Proposed Occupant Comfort Criteria for Tall Buildings Subjected to Wind-Induced Vibration, Based on Peak and Standard Deviation Acceleration

Melissa D. Burton[1], Kenny C.S. Kwok[2], Peter A. Hitchcock[3]

[1]*Research Student, Dept. of Civil Engineering, The Hong Kong University of Science and Technology (HKUST), Clear Water Bay, Kowloon, Hong Kong, melissab@ust.hk*
[2]*Professor, Dept. of Civil Engineering, Director, WWTF, HKUST, kkwok@ust.hk*
[3]*Associate Director, CLP Wind and Wave Tunnel Facility (WWTF), HKUST, wtpete@ust.hk*

Introduction

Up until the 1970's tall building construction was in its infancy (Robertson, 1973). It was during that decade that the methodologies employed by structural engineers in the design of tall buildings showed a marked increase in complexity, and the design trends of massive unresponsive structures were retired. Individuals were given the opportunities to work and live in these new tall structures, but their expectations, which were translated up from low-rise buildings, were such that they believed the high-rise buildings should be immune to wind-induced vibration. Unfortunately, it would be prohibitively expensive to design and construct a building that would not move in a severe windstorm. Granting that minimal wind-induced vibration must be permitted, it is imperative to determine levels of motion that are acceptable to both building inhabitants and building owners.

Implementation of a proposed criterion for assuring occupant comfort requires the consideration of many design aspects. A representation of the probability of windstorm occurrence, the duration of the event, the wind speed, and the wind direction needs to be considered. A relationship between these characteristic wind parameters and the motion of tall buildings can then be defined. Occupant comfort criterion, in terms of the building motion, may then be determined.

Requirements of Wind-Induced Motion Serviceability Criteria

The principle aim behind designing for wind-induced vibration in occupied buildings is to provide an environment in which the inhabitants are comfortable and content, while ensuring that cognitive and manual task performance is not degraded. Two factors need to be considered in order to maintain an acceptable environment for occupants: the mitigation of fear for safety and the elimination of discomfort. Fear and alarm resulting from an experience with wind-induced vibration is associated with two things: the occurrence of an extreme wind event and/or the belief that a tall building should remain stationary. Discomfort results from sustained or frequently occurring motions and is associated with extreme or regularly occurring wind events.

This leads to the proposed criteria suggested herein, where the performance of a tall building in a windstorm is evaluated for accelerations exceeding a particular threshold likely to induce a fear for safety and in addition, for sustained and more frequently occurring accelerations inducing occupant discomfort.

Wind-Induced Motion Serviceability Criteria

In our modern world where buildings continue to seek new heights and optimization of the usage of structural material becomes more prevalent in the design community, it has become unrealistic to demand that no perceptible motions occur in severe windstorms. The new questions have become, 'what level of acceleration is tolerable' and 'how frequently can it occur'? In order to address both issues, previously published studies, motion simulator investigations carried out at HKUST, results from a large full-scale survey conducted in Hong Kong, and anecdotal advice from a number of prominent wind engineers worldwide has been taken into account.

Peak Acceleration Criteria

The criteria for infrequently induced low frequency vibration of structures caused by wind storms is the fear for safety and the alarm experienced by the occupants. In order to mitigate the complaint rate arising from occupant fear for safety the acceleration level experienced in tall buildings due to wind action needs to be considered in terms of a discrete maximum. For inhabitants of tall buildings experiencing wind-induced vibration who expect buildings not to move, or fear for the integrity of the structure, perception of vibration for even very short periods can result in complaint. Therefore, probabilistic perception thresholds can be used to predict complaint rate in full-scale.

Results from a series of motion simulator investigations carried out at HKUST, [1] and [2], were related to wind-induced motions experienced in full-scale in order to develop peak acceleration criteria. Information regarding experienced wind-induced motion was collected from approximately 5000 individuals in a field survey. The percentage of respondents claiming to have perceived vibration in their place of residence or place of employment is equal to 6.0 %. The percentage of respondents claiming to have issued a complaint following the perception of wind-induced motion was 0.15 % of all those interviewed, and 2.3 % of those who experienced motion in their home or office. It is assumed that the respondent sample is representative of the Hong Kong population.

During a windstorm, of all the people that will be expected to perceive wind-induced vibration in their place of residence or place of employment, a 2.3 % complaint rate can be expected to result. Therefore, a 2 %, 1 % and 'zero tolerance' complaint rate can be calculated from the ratio of the percent of people complaining to the percent of people perceiving the peak acceleration.

$$\frac{2.3\%}{100\%} \approx \frac{2\%}{88\%} \approx \frac{1\%}{44\%}$$

Utilizing the probabilistic perception thresholds derived in the motion simulator it is possible to specify the 2 %, 1 % and 'zero tolerance' in full-scale by equating them to the 88th, 44th, and 10th percentile perception curves, as shown in Figure 1. The 'zero tolerance' threshold is similar to the lower threshold of perception curve defined in the ISO6897-1984 [4] criteria for sensitive buildings, such as hospitals, where the level of acceleration should remain below the minimum threshold of motion perception. Maintaining the wind-induced vibration of a structure below the 'zero tolerance' threshold will uphold an approximately 0 % complaint rate resulting from perceived motion from building inhabitants.

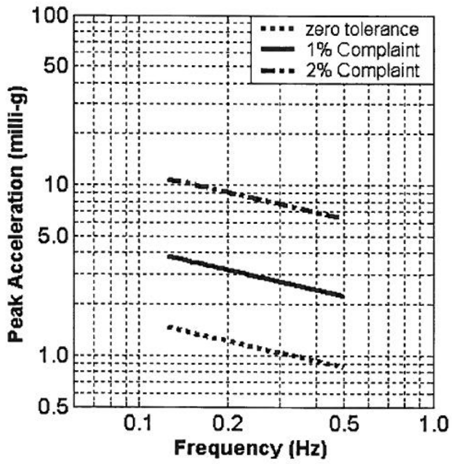

Figure 1: Probabilistic complaint rate, prior to mitigation of fear for safety.

The curves shown in Figure 1 are prior to any mitigation for fear for safety. Findings of Denoon [3] showed that fear and alarm diminished following education of structural integrity. These complaint rates cited in Figure 1 are defined for a one-year return period windstorm with maximum response over a 10-minute period. The one-year return period is specified because each of the respondents to the full-scale survey, who issued a complaint subsequent to their experience with tall-building motion, suggested the experience was related to a typical yearly typhoon windstorm. The period of 10-minutes has been chosen because it is believed that motions of duration less than 10-minutes associated with windstorms are not sufficiently severe to impress significantly the memory of building inhabitants [4]. This period of 10-minutes suitably takes into account typhoon windstorms, synoptic gales and thunderstorms. Therefore, from Figure 1 it can be seen that a building with a dominant frequency of oscillation occurring at 0.20 Hz experiencing peak accelerations on the order of 9 milli-g once a year can expect a 2 % complaint rate.

Previous research by Melbourne and Cheung [5] has highlighted a method of generalizing acceleration criteria for various return periods. Utilizing this method it is possible to define limiting peak accelerations for various return period windstorms, as shown in Figure 2 for the 2 % and 1 % complaint rate. It is not suitable to suggest a return period for the 'zero tolerance' threshold, as sensitive buildings where any perceptible motion is unacceptable should be designed such that the threshold of 'zero tolerance' acceleration resulting from the worst windstorm of any description is not exceeded. Also shown in Figure 2 are the limiting peak accelerations where movement becomes difficult [6]. In order to ensure occupant safety it is important to make certain that peak accelerations hindering movement are not surpassed.

One curve representing the acceptable magnitude of vibration in both office and residential tall buildings is believed to be sufficient, as the perception threshold of motion resulting in individual fear for safety would be equal in both environments (office and residence). A;though office buildings are likely to be evacuated during severe wind events, the consideration of less severe wind events on inhabitants fear for safety is imperative. During these less severe wind events, it is unlikely that office buildings will be vacated.

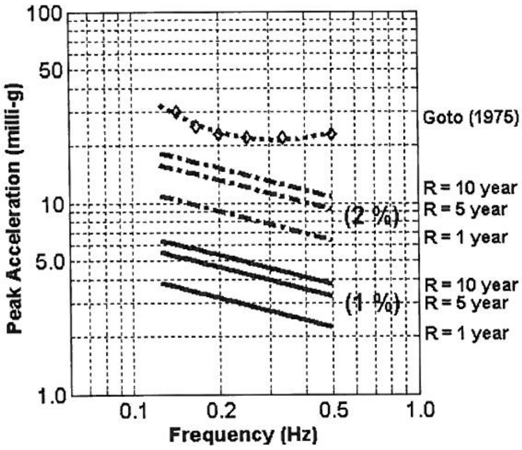

Figure 2: Complaint rate curves for various return period windstorms.

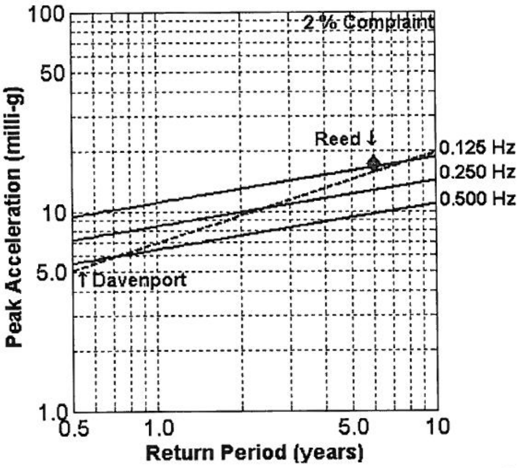

Figure 3: Peak acceleration vs. return period of a windstorm, expected complaint rate of 2 %.

Shown in Figure 3 are the suggested 2 % complaint rate curves for various frequencies of oscillation for experienced peak accelerations versus the return period of the windstorm. For comparison, and also shown in Figure 3, is the quantitative measure of inhabitant's objection to building motion, expressed in standard deviation acceleration and multiplied by a peak factor of 3.5 to convert to peak acceleration, recommended by Reed et al. [7]. The natural frequency of the building for which the criteria was defined was 0.14 Hz [7]. Summing up numerous experiences with tall-building motion, Davenport derived acceptability criteria based on a 2 % complaint rate [8]. The criteria suggested herein are shown to correlate well with previous full-scale studies [7] and recommended acceptance criteria [8].

A comparison of the proposed criteria based on the profiles for the 2 %, 1 % and 'zero tolerance' complaint rate to currently existing criteria is provided in Figure 4. The curves for the frequencies of oscillation investigated in the study expressed herein have been forward extrapolated form 0.5 to 1.0 Hz and backward extrapolated from 0.125 to 0.1 Hz. This extrapolation was carried out to determine the consistency of the current data set with recommended criteria. The extrapolated data are shown in Figure 4 in lighter weight font. The AIJ-2004 guidelines [9] are most relevant for comparison to the suggested criteria as they are specified for a one-year return period windstorm and are based on peak accelerations. The proposed recommendations are shown to be more conservative than the AIJ-2004 recommendations for office buildings, but less conservative than those for residences.

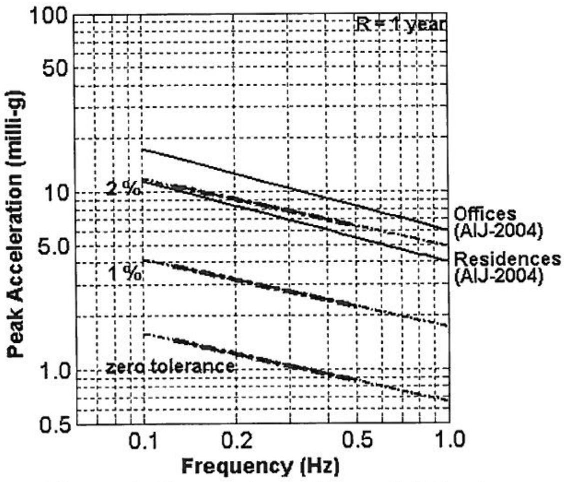

Figure 4: Comparison of complaint rate criteria versus AIJ-2004 recommendations.

It has been noted that in tall residential buildings in Japan, complaints from building inhabitants are said to be based on the frequency of occurrence of wind-induced vibration, and not on extreme motions inducing fear for safety [10]. Based on this statement, it is understandable that the AIJ-2004 recommendations are marginally less conservative than the proposed complaint rate criteria, as half of those respondents in the field survey issuing a complaint to the building owner, following their experience with wind-induced vibration did so due to fear for their safety. This same portion suggests that if they had been properly informed of the structural integrity of their home or office they would not have issued a complaint. The remaining portion of respondents issuing a complaint alleged that they would still have issued a complaint even if they had been educated on the safety of the structure or warned about wind-induced vibration, because the motion made them feel uncomfortable: some reporting nausea and dizziness. This percent reduction in complaint rate highlights the importance of educating the public about wind-induced vibration of tall-buildings.

Standard Deviation Acceleration Criteria

Assuming that occupants have been properly educated about the structural integrity of their place of residence or place of employment, it is more appropriate to discuss sustained duration wind events inducing nausea or task disruption. Generally, occupants of buildings subjected to wind-induced motion find sustained vibrations more objectionable than transient vibrations [11]. The level of adverse comment due to such discomfort has been noted to be dependent upon the return period of the windstorm, and unacceptable levels of vibration [12]. The shorter the interval between the occurrences, and the length of time over which a particular vibration intensity is maintained, the higher the level of adverse comment. Earlier research investigating nausea induced by vertical motions has noted that [11]:

> "Common observation suggests that the time character of stimulation and not its intensity is the crucial consideration. Large magnitudes of peak accelerations are not the cause of nausea."

This is a very important consideration to take account of as the majority of acceptability criteria currently in use specify limiting peak accelerations solely, they do not account for sustained duration motions. It is well known in other fields of vibration that individual comfort decreases with increased exposure time to a vibration stimulus [13]. This decrease in well-being associated with increased duration suggests that criteria limiting standard deviation accelerations may be equally as necessary as those limiting peak accelerations.

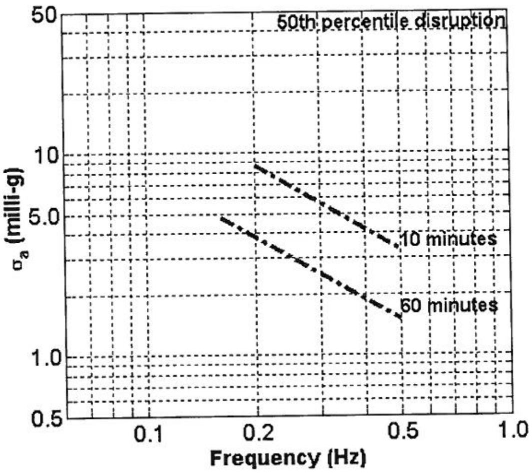

Figure 5: Acceptability of standard deviation accelerations based on motion duration.

Results from the motion simulator investigations carried out at HKUST suggest that longer duration vibration induces greater participant disruption [2]. This disruption was attributed to nauseogenic symptoms in the frequency range 0.160 – 0.315 Hz, and annoyance in the frequency range 0.315 – 0.500 Hz. A shorter duration stimulus, 10-minutes, also induced participant disruption but at higher levels of sustained acceleration [2]. Shown in Figure 5 are the curves representing the 50th percentile disruption for the two motion durations. Standard deviation accelerations exceeding these curves can be expected to induce disruption in more than 50 % of those individuals subjected to the vibration stimulus. The curve for the 10-minute stimulus is 2.2 times that of the one-hour stimulus. From the Figure 5 it is obvious that shorter duration wind events are less likely to induce disruption, and therefore higher levels of standard deviation acceleration may be acceptable. This observation highlights the necessity of defining acceptability curves based on specific wind events. Thunderstorm winds may be suitably defined by a 10-minute duration, whereas synoptic gales and typhoons or hurricanes are generally longer duration events and are therefore suitably characterized by a 60-minute duration. For simplicity, only two curves will be retained.

It is important to note that at the higher levels of standard deviation acceleration, the majority of the participants in the testing had difficulty maintaining balance. It is recommended that motion with a standard deviation acceleration surpassing the 50th percentile curve, for the 10-minute stimulus, be avoided for regular occurring vibrations in tall-building design. Therefore, the expression defining the limiting standard deviation acceleration for the 10-minute duration stimulus should be seen as being the upper limit of acceptability. This upper limit curve for acceptability, when converted to peak accelerations is well correlated with the 10-year return period peak acceleration suggestion provided above for the 2 % complaint rate.

From previous full-scale studies, it was shown that inhabitants with sickness symptoms more frequently indicated that the motion experienced in a windstorm was a nuisance [7]. These same inhabitants were shown to be significantly more likely to object to motion occurring more than once a year. Based on Reed's [7] results and questionnaire responses from the motion simulator investigations detailed herein it can be concluded that the standard deviation acceleration evaluated over a 10 and 60-minute duration should not exceed these recommended values more than once a year. However, it is noted that more full-scale research investigating the frequency of occurrence of sustained duration vibrations is of immediate importance.

Conclusions

Acceptability criteria limiting the peak acceleration occurring due to wind-induced vibration, based on probabilistic complaint rates, have been defined for various return periods. The proposed criteria ensures occupant safety and expresses the importance of educating tall building inhabitants about wind-induced vibrations in order to mitigate occupants fear for their safety, thereby reducing the complaint rate. A 'zero tolerance' threshold was proposed for buildings in which sensitive tasks will be carried out or where any complaints are seen as being of deleterious consequence.

It has been demonstrated that it is equally as important to consider the effects of the duration of the wind event on inhabitants, as it is to consider the effects resulting from a discrete maximum. The duration of the wind event must be considered in order to reduce the complaint rate arising from individuals suffering nauseogenic symptoms or disruption from a task. Fear for safety may be well represented by peak accelerations, but the induction of nausea and annoyance is related to sustained vibration, and is therefore better represented by the standard deviation acceleration.

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Acknowledgements

This research project was generously supported by funding provided by the Research Grants Council of Hong Kong (Project HKUST6239/00E), and the Central Allocation Project (CA04/05 EG01). The experiments were approved by the Human Subject Panel of the HKUST Committee on Research Practices. Thanks to the many volunteers who participated in these studies. I gratefully acknowledge the enthusiastic participation and contribution of members of the HKUST community and WWTF staff.