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Implications of full-scale building motion experience for serviceability design

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Abstract. While there are a number of guidelines used throughout the world in the assessment of acceptability of tall building accelerations, none are based on systematically conducted surveys of occupant reaction to wind-induced motion. In this study, occupant response data were gathered by both a self-reporting mechanism and by interviewer-conducted surveys in control tower structures over a period of four years. These two approaches were designed in conjunction with experimental psychologists to ensure unbiased reporting. The data allowed analysis of perception thresholds and tolerability at different building frequencies and in different wind climates. The long-term nature of the studies also allowed an investigation of the causes and effects of adaptation to building motion. As the surveys were designed to allow multiple use during single storms, the effects of exposure duration were investigated. A final exit survey was conducted at the primary survey location to investigate views of the acceptability of wind-induced motion and the factors underlying these views. The findings of the field studies indicate that none of the currently used acceleration guidelines address all of the factors that contribute to occupant dissatisfaction. An alternative framework for assessing acceleration acceptability is proposed.

Keywords: building motion; serviceability acceleration; motion perception; occupant comfort.

1. Introduction

Past studies on human perception of motion and tolerance thresholds of wind-induced building vibration generally fall into three groups: field experiments and surveys of building occupants conducted in wind-excited tall buildings; motion simulator and shake table experiments testing human test subjects; and field experiments conducted in artificially excited buildings. The majority of studies were conducted using motion simulators and shake tables and focused on vibration perception based mostly on sinusoidal vibration without a task distraction. There have only been a few studies conducted on the effects of building vibration on occupant comfort and well-being, cognitive performance and task performance but the results of these studies are mostly inconclusive. There are also vast amounts of data on human response to high frequency industrial vibrations and vibrations associated with transportation such as ships, trains and automobiles. These data serve to complement those studies conducted at frequency range of 0.1 to 1.0 Hz more relevant to wind-induced building vibration.

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Occupant responses to wind-induced building vibration can be very variable both within and between subjects. This variability applies both to the more objective perception and the subjective aspects of tolerance. Human responses to this type of external stimulus are dependent on many physiological and psychological factors, including tactile, vestibular, proprioceptive, kinaesthetic, visual and auditory cues, visual-vestibular interaction, prior experience, vibration expectation, habituation, personality, and even job satisfaction. Not surprisingly, there are significant differences and uncertainties in the building vibration acceptability and occupant comfort criteria and the assessment methodology currently in use, and there is no universally accepted occupant comfort serviceability criterion which sets a definitive and uncontested design standard for acceptable levels of building acceleration.

Current acceptable building acceleration guidelines are based largely on the experiences of their authors or rely on the experience of their users. In the first category are the ISO6897-1984 guidelines and the National Building Code of Canada (NBCC, Isyumov 1993) advice. The ISO6897-1984 guidance was based on a collection of discrete measurements in buildings and structures that were both performing acceptably and in those where there had been complaints. Most of the buildings used where there were complaints were in Europe and North America, and most were located in areas dominated by synoptic wind events. The NBCC advice, as well as the advice given by many wind tunnel laboratories, is based primarily on experience of comparing predicted wind tunnel performance with whether complaints were received in the buildings, rather than field measurements of accelerations.

In the second category are the Architectural Institute of Japan (AIJ) guidelines. These give curves for percentage of occupants perceiving the motion with advice for the user to choose a suitable curve for assessment at the 1-year return period interval.

None of the current guidelines are based on long-term, repeated measure, systematic investigations of the factors underlying motion perception and tolerance in occupied flexible structures. They do not, therefore, necessarily address the causes of complaints about wind-induced motion. This paper describes a number of long-term experiments in control towers in Australia where the authors and colleagues were able to install instrumentation to measure accelerations, wind speeds, and to have access to the occupants through a self-reporting mechanism and interviewer-conducted surveys.

2. Field measurement locations and instrumentation

Three control towers located in Australia were used in this study: Brisbane Airport Control Tower (Brisbane ACT), Sydney Airport Control Tower (Sydney ACT), and the Port Operations and Communications Centre (POCC) in Sydney. These towers are shown in Fig. 1.

Brisbane ACT is a 71 m high reinforced concrete control tower with an 18 faceted polygonal cross-section. The control level is located at a height of 63.2 m. The tower's first mode natural frequency of 0.54 Hz and first mode structural damping of around 0.5% of critical damping were identified using forced excitation by synchronised human movement (Denoon *et al*. 1997).

Sydney ACT is a 43 m high composite concrete and steel structure of very unusual design. The tower consists of a concrete core which is connected to the turret by a cylindrical steel section. A steel framed lift shaft is attached to the core. The structure is guyed in three directions by pairs of stays. One stay of each pair is connected directly to the turret while the other is connected to the

(a) (b) (c)

Fig. 1 (a) Brisbane Airport Control Tower, (b) Sydney Airport Control Tower and (c) Port Operations and Communications Centre

top of the concrete section of the core. A further steel member connects these two attachment points. There is also a fire escape stairway which spirals from the turret to the ground, and connects to the core by way of a bridge at approximately mid-height between the ground and the turret. The tower's first mode natural frequency of 0.95 Hz and first mode structural damping of around 0.75% of critical damping were identified using forced excitation by synchronised human movement (Denoon *et al*. 1997).

The POCC is located close to the Sydney city centre on the eastern edge of Darling Harbour. The tower was opened in 1974 to control all shipping movements within the Port of Sydney. The tower consists of a 9.8 m diameter stainless steel clad turret mounted on top of a 4.9 m diameter reinforced concrete shaft. The space frame roof on the turret has a diameter of 14.7 m. The tower has a first mode natural frequency of 0.39 Hz and first mode structural damping ratio of around 0.8% of critical damping (Denoon and Kwok 1996).

Brisbane ACT was instrumented with an orthogonally mounted (East-West & North-South or x & y) pair of accelerometers and a propeller-vane anemometer on a mast above the roof. The accelerometers were located in the crawl space directly below the floor of the control cabin. The accelerometers used were connected to custom-built signal conditioners which amplified the signal and low-pass filtered the output with a cut-off frequency of 10 Hz. Data was gathered by a personal computer for 14 minutes and 50 seconds, reduced to summary information and then stored as summary information with raw data stored if pre-determined acceleration or wind speed thresholds were exceeded.

Sydney ACT was instrumented in a similar fashion to Brisbane ACT but instead of a single pair of accelerometers and a single anemometer, two pairs of orthogonally mounted accelerometers and two anemometers were installed. The accelerometers were mounted below the false floor of the control level with one pair of accelerometers at the centre of the floor and one pair at the perimeter. This instrumentation configuration was adopted to allow the detection of torsional components of the motion. The additional anemometer was required as an anemometer could not be mounted above the roof due to airport operational constraints. Hence a pair of anemometers were mounted on the stays below cab level in such a way that at all times at least one anemometer was sufficiently exposed to be able to accurately measure the local wind velocity. There were still shielding effects caused by the lift shaft and spiral stairway, and correction factors were derived from a wind tunnel test.

The instrumentation installed at the POCC was broadly similar to that at Brisbane ACT and has been described previously by Denoon and Kwok (1996). For the experiments described later in this paper, accelerometers were installed on the floor adjacent to the participants.

3. Acceleration performance of the towers

Brisbane Airport was opened in 1988 and at the beginning of this study the tower had been operational for around seven years. At the beginning of this project Sydney Airport tower had just been completed and controllers had begun training in the new tower before commencement of operations. The previous tower was a squat brick structure with no reported incidence of wind-induced vibration. However, there were immediate complaints about the motion in the new tower. The Port Operations and Communications Centre was opened in 1974 and is well known to be lively in the wind. The authors did not have formal access to the staff in the POCC, but anecdotally it is understood that most of the staff who work in the POCC (who are mostly former mariners) are accustomed to the motion although there were some reports of a few staff over the years not being able to tolerate the motion on windy days.

The predicted acceleration responses of the three towers (Denoon 2000) are compared with the acceleration criteria suggested in ISO6897-1984 as shown in Table 1. While both Brisbane ACT and Sydney ACT appear to meet the ISO6897-1984 acceleration criteria, the acceleration response of POCC is well above the acceleration criterion and generally supports the anecdotal evidence collected by the authors.

4. Test methodology to investigate occupant response to wind-induced motion

The control desks in the tower cabins at Sydney and Brisbane ACTs were instrumented with five sets of push-button units. These push-button units, illustrated in Fig. 2, were installed to allow the air traffic controllers to register motion perception. Each unit contained 5 separately labelled buttons, the labelling being used for scales of motion perception or acceptability.

4.1 Magnitude of motion self-reporting push button data

The first set of labelling on the push-buttons was designed to reflect perception of motion and

Table 1 Comparison of tower responses with acceleration criteria

Location	Predicted 5 yr return period r.m.s. acceleration (milli-g)	ISO6897-1984 5 yr return period r.m.s. acceleration criterion (milli-g)	Complaints
Brisbane ACT	3.24	3.43	No
Sydney ACT	2.75	2.73	Yes
POCC	9.25	3.90	Not known

Fig. 2 Motion reporting push buttons in Brisbane Airport Control Tower

perceived magnitude of motion. This labelling was used from July 1995 to December 1997 at Brisbane ACT and from September 1997 to June 1998 at Sydney ACT. The labels on the buttons were:

1. Tower stationary.
2. Very small motion (barely perceptible).
3. Small motion (definitely perceptible).
4. Moderate motion.
5. Large motion.

Air traffic controllers were originally asked to push a button at the start and finish of every shift, and also to press a button when perceptible motion occurred. As is the way of human nature, the button pushing soon reduced to buttons being pushed only on occurrence of perceptible motion. As a result of this, the button pushes actually became more useful in a practical sense after time, as they became a measure solely of "distraction", or when the motion was large enough to distract an occupant from their primary activities, rather than "perception" as it is normally understood in human factors research. In the field of building design, it is potentially the "distraction" threshold that is of more importance than the pure "perception" threshold which implies an subject concentrating on whether or not a movement can be perceived.

4.2 Perception and acceptability of motion self-reporting push button data

Mid-way through the project, the buttons were re-labelled to reflect measures of perception and acceptability. These buttons were used from August 1998 to May 1999 at Brisbane ACT and from June 1998 to December 1999 at Sydney ACT. The buttons were relabelled as follows:

1. Motion imperceptible.
2. Motion barely perceptible.
3. Motion clearly perceptible.
4. Motion annoying/irritating.
5. Motion disturbing/frightening/nauseating.

The above 5 ratings do not appear to form a logical scale, as nausea is not necessarily associated with fear and does not necessarily form a higher perception level than annoyance. The scale is not, however, intended to be a scale of perception but instead a serviceability design scale. Each of the 5 points is related to an acceptability design level. While perception may be acceptable on a regular basis, annoyance is not regularly acceptable, and fear or nausea is not acceptable except during rare, extreme wind events. Hence, the five labels form a design scale while providing information about both perception and acceptability.

4.3 Long term survey of motion perception and tolerance at Sydney Airport Control Tower

Although the push button sets provided useful long-term data on the acceleration levels at which the tower occupants perceived motion, they did not provide any guidance on either the proportion of the population which perceives motion (or finds it uncomfortable) at a given acceleration level. In order to provide additional data on other environmental factors which may have influenced motion perception or dissatisfaction, a long term survey was implemented to investigate the effects of each of these factors on motion perception and tolerance.

The long term survey was conducted over 19 months from April 1998 to November 1999. During this period, 1270 interviews were conducted under a wide range of wind, and hence motion, conditions. The surveys were conducted in the tea room of Sydney ACT, which is directly underneath the control cabin. The controllers were interviewed when they entered the tea room at the start of breaks. Controllers were asked for their impressions, using a scale card, of the previous fifteen minutes regarding motion and temperature. Busyness and posture were later added as further variables on the basis of controllers' comments. This method ensured that the threshold of distraction was being measured, with the controllers being interviewed about what level of motion they had noticed rather than asking for the level of motion that could be felt at the time of interview.

The respondents were presented with a card containing each of these scales at the beginning of each interview. The scale card is shown in Fig. 3. The date and time of day were recorded in order to correlate the interview data with the acceleration data. Care was taken to ensure correct synchronisation of computer and interviewer clock times at the start of each interview session.

The five levels of motion on the scale card corresponded to the second set of labelling on the push button sets on the desks in the cabin i.e., acceptability levels. The temperature scale was: hot; warm; comfortable; cool; and cold. This temperature scale provided a subjective assessment of the thermal comfort of the interviewee rather than a measure of the air temperature. This is a well known approach to determining thermal comfort and is used (albeit with a seven point scale) in international standards such as ASHRAE55-2010 for "Thermal Environmental Conditions for Human Occupancy". The busyness scale was a subjective scale relating to the perceived busyness of the interviewee. The four postures corresponded to the most common postures adopted in the control cabin, namely: walking about; standing; sitting; and standing, leaning on the console. As noted above, the busyness and posture scales were added as a result of controller comments about factors that they perceived as affecting the magnitude of motion required to distract them from their primary task such that they became aware of the motion. The busyness scale was limited to a 5-point scale, consistent with the thermal comfort scale, as the investigators wanted to keep the ratings simple to ensure as much consistency as possible between reports on different occasions with the same conditions. The four postures were based on the four postures adopted within the control cab

LEVELS OF MOTION

1	-	Motion Not Perceptible
2	-	Motion Just Perceptible
3	-	Motion Definitely Perceptible
4	-	Motion Annoying / Irritating
5	-	Motion Disturbing / Frightening / Inducing Sickness

TEMPERATURE			BUSYNESS		
1	-	Cold	1	-	Much less busy than normal
2	-	Cool	2	-	Less busy than normal
3	-	Comfortable	3	-	Normal
4	-	Warm	4	-	Busier than normal
5	-	Hot	5	-	Much busier than normal

POSTURE

1	-	Mostly seated
2	-	Mostly standing
3	-	Mostly standing leaning on console
4	-	Mostly walking about

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Airport Control
Tower Project

Fig. 3 Scale card presented to air traffic controllers in Sydney during long-term survey

environment. The extent of the survey questions was also limited compared with a typical, fully controlled, experimental design as each subject was answering the questions voluntarily on multiple occasions during their rest and break periods. As a result of how quickly and easily this could be completed, there was almost complete participation from the tower occupants.

4.4 Exit survey of motion perception and tolerance at Sydney Airport Control Tower

At the conclusion of testing and long-term surveys at Sydney ACT, an exit survey was conducted to gauge the opinions of the controllers about the tower motion. The primary aim of the survey was to investigate the acceptability of motion from the perspective of subjects who have been subjected to regular motion in their workplace.

The survey was distributed to current and recent past occupants of the tower in late December 1999 with returns due by mid-February 2000. The survey contained 40 questions covering aspects of motion perception and tolerance including perceived environmental influences and temporal modifications. 48 surveys were distributed and 38 were completed and returned.

4.5 Survey of motion perception and tolerance at the Port Operations & Communications Centre

An experiment was designed to investigate the effects of motion on cognitive performance in a field environment, and this experiment has been fully described by Denoon (2000). At the completion of each task battery at the POCC, subjects were taken individually into an adjacent room and interviewed about their perception of motion while engaged in the task battery. The survey was similar to that used at Sydney Airport Control Tower with subjects asked to rank the motion on a five point scale: motion imperceptible; motion barely perceptible; motion clearly perceptible; motion annoying/irritating; and motion disturbing/frightening/inducing nausea.

Eight test subjects were involved in this survey, based on a repeated measures design. In most cases, the test subjects were interviewed three times per visit to the POCC at approximately 30 minute intervals. The subjects interviewed were naïve to wind-induced building motion.

5. Key findings of the investigations

5.1 Magnitude of motion self-reporting push button data

Standard deviation accelerations referred to in this, and following, sections are combined standard deviation accelerations which reflect the standard deviation of the dynamic response of the tower, irrespective of direction. However, because the data in this section is based on summary data files, the peak accelerations referred to are not true peak accelerations. The summary data files stored only the peak accelerations in the two orthogonal directions of the accelerometers, not the absolute peak acceleration value. The reason for this is that when the data acquisition system was originally developed, the calculation of the absolute peak acceleration significantly increased the computer downtime between recording cycles. The peak acceleration values quoted are the larger of the x and y acceleration values for each data record. Thus, they are an underestimate of the true peak acceleration values. An analysis of 1016 raw data records from Brisbane ACT found that the mean value of the absolute peak acceleration divided by the maximum directional peak acceleration was 1.10. A similar analysis of 1324 records from Sydney ACT showed a ratio of 1.05. At acceleration levels below the threshold at which raw data was stored, this ratio may be expected to be consistent, or even slightly smaller as a result of a higher noise to signal ratio. Hence the peak acceleration values reported here can be expected to be from 5% to 10% lower than the true peak acceleration values.

The results from the button pushing of the air traffic controllers are presented as the number of pushes per acceleration record within acceleration bands of a given width. The acceleration band widths selected were 0.1 milli-g when standard deviation accelerations were being examined and 0.5 milli-g in the case of peak accelerations. These bandwidths are a balance between acceleration resolution and obtaining sufficient samples in each band to ensure statistical reliability. The maximum number of button pushes per data record would be five, because there were five sets of buttons. However, it was uncommon for all five button locations to be occupied at any given time. It should also be recognised that controllers would only push the buttons when they were not entirely occupied with their primary activities. It was also the case that during prolonged wind storms, controllers would not push the buttons every fifteen minutes, but only early in the storm or

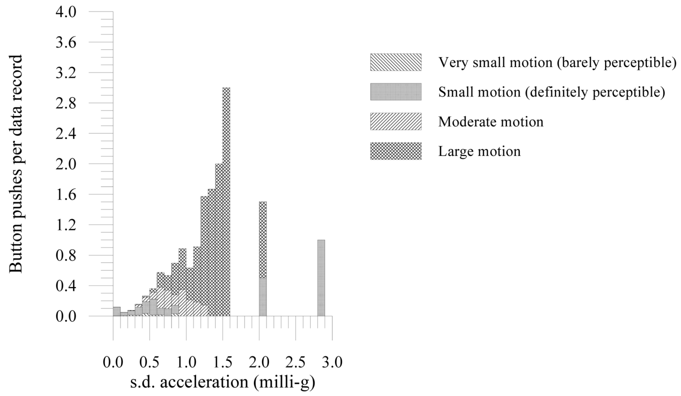

Fig. 4 Rates of button pushing versus standard deviation acceleration for all motion – magnitude labelling, Brisbane Airport Control Tower

when particularly large accelerations occurred. Thus, acceleration which would be perceived by 100% of the population would be represented by a button pushing rate of much less than 5.

The rates of button pushing of all (motion) buttons versus combined standard deviation acceleration are shown in Fig. 4.

Fig. 4 shows that, as expected, the rate of button pushing increases with increasing amplitude. It can also be seen that when rates of button pushing becomes significant, implying accelerations above the average threshold of perception, most subjects perceived the motion as being of moderate or large magnitude. This is consistent with an underlying expectation of the general population of buildings as static, rather than dynamic, structures. It is noted that the standard deviation acceleration bands above 1 milli-g contain fewer than 10 records each, and therefore do not have statistical validity in the breakdown of motion magnitude reported. It would be expected that an average perception threshold could be identified by a sudden increase in the rate of button pushing above the perception threshold. In fact, when only the pushes of buttons for moderate and large motions are examined, a step change in the rate of button pushing can be identified between standard deviation accelerations of 0.6 and 0.7 milli-g, suggesting an average perception threshold of around 0.65 milli-g.

Rates of button pushing relative to peak accelerations for Brisbane Airport are presented in the same format as for standard deviation accelerations in Fig. 5. From this it would appear that the average threshold of perception is between 2 and 2.5 milli-g. Taking into account the 10 % underestimate of true peak acceleration as a result of only directional peak measurements being presented, the true peak acceleration threshold at Brisbane ACT appears to be around 2.5 milli-g. This is also consistent with the peak factor of around 3.5 for Brisbane ACT described by Denoon (2000).

The rates of button pushing of all buttons at Sydney ACT, labelled in terms of magnitude estimation, are shown versus standard deviation acceleration in Fig. 6. As was the case at Brisbane ACT, button pushing can be seen to be dominated by pushing of the moderate and large motion buttons. The rate of button pushing can be seen to increase significantly in the standard deviation acceleration band of 0.6 milli-g to 0.7 milli-g, indicating a similar perception threshold to that at Brisbane ACT. The rate of button pushing around the threshold of perception (or distraction) is

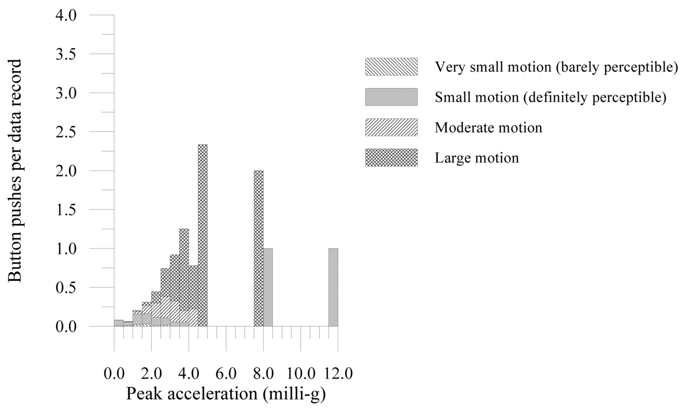

Fig. 5 Rates of button pushing versus peak acceleration for all motion – magnitude labelling, Brisbane Airport Control Tower

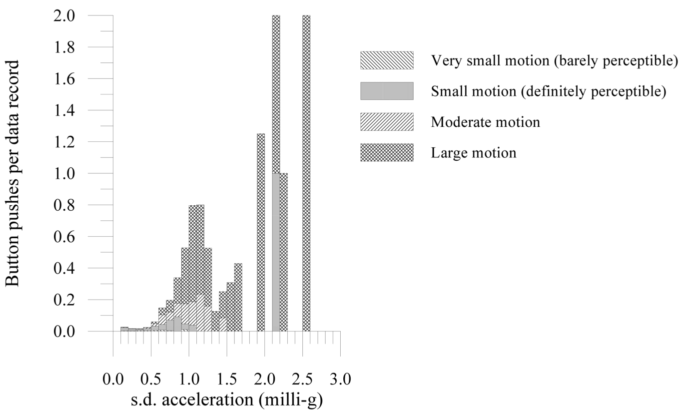

Fig. 6 Rates of button pushing versus standard deviation acceleration for all motion – magnitude labelling, Sydney Airport Control Tower

about half of that at Brisbane ACT. This may be due to the frequency with which perceptible motion occurs and also the fact that a greater proportion of the wind-induced perceptible motion at Sydney ACT was due to synoptic winds rather than the thunderstorm winds which dominated in Brisbane, with the synoptic storms having a longer duration. In effect, there have been the same, or a greater, number of button-pushes per storm at Sydney ACT, but because of the longer duration of the average storm, the number of button pushes per 15 minute data record was lower. Examining only button pushes of small to large motion, the average threshold of perception can again be clearly identified, with a lower standard deviation acceleration perception threshold between 0.5 milli-g and 0.6 milli-g.

Rates of magnitude labelled button pushing versus peak accelerations are shown in Fig. 7. The average threshold of perception, based on an increase in the rate of button pushing, appears to occur between 2.0 milli-g and 2.5 milli-g, although it is less clear than other examples which demonstrated a clear step change. Taking into account the 5% average underestimate of true peak acceleration resulting from the use of directional peak accelerations, the average threshold of

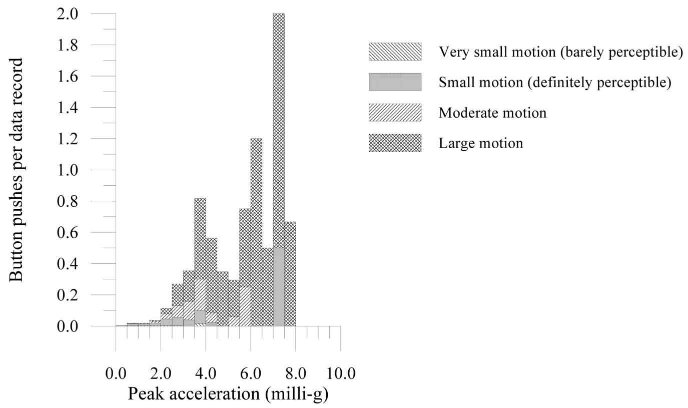

Fig. 7 Rates of button pushing versus peak acceleration for all motion – magnitude labelling, Sydney Airport Control Tower

perception would appear to be of the order of 2.4 milli-g.

5.2 Perception and acceptability of motion self-reporting push button data

Fig. 8 shows the rate of button pushing of all the buttons registering motion at Brisbane ACT for peak accelerations. It can be seen that above the average threshold of perception, the vast majority of button pushes are in the annoying and disturbing ranges. Two possible interpretations of this are that the controllers found almost all perceptible motion annoying or disturbing, or alternatively that the controllers had become accustomed to pushing the moderate or large motion buttons during the period of original labelling.

Raw data records which included button pushes were re-analysed to determine correlations between the number (2-5) of the button pushed and the peak, standard deviation and root-mean-

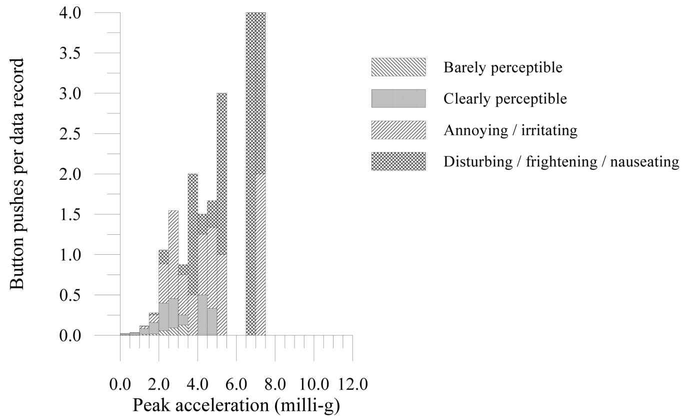

Fig. 8 Rates of button pushing versus peak acceleration for all motion – acceptability labelling, Brisbane Airport Control Tower

Table 2 Correlation of acceleration measures with button number at Brisbane Airport Control Tower

Acceleration measure	Correlation coefficient with button pushing
Absolute peak acceleration	0.551**
Combined s.d. acceleration	0.580**
r.m.q. acceleration	0.592**

N = 297
** - significant at 0.0005 confidence level

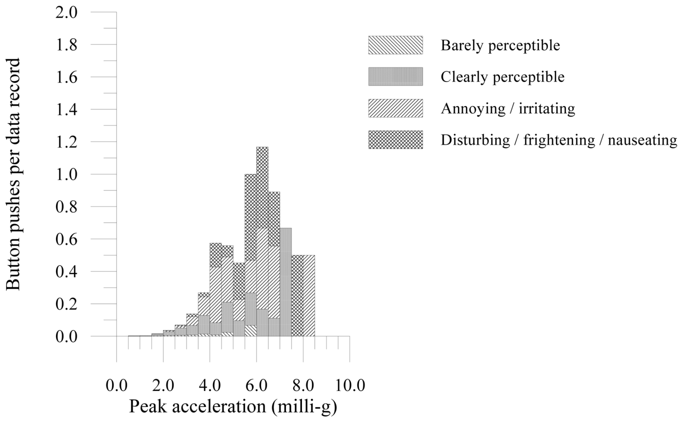

Fig. 9 Rates of button pushing versus peak acceleration for all motion – acceptability labelling, Sydney Airport Control Tower

quad (*r.m.q.*) (see Griffin (1990) for definition) accelerations. Due to the relatively low number of raw data records containing button pushes (297), the correlations were conducted on a composite of both the magnitude and acceptability labelled button data. These three correlations are shown in Table 2. It can be seen that each of the correlations is significant at the 0.0005 level. It can also be seen that the highest correlation is between r.m.q. acceleration and button number, with the lowest between peak acceleration and button number, although the differences are very small. The motivation for button pushing may be considered to be similar to the motivation behind complaining, in that both require a conscious act by the subject, unprompted by the investigator. As standard deviation and r.m.q. accelerations are time dependent measures, there is, thus, some evidence of time dependence in measures of annoyance or discomfort as a result of wind-induced building motion. It should be noted that these correlations were calculated on a short data record of 15 minutes. The differences found in correlations between button pushing and acceleration may underestimate the differences that would have been found had a longer record length been chosen.

Rates of button pushing versus standard deviation accelerations for the acceptability labelling phase of the project at Sydney ACT are shown in Fig. 9. The graph shows an increase in the rate of pushing of each button with increasing amplitude. It is not possible to pick perception (distraction) thresholds from any of the graphs of peak acceleration versus rates of acceptability labelled button pushing, but discomfort rates do increase significantly above peak directional accelerations of 4.0 milli-g. This corresponds to an average true peak acceleration of around 4.2 milli-g. This button data set is encouraging in that it does not display tendencies for the subjects to press the highest level of motion button every time motion was perceived. This suggests an 'honest' use of the

Table 3 Correlation of acceleration measures with button number of magnitude labelled buttons at Sydney Airport Control Tower

Acceleration measure	Correlation coefficient with button pushing
Absolute peak acceleration	0.566**
Combined s.d. acceleration	0.556**
r.m.q. acceleration	0.565**

N = 539
** - significant at 0.0005 confidence level

buttons. This may have been helped by the investigators' concurrent long term interviews which used the same motion scale as on the buttons.

Correlations of acceleration measures with button number pushed were conducted for the acceptability labelling of the Sydney ACT push-button responses. The results of these correlations are shown in Table 3. These correlations are all significant at the 0.0005 confidence level, but show no duration effects, with very similar correlations for each of the three acceleration measures. This result is in contrast to the correlations from Brisbane ACT, which showed weak evidence of a duration effect on perception and discomfort as measured by button pushing. This may be due to the short measurement period compared with the average length of a storm resulting in perceptible motion in the Sydney ACT, which can be shown to be around 4.5 hours.

5.3 Long term survey of motion perception and tolerance at Sydney Airport Control Tower

All the survey data which was gathered is shown in Fig. 10. The numbers presented above each bar are the total number of interview points in that acceleration band. It can be seen from this graph that the average threshold of perception (50% of sample in the acceleration band perceiving motion) of standard deviation acceleration was 0.7 milli-g, and of directional peak acceleration was 2.0 milli-g. This agrees well with the figures deduced from the button pushing data, thereby verifying the method of identification of average thresholds from the push-button data.

The cumulative perception data takes the form of a lognormal curve, as found by a number of previous researchers (e.g., Jeary *et al.* 1988, Kanda *et al.* 1990), even though this data contains a much larger number of environmental variables than in previous controlled experiments.

The graph also shows a much greater use of the "barely perceptible" motion ranking than was the case with the button data. This is the predominant ranking up to the average perception threshold.

There were very few responses in the "annoying" or "disturbing" categories below the average threshold of perception, but the responses in these categories increase rapidly above the average perception threshold. This indicates that a significant proportion of the population found any perceptible motion annoying. There is also a fairly even distribution between "clearly perceptible" motion and "annoying" and "disturbing" motion at higher acceleration levels. It is interesting to note that within the range of accelerations encountered during the surveying, there is not a great increase in the proportion of the population annoyed or disturbed by the motion above a standard deviation acceleration of 1.2 milli-g or a peak acceleration of 4.0 milli-g.

It can be seen that the proportion of the population being annoyed by the motion increases significantly above a standard deviation acceleration of 1.0 milli-g or a peak directional acceleration of 3.5 milli-g. Above these levels, the increase in the levels of annoyance appears to be small,

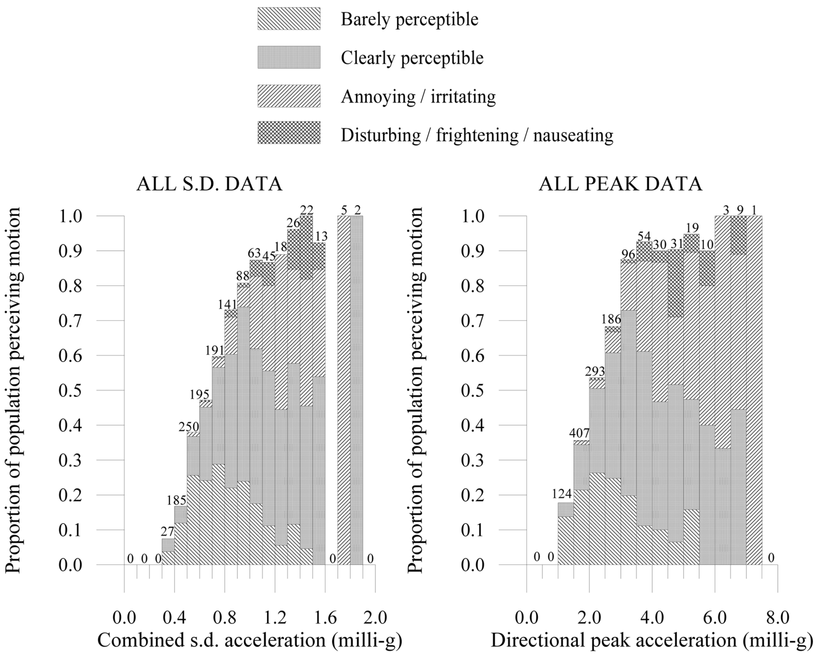

Fig. 10 All Sydney Airport survey data versus acceleration

although at the higher amplitudes the small number of samples does not permit a reliable analysis.

It is of interest to note the disparity between the number of interviews reporting annoyance or irritation and the number of interviews reporting fear or nausea. There were very few reports of fear, most of these responses being symptoms of nausea such as headaches or mild queasiness. Many of the interviewees did, however, ask the interviewer about the structural safety of the tower during strong wind events. The interviewer replied on each occasion that if the tower was unsafe, he would not be sitting in it conducting interviews. This process of education may have reduced the number of tower occupants who were disturbed or frightened by the tower motion.

An interesting anecdote to support this supposition, is an event which occurred during determination of the dynamic properties of the tower. The principal author and two colleagues conducted a forced vibration of the tower before the tower was fully operational. At this stage, air traffic controllers were undergoing training in the new tower and ‘shadowing’ the operations of the old control tower. When the tower was excited to perceptible levels, the controllers exited the cabin, fearing an earthquake. This, although a different situation, demonstrated fear for structural safety under low amplitude perceptible motion.

Not surprisingly, there appears, by inspection, to be a stronger correlation between standard deviation acceleration and fear or nausea, than between peak acceleration and fear or nausea. As most of the reports in this range resulted from reports of nausea, a strong time dependence, reflected by a standard deviation amplitude measure, would be expected.

None of the other environmental factors investigated (temperature, busyness, work time, and posture) were found to have any influence on either perception or acceptability. The most surprising null result here is that regarding posture. Anyone who has spent time in a moving environment will know that posture significantly affects perceptibility of motion. However, it is postulated that in a working environment enough different postures are adopted over the length of a storm that it does not have a practical influence on motion perception or tolerance.

5.4 Exit survey of motion perception and tolerance at Sydney Airport Control Tower

Tower motion was readily perceptible to all of the tower occupants on a regular basis. More than 80% of the occupants believed that they perceived motion at least once a fortnight. The 14 day return period peak acceleration for Sydney ACT is around 5.8 milli-g. However, on the basis that any worker was only in the tower for around one fifth of the opening hours of the tower, the more appropriate comparison would be a 3 day return period acceleration. The peak acceleration associated with a 3 day return period acceleration is around 4.4 milli-g which is well above the average threshold of perception of 2.4 milli-g measured at Sydney ACT. However, these figures do not reflect storm length, nor do they necessarily reflect the percentage of days on which perceptible motion occurs. An analysis of 709 days of data found that perceptible motion with a standard deviation acceleration greater than 0.7 milli-g occurred on 359 of those days, for an average of nearly four hours on each of those days. Thus, a controller with an average perception threshold would be likely to encounter perceptible motion between once a week and once a fortnight. It is noted that this compares with 47 perceptible motion days out of 856 measurement days at Brisbane ACT. Thus, significant over-reporting of wind-induced motion did not occur in this question, with most participants answering in the correct range of frequency of occurrence of perceptible motion.

34% of the sample believed they notice the tower motion less at the time of the survey than when they started work at the tower, while only 8% believed they noticed it more. Only 16% of the sample believed that tower motion occurred less often than when they started work at the tower, but 24% believed the motion to be smaller. This supports the hypothesis that although subjects notice motion less with repeated regular exposure, this is not due to an elevated perception threshold, but due to an elevated ‘distraction’ threshold.

58% of those interviewed responded that they found the tower motion irritating and annoying. This would suggest an unacceptable motion environment, especially as more than half of those who were annoyed by the motion reported annoyance once per month or more frequently. Over 40% of those who reported annoyance did, however, report that they found the motion less annoying at the time of the survey than they did when they started work at the tower. This corresponds very closely to the responses to a further question which found that no-one was annoyed by the motion more frequently than when they started work at the tower, but 46% found the motion annoyed them less frequently, including 9% who reported that they were no longer annoyed. Along with the elevated distraction threshold, this is clear evidence of habituation to wind-induced building motion.

A number of questions investigated occurrence of fear and disturbance as a result of tower motion. Nearly 40% of respondents reported that they had been disturbed or frightened by the motion, with average occurrences of between once per month and once per year. Of these, 40% reported that they found the motion less frightening or disturbing than when they had started work at the tower, and 50% reported that they were frightened or disturbed by the motion less frequently than when they had started work there. The maximum time which anyone had worked in the tower was three and a half years, with many of the respondents having worked there for that length of time, while some had only worked there for a few months. These results again demonstrate adaptation, or habituation, to the motion. The main cause of fear or disturbance was a lack of confidence in the structural integrity of the tower. The reduction in the occurrence of fear or disturbance over this short period of time may have been largely due to the education process of talking to the interviewer and learning that the motion was not inherently unsafe. This highlights the potential benefits of education of occupants of wind-sensitive structures.

It can be seen that several subjects suffered nausea, and a few reported headaches, as a result of tower motion, but none reported emesis. These symptoms were experienced only rarely in each case. Other symptoms reported included anxiety, distraction and imbalance (both in and on leaving the tower). Again, as was the trend for annoyance and disturbance, around 50% of those who reported suffering physiological symptoms as a result of wind-induced tower motion, reported that their symptoms were less severe at the time of the survey and that they suffered from them less frequently than when they started work in the tower.

Perceived effects of busyness were investigated again in the exit survey. Responses showed a strong belief that motion was noticed less when the respondent was busy and vice versa. This was consistent with the comments received from the air traffic controllers, but was not reflected in average perception thresholds obtained from the long-term survey. This may be a result of the method by which the long-term survey was conducted, in that, although the controllers were asked about previous experience, they were still being prompted to give a response. It would have been instructive to have a method, such as the button-pushing, which would also reflect busyness, as it can be envisaged that button pushing would be significantly reduced during periods of high work stress. Similarly, during periods of intense concentration and high work load, the complaint level as a result of wind-induced motion may actually be reduced.

Past, and future, complaints about wind-induced tower motion were also investigated. It was found that 34% of respondents recorded having made at least one verbal complaint to a senior staff member, but none had gone so far as to make a written complaint. Twenty one percent of respondents envisaged making future verbal complaints and the majority of those who had already complained had complained on multiple occasions.

The final questions posed to the controllers in the exit survey were about their acceptance of the wind-induced motion environment at Sydney ACT when they first started work there and also at the time of survey completion. The results of these questions are shown in Tables 4 and 5. These tables show that 50% of the population sample originally thought the motion environment unacceptable compared with 29% at the time of the survey. This is strong evidence of growing acceptance of wind-induced building motion with increasing habituation. These results also included one respondent who originally thought the motion environment acceptable but had come to regard the

Table 4 Responses to Question 37: When you first started work in the new Sydney Airport tower, did you consider the wind-induced motion environment to be acceptable?

Yes	19	50%
No	19	50%
Total responses	38	

Professor

Table 5 Responses to Question 38: Do you now find the wind-induced motion environment to be acceptable?

Yes	27	71%
No	11	29%
Total responses	38	

motion as unacceptable.

A factor analysis identified underlying constructs determining motion perception, tolerance and acceptability. This found that views on how often motion should be perceptible were independent from complaints. This finding demonstrates that surveys (such as Hansen *et al*. 1973) that were used to define the acceptable occurrence rate of perceptible motions are not an appropriate method of predicting how the building will perform in terms of complaint rate.

Overall, many of the exit survey questions were designed to mimic the questions used in surveys by other investigators, such as Hansen *et al*. (1973) in isolation for discrete interviews following complaints. The combination of the exit survey in this case with the long-term statistics highlights the unreliability inherent in taking isolated surveys where building occupants are asked to offer their opinions. It can clearly be seen that these opinions do not correlate well with actual occupant reaction during wind events, and that they do not take account of the longer-term habituation that will occur in a new building. These are important factors to consider in the development of acceptability criteria.

5.5 Survey of motion perception and tolerance at the Port Operations & Communications Centre

Survey responses to motion at the POCC are shown in Fig. 11. The average threshold of perception of standard deviation acceleration can be seen to be around 0.8 milli-g to 1.0 milli-g. As the proportion of the sample perceiving motion in the acceleration band from 0.6 milli-g to 0.8 milli-g, is close to 50%, it is likely that the threshold of perception is quite close to 0.8 milli-g. The peak acceleration data shows that between 2.0 milli-g and 2.5 milli-g, around 55% of the sample interviewed in this acceleration band perceived motion. However, this sample comprised only 9 interviews. In the acceleration band from 2.5 milli-g to 3 milli-g, 22 interviews were conducted, and the proportion of population perceiving motion was around 60%. It is thus likely that the true threshold of perception of peak acceleration is between 2.5 milli-g and 3.0 milli-g.

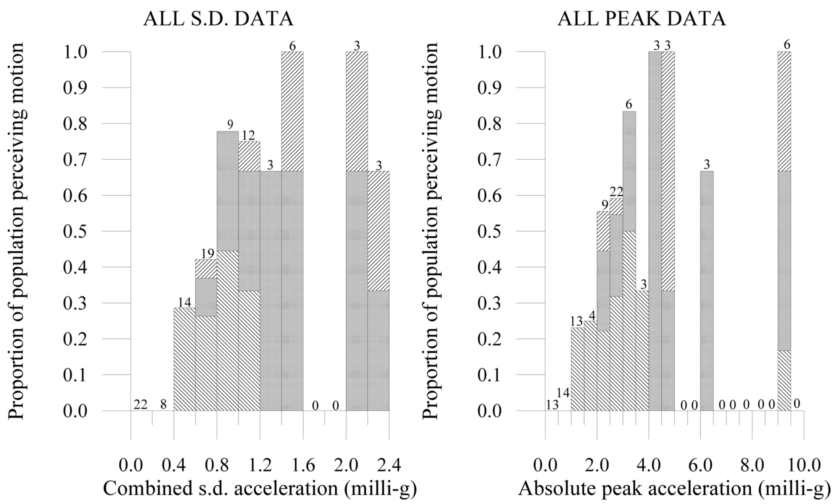

Fig. 11 Motion perception at POCC

The thresholds of perception of wind-induced motion at the POCC are slightly higher than those found at Brisbane and Sydney ACTs. This is consistent with the lower natural frequency at the POCC and the findings of numerous researchers in human response to vibration who have shown frequency dependence in perception thresholds.

A re-analysis of wind-induced response data previously gathered at the POCC (Denoon 1994) showed that, on the basis of 358 days data, that perceptible motion was experienced on 193 days, for a total of 867 hours.

One interesting, and anecdotal, finding from informal discussions with the normal occupants of the POCC is their acceptance of the wind-induced motion of the tower without any concerns regarding structural safety. This is further evidence of habituation. In this case, any concerns about structural safety have not been allayed by an outsider explaining the motion, but by existing occupants explaining the motion to new occupants, combined with the length of time for which the tower has been present without damage.

6. Design implications

The findings of the studies have a number of significant implications for serviceability acceleration criteria. The results shown in Table 1 illustrate that a simple single return period acceleration criterion does not adequately address all the factors that will determine the acceptability of motion in tall flexible wind-sensitive buildings.

The average perception thresholds found in the field were found to agree with the peak acceleration perception thresholds found in previous laboratory experiments (Denoon 2000). This confirms that perception of acceleration is dependent on peak accelerations rather than standard deviation accelerations.

Very high inter- and intra-subject variabilities were recorded during the surveying. This means that to develop statistically reliable measures, a great deal of data must be gathered. In the case of the least (and most) sensitive proportions of the population, the amount of data required to define their response characteristics makes such an approach unfeasible in the field.

The reliable measures that can be obtained are: the average perception threshold of a whole population; the number of hours or days this is exceeded on average per year; and whether complaints have been made about the wind-induced motion environment. These measures are summarised for each of the locations in Table 6. The values of days/year and hours/year were calculated from data presented in Denoon (2000, 1994).

As shown in Table 1, the predicted 5-year accelerations for Brisbane ACT and Sydney ACT predict similar performance with respect to ISO6897-1984, but complaints were only received at

Table 6 Influence of wind climate on motion acceptability

Location	Peak acceleration threshold (milli-g)	Hours/year perceptible acceleration	Days/year perceptible acceleration	Complaints	Storm type
Brisbane ACT	2.5	30	20	No	Thunderstorms
Sydney ACT	2.4	705	185	Yes	Gales
POCC	2.8	897	187	Not known	Gales

Sydney ACT. There are two possible reasons for this: the frequency of occurrence of perceptible motion leading to annoyance, and a naïve population experiencing fear and alarm at unexpected building motion. Both of these effects need to be accounted for in design criteria: large motions leading to fear and alarm, and regularly occurring motion leading to annoyance.

An example of the effects of experience and habituation is the POCC where very large accelerations have been experienced over many years without significant complaints from the long-term occupants. The effects of habituation and education can also be seen in the changing views of the Sydney ACT controllers between the beginning and the end of the study. Where occupants are aware, or can be educated, that wind-induced motion does not imply a lack of structural integrity, then more relaxed fear and alarm criteria can be applied. This fear and alarm criteria thus needs to take into account the occupants and their sociological conditioning.

Table 6 shows the predominant storm type at each location and it can be seen that this influences the relationship between the number of hours during which perceptible motion occurs each year and the number of days during which perceptible motion occurs. While no explicit time-dependence was found in the results, it could be expected that the longer the duration of a storm, the greater the annoyance as a result of more occurrences of perceptible motion. It is therefore proposed that storm separation techniques can be used in the determination of acceptability of motion. For example, a stricter criterion is needed where the local wind climate is dominated by regularly occurring synoptic storms of several hours duration than in a climate where the only accelerations occur as a result of short-duration, discrete thunderstorm events. Again the criterion needs to take into account sociological factors that recognise that some potential building occupants will be more tolerant of motion than others.

7. Conclusions

An extensive series of field experiments was undertaken in control towers to investigate occupant reaction to wind-induced motion. These experiments included self-reporting mechanisms for tower occupants, regular surveys of occupants, and an extensive exit survey.

The long-term surveys at Sydney ACT where occupants were asked objective questions about recent motion experience provided both variability in the responses between, and within, subjects on different occasions, and importantly this methodological approach provided significantly different responses to those more subjective responses obtained during the exit survey. This more subjective type of survey about past experiences has formed the basis of much of the published information about occupant reaction to wind-induced building motion. It also needs to be noted that while it would have been of value to conduct more extensive regular surveys, this is not practical within a functioning work environment in the field, and the long-term access to building occupants, with the freedom to publish the results, has been unprecedented to date.

It was found that field perception of motion was dependent on peak accelerations and agreed well with laboratory peak acceleration perception thresholds. The critical factors influencing acceptability of motion were found to be fear and alarm as a result of unexpected motion, the effects of which were mitigated with habituation and education, and frequently occurring perceptible motion leading to annoyance. Both of these factors need to be taken into account in providing recommendations about acceptability of motions in tall buildings criteria. One of the key issues that links these two factors, and that has not been considered in previous criteria, is the contribution of different storm types in the wind climate. This is one area that requires further research to be able to develop more robust criteria that are consistent with both reliable wind climate analysis and wind tunnel measurements.

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