HUMAN EXPOSURE TO WIND-INDUCED MOTION IN TALL BUILDINGS: AN ASSESSMENT OF GUIDANCE IN ISO 6897 AND ISO 10137

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Abstract

The excitation of tall structures by wind can induce motion at frequencies less than 1 Hz that can provoke fear, discomfort and symptoms of motion sickness in building occupants. This paper reviews guidance on the measurement, evaluation and assessment of human exposure to motion over the frequency range 0.063 to 1.0 Hz as provided in International Standard 6897 (1984) and over the frequency range 0.06 to 0.5 Hz as in International Standard 10137 (2007). Root-mean-square acceleration limits in ISO 6897 are compared with peak accelerations in ISO 10137, assuming a crest factor of 3.5. Limits in ISO 10137 for offices subjected to motions with a one-year return period are consistent with one-year return limits in ISO 6897 for buildings used for general purposes. Average perception thresholds in ISO 6897 are a little higher than those in ISO 2631-1:1997. Possible differences in acceptability criteria based on perception, comfort, motion sickness and incidence of complaint are discussed. It is concluded that ISO 6897 and ISO 10137 do not adequately allow for the effects of exposure duration nor allow for differences in the effects of motion on alarm, perception, comfort and motion sickness.

1. Introduction

Innovations in structural and materials engineering over recent decades have allowed the number and height of super-tall towers and skyscrapers to increase world-wide. However, increased height is often achieved using longer spans of lighter and stronger materials, with associated increased structure flexibility and susceptibility to movement when exposed to forces of wind.

Excitation of tall buildings by high winds induces motion at frequencies less than 1 Hz. Wind-induced building motion may be dominated by bending (sway) about orthogonal structural axes in the first and second mode, or by rotational motion about the vertical axis (torsion) at second or higher modes, or some combination of these. For buildings with mass or stiffness asymmetry, complex bending combined with torsion may occur (Melbourne and Palmer, 1992). The buffeting forces of wind typically induce motions characterised by narrow-band random oscillation with crest factors (ratio of peak to r.m.s. acceleration) of around 3.5 (Burton *et al*., 2005; Tamura *et al*., 2006). An example of wind-induced horizontal acceleration measured in a 'wind-sensitive' building in the Central Business District of the city of Wellington, New Zealand, is shown in Figure 1 (Lamb *et al.*, 2014).

Low-frequency motion induced by high winds, while meeting building strength and safety requirements, may cause a range of adverse effects on building occupants. Reported responses include alarm or fear, discomfort, difficulty concentrating and symptoms of motion sickness

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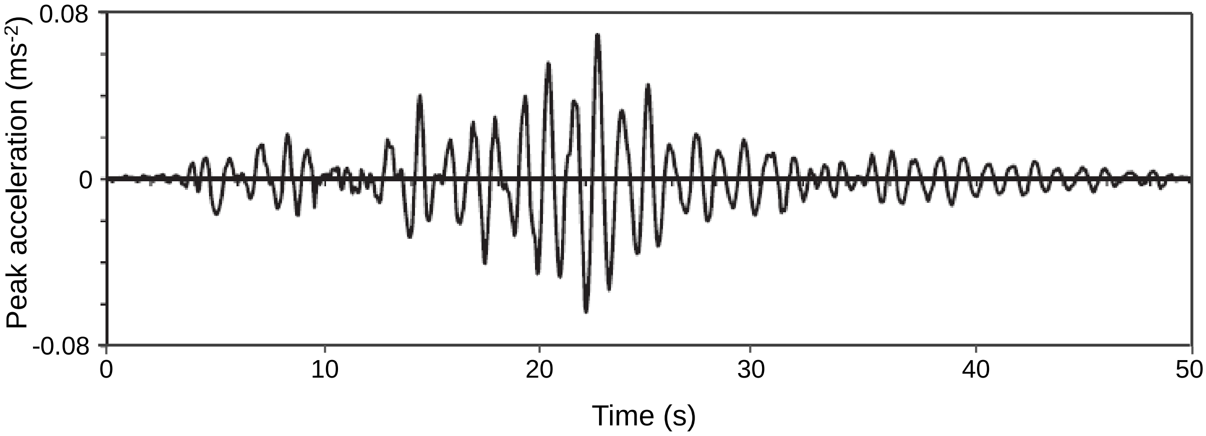

Figure 1 Acceleration time history of wind-induced motion measured in one horizontal axis of a building in the city of Wellington, New Zealand. From Lamb *et al.* (2014).

(Hansen *et al*., 1973; Goto, 1983; Denoon *et al.*, 1999; 2000; Lamb *et al.*, 2013). Kwok *et al.* (2009) suggested motion induced by frequent sustained wind events such as gales and monsoons may cause discomfort, while extreme infrequent events such as tropical storms, typhoons or hurricanes may elicit alarm or fear. The more extreme events may last several hours with maximum wind forces occurring over 10 to 30 minutes (Irwin, 1975; Melbourne and Palmer, 1992).

International Standard 6897 (1984) provides guidance on magnitudes of low-frequency horizontal motion over the frequency range 0.063 to 1.0 Hz expected to be satisfactory for people living and working in buildings. Mean perception thresholds in ISO 6897 are derived from thresholds for sinusoidal motion at frequencies between 0.067 and 0.2 Hz determined by Chen and Robertson (1972) and from equal sensation contours at frequencies between 0.5 and 100 Hz reported by Miwa (1967). Irwin (1975) used these findings and results from field surveys following wind storms (e.g., Hansen *et al.,* 1973) to propose acceptable magnitudes of r.m.s. acceleration for the worst 10 minutes of a wind storm. The criterion of acceptability was that no more than 2% of building occupants should object to the motion. Laboratory studies of perception and equal sensation during yaw motion (Irwin, 1981) and combined yaw and translational motion (Irwin and Goto, 1984) provided additional evidence which, together with the earlier findings, formed the basis of acceptability criteria in ISO 6897. The standard proposes acceptable magnitudes of r.m.s. acceleration over the frequency range 0.063 to 1.0 Hz for the worst 10 minutes of a wind storm with one-year and five-year return periods. The equivalent British Standard 6611 (1985) provides identical guidance.

Perception thresholds determined from laboratory studies involving sinusoidal motion (Shioya *et al*., 1992; Nagata *et al*., 1993; Kanda *et al*. 1994; Tamura, 1998) form the basis of 'Guidelines for Evaluation of Habitability' published by the Architectural Institute of Japan (Architectural Institute of Japan (AIJ), 2004). The AJH guidance is given in terms of 10^{th} to 90^{th} percentiles of the threshold of perception. International Standard 10137 (2007) presents similar guidance for assessing human response to wind-induced motion in buildings. International Standard 10137 specifies peak acceleration magnitudes over the frequency range 0.06 to 5.0 Hz expected to be satisfactory for people living and working in tall buildings during wind storms with a return period of one year. Limits in

ISO 10137 are said to be adapted from the 90th percentile of the threshold of perception as published by the Architectural Institute of Japan (AIJ, 2004; Kwok *et al.,* 2009).

This paper reviews guidance for the evaluation of human exposure to horizontal motion in tall buildings in International Standards ISO 6897 and ISO 10137. Differences in evaluation methods and acceptability criteria are discussed.

2. Measurement, evaluation and assessment guidance in ISO 6897 and ISO 10137

In ISO 6897 there is guidance on measurement, evaluation, and assessment of low-frequency horizontal motion. International Standard 10137 provides guidance on measurements for motion assessments with respect to human response. Guidance on assessment of wind-induced motion with respect to building habitability is contained in a separate annex.

2.1 Motion measurement

Guidance on the measurement of motion in ISO 6897 is in accord with guidance in ISO 2631 Part 2 (2003) and BS 6472 Part 1 (2008) for the evaluation of human exposure to building vibration. International Standard 6897 states that the magnitude and direction of the greatest horizontal motion shall be determined by measurements of motion on a structural surface supporting the body at the point of entry to the body. If measurements are made at locations other than at the point of entry, transfer functions must be applied. A note indicates that the highest acceleration magnitudes generally occur near the top of a building at the first natural frequency of the structure, though unacceptable accelerations at higher frequencies may occur elsewhere. A measurement duration of at least 10 minutes is required. International Standard 6897 provides no guidance on measurement instrumentation.

Guidance in ISO 10137 on wind-induced horizontal motion in tall buildings states that measurements of acceleration, velocity or displacement should be made on three or more storeys at measurement locations on or near walls. Measurements must be carried out using methods in accord with guidance for measurement instrumentation in ISO 8041 (2005). International Standard 10137 provides no guidance on appropriate measurement duration of wind-induced motion.

2.2 Motion Evaluation

The evaluation methods employed in ISO 6897 and ISO 10137 are not consistent with the methods defined in ISO 2631 Part 2 or BS 6472 Part 1: there are no frequency weightings.

In ISO 6897, either the highest acceleration of each discrete frequency, or the centre frequency of each one-third octave band, is determined and assessed separately. International Standard 6897 states that the r.m.s. acceleration of motion over the frequency range 0.063 Hz to 1 Hz must be determined; an averaging time of at least 200 s for one-third octave frequency analysis is required. Motion outside the range 0.063 to 1 Hz must be filtered with an attenuation rate of at least 24 dB per octave. If motion occurs in more than one horizontal axis, guidance in ISO 6897 states that the components shall be added vectorially. The vector addition of two axes differs from guidance in

ISO 2631 Part 2 and BS 6472 Part 1 for motion in the range 0.5 to 80 Hz, where only vibration in the axis of greatest motion is used in the evaluation.

There is no guidance on the influence of motion duration in ISO 6897 or ISO 10137. In ISO 6897, advice is limited to the categorisation of motion as either ‘infrequently’ or ‘frequently’ induced. No account is taken of the duration of an event or the number of events in a day; limits are provided simply for frequent occurrences ‘of an everyday nature’ and infrequent events associated with wind storms with duration in excess of 10 minutes and for return periods of one year and five years only. A note indicates that motions of duration less than 10 minutes associated with wind storms are assumed to have no lasting impact on occupants and are therefore excluded from evaluation.

In ISO 10137 it is advised that peak accelerations of wind-induced building motion are determined according to methods in ISO 4354 (2009) that include derivation of peak acceleration from displacement. The frequency range of measurements of wind-induced motion is not specified. Limits of wind-induced motion apply to frequencies in the range 0.06 to 5 Hz. However, it is not clear what to do with motion outside this range. Peak accelerations at the first natural frequency in the principal structural directions and in torsion (equivalent translational acceleration defined as the distance from the centre of torsion multiplied by the angular acceleration) are evaluated separately. No account is taken of the effects of modes at higher frequencies though they may contribute to overall response. It is not clear how to predict overall response when there is significant motion in more than one axis.

2.3 Motion Assessment

Three curves in ISO 6897 (Curves A to C in Figure 2) correspond to satisfactory magnitudes of wind-induced events. Curves A, B and C suggest that sensitivity to horizontal acceleration increases with increasing frequency between 0.063 and 1.0 Hz. The limits are categorized according to the use of the structure and the frequency of occurrence of the excitation forces. Information on structure type, frequency of events, and the activities of occupants relating to each curve is summarised in Table 1.

2.3.1 Perception thresholds

International Standard 6897 states that Curves A and B in Figure 2 correspond to acceptable

Table 1 Application of the limit curves in ISO 6897 applicable to horizontal motion events in tall buildings (see Figure 2).

Curve	Type of structure	Activities of occupants	Frequency of event	Criterion of limit
C	Buildings	General purpose	Worst 10 minutes of infrequent events, return period at least 5 years	Adverse comment level of 2%
B	Buildings	Special purposes, routine precision work	Frequent events, everyday occurrence	Mean threshold of perception
A	Buildings	Special purposes, requirement for apparently stationary environment	Frequent events, everyday occurrence	0.25 x threshold of perception

magnitudes of regularly occurring horizontal building motions for events with duration in excess of 10 minutes based on the average and lower perception thresholds respectively. The mean acceleration perception threshold in ISO 6897 (Curve B in Figure 2) is consistent with thresholds for sinusoidal motion determined by Shioya *et al*. (1992) and Nagata *et al*. (1993). However, at the highest frequency of 1 Hz, the mean acceleration perception threshold of Curve B is 0.014 ms^{-2} r.m.s. and 40% higher than the mean perception threshold of 0.01 ms^{-2} r.m.s. at 1 Hz in ISO 2631-1 (Figure 2). International Standard 2631-1 states that the inter-quartile range of weighted vertical acceleration for the threshold of perception may extend from about 0.007 to 0.014 ms^{-2} r.m.s. On this basis, the mean perception threshold for horizontal vibration in ISO 6897 may correspond to approximately the 75th percentile threshold implied by ISO 2631-1.

A “lower perception threshold” for horizontal motion in ISO 6897 (Curve A in Figure 2) applies where there is a requirement for the building to be apparently stationary. At a frequency of 1 Hz, the lower perception threshold corresponds approximately to the first percentile for the perception of vibration reported by Tamura (1998) and therefore is consistent in saying that a building would be apparently stationary to most building occupants.

2.3.2 Satisfactory magnitudes

International Standard 6897 provides limits for the worst 10 minutes of motion in “buildings used for general purposes” (Curve C in Figure 2). According to ISO 6897, at magnitudes below Curve C not

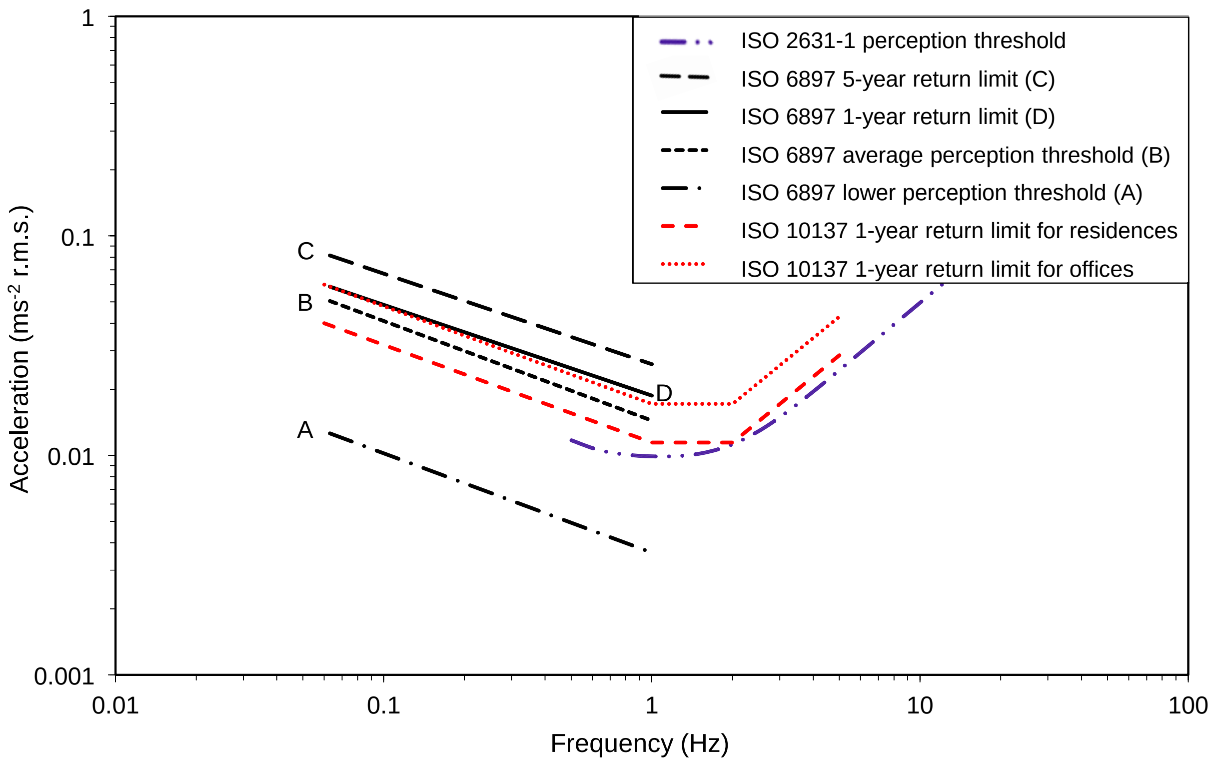

Figure 2 Limit curves for horizontal motion as given in ISO 6897 (1984) and ISO 10137 (2007), and perception thresholds in ISO 2631 Part 1 (1997). Peak acceleration limits of ISO 10137 are converted to r.m.s. acceleration limits assuming a crest factor of 3.5, i.e., a typical crest factor of wind-induced motion of tall buildings.

Curves A - C: ISO 6897 - satisfactory magnitudes for criteria as specified in Table 1
Curve D: ISO 6897 - satisfactory magnitudes for a storm with a return period of one year

more than 2% of occupants comment adversely about the motion caused by the worst 10 minutes of a wind storm with a return period of five years or more. Curve C is said to take into account the alarm or fear caused by infrequently induced motions caused by wind storms. It is tentatively suggested that at magnitudes of 72% of Curve C, not more than 2% of occupants comment adversely about the motion caused by the worst 10 minutes of a storm with a return period of one year (Curve D in Figure 2).

International Standard 10137 provides limits for wind-induced motion said to correspond to magnitudes giving rise to minimum adverse comments. Limits for residential buildings are two-thirds of the limits for offices. Limits in ISO 10137 apply to motions with a one-year return period. There is no guidance for other return periods.

Assuming a crest factor of 3.5, limits in ISO 10137 for offices subjected to motions with a one-year return period (Figure 2) are consistent with one-year return limits in ISO 6897 for buildings used for “general purpose” (Curve D in Figure 2). Limits in ISO 10137 for residential buildings subjected to motions with a one-year return (Figure 2) are around four-fifths of limits in ISO 6897 for frequent events occurring in buildings used for “special purpose” (Curve B in Figure 2), assuming a crest factor of 3.5.

3. Discussion

There has been much debate about whether r.m.s. acceleration or peak acceleration is a more appropriate measure for evaluating wind-induced building motion with respect to occupant acceptability (e.g., Bashor *et al.*, 2005; Burton e*t al*., 2005; Tamura, *et al*., 2006). The peak acceleration has been proposed as an appropriate predictor of acceptability on the grounds that building occupants are highly influenced by the peak acceleration of a storm event (e.g., Melbourne and Cheung, 1988; McNamara *et al.*, 2002). Tamura *et al.* (2006) indicated that peak acceleration is used for limits in ISO 10137 and AIJ guidance (Architectural Institute of Japan) simply because it is easier to apply and more generally understood by building owners and designers than r.m.s. acceleration.

It has been suggested that the r.m.s. acceleration, as used in ISO 6897, predicts tolerance of long duration motion exposures more accurately than peak acceleration (e.g., Kwok *et al.,* 2005). According to Bashor *et al*. (2005), the r.m.s. average of wind-induced acceleration is more accurately predicted and measured, and offers an appropriate means of combining motions in different axes by root-sums-of-squares summation to predict overall response.

To apply peak acceleration limits in ISO 10137 to measurements of r.m.s. acceleration, the ratio of peak to r.m.s. acceleration must be known or estimated. However, the crest factor of wind-induced motion has been shown to vary widely and may deviate significantly from that of a Gaussian amplitude probability distribution (i.e., a crest factor approaching 4.0; Melbourne and Palmer, 1992). In ISO 6987 it is stated that the r.m.s. acceleration limits take into account the influence of short periods of higher acceleration, implying a typical crest factor is assumed. However, the range of crest factors to which the limits apply is not stated. The crest factor of wind-induced motion has been reported to influence the severity and types of effects on building occupants (Burton *et al.*, 2005). The range of effects may not be well predicted by methods in ISO 6897 which assume an unspecified crest factor.

Limits in ISO 6897 and ISO 10137 are said to correspond to low rates of adverse comment. Curve C in ISO 6897 (Figure 2), said to take into account alarm or fear caused by infrequent more extreme motions, was based on 2% objection rates reported by Hansen *et al.* (1973) from occupant surveys following major wind storms. Lamb *et al*. (2013) questioned the widely-held assumption that complaint incidence is an appropriate criteria for assessing building motion following surveys in tall office buildings that found workers almost never made formal complaints. Almost half of those surveyed complained about building motion to co-workers and family, but only about 5% complained to 'team leaders'. Denoon *et al.* (2000) and Burton (2006) also reported little or no correlation between acceptability of motion and formal complaint.

There is evidence from field surveys of workers in tall buildings that the frequency of occurrence and the duration of exposure is an important factor influencing complaint. Frequent sustained exposures have been shown to result in more complaints than infrequent short periods of high acceleration (Kwok *et al.,* 2009). International Standard 6897 offers no guidance on how to assess short periods of high acceleration motions reoccurring more than once a year or extreme events with return periods of more than five years. There is no advice in ISO 10137 on how to assess typical daily motions or motions with return periods of more than one year. Burton *et al.* (2007) showed that discomfort and the likelihood of complaint increases as exposure duration increases, and proposed different comfort criteria for motions of 'short' duration (around 10 minutes) and 'long' duration (exceeding 60 minutes). The influence of daily exposure duration is not accounted for in ISO 6897 or ISO 10137.

Burton *et al.*, 2005 conducted a laboratory study involving simulation of motions with similar overall r.m.s. accelerations but different crest factors. A crest factor of 3.3 was found to provoke greater incidence of motion sickness and increased task disruption than motions with crest factors of 1.7 and 4.8. Field studies in tall buildings have also found evidence that wind-induced motion may induce symptoms similar to motion sickness. An eight-month survey of office workers during 'low', 'medium' and 'high' wind conditions found a significant incidence of symptoms of sopite syndrome associated with building motion, including drowsiness, lethargy, depressed mood and feeling generally unwell (Lamb *et al.*, 2014). Those affected reported reduced work performance during periods of building motion and attempts to minimise symptoms by taking analgesic medication and longer breaks. Despite this, reported numbers of objections to motion were small and there were no instances of complaint to building owners. It was concluded that long duration frequent exposures to motion around the threshold of perception may provoke a range of symptoms that impact on performance. Such motion effects are not accounted for in guidance of ISO 10137 and ISO 6897.

4. Conclusions

Assuming a crest factor of 3.5, there is consistency between limits in ISO 10137 for offices subjected to motions with a one-year return period and one-year return limits in ISO 6897 for buildings used for general purposes. The mean threshold for perception of horizontal motion at a frequency of 1 Hz given in ISO 6897 is somewhat higher than the threshold in ISO 2631-1. It would seem appropriate to harmonise the guidance on thresholds of perception so that it is consistent between the standards.

Methods of evaluating motion in ISO 6897 and ISO 10137 do not allow for the effects of exposure duration. The influence of occasional short periods of higher acceleration is not well predicted by the r.m.s. averaging procedure in ISO 6897. The peak acceleration method in ISO 10137 does not take into account the effects of the total motion exposure. An evaluation procedure that accumulates motion over a day, but that also identifies the worst periods of motion, would appear preferable to the use of r.m.s. averaging or peak acceleration as recommended in the current standards.

The procedures in ISO 6897 and ISO 10137 do not adequately allow for differences in the effects of motion on alarm, discomfort and motion sickness. The methods of evaluating oscillatory motion given in ISO 6897 and ISO 10137 are not consistent with other current standards that define frequency weightings and band limiting filters. Differences in the effects of motion on alarm, discomfort and motion sickness on building occupants are such that a single frequency weighting may not be appropriate.

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