in Figure 4-3.



Range	
A	No perception
B	Perception threshold
C	Discomfort begins
D	Difficulty walking
E	Cannot maintain balance
F	Intolerable
G	Movement impossible
H	Intolerable
I	Safety limit

Figure 4-3. Vibration limits and habitability
SOURCE: Adapted from Goto (1975).

4.7 DETERMINISTIC VERSUS PROBABILISTIC

The definition of terminologies such as “strongly feel,” “clearly feel,” “slightly feel,” “comfortable,” “acceptable,” “tolerable,” and “intolerable” are unclear and understanding can be quite different from person to person. These ambiguous terminologies can cause dispersion of results from motion simulator studies due to a different understanding of the definitions, not due to physical or psychological reasons, which should be the target of research. The definition of “perception threshold,” which is the boundary between perceiving and not perceiving vibrations is clear. Tamura et al. (2006) has summarized, in the results of questionnaire studies on human perception threshold, the effects of vibration frequency, randomness and motion shapes based on a series of experimental studies and derived a probabilistic perception threshold as shown in Figure 4-4.

As discussed in Section 4.4.2, Jeary et al. (1988) reported field test results on probabilistic perception thresholds using an actual 10-storey building under artificially excited conditions. These results are also shown in Figure 4-4 as the hollow circles at 90%, 10% and 2% percentile of perception for ascending fore-aft vibrations. Although their data were obtained under field conditions for an actual building and a slightly wider dispersion is recognized, they coincide closely with the laboratory data obtained by the authors. Figure 4-4 also illustrates the average

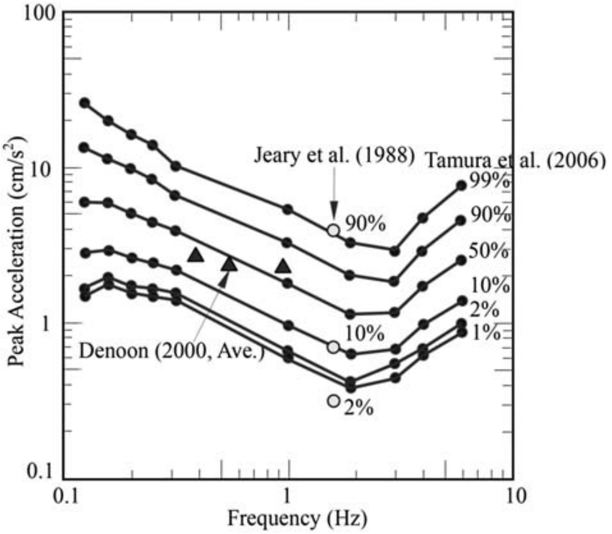


Figure 4-4. Probabilistic perception thresholds for horizontal vibrations

SOURCE: Data from Tamura et al. 2006; Kanda et al. 1993; Shioya et al. 1992.

perception thresholds based on full-scale data reported by Denoon (2000), which lie near the 50% curve. The results obtained under laboratory conditions are shown using constant amplitudes, and the results from full-scale measurements are shown using peak values of random vibration.

The procedure of the deterministic evaluation methods is to plot 1-year-recurrence peak accelerations of two principal translational axes, e.g., A_X and A_Y, against these curves with the first mode natural frequencies f_X and f_Y for each direction for comparison with the target curve.

A more sophisticated probabilistic method was proposed by Kanda et al. (1993) and explained in Tamura et al. (2006) to deal with the fact that the evaluation of the wind-induced response of a building has some uncertainty due to the inherent uncertainty of the design wind speed estimation and many other parameters such as wind flow conditions, dynamic properties of the building and so on. It is therefore better to treat both the human reaction and the building response as random variables (Kanda et al. 1988, 1990). Evaluation of building responses is generally based on probabilistic and statistical methods, but the evaluation of building habitability is made not to exceed a specific target guideline in a deterministic manner.

Among the guidelines and evaluation curves, only AIJ-GEH-2004 does not specify any allowable or recommended level of acceleration, and the decision of a target level of acceleration to be satisfied is left to building owners and designers. However, once they have decided upon a target design level by selecting one of the percentile of perception curves, there is no difference from the other deterministic evaluation methods.

Table 4-1. Values of perception index and corresponding occupants' reactions to wind-induced building vibrations (Kanda et al. 1993)

Perception Index β	*Possible Occupants' Reactions*
$\beta < 0$	Complaints will occur
$0 \leq \beta < 1$	Complaints may occur
$1 \leq \beta < 2$	Perceptible but no complaints
$2 \leq \beta$	Not perceptible for majority

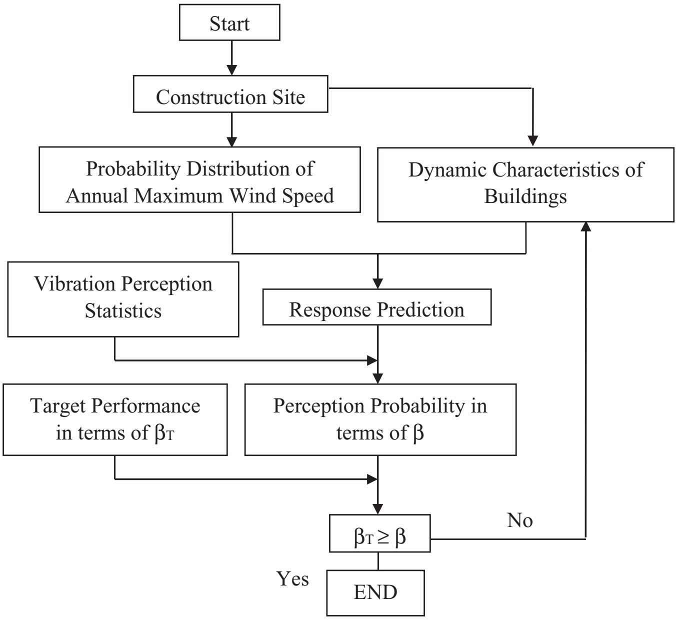


Figure 4-5. Schematic flow of probabilistic habitability design method for wind-induced building vibrations

SOURCE: Kanda et al. 1993; reproduced with permission.

For the probabilistic evaluation method, once a construction site is decided, the probability distribution of annual maximum wind speed is estimated from statistical meteorological data. The magnitude of wind-induced response can be calculated in several ways for buildings with known dynamic characteristics. The probability of perception of motion is then estimated. The derived perception index β of this is compared with the target value β_T, as shown in Table 4-1. As long as $\beta < \beta_T$, some changes in design characteristics are required, as indicated by the flow chart in Figure 4-5.

Both the building response estimates and the human comfort considerations have inherent uncertainties. Bashor and Kareem (2007) presented a FORM-based probabilistic assessment method similar to Kanda et al. (1993) and Tamura et al. (2006) to account for the uncertainty in both the estimation of building acceleration and the occupant comfort criteria. This study also caste this formulation in terms of a performance based format and expressed the outcomes by means of a traditional qualitative risk assessment performance matrix (Bashor and Kareem 2009).

CHAPTER 5

Human Perception and Tolerance of Building Motion under Real Conditions

5.1 INTRODUCTION

The ideal approach to addressing human perception and tolerance of motion in tall buildings is to monitor occupants under real conditions. Unfortunately, building owners are often reluctant to offer such access to their occupants. Despite this difficulty, observing occupants in real buildings has been accomplished in artificially excited buildings and also in monitored wind-excited tall buildings. Increasing such efforts will continue to provide insights into the issue of occupant comfort, a key factor in improving the habitability performance of tall buildings.

5.2 FIELD EXPERIMENTS

Human perception of motion is dependent upon many factors, some of which are more difficult to quantify than others. While researchers have studied the effects of frequency, amplitude, duration of motion, and waveform (peak factors) on human comfort using motion simulators, there are still other contributing factors which are difficult to accurately capture within motion simulators.

Field experiments and surveys of building occupants conducted in wind-excited tall buildings during wind storms provide vibration perceptibility and acceptability information for various levels of accelerations and at different frequencies (e.g., Hansen et al. 1973; Goto 1983; Lee 1983; Isyumov et al. 1988; Isyumov and Kilpatrick 1996; Denoon et al. 1999, 2000b; Kijewski-Correa et al. 2007; Lamb et al. 2013).

Full-scale assessments of human perception and tolerance offer the most faithful testing environment that captures the complexity of lateral-torsional motions as well as visual and audio cues that cannot be simulated. Thus, realistic conditions that cannot be incorporated into motion simulator studies are naturally included. For example, occupants of tall buildings might have higher levels of tolerance due to experience or education; on the other hand, participants in motion simulator studies may go into the experiment expecting motion (Pirnia 2009). The role of occupancy type also comes into play as an important consideration that cannot be captured in motion simulator studies. Monitoring human perception and tolerance of motion under real conditions is the only way to incorporate such aspects of the natural environment of tall buildings.

5.3 ARTIFICIALLY EXCITED BUILDINGS

Vibration perception experiments have also been conducted in artificially excited buildings (e.g., Jeary et al. 1988; Nakata et al. 1993). In these experiments, vibration generators such as counter rotating mass drivers or eccentric mass drivers were employed to excite real buildings in a controlled manner so that the vibration amplitude, and to a lesser extent the frequency of vibration, can be varied. The major advantage of this type of test is the control over the test parameter, including vibration amplitude, frequency of vibration and modes of vibration: fore-aft, lateral or torsional. Although these tests were conducted in an actual building environment, the test buildings only underwent sinusoidal vibrations, which differ greatly from the random responses normally encountered in wind-excited buildings.

A study on the perception threshold of motion was carried out by using a test room on the 4th floor of a 7-storey building (Nakata 1993). The building was vibrated uni-axially by two exciters, which were actually hybrid-mass dampers installed on the 5th floor. Isolation from acoustic and high-frequency disturbances was almost perfect because the room was made from soundproofed walls and the floor was mounted on shock absorbing supports laid on the building floor. Thus, the envelope of the test room was double layered. Two subjects with different orientations were tested simultaneously. Incidentally, the subjects could only see the sky through the window glass, but no outside features. According to questionnaire studies, nobody became aware of vibration from visual cues.

5.4 MONITORED BUILDINGS

There have been relatively few tall buildings that have been monitored over extended periods of time. Of those that have, only in a few cases have investigators been given access to the building occupants to interview them about their motion experiences. In even fewer cases have the investigators been given permission to publish the results of interviews. As such, much of the information about occupant response to motion in buildings, even monitored buildings, is anecdotal. In buildings where surveys have been conducted correctly and/or occupants have been given the ability to independently record motion perception on a long-term basis the perception thresholds (but not necessarily acceptance or tolerance thresholds) have been found to agree well with laboratory experiments when accelerations have been recorded using peak acceleration as the measure.

CHAPTER 6

Post Event Review of Motion in Buildings

6.1 INTRODUCTION

From a design point of view the biggest question left in relation to occupancy tolerance to motion in tall buildings is not what is perceivable, but what is acceptable. Only through post-event studies in actual buildings can this question ever be answered. This chapter will review our present knowledge of what motions have been observed in tall buildings and what level of motion might be acceptable, enveloped by the breadth of human perception with the associated variability of human response. Does acceptability go up to the edge of litigation? Should it involve unrealistic anxiety in relation to safety? Or is it simply to be limited by a small percentage of people who can perceive low levels of motion and might feel uncomfortable? These questions are not answered in this chapter, but it will give food for thought and further study on the last question.

6.2 FULL-SCALE SURVEY RESULTS

In the early seventies, Hansen et al. (1973) and Reed et al. (1973) performed a landmark study where occupants of two buildings, located in Boston and Seattle USA, were interviewed following two major wind events. A review of the survey results at a conference with several architects, building owners and developers was conducted where it was concluded that approximately 2% of the occupants in the top one-third of a building greater than seven stories may object to a building's motion each year without seriously affecting the renting program. They determined that limiting the objections of building inhabitants to 2% over the top one-third of the building required, in this specific case, imposing a limit of 5 milli-g (rms) acceleration occurring no more than once every 6 years on average.

Lee (1983,1984) presented a case study of occupants' reactions to the oscillation of a building during a wind storm. Lee's study examined the reaction of people who were situated in the 19th floor coffee bar of a 78 m high building at

Sheffield University during a severe storm. Though the motion was perceptible, none of the individuals reported suffering from nausea or motion sickness, and no one reported any fear or concern for their safety. It was noted that the perception of the motion was heightened by leaning against a wall, and also that the movement of some objects, such as the oscillation of liquid surfaces, helped trigger the perception of motion.

Goto et al. (1990) surveyed occupants from five tall buildings after a strong Typhoon struck the Kanto region of Japan in 1979. Over a period of one month the research team managed to collect 90% of the total number of surveys distributed. The results of the study showed that 90% of the people living on floor thirteen or higher, up to floor fifty-five, perceived the building motion caused by the typhoon. Thirty percent of those occupants perceiving vibration stated that they would “never” tolerate a similar level of motion in the future.

The Survey of Wind-Induced Accelerations of Tall Buildings was sent out by ASCE Technical Committees and the Council on Tall Buildings and Urban Habitat (CTBUH) and was reported in Isyumov & Kilpatrick (1996). Measured wind-induced accelerations of twenty-seven tall buildings located in the USA and Japan were recorded. In addition to reporting wind-induced motions, the authors also reconstructed the performance of forty-seven other tall buildings using wind tunnel data. Accelerations were then compared to survey information provided by building developers and owners reporting motion perception.

At the John Hancock Centre in Chicago, a survey of occupants showed that 75% had at some point experienced wind-induced motion. Anecdotal evidence suggested that the majority of these individuals had come to accept the sway vibration after being assured of the buildings structural integrity (Brown and Maryon 1975).

Denoon (2000) completed a long-term, full-scale survey investigating the perception and tolerance of motion, while simultaneously monitoring wind-induced building response. Over the course of two years, field experiments were completed in three air traffic control towers located in south-eastern Australia. From the survey results he determined that factors affecting the tolerance of motion were: the magnitude of motion that led to fear and alarm, and the frequency of occurrence of perceptible motion. The study also found that both education and habituation increased the tolerance of occupants to wind-induced vibration.

Burton et al. (2006c) reported on a general population survey conducted involving over 5000 residents of Hong Kong. This specific study reported that the perception of motion of 73% of individuals was triggered by an overheard comment.

One of the longest on-going and perhaps most monumental studies in the field of full-scale monitoring and surveys is the Chicago Full-Scale Monitoring Project (Kijewski-Correa et al. 2006). The project was established in 2001 to facilitate the monitoring of several tall buildings for validation of performance against predicted wind tunnel and analytical models in order to calibrate the current state-of-the-art in design.

6.3 RESULTS OF NSF CHICAGO TALL BUILDING SURVEY

An informal, voluntary online survey was developed and launched in 2006 by a team of researchers associated with the Chicago Full-Scale Monitoring Program to collect qualitative data on motion perception and tolerance in tall buildings from occupants. The survey was publicized through email to a number of interested communities, e.g., tall building designers, high rise committees, wind engineering professional organizations, and networks of residents in Chicago and can be accessed at www.nd.edu/~tallbldg/survey.html. Questions in the survey address some of the physical, mental, and emotional effects of the motion, which are directly related to occupant comfort and task disruption. Respondents have the option to specify the name and location of the building in question. To date, entries have been logged for 25 different buildings in at least 9 cities in 3 countries.

Initial findings presented in Kijewski-Correa et al. (2007) chronicled multiple responses to a particular wind event where 70% of the respondents were looking out the window at the time they first perceived the motion. Interestingly, while 20% were first alerted by these visual cues, 80% did acknowledge the role of others in triggering their own perception. In responses to other events, 47% of solitary respondents (residential) indicate that they first perceived motion through audio cues such as squeaking, cracking and whistling, while 42% indicate that they felt the motion first. The remaining respondents indicated visual cues as their first perception mechanism, with 6% citing external motion cues and an equal number citing internal motion cues. It is interesting to note that visual cues were not a common perception trigger for the respondents, even though 57% of respondents were looking out a window while experiencing the motion.

Such survey responses are most valuable when they are supplied for buildings that are instrumented, so that in-situ accelerations can be correlated to the occupant experiences. This provides rare insights into the actual frequency, amplitude and waveform of motions causing disturbances to occupants in the most faithful testing environment. Unfortunately, these instances are rare since the survey is a voluntary tool open to the public and is not explicitly supplied to tenants of monitored buildings. In addition, the usefulness of the responses in this respect depends on the accuracy and completeness of the subject's responses, particularly with regards to the date and approximate time of the experience. However, for three wind events, voluntary online responses could be correlated in this way with buildings monitored as part of the Chicago Full-Scale Monitoring Program (Kijewski-Correa et al. 2005).

In order to provide a rational framework to evaluate these occupant responses and project some form of performance assessment using in-situ accelerations, the recorded data for these events was analyzed by a pseudo-full-scale evaluation tool developed by Kijewski-Correa and Pirnia (2009) and showed to agree well with the survey responses. The framework projects the likelihood of occupant discomfort by correlating measured accelerations with human subject response rates based on results from motion simulator studies by Burton et al. (2005).

6.4 SUMMARY

This chapter has described, mostly qualitatively, a number of the post-review studies that have been undertaken to understand human response to building motion and the level of motion in tall buildings that might be acceptable. The first study by Hansen et al. (1973) and Reed et al. (1973) makes a quantitative statement as to the acceleration levels that might be acceptable, and this is similar (for the frequencies involved) to the recommendations in ISO 10137(offices). A step towards establishing levels of acceptability has been discussed qualitatively by Kijewski-Correa and Pirnia (2009), and supports the observations by Burton et al. (2005) that the narrow-band waveform is most disruptive. There is also evidence that objection levels are subject to "habituation," i.e., the notion that experience, education, or reassurance can be effective in placating initial concerns.

CHAPTER 7
Design Criteria and International Practice

7.1 INTRODUCTION AND BRIEF HISTORY

Building codes and standards evolved originally to promote safety of buildings. Serviceability issues such as building deflections, velocities and accelerations have often been regarded as being related more to the quality of the building than to safety. Therefore codes and standards (e.g., ASCE 7) have tended to steer clear of rigidly defined serviceability criteria since this area could be regarded as something to be negotiated between the owner and the designers, depending on the desired level of quality for the building. Nonetheless, in response to the need of designers for some guidance on acceptable motions in buildings, a number of design guidelines have been published with respect to allowable building motions and these are the subject of this chapter.

The first building code where any reference to acceptable ranges of motion was made was in the National Building Code of Canada, in the 1975 edition in the non-mandatory part of the code (called the Commentary). The criteria, which were drafted by A.G. Davenport, were based on building acceleration, and they proposed that the acceptable range for the peak 10-year acceleration was between 10 and 30 milli-g. The lower end of the range was suggested as appropriate for residential buildings and the upper end for office buildings. These criteria were based on earlier research by Khan and Parmelee (1971), Chen and Robertson (1972), Chang (1973) and Hansen et al. (1973). Using similar research, in 1981 the Council on Tall Buildings and Urban Habitat also published guidance on people's tolerance of motion in its monograph (CTBUH 1981). Subsequently, ISO published criteria ISO6897 (International Organization for Standardization 1984) largely based on the work of Irwin (1978). The ISO criteria were still based on acceleration, but brought in a dependence of the criteria on the building frequency. These criteria were expressed as rms accelerations rather than peak and used a return period of 5 years rather than 10 years. In 1991, AIJ, the Architectural Institute of Japan, (1991) and Kanda et al. (1993) also published criteria with frequency dependence as well as introducing the concept of criteria that were graduated according to the target quality of the building. These criteria were based on peak accelerations at the 1-year return period. More recently the 1-year return period has become more favored over 5 or 10 years. Melbourne and Palmer (1992) from Australia published criteria for a selection of return periods, from 0.5 to 10 years, with similar frequency dependence to that of ISO 6897 (1984). A more current ISO standard, ISO 10137 (2007), which supersedes ISO 6897, has also moved to the 1-year return period and retains the previous dependence on frequency. However, like the AIJ guidelines and the early criteria of Davenport, it uses peak acceleration rather than rms.

7.2 INTERNATIONAL CRITERIA

A number of national, regional and international bodies have published acceptance criteria for wind-induced motions of tall buildings and structures. Below is a brief review of the various standards. In this section, equations are presented from these standards using the variables defined therein, which, as a result, may not be consistent with notation elsewhere in this monograph.

In addition to the international guidelines, acceleration criteria were developed based on a consensus between design teams, developers, and the wind engineering community, based on experience with many buildings and towers constructed and wind tunnel tested during the 1980's and 1990's. The Council on Tall Buildings and Urban Habitat (CTBUH) recommends 10-year accelerations of 10 to 15 milli-g for residential buildings and 20 to 25 milli-g for office buildings (Isyumov 1993). The CTBUH guidelines also include the recommendation to limit the 10-year peak torsional velocity to 3 milli-rads/sec for all buildings regardless of intended occupancy.

7.2.1 International Organization for Standardization (ISO)

The criteria suggested by the International Organization for Standardization (ISO) are expressed as a function of frequency. The upper limit of the ISO criteria is based on magnitudes of acceleration that approximately 2% of those occupying the upper third of a building may find objectionable. The ISO Criteria generally have used shorter return periods than 10 years.

ISO initially published criteria (ISO 6897:1984, International Organization for Standardization 1984) based on a 5-year return period, which were expressed in terms of rms acceleration. The corresponding 1-year criterion was tentatively suggested by ISO to be 0.72 times the 5-year criterion. It should be noted that the ISO 6897 made reference to "buildings used for general purposes," in reference to the above criteria, with no distinction between commercial and residential occupancies.

In the revised ISO standard on building serviceability (ISO 10137:2007(E) – Annex D), the acceleration criteria are expressed as peak values at the 1-year return period, as shown in Figure 7-1. Two curves are presented for residential and office criteria where the former is 2/3 of the latter.

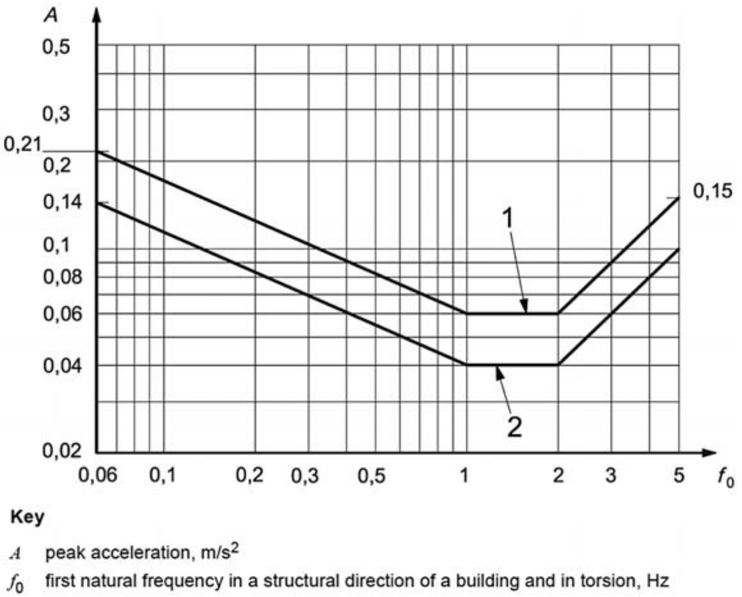


Figure 7-1. ISO 10137:2007 Evaluation curves for wind-induced vibrations in buildings in a horizontal (x, y) direction for a one-year return period. Curve labeled 1 is for offices and 2 is for residences

7.2.2 United Kingdom Practice: BS6611

British Standard 6611 (1985) is a reissue of the ISO 6897 Standard (International Organization for Standardization 1984). The criteria were based on a 5-year return period, which were expressed in terms of the rms acceleration as follows:

$$\tilde{a} = \exp\left(-3.65 - 0.41 ln\, n\right) \tag{4}$$

where $\tilde{a}$ is the root-mean-square value of acceleration in m/s^2 and n is the frequency of motion in Hz.

7.2.3 Canada: National Building Code of Canada (NBCC)

The first building code document to give guidance on building motions was the National Building Code of Canada (NBCC) (National Research Council of Canada 1995). It suggested that 10-year return period accelerations in the range of 1.0% to 3.0% of gravity (10 to 30 milli-g) were acceptable, with the upper end of the range being appropriate for office buildings and the lower end for residential buildings.

Research conducted during the development of the ISO acceleration criteria indicated that sensitivity to motion reduces as the natural frequency of the building becomes lower (at least in the range of interest for tall buildings, 0.1 Hz to 1.0 Hz). This dependence is not reflected in the NBCC, which provides a single set of criteria based on results for frequencies primarily in the range 0.15 to 0.3 Hz. It should be noted that these criteria, which are not expressed as functions of frequency, may not be appropriate for buildings with unusually high or low frequencies.

The most recent version of the NBCC (2010) discusses North American practice for tall building design with a peak 10-year acceleration criterion of 15 to 25 milli-g. There is also reference in the standard to ISO 10137 (International Organization for Standardization 2007).

7.2.4 Japanese Practice: AIJ- GBV-2004

The Architectural Institute of Japan (AIJ) published guidelines, rather than criteria of acceptance, for the evaluation of building motion (AIJ-GBV-2004). The guidelines, shown in Figure 7-2, are presented as peak acceleration perception thresholds in a probabilistic format, thus putting the final decision on acceptance criteria at the discretion of the owner. The guidelines also take into account the frequency of motion as a factor in perception and have been calibrated to research in Japan and in motion simulators available at the time of publication. The guidelines include five curves: H-10, H-30, H-50, H-70 and H-90, where the number indicates the percentage of the population that would perceive the motion at the level indicated. Each component of acceleration (i.e., crosswind and alongwind) is considered separately with the dominant frequency of motion in the respective direction used to determine the perception threshold.

7.2.5 Australia and New Zealand Wind Standard: AS/NZS 170.2:2002 and AS/NZS 1170.2:2011

The recently superseded Australia and New Zealand wind standard gives a simplified acceptance criteria for motion of not more than 10 milli-g without specific

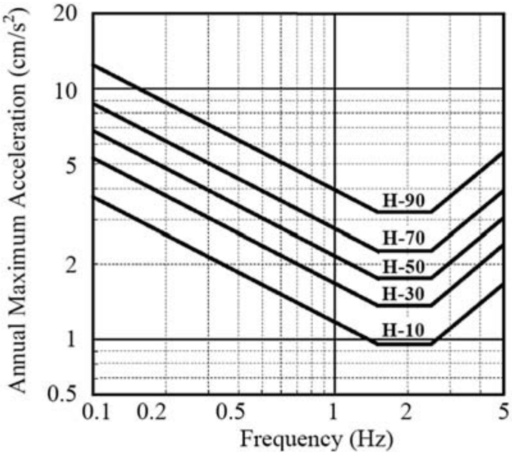


Figure 7-2. Probabilistic perception thresholds given in AIJ-GBV-2004

mention of wind speed or return period. A reference to the acceptance criteria suggested by Melbourne and Cheung (1988) suggests that the return period for the simple criteria is one year.

In the cited reference, a comprehensive review of early studies on perception and acceptance of wind-induced motion is presented and the following acceptance criteria for peak acceleration were put forward:

$$\hat{a} = \sqrt{2\ln(nT)}\left(0.68 + \frac{lnR}{5}\right)\exp\left(-3.65 - 0.41ln\, n\right) \tag{5}$$

where $\hat{a}$ is the peak horizontal acceleration in m/s^2,

n is the frequency of motion in Hz,

T is the time interval in seconds (taken as 600), and

R is the return period of motion in years.

The current standard AS/NZS 1107.2:2011 does not specify an acceptable acceleration level for tall buildings. Instead, the wind loading handbook published by the Australasian Wind Engineering Society (Holmes et al. 2012) suggests that buildings that frequently exhibit wind-induced vibrations greater than 10 milli-g are unlikely to be acceptable to most occupants.

7.2.6 Russian Practice

The national standard of Loads and Effects of Russia (SNiP 2.01.07-85) does not specify criteria of acceptance for wind-induced motion. However, criteria are stated in Moscow's standards for design of multi-functional high-rise buildings, MGSN 4.19-05 (2005). A peak acceleration limit of 8 milli-g is stated. It should be noted that the return period of the design wind event corresponding to this acceleration limit is not explicitly mentioned in the MGSN 4.19-05; however, the requirement to use a wind load reliability factor of 0.7 is an indication that the reference return period recommended for the assessment of occupant comfort in tall buildings is 1 year.

7.3 COMMON PRACTICE

It is hard to find building owners who disclose publicly motions of their buildings and readers hoping to find specific examples here will be disappointed.

After meeting rules for strength and deflection, achieving acceptable comfort for building users is often the next most critical design limit. Meeting the deflection limits gives no automatic immunity from potential dynamic motion issues.

For a tall building, it is desirable in the early stages of design to make preliminary estimates of accelerations using available formulae from appropriate wind loading codes/standards. The results may then be compared with the selected criteria. More refined estimates can be obtained from aerodynamic databases, either proprietary databases that exist at wind tunnel laboratories or in the public domain such as that described by Zhou et al. (2003) and included in newer editions of ASCE 7. However, since accelerations can be highly sensitive to the building shape and surrounding structures, some critical aerodynamic behavior may well be missed. Therefore the usual practice for final design is to undertake project-specific wind tunnel tests on buildings that are dynamically sensitive, and in some cases to do these tests even at the preliminary design stage, rather than rely on estimates. Over the last three decades, the final predictions of building motions on most tall buildings came from wind tunnel tests.

For a given building form and wind exposure, there are three primary structural parameters to work with: stiffness, mass and damping. It has been shown that these typically have a similar effect on acceptability of motions, which improves roughly as the square root of each. Of these, damping was often taken in the past as an assumed constant, leaving only stiffness and mass.

Inherent damping is at least as important as mass and stiffness in controlling motions but is known to less accuracy, based on the scattered measurements that are available from a limited number of existing buildings. Furthermore, measurement of damping tends to be systematically optimistic unless a sufficient quality and duration of data is obtained. Use of lower bound damping estimates based on the measurements to meet nominal design criteria would necessitate significant changes in the way we have been successfully designing major buildings. However, since measurement of damping tends to be systematically optimistic, it is highly likely that there are other factors in our procedures that are normally conservative. Problems that have been experienced in practice are likely to be in cases where the beneficial factors are minimized. Considering the latest damping systems and technologies, it is important for designers to consider introducing a reliable form of damping, or a modern structural system, to assure building performance.

Therefore, it is of interest to compare motions actually experienced in existing buildings with predictions. The relatively few measurements that have been made (e.g., Hansen et al. 1973; Isyumov and Halvorson 1984; Kijewski-Correa et al. 2013) indicate that the wind tunnel predictions of motion correlate reasonably well with full scale, but they do not in themselves verify the criteria as to what is acceptable. To gain a direct understanding of the occupant comfort performance of a number of buildings, Irwin and Myslimaj (2008) reviewed 19 buildings constructed after 1984 and prior to 2000, all of which underwent wind tunnel tests and were designed using the normal set of assumptions for that era. More than a third of them had been occupied for more than twenty years. All the 19 buildings reviewed by Irwin and Myslimaj were, with aid of dampers in five cases, predicted to be in the 15 to 18 milli-g range (on a 10-year recurrence interval). The experience has been that no serious complaints materialized on any of the 19 towers except in one case, which was for one with a damping system when the damping system had been inadvertently turned off (in this condition its predicted 10-year acceleration was 24 milli-g).

This experience does indicate that the end effect of all the various assumptions made in design was to produce satisfactory buildings from a motion point of view. However, this does not mean all the assumptions were individually correct. It is quite possible that the effects of inaccuracies in some assumptions were being cancelled by the effects of others. A thorough examination of all the various assumptions is needed rather than looking at each one in isolation, which could actually lead to a false sense of improved precision.

Therefore, there is still much to be learned. Accurate full-scale measurements combined with surveys of occupants would help refine the design assumptions made and verify whether the criteria need further improvements in the light of improved knowledge of structural and wind behaviors.

7.4 SUMMARY

This chapter has given a brief history of the development of criteria for occupant comfort with respect to wind-induced building motions and summarized the motion acceptability criteria adopted by various wind or building codes and standards. The setting of definitive criteria for motions is challenging because, as described in earlier chapters, the comfort of people in buildings is affected by many factors: individual sensitivity to motion, which varies over a broad range, cues other than acceleration (e.g., noises) that sensitize people, nature of the human activity in the building (lying down, sitting, standing, reading, working at a computer screen, walking, etc.), frequency of occurrence of noticeable events, expectations of the occupants (including habituation considerations), appropriateness of rms vs. peak (or other) values, and whether such values should be associated with various human concerns (perception, physiological discomfort, fear). In the end, the degree to which all these factors has to be accounted for is not clear and, from a practical point of view, designers need relatively simple criteria that have been proven to yield acceptable buildings in the past for the general population of occupants. The commonly used criteria and those in codes and standards attempt to do this.

CHAPTER 8

Design Strategies for Mitigating Motion

8.1 INTRODUCTION

The strategies that can be adopted to reduce wind-induced building motion are either by aerodynamic treatment (such as changing the building shape along the height, tapering the buildings along its height, varying plan shape, introducing porosity, changing the corner shape, and adding spoilers) or by alteration of the dynamic characteristics of the buildings (including mass, stiffness, mode shape and damping), or a combination of both (Kareem et al. 1999). In the early days of wind engineering, the usual approach was to stiffen the building. This approach is attractive since it avoids impacting the exterior architecture but does lead to increased structural cost and may impact the functionality of the interior spaces (e.g., by increasing the sizes of the structural columns).

For a tall building, it is usually difficult to further increase stiffness without significantly increasing mass, and adding the extra material is highly expensive. The primary choices here concern location and arrangement of structure and choice of material. Most tall buildings therefore place much of their supporting structure on the perimeter to maximize stiffness for a given amount of material and use concrete as well as steel in the columns to provide stiffness at a cheaper cost. Once this has been done in an efficient way, it is difficult to make further significant improvement with conventional approaches.

The remaining purely structural or mechanical property of the building that can be altered is its damping and so various methods for adding damping have been developed. This can be effective since the accelerations of a building vary roughly in inverse proportion to the square root of the damping ratio. It is quite feasible to double or triple the damping of a building, thus achieving 30% to 40% reductions in the accelerations. Alternatively, there is the option to tackle the problem at its aerodynamic source, i.e. to modify the building's shape. As building heights and slenderness become more and more extreme, it becomes increasingly imperative that aerodynamics be considered by the architect even at the conceptual design stage. This section discusses both the aerodynamic and damping strategies for mitigating building motions.

8.2 AERODYNAMIC MODIFICATION

The feasibility of making simple improvements to the shape depends on the nature of the aerodynamic effect causing the motions. Buffeting forces from other structures are particularly difficult to reduce without major changes to building form. On the other hand, self-induced vortex shedding forces—the primary source of wind excitation causing undesirable building motions—can sometimes be reduced by relatively small measures that modify the basic plan shape of the building or introduce more three-dimensionality to the building form, particularly towards the upper levels. Classic examples to reduce crosswind (vortex shedding induced) dynamic motions include tapering towards the top, progressive corner cut-outs, and, for more circular plan buildings, spiral forms and even irregular surface roughness arrangements and porosity.

Significant movements of less slender buildings may also be caused by buffeting from wind turbulence, but are more often caused by turbulence generated by other buildings. Since the turbulence associated with the exciting energy is not self-generated in this case, the only option is a more streamlined form. Rounded forms may be better as long as the frequencies of self-induced turbulence are not close to those in the on-coming turbulence. Elongated plan shapes may suffer from crosswind buffeting, and hence streamlining for winds from the direction of the other building is not generally sufficient.

Shape changes through add-on deflectors are often considered to suppress vertical or torsional excitation of bridges and could theoretically be of benefit to buildings too. However, for bridges the problem is simpler because the only wind direction of concern is normal to the span and the mean wind typically stays close to horizontal, implying the add-on deflectors need only be effective over a narrow range of wind direction and inclination to the horizontal. For buildings the deflectors must be effective over a wide range of wind directions and this is difficult to achieve. Also, practical issues of obstruction of views-from and light-into the building can be problematic. In some cases the use of large external radial fins may significantly reduce the magnitude of vortex shedding responses at the expense of significantly increasing the alongwind forces.

Irregularity of plan may be highly effective in disrupting self-generated vortex shedding forces and may be achieved through regular changes to plan form down the building, through arrangement of balconies, and sometimes with ventilation through plant and refuge floors. Note however that Reynolds' Number effects that occur in model-scale testing of smooth rounded shapes may result in effects that vary significantly from the full-scale behavior.

Further aerodynamic modifications of building shape, including recessed, slotted or chamfered corners (Figure 8-1), horizontal and vertical through-building openings, a sculptured building top, tapering, and dropping off corners have been shown to significantly reduce the wind-induced loads and responses of tall buildings (e.g., Kwok 1988; Dutton and Isyumov 1990; Irwin and Baker 2005; Irwin 2007). In general, modifications to the building corners, such as slotted or chamfered corners, need to be greater than about 10% of the building breadth to

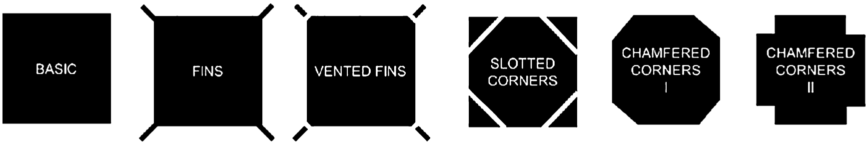


Figure 8-1. Aerodynamic modifications to a square building shape

be beneficial. However, modifications which increase the projected area or the effective breadth of the building would in general not be beneficial.

Thus, aerodynamic modification is certainly worth exploring with the architect at early stages of a project. Early qualitative wind engineering advice is cheap compared to costs resulting from heading in an undesirable direction.

8.3 DAMPING DEVICES

In addition to aerodynamic and structural modifications, implementation of supplementary damping systems has also gained much recognition as a workable and reliable technology for the mitigation of wind-induced motions in tall buildings and other dynamically sensitive structures.

Historically, tall building designers tended to be cautious about using damping systems because they involved unfamiliar concepts. However, significant advances in damping systems have been made, and these systems are now more cost effective, readily available, and can effectively be incorporated as an integral part of the structural system. Thus, the use of these damping devices has become more accepted by the profession, as it is being recognized that they will improve the overall stability, safety, and performance of a building under both regular and severe events, including seismic and unexpected loads.

There is increasing understanding of costs and space issues of installing typical supplementary damping, which may be highly cost effective compared with other alternatives for mitigation.

Installation of viscoelastic dampers in the twin towers of World Trade Center in 1969 marks the beginning of the application of innovative technologies to tall building structures to achieve the desired performance in terms of occupant comfort (Caldwell 1986; Mahmoodi 1969; Mahmodi et al. 1987). Approximately ten thousand viscoelastic damper units were installed in each tower, evenly distributed throughout the building from the 7th to the 107th floor. Damper units were installed between the lower struts of the horizontal trusses and the perimeter columns of the tower. The selection, quantity, shape and location of the dampers was based on the dynamic behavior of the towers under wind loading and on the amount of additional damping required to achieve the performance targets (Mahmoodi et al. 1987). Until their destruction on September 11, 2001, the towers experienced a number of moderate to severe wind storms. The observed performance of both the dampers and the towers has been reported to be consistent with analytical predictions and design objectives (Soong and Dargush 1997; Faschan and Garlock 2005). Based on the data collected after Hurricane Gloria in 1978, it was found that the total equivalent damping of the building was in the range of 2.5% to 3% of critical (Mahmoodi et al. 1987).

Columbia SeaFirst Building in Seattle, Washington is also among the first wind-sensitive tall buildings that benefited from the installation of viscoelastic dampers. Two hundred and sixty viscoelastic dampers were installed alongside the main diagonal members in the building core (Keel and Mahmoodi 1986). The addition of dampers to the structural design scheme of this tower was calculated to increase the damping ratio in the fundamental mode of vibration from 0.8% to 6.4% during frequent wind storms (Keel and Mahmoodi 1986), hence noticeably improving its performance in terms of occupant comfort.

These early applications of viscoelastic dampers to reduce wind-induced motions in tall buildings were followed by other types of damping devices such as tuned mass dampers (TMDs), tuned sloshing dampers (TSDs), tuned liquid column dampers (TLCDs), active mass dampers (AMDs), etc. A wide-ranging review of all types of supplemental damping systems used for the purpose of controlling wind-induced vibrations of tall buildings and other wind-sensitive structures was conducted by Kareem et al. (1999).

Among the passive damping systems, the most popular concept that has been widely implemented in actual tall buildings and other wind-sensitive structures around the world is the tuned mass damper (TMD) (Banavalkar and Isyumov 1998; Breukelman et al. 1998; Kawamura et al. 1993; Kitamura et al. 1988; Mataki et al. 1989; Kwok and Samali 1995; McNamara 1977; Tamura 1997; Tamura et al. 1995). A TMD is a damped secondary inertial system which consists of a mass attached to the building (generally at a location near the position of maximum motion in the relevant modes) through a spring and damping mechanism, usually a viscous damping device. Tuning of the frequency of the TMD to that of the building generates inertial forces that counteract the lateral wind forces acting on the building, resulting in reduced wind-induced motions of the building. The effectiveness of TMDs is determined by their basic design parameters: mass ratio (the ratio of TMD mass to the generalized mass of the building in its target mode of vibration) and TMD mass displacement.

The first TMD design was to be used for the Citicorp Center in New York; however, before that building was completed the recently completed John Hancock Building in Boston began to exhibit severe motion problems, and a similar TMD was developed and installed for it. The damper for that building is unique in consisting of two masses (300 tons each) at opposite ends of an upper floor, which often work out-of-phase to control twisting motions. Other notable TMD installations (single-mass, two-axis) that soon followed include the Landmark Tower in Yokohama and the TC Tower in Kaohsiung.

The largest simple-pendulum TMD designed so far to control wind-induced motions of a skyscraper is the 660 ton ball-shaped tuned mass damper installed at the top of the Taipei 101 building in Taipei, Taiwan (Haskett et al. 2003; Joseph et al. 2006).

Meanwhile, the idea of applying tuned liquid dampers (TLDs) to reduce vibrations in civil engineering structures began in the 1980's (Bauer 1984; Kareem and Sun 1987; Modi and Welt 1987). Since then TLDs, encompassing both Tuned Sloshing Dampers (TSDs) and Tuned Liquid Column Dampers (TLCDs), have become a popular form of supplemental damping system for mitigation of wind-induced motions (Fujino et al. 1992; Kareem 1990,1993; Hitchcock and Kwok 1993; Kareem and Tognarelli 1994; Sakai et al. 1989; Hitchcock et al. 1997; Tait and Isyumov 2007; Vickery 2001). In comparison with tuned mass dampers, the advantages associated with tuned liquid dampers include low initial cost, nearly maintenance-free operation, and simplicity in construction and frequency tuning. However, there are disadvantages as well which relate to the effectiveness of water mass participation in counteracting the building motion, resulting in a need for additional mass, and uncertainties associated with nonlinear behaviors.

The earliest implementations of tuned liquid dampers for suppressing wind-induced motions of tall buildings and other dynamically sensitive structures have taken place primarily in Japan, in the late 1980s and early 1990s. The list of pioneering buildings and structures equipped with TLDs include Nagasaki Airport Tower, Yokohama Marine Tower, Shin-Yokohama Prince Hotel and Haneda Airport Control Tower (Tamura et al. 1995).

In recent years larger size, deep TSDs and TLCDs have been implemented in the design of several tall buildings around the world, such as Wall Center in Vancouver (Irwin and Breukelman 2001), Highcliff in Hong Kong (Youngs 2003), Random House in New York City (Tamboli et al. 2005), Comcast Center in Philadelphia (Stephens 2009), 10 Barclay Street, New York (Morava et al. 2010).

The design of liquid sloshing dampers is not as straightforward as TMDs due to nonlinear free surface that has amplitude dependence and other nonlinear features that require more extensive computational models, especially to account for large amplitude sloshing characterized by wave breaking and slamming (Kareem et al. 2009). In view of these nonlinear effects, the performance and effectiveness of sloshing dampers is assessed using scale models. One such recent advanced system involves hybrid testing in which the building is modeled on computer, whereas the sloshing tank is physically modeled with a real-time communication between the two models (McNamara et al. 2012). In this case the sloshing action is not approximated by a model rather it is physically reproduced thus it offers an effective way to validate the design of the sloshing damper based on simplified sloshing models.

Both TMDs and TLDs and their various configurations are essentially damped inertial secondary systems appended to buildings that impart indirect damping through modification of the building dynamics. To be most effective, they need to be optimally tuned to the building mode that needs to be controlled. The robustness of these devices demands that they be tuned to the frequency as any departure beyond a narrow tuning range may compromise their effectiveness. In order to overcome this shortcoming, alternatives are available such as multiple damper configurations in which a number of dampers with the total mass equal to the single damper are utilized, tuned over a small range of frequencies (Kareem and Kline 1995). This configuration has the promise of more robustness; therefore, small detuning does not seriously impact the performance of damper system. It has been noted that for concrete structures the prediction of frequencies, especially in the low levels of amplitude, exhibits departure from as-built frequencies due the level of cracking and uncertainty surrounding the modulus of elasticity; therefore full-scale measurements of the building frequencies are essential for fine tuning the sloshing damper.

The implementation of viscous dampers or hydraulic shock absorbers in civil engineering structures took place in early 1990's. These damping devices are capable of providing added energy dissipation or damping to fundamental modes of vibration, increasing significantly the overall structural damping ratio. Early applications of viscous dampers were in the seismic design of vulnerable structures (Taylor and Constantinou 1996). They have also been implemented in several structures in USA and Japan for the sole purpose of reducing wind-induced vibrations. In 1996, a total of forty viscous dampers were installed in the 28 State Street tower, a 35-story high-rise building in Boston, as part of a retrofitting scheme to improve the occupant comfort during moderate to high wind conditions (Soong and Dargush 1997).

Recently, an innovative application of viscous dampers to control wind and seismic responses of two tall buildings in Manila has been carried out (Smith and Wilford 2008). It is a new approach to control the dynamic response of tall, flexible buildings using the damped outrigger concept.

As an alternative to the passive tuned mass dampers and tuned liquid dampers described above, active mass dampers (AMDs) were developed and implemented in late 1980's. AMDs are response control devices that are based on the feedback of wind-induced velocities and accelerations of the structure. These responses are used to determine the amount and timing of the force to drive the moving/sliding mass of the AMD to counteract the excessive building motions. The world's first AMD was implemented in Japan in 1989. This pioneering AMD was designed by Kajima Corporation and was installed in the Kyobashi Seiwa Building (Kobori et al. 1991).

The pioneering work in the Kyobashi Seiwa Building was followed by other installations of active mass dampers in Japan. Currently, there are more than 40 buildings in Japan which use active response control systems to enhance their structural performance under wind excitation.

8.4 FAMILIARIZATION OF MOTION IN SIMULATORS

As people do not have much occasion to actually quantify the acceleration levels they are experiencing as they go about their daily lives, they usually do not have a sense of what 5, 10 or 20 milli-g actually feels like. Therefore when discussions between designers, owners and wind engineering experts take place on building motion effects, it can be helpful to go into a "moving room" or chamber, which is capable of duplicating the predicted motions of the building, and to actually experience various levels of motion. This can be educational, and while it is not the ideal statistical sampling of the building occupants that one would like, it has been found to be a useful aid to decision making.

Previous studies (e.g., Burton 2006) have shown that the majority of the general population (approximately 70% to 80%) has never experienced wind-induced building motion, either at work or at home. Tall building motion simulators (e.g., Kwok and Hitchcock 2008) or modified flight/ship simulators (such as the Centre for Marine Simulations, Marine Institute, Memorial University, Newfoundland, Canada) have been utilized to address the needs of special interest groups, including building developers/owners and design professionals, to gain a first-hand experience, appreciate the sensation, and assess the potential impact of low frequency and low amplitude building motion typically experienced in wind-sensitive buildings. Through specially designed workshop and demonstration sessions involving lectures/seminars and occupant comfort tests in a simulator, these interest groups are able to learn about human perception of motion and experience a range of simulated wind-induced tall building motions.

The aims of these workshop and demonstration sessions typically involve one or more of the following:

- To assess the acceptability of these vibrations in terms of comfort level and/or frequency of occurrence;
- To assess the need to adopt vibration mitigation measures; and
- To experience and assess the potential benefits of expected reductions in building vibration if selected vibration mitigation measure(s) is(are) adopted.

The demonstration session can be a simple demonstration in which participants experience a sample of simulated building motion. A more informative session can be designed to include an extended occupant comfort test session in which a number of test motion conditions are presented in a random order to the participants.

By simulating building motion for wind speeds of different recurrence intervals, participants are able to appreciate the relationship between comfort, exposure duration, and frequency of occurrence.

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CHAPTER 9
Conclusions

The second half of the 20th century has witnessed a tremendous increase in the construction of tall buildings and structures, particularly in growing economies in east and south Asia, the Pacific Rim, and the Middle East. Advances in engineering material, computer-aided design and analysis, knowledge of wind-structure interaction, and wind tunnel testing techniques ensure this new generation of tall buildings (with ever increasing height and striking architectural shapes), meet strength and safety requirements imposed by wind actions. Although significant research efforts in the past four decades have provided a better understanding on the subject, occupant response to wind-induced building motion remains a major challenge in the design of tall buildings today. 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.

The subject of human perception and acceptability of motion is complex. Sense of motion depends on a series of physiological structures that enable humans to detect motion, including the effects of body orientation, balance, and relative movement of fixed objects. The vestibular system in the inner ear is the primary organ that detects orientation and movement. Natural variations between individuals produce a wide range of sensitivity to motion and susceptibility to motion sickness. This coupled with complex psychological and behavioural traits render the study of occupant response to wind-induced building motion a difficult task.

The study of occupant response to wind-induced building motion is best studied in real buildings under real wind actions. However, weather unpredictability necessitates a long-term monitoring program. Unfortunately, the reluctance of building owners and tenants to participate, due to a combination of commercial, legal, operational and security reasons, has stifled many research efforts to generate meaningful results. Attempts to mimic a real-life living and working environment by artificially exciting a real building for test purposes have met with limited success mainly because the resultant motions are restricted to sine waves, which bear little semblance to the narrow-band random motion a building undergoes under wind actions.

Experiments conducted on human test subjects using shake tables and purpose-built motion simulators is the most commonly adopted research approach to study human response to wind-induced building motion. The ability to conduct experiments under carefully controlled test conditions compensates for the potentially biased findings associated with the inability to reproduce a realistic living and working environment and test subjects' motion expectation and motivation to participate. The primary parameters studied include: frequency, acceleration amplitude, posture and orientation, motion shape and wave form, and test duration. Despite the variations in experimental setup and test methodology, a number of important observations and conclusions can be drawn from research conducted using motion simulators. Generally, human perception of motion is dependent on frequency, but independent of motion waveform. There is little doubt wind-induced building motion at acceleration levels above perception thresholds can cause some degradation in occupant comfort, well-being and manual task performance, and may elicit fear and alarm. Prolonged exposure to wind-induced building motion will accentuate the above adverse occupant responses, with fatigue playing an equally important role. Despite the self-reporting of a plethora of adverse responses to wind-induced building motion, occupant complaint behaviour is not well-understood due to the complexity of human psychology and behavioural traits that are influenced by societal and cultural factors. Not surprisingly, education of occupants has the desirable effect to alleviate fear and alarm and instil acceptance of infrequently occurring, perceptible wind-induced building motions.

A number of international and country-based standards organizations have adopted these research findings to formulate serviceability criteria to assess the acceptability of wind-induced building motion. These criteria generally suggest acceptable acceleration values for frequencies typically within the range 0.1 to 1.0 Hz. The format and complexity of these criteria vary, with acceleration values given in rms or peak values, recurrence interval ranging from 1 year to 10 years, and either no distinction in building type or separate values for residential and office buildings. Not surprisingly, the proposed acceptable acceleration values vary greatly even after they have been standardized for comparison purposes. This coupled with uncertainties associated with commonly adopted acceleration prediction methodology, which relies on wind tunnel model testing and integration with statistical wind climate models, makes assessment for acceptability of wind-induced motion in habitable buildings a difficult exercise.

Notwithstanding the complex nature of occupant response to and acceptability of wind-induced building motion, the following peak acceleration thresholds are recommended as general guidelines with which habitability and the need for mitigation can be assessed:

- 5 milli-g is a threshold which, while perceptible to many occupants, is unlikely to cause significant adverse occupant response or alarm, provided that such building motion does not occur frequently or continuously for an extended period of time.
- 10 milli-g is a comfort and well-being threshold that 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. The upper value would be more acceptable for buildings with lower natural frequencies (~0.1 Hz), whereas the lower value would be more relevant for buildings with higher natural frequencies (~0.4 Hz). 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.

Advances in structural analysis, wind engineering and vibration control have facilitated effective mitigation strategies to reduce wind-induced building motion through structural optimization, aerodynamic treatment and vibration dissipation/absorption. Although dampers of various designs have proven vibration mitigation ability and have increasingly been incorporated in wind-sensitive buildings worldwide, they are costly to maintain and occupy valuable building space.

It is educational for building owners and designers to gain a first-hand experience, through a suitable motion simulator, of the predicted building motion to assess the need for and benefit of aerodynamic shaping, structural system modifications, or a damper through a suitable motion simulator. A period of continuous monitoring of wind-induced building motion will also provide valuable real-life data to assess occupant response and the need and benefit of installing a damper.

Research in this subject is on-going, and it is hopeful that the outcomes of these investigations will advance the understanding of the effect of wind-induced building motion on the well-being of building occupants and facilitate the implementation of an evidence-based assessment methodology to assess the acceptability of wind-excited buildings.

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