Wind and Structures, *Vol. 27, No. 5 (2018) 337-345*
DOI: https://doi.org/10.12989/was.2018.27.5.337

A simple procedure to evaluate the wind-induced acceleration in tall buildings: an application to Mexico

Adrian Pozos-Estrada*

Instituto de Ingeniería, Universidad Nacional Autónoma de México, Coyoacán C.P. 04510, Mexico City, Mexico

(Received April 16, 2017, Revised December 15, 2017, Accepted January 5, 2018)

Abstract. Tall buildings are subjected to wind loading that can cause excessive wind-induced vibration. This vibration can affect the activities of the inhabitants of a building and in some cases fear for safety. Many codes and standards propose the use of curves of perception of acceleration that can be used to verify the serviceability limit state; however, these curves of perception do not take into account the uncertainty in wind-climate, structural properties, perception of motion and maximum response. The main objective of this study is to develop an empirical expression that includes these uncertainties in order to be incorporated into a simple procedure to evaluate the wind-induced acceleration in tall buildings. The use of the proposed procedure is described with a numerical example of a tall building located in Mexico.

Keywords: wind-induced motion; tall buildings; serviceability limit state; mean peak acceleration; Mexico

1. Introduction

Aerodynamic forces acting on tall buildings can cause vibration in sway and torsional modes. Further, if the structure is light and with low structural damping, the wind-induced vibration can exceed predefined perception thresholds of acceleration. Excessive vibration in a building can cause the interruption of the activities of the inhabitants and in some cases fear for safety.

The study of wind-induced motion on the human perception has been carried out by several researchers (Reed 1971, Chen and Robertson 1972, Goto 1975, 1983, Irwin 1979, Melbourne and Cheung 1988, Isyumov 1993, Isyumov and Kilpatrick 1996, Tamura 2003, Tamura *et al*. 2006, Burton *et al*. 2006, Kim and Kanda 2008, Kwok *et al.* 2015). The general agreement among these studies is that the mean peak acceleration (expected value of the peak acceleration) and the standard deviation of acceleration are good measures of human perception of motion. Other observation from these studies is that the level of perception of acceleration is frequency dependent.

Serviceability criteria based on perception curves of peak acceleration or standard deviation of acceleration for different uses of a building have been proposed in the literature (Irwin 1979, Isyumov 1993, Tamura 2003, Tamura *et al.* 2006). Based on these studies, major codes and their commentaries propose perception curves of acceleration for design checking of wind-sensitive buildings. These perception curves, that include the uncertainty in the perception of motion, are employed to compare the wind-induced acceleration in a building calculated with analytical (Huang *et al*. 2011, Huang and Chen 2007) or experimental procedures, and in some cases based on field measurements results (Zhi *et al.* 2011). When analytical procedures are employed to calculate the wind-induced acceleration of a tall building with coupled response, the higher mode contributions to the response should be evaluated, since they could have an important contribution to the top acceleration (Huang and Chen 2007).

Besides the uncertainty in the perception of motion, other works have included the uncertainty in the dynamic and wind characteristics (Bashor *et al*. 2005; Pozos-Estrada *et al.* 2010) to evaluate the human perception of acceleration, in particular Pozos-Estrada *et al.* (2010) calibrated serviceability design factors for selected annual probability of perception levels. These factors are to be used with the estimated mean peak acceleration caused by along-wind or cross-wind excitations according to the commentaries of the 2005 edition of the National building code of Canada (NBCC) (NRCC 2005).

Recent studies on the wind-induced building motion of tall buildings have dealt with the occupant comfort (Walton *et al.* 2011, Michaels *et al*. 2013). Further, comprehensive surveys regarding the impact of the effects of wind-induced building motion on occupant well-being, work interruption and motion sickness have also been carried out (Lamb *et al.* 2014, Lamb *et al*. 2013, Denoon and Kwok 2011). In these studies, arguments are given to show the need of designing for occupant comfort and improve the current used acceleration guidelines.

Although the previous studies provided a step towards the understanding of the human perception of motion and the most important parameters to evaluate it, yet a simple procedure to evaluate the wind-induced acceleration in tall buildings is not available. The main objective of this work is to develop an expression to evaluate the wind-induced acceleration in tall buildings that can be used for design checking. The expression is incorporated into a simple procedure to evaluate the serviceability limit state in terms

*Corresponding author, Associate Researcher
E-mail: APozosE@iingen.unam.mx

http://www.techno-press.com/journals/was&subpage=7
ISSN: 1226-6116 (Print), 1598-6225 (Online)

of the peak acceleration. The use of the proposed procedure is described with a numerical example of a tall building located in Mexico.

2. Formulation of an acceleration factor to evaluate the wind-induced acceleration

Consider that a tall building can be modeled as a single degree of freedom (SDOF) system. If the system is subjected to turbulent wind forces in the along-wind direction, based on random vibration theory, the power spectral density function (PSDF) of the acceleration response to gusting wind can be expressed as

$$S_{\hat{\ddot{x}}}(f) = \frac{(F_0 V)^2}{m^2} S_v(f) |H(f)|^2 \quad (1)$$

where F_0 represents the transformation factor from mean wind speed (V) to force for the considered structure, m is the mass of the SDOF system, $S_v(f)$ is the PSDF of the turbulent wind and $|H(f)|^2$ is the square of the frequency response function. By integrating Eq. (1), the RMS of the acceleration response for a given mean wind speed, by considering only the resonant dominated response, can be written as

$$\sigma_{\hat{\ddot{x}}}(V) = \frac{F_0}{m} \cdot V \cdot \sqrt{\frac{\pi f_n S_v(f_n)}{\xi}} \quad (2)$$

where f_n and ξ are the natural frequency and the ratio of damping of the structure, respectively. Further, the mean peak acceleration ($\hat{\ddot{x}}$) is related to the standard deviation of acceleration for a given wind speed ($\sigma_{\hat{\ddot{x}}}(V)$) as follows

$$\hat{\ddot{x}} = g\sigma_{\hat{\ddot{x}}}(V) \quad (3)$$

where g is defined as $\sqrt{2\ln(f_n T)} + 0.577/\sqrt{2\ln(f_n T)}$, and T is the time of observation.

By substituting Eq. (2) into Eq. (3) yields

$$\hat{\ddot{x}} = g\frac{F_0}{m} \cdot V \cdot \sqrt{\frac{\pi f_n S_v(f_n)}{\xi}} \quad (4)$$

Eq. (4) can be used for design checking of the mean peak acceleration for a predefined mean wind speed, associated with a given return period (V_T). However, the direct use of random vibration is not common for design, and the adoption of an analytical expression for the evaluation of the peak acceleration is preferred. An expression to calculate the peak acceleration for a SDOF system subjected to gusting wind was given by Solari (1993), this expression was adopted in Eurocode EN 1-4 WIND ACTIONS (1994) and in the CFE Manual of Civil Works for Wind Design of Mexico (2008), and is written as

$$\hat{\ddot{x}} = g\frac{\rho BHC_D V^2(h)}{m} I_v(h) \sqrt{\frac{\pi S_v(h,V,f_n) R_H(f_n,V) R_B(f_n,V)}{\xi}} \quad (5)$$

where ρ is air density, B is the width of the structure, H is the height of the structure, C_D is a drag coefficient, $I_v(h)$ is the turbulence intensity evaluated at a reference height h (60% of the total height of the structure), $S_v(h,V,f_n)$ is a normalized PSDF of turbulent wind evaluated at height h, and $R_H(f_n,V)$ and $R_B(f_n,V)$ are aerodynamic admittance functions related to H and B, respectively. The expressions suggested in the CFE Manual of Civil Works for Wind Design of Mexico (2008) to calculate $S_v(h,V,f_n)$, $R_H(f_n,V)$ and $R_B(f_n,V)$ are summarized in Table 1.

By simple algebraic manipulation, Eq. (5) can be re-written as

$$\hat{\ddot{x}} = 4\pi f_n^2 I_v(h) g \sqrt{\frac{\pi S_v(h,V,f_n) R_H(f_n,V) R_B(f_n,V)}{\xi}} \bar{\Delta} \quad (6)$$

where the calculation of $\bar{\Delta}$ for a predefined mean wind speed depends on the analysis coefficient (C) including the air density and the exposed area, the drag coefficient (C_D) as well as an exposure factor (C_α) (i.e., $\bar{\Delta} = CC_\alpha C_D V^2$). These coefficients and factors are uncertain (Davenport 1981).

In order to calibrate the acceleration factor (F_{AI}), the procedure suggested by Pozos-Estrada *et al.* (2010) is adopted. This procedure considers that an existing perception curve of acceleration is adopted and used to compare a factored wind-induced acceleration, which can be calculated analytically. If the design requires that the wind-induced acceleration of the structure just meets a critical peak acceleration ($\hat{\ddot{x}}_c$) from a perception curve, the following expression should be satisfied

$$\hat{\ddot{x}}_c = F_{AI} \left(4\pi f_n^2 I_v(h) g \sqrt{\frac{\pi S_v(h,V,f_n) R_H(f_n,V) R_B(f_n,V)}{\xi}} \bar{\Delta} \right) \quad (7)$$

where each parameter inside the brackets takes its mean or nominal value.

The procedure adopted requires the use of a perception curve of acceleration, which can be adopted from major codes or standards. We note that the Architectural Institute of Japan (AIJ) (2004) proposes serviceability limits for different levels of the probability of perception denoted by H-10, H-30, H-50, H-70 and H-90. These limits are to be used to compare the mean peak acceleration based on 1-year return period value of 10 min wind speed. Fig. 1 presents a comparison of the AIJ (2004) scaled criteria to compare

Table 1 Functional forms of $S_v(h,V,f_n)$, $R_H(f_n,V)$ and $R_B(f_n,V)$ according to the CFE Civil Works for Wind Design of Mexico (2008)

Factor	Equations*
$S_v(h,V,f_n)$	$6.8\left(\frac{f_n L(h)}{V(h)}\right) \Big/ \left[1+10.2\left(\frac{f_n L(h)}{V(h)}\right)\right]^{\frac{5}{3}}$; $L(h)=300(h/200)^{0.67}$
$R_H(f_n,V)$	$\frac{1}{\eta_H}-\frac{1}{2\eta_H^2}\left(1-e^{-2\eta_H}\right)$; $\eta_H=\frac{4.6Hf_n}{V(h)}$
$R_B(f_n,V)$	$\frac{1}{\eta_B}-\frac{1}{2\eta_B^2}\left(1-e^{-2\eta_B}\right)$; $\eta_B=\frac{4.6Bf_n}{V(h)}$

* The expression for L(h) is for rough terrain

the mean peak acceleration based on 10-year return period value to be consistent with the Mexican practice. Details of the scaling procedure can be found in Pozos-Estrada (2009). Note that the CFE Manual of Civil Works for Wind Design of Mexico (2008) only proposes levels of mean peak acceleration for two frequencies of vibration, and that the Mexican standard for wind design considers a single level of mean peak acceleration independent of frequency. For this reason they were not used.

According to Burton (2006), the conditional probability of perception for a given level of $\hat{\ddot{x}}$ is written as

$$P_{fP|\hat{\ddot{x}}}\left(\hat{\ddot{x}}\right)=\Phi\left(\frac{\ln\left(\hat{\ddot{x}}/c_1\right)}{c_2}\right) \tag{8}$$

where c_1 and c_2 are model parameters that depend on the frequency and are shown in Fig. 2. c_1 and c_2 for f = 0.1 Hz from Burton (2006) were obtained by extrapolation.

By considering the uncertainty in the peak acceleration, structural dynamic properties, wind characteristics and human perception of motion through the total probability theorem, the unconditional probability of perception of wind-induced motion by the inhabitants of a building P_{fP} is given by

$$P_{fP}=\int \Phi\left(\frac{\ln\left(\tilde{\ddot{x}}H(\tilde{v})/c_1\right)}{c_2}\right) f_{\hat{\ddot{X}}}\left(\tilde{\ddot{x}}\right) f_{\tilde{V}}(\tilde{v}) f_{\tilde{f}_n}(\tilde{f}_n) f_{\tilde{\xi}}\left(\tilde{\xi}\right) f_{\chi}(\chi)\, d\chi\, d\tilde{\xi}\, d\tilde{f}_n\, d\tilde{v}\, d\tilde{\ddot{x}} \tag{9}$$

where

$$H(\tilde{v})=\frac{\hat{\ddot{x}}_c \tilde{f}_n^2\chi}{F_{Al}\, g\left(m_{f_n}\right)\sqrt{\tilde{\xi}}} \frac{\sqrt{S_v\left(h,m_V\tilde{V},m_{f_n}\tilde{f}_n\right)R_H\left(m_{f_n}\tilde{f}_n,m_V\tilde{V}\right)R_B\left(m_{f_n}\tilde{f}_n,m_V\tilde{V}\right)}}{\sqrt{S_v\left(h,V_T,m_{f_n}\right)R_H\left(m_{f_n},V_T\right)R_B\left(m_{f_n},V_T\right)}} \left(\frac{m_V\tilde{V}}{V_T}\right)^2 \tag{10}$$

where $\chi=CC_\alpha C_D/\left(CC_\alpha C_D\right)_N$, $\hat{\ddot{x}}=\tilde{\ddot{x}}H(\tilde{v})$, and $\tilde{f}_n=f_n/m_{f_n}$, $\tilde{\xi}=\xi/m_\xi$, $\tilde{V}=V/m_V$ are normalized random variables, m_{fn}, m_ξ and m_V are the mean values of the random variables f_n, ξ and V, respectively. In Eq. (9), the integration is over the domain of all the considered random variables, and $f_{\hat{\ddot{X}}}(\tilde{\ddot{x}})$, $f_{\tilde{V}}(\tilde{v})$, $f_{\tilde{f}_n}(\tilde{f}_n)$, $f_{\tilde{\xi}}(\tilde{\xi})$ and $f_\chi(\chi)$ represent the probability density functions (PDFs) of the normalized random variables considered. The type of PDF as well as the parameters that characterize them are summarized in Table 2.

2.1 Calibration procedure of the acceleration factor (F_{Al})

To calibrate F_{Al}, Eqs. (9) and (10) are used to solve the critical peak acceleration ($\hat{\ddot{x}}_c$, which is taken from the H-50 curve) such that the unconditional probability of perception of wind-induced motion by the inhabitants of a building P_{fP} equals a predefined probability of perception of motion P_{fP0}. This solution procedure can be carried out as follows:

1. Find the distribution parameters for all the PDFs.
2. Solve Eqs. (9) and (10) iteratively to find F_{Al} such that P_{fP} equals P_{fP0} for given values of m_{fn}, m_V, V_T and COV values of the random variables.
3. Repeat steps 1 and 2 for sets of values of m_{fn}, m_V, V_T and COV values of the random variables.

Note that the above procedure requires the calculation of the peak factor g, which depends on the time of observation (T). This time of observation is set equal to 600 s to be consistent with CFE Manual of Civil Works for Wind Design of Mexico (2008). Further, the return period (T_r) considered to evaluate V_T is equal to 10 years for serviceability design checking, according to the Mexican practice.

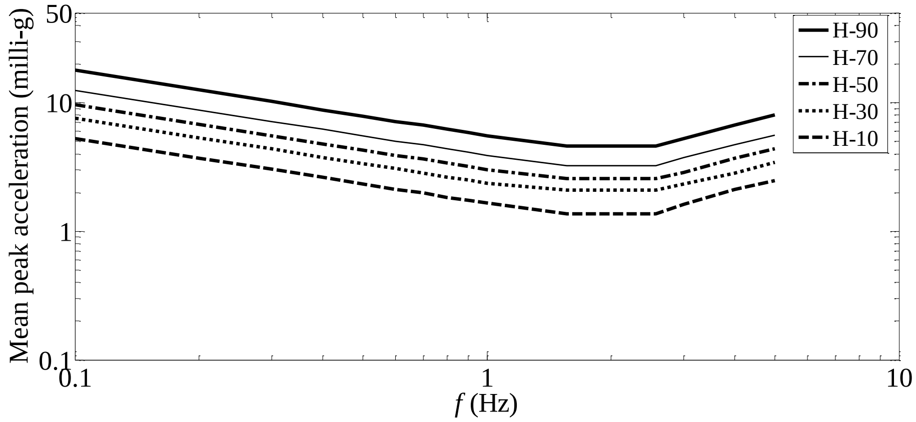


Fig. 1 Perception curves of acceleration proposed by AIJ (2004)

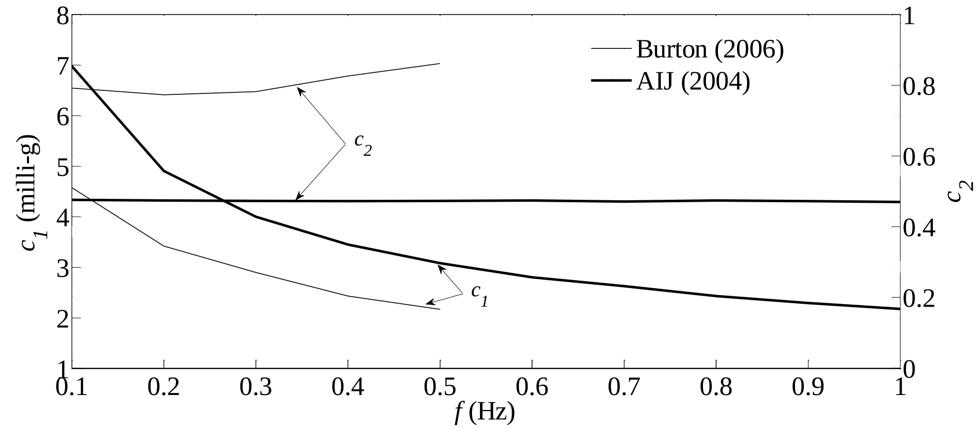
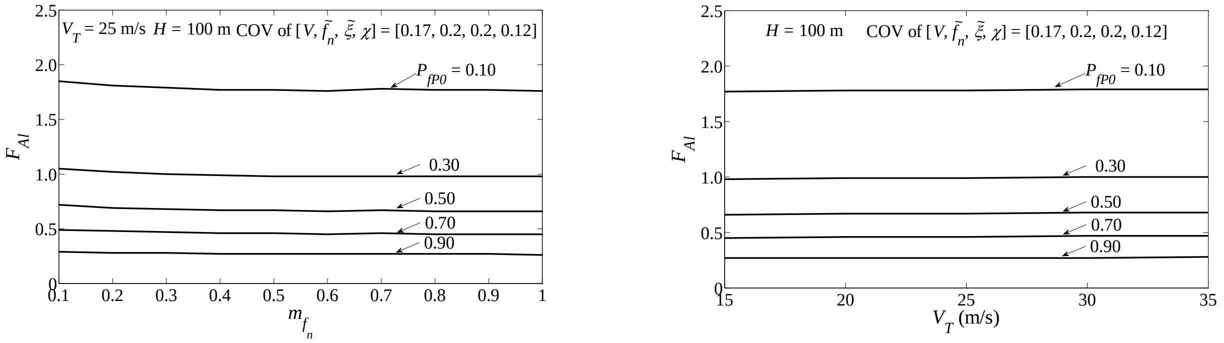


Fig. 2 Variation of c_1 and c_2 with frequency

Table 2 Summary of PDFs and parameters employed in Eq. (9)

Reference	Random variable	PDF	Mean	COV
Davenport (1964)	$\tilde{\ddot{X}}$	Gumbel	$\sqrt{2\ln\left(f_n T\right)}+\frac{0.577}{\sqrt{2\ln\left(f_n T\right)}}$	$\frac{\pi}{\sqrt{6}}\cdot\left(1\Big/\left(1+\frac{0.577}{\left(2\ln\left(f_n T\right)\right)}\right)\right)$
Simiu and Scanlan (1996)	$\tilde{V}$ *	Gumbel	1	δ_V***
Kim and Kanda (2008),	$\tilde{f}_n$	Lognormal	1	[0.15, 0.2, 0.3]
Haviland (1976)	$\tilde{\xi}$	Lognormal	1	[0.15, 0.2, 0.3]
**	χ	Lognormal	1	0.12

* The mean value of the non-normalized random variable V is given by $m_V = V_T/[1-\{0.577+\ln(-\ln(1-1/T_r))\}(\sqrt{6}\,\delta_V/\pi)]$; **It is assumed that χ is lognormally distributed with the parameters shown in the table, based on the works by Davenport (1981, 2000), Ellingwood *et al.* (1980), Ellingwood and Tekie (1999), Bartlett *et al.* (2003); *** Values of δv that reflect the wind climate at sites of interest for the Mexican practice can be found in López-Ibarra (2016), these values range from 0.08 to 0.6.



(a) (b)

Fig. 3 Sensitivity of F_{Al} to: (a) m_{fn} and (b) V_T

3. Calibration analysis

3.1 Assessment of the sensitivity of F_{Al} to the variation of m_{fn}, V_T and COV values of V, $\tilde{f}_n$, $\tilde{\xi}$ and χ

The procedure described in Section 2.1 was employed to evaluate the impact of m_{fn} and V_T on F_{Al}. Typical values of m_{fn} for tall buildings ranging from 0.1 to 1 Hz are employed, and values of V_T within 15 to 35 m/s and COV values of V within 0.1 to 0.3 are used since they represent the wind characteristics at many Mexican cities (CFE Manual of Civil Works for Wind Design of Mexico, 2008). Fig. 3 presents the variation of F_{Al} with respect to m_{fn} and V_T for selected COV values of $\tilde{f}_n$, $\tilde{\xi}$ and χ, and for P_{fP0} values equal to 0.1, 0.3, 0.5, 0.7 and 0.9.

It is observed from Fig. 3 that the calculated values of F_{Al} for a given P_{fP0} are not impacted by m_{fn} and V_T. This observation is advantageous, since a single value of F_{Al} (averaged over m_{fn} and V_T) can be associated with a predefined value of P_{fP0}. To further evaluate the sensitivity of F_{Al} to the COV values of V, $\tilde{f}_n$, $\tilde{\xi}$ and χ, Fig. 4 presents the variation of F_{Al} with respect to P_{fP0} and the COV values of V, $\tilde{f}_n$, $\tilde{\xi}$ and χ.

Since a single value of the COV of χ is indicated in Table 1, for completeness and to evaluate the sensitivity of F_{Al} to the COV of χ, a COV value of χ equal to 0.2 is assumed. It is observed in Figure 4 that F_{Al} is insensitive to the COV values of $\tilde{f}_n$, $\tilde{\xi}$ and χ; however, F_{Al} is affected by the COV values of V (δ_V), indicating that F_{Al} depends on the wind climate of the site of construction considered. In Fig. 4, an aspect ratio (H/B) equal to 5 was employed in the analyses. Further analyses were carried out to evaluate the impact of the aspect ratio and the height of the building on the calculation of F_{Al}, the analyses results indicated that F_{Al} is not affected by these parameters and for this reason, the results are not presented.

3.2 Development of an empirical equation of F_{Al}

It was shown in Section 3.1 that F_{Al} is a function of the probability of perception of motion (P_{fP0}) and δ_V. To develop a simple empirical equation of F_{Al} that includes the wind characteristics at many Mexican cities, values of the COV of V (δ_V) within 0.1 to 0.3 and P_{fP0} from 10 to 90 % are employed. By using the procedure described in Section 2.1, Fig. 5 presents the variation of F_{Al} with respect to P_{fP0} for δ_V values ranging from 0.1 to 0.3 with increments of 0.005.
The variation of F_{Al} shown in Fig. 5 suggests that one may consider, as an approximation, that F_{Al} is a linear function of the logarithmic of P_{fP0}. This can be expressed as

$$F_{Al} = \alpha \ln\left(P_{fP0}\right) + \beta \tag{11}$$

where α and β are model parameters that depend on the coefficient of variation of V (δ_V). By using the least square method, the error (ε) defined as

$$\varepsilon = \sum\left(F_{Al}\left(P_{fP0}\middle|\theta\right) - F_{Ali}\right)^2 \tag{12}$$

should be minimized. In Eq. (12) $F_{Al}(P_{fP0} \mid \theta)$ is the predicted value of F_{Al} by using Eq. (11), and F_{Ali} represents the F_{Al} values from the samples. By adopting Eq. (11), the values of α and β obtained from the regression analyses are presented in Fig. 6. The following simple empirical equations may be used to predict α and β

$$\alpha = \begin{cases} a_1 - a_2 \ln\left(\delta_V/0.15\right)/\ln\left(0.05/0.15\right) & \text{for } 0.10 \le \delta_V \le 0.15 \\ a_3 + a_4\delta_V - \left(a_5 - a_1\right)\ln\left(\delta_V/0.15\right)/\ln\left(7.5/0.15\right) & \text{for } 0.15 < \delta_V \le 0.30 \end{cases} \tag{13}$$

$$\beta = b_1 \ln\left(\delta_V\right) + b_2 \qquad \text{for } 0.1 \le \delta_V \le 0.3 \tag{14}$$

where the values of a_1, a_2, a_3, a_4, a_5, b_1 and b_2 are summarized in Table 3. Eqs. (13) and (14) are also shown in Fig. 6.

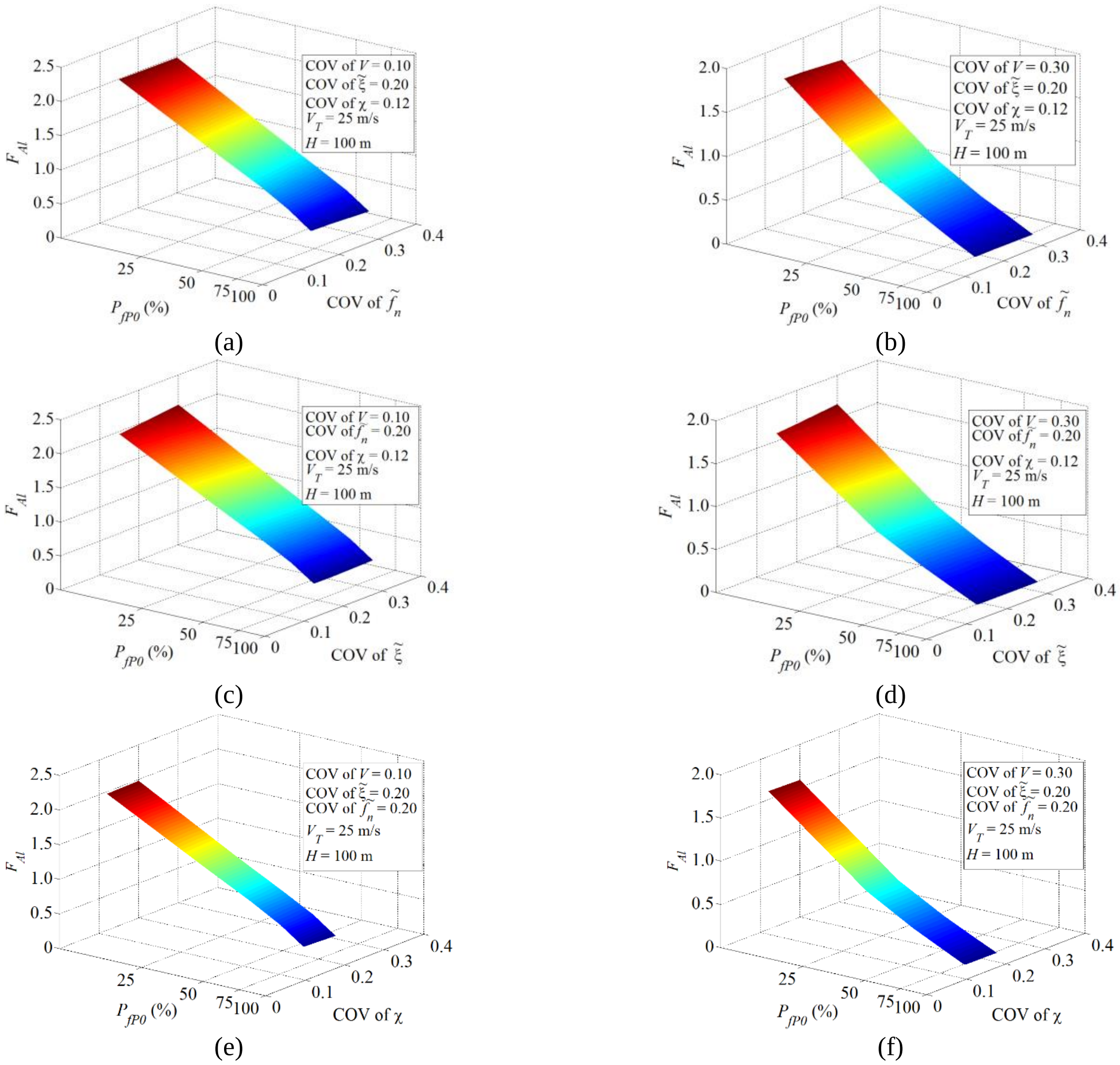


Fig. 4 Sensitivity of F_{Al} to the COV values of V, $\tilde{f}_n$, $\tilde{\xi}$ and χ

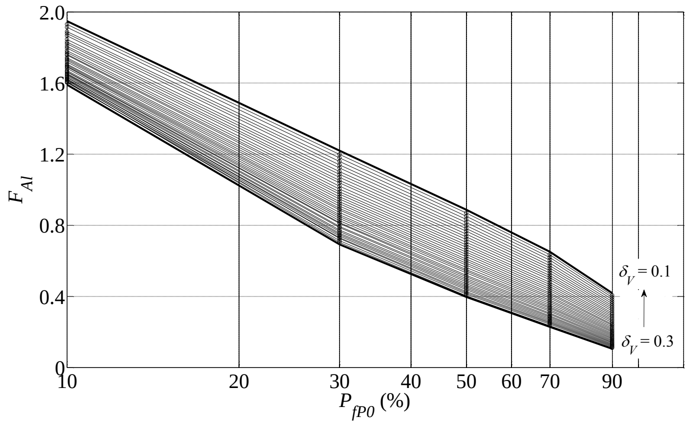
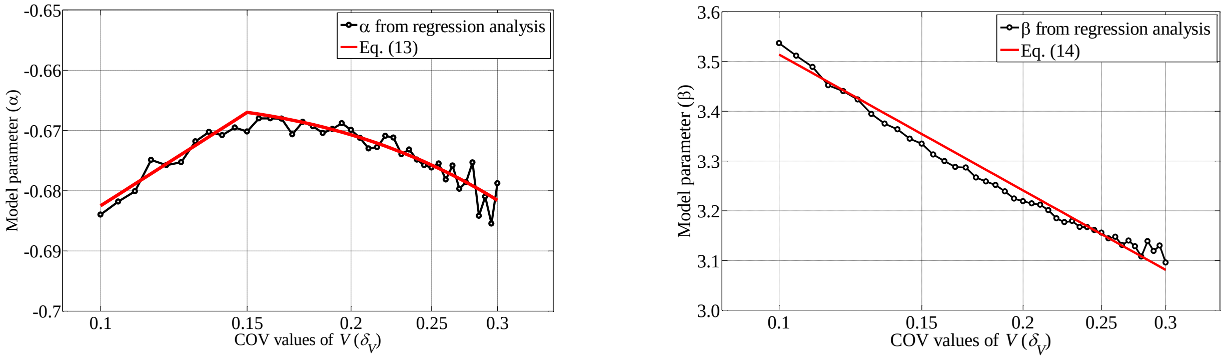


Fig. 5 Variation of F_{Al} with respect to P_{fP0} for different δ_V values. The arrow indicates the trend of the curves as δ_V decreases from 0.3 to 0.1



(a) (b)

Fig. 6 Model parameters for F_{Al} given by Eq. (11): (a) α and (b) β

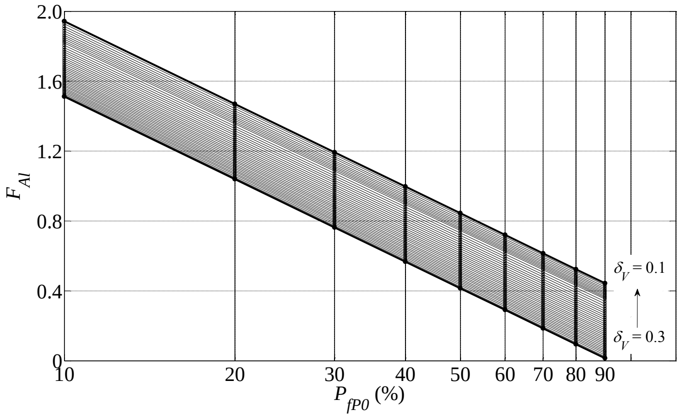


Fig. 7 Values of F_{Al} predicted with Eq. (11). The arrow indicates the trend of the curves as δ_V decreases from 0.3 to 0.1

Table 3 Parameters used in Eqs. (13) and (14)

Parameter Eq. (13)	Value	Parameter Eq. (14)	Value
a_1	-0.667	b_1	-0.394
a_2	0.042	b_2	2.607
a_3	-0.638	-	-
a_4	-0.191	-	-
a_5	-0.746	-	-

The predicted values of F_{Al} by using Eqs. (11), (13) and (14) are illustrated in Fig. 7. A comparison of the F_{Al} values shown in Fig. 5 and those presented in Fig. 7 indicates that Eq. (11) provides good estimates of F_{Al}.

Further analyses were carried out to evaluate whether Eq. (11) can be considered general. This was carried out by repeating the analyses described in Section 2.1, but this time the H-10, H-30, H-70 and H-90 perception curves from the AIJ (2004) were considered. The analyses results indicated that the acceleration factors vary approximately linearly with the logarithmic of the total probability of perception, according to Eq. (11), regardless of the perception curve of acceleration adopted. Since Figs. 5 and 7 show this tendency of F_{Al} with respect to P_{fP0}, no other figures are included.

In the following section, an illustrative numerical example of the use of the acceleration factor (F_{Al}) is presented.

3.3 Numerical example

Consider that there is a need for a tall building in Mexico with the dimensions and dynamic properties summarized in Table 4. Further, the design requires that P_{fP0} values equal to 10, 50 and 80% for wind speed conditions such that δ_V equals 0.1, 0.2 and 0.3 be evaluated with the use of Eq. (11). The aerodynamic information as well as the parameters that are needed to calculate the mean peak acceleration ($\hat{\ddot{x}}$) are also given in Table 4.

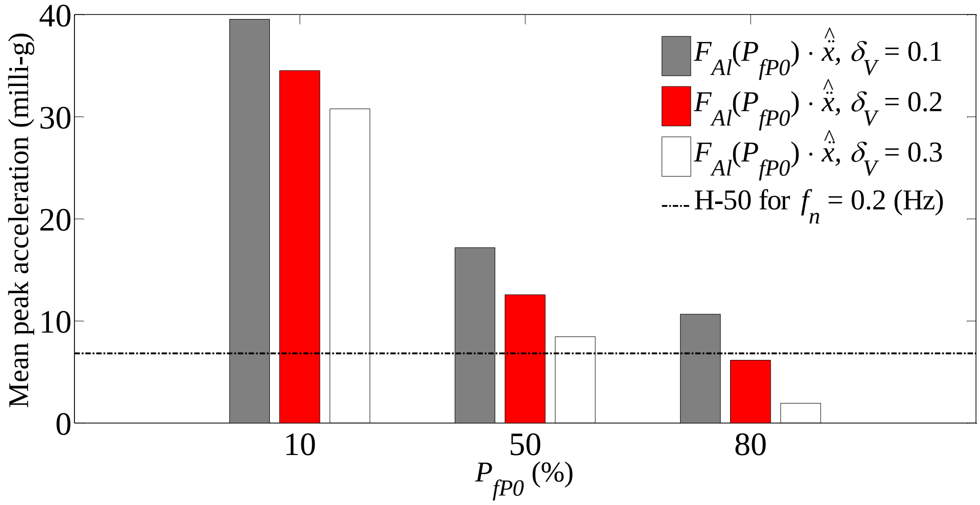


Fig. 8 Comparison of factored accelerations and acceleration from the H-50 curve for f = 0.2 (Hz)

Table 4 Information employed for the numerical example

Structural design	B =30 m; H =183 m; f_n =0.2 Hz; m =11x10^6 kg; ξ =1.5%
Aerodynamic information	ρ =1.23 kg/m^3; C_D =1.2; $V(h)$ =20 m/s; $I_v(h)$ =21.5%; Rough terrain
Parameters to calculate $\hat{\hat{x}}$	g =3.28; $S_v(h,V,f_n)$ =0.0822; $R_H(f_n,V)$ = 0.112; $R_B(f_n,V)$ =0.479

By using Eq. (5), the calculated mean peak acceleration ($\hat{\hat{x}}$) is 20.35 (milli-g). According to the procedure proposed, the factored acceleration ($F_{Al} \times \hat{\hat{x}}$) has to be less than or equal to $\hat{\hat{x}}_c$ (read from the H-50 curve for f = 0.2 (Hz)). The evaluation of this criterion for the P_{fP0} and δ_V values considered is illustrated in Fig. 8.

It is observed from Fig. 8 that the criterion is acceptable for P_{fP0} equal to 80% and δ_V values equal to 0.2 and 0.3, respectively. For the rest of the cases considered, the design is not acceptable and alternatives to reduce the wind-induced acceleration are necessary.

4. Conclusions

A simple procedure to evaluate the wind-induced acceleration for tall buildings in Mexico was proposed. The procedure includes the use of an expression to calculate acceleration factors (F_{Al}) that depend on the wind characteristics at the site of construction (i.e., δ_V) and the probability of perception of motion (P_{fP0}). More specifically, the following conclusions are drawn:

- The acceleration factors (F_{Al}) for a given P_{fP0} are not impacted by the mean value of the natural frequency (m_{fn}), the return period value of mean wind speed (V_T), height of the building (H) and aspect ratio (H/B). Further, the parametric analysis indicated that F_{Al} is insensitive to the COV values of $\tilde{f}_n$, $\tilde{\xi}$ and χ.
- When the P_{fP0} and F_{Al} values are plotted in semi logarithmic paper (logarithmic in the P_{fP0}-axis), they follow approximately a straight line. This observation was used to propose a simple empirical equation to calculate F_{Al} as a function of P_{fP0}. Parameters to characterize the empirical equation were proposed for δ_V values from 0.1 to 0.3, which are typical at many Mexican cities.

Acknowledgments

The research described in this paper was financially supported by the Instituto de Ingeniería de la Universidad Nacional Autónoma de México through project “Propuesta de un Estado Límite de Servicio para Edificios Sensibles al Viento en México”. The financial support of the National Council of Science and Technology (CONACYT) of Mexico is gratefully acknowledged as well. We thank Isaac Lima-Castillo for many fruitful discussions, constructive comments and suggestions. We are very thankful to Roberto Gómez and J. Alberto Escobar for providing insightful comments and suggestions.

References

Architectural Institute of Japan Recommendations. (2004), “Guidelines for the evaluation of habitability to building vibration”, *AIJES-V001-2004*, Tokyo, Japan.

Bartlett, F.M., Hong, H.P. and Zhou, W. (2003), “Load factor calibration for the proposed 2005 edition of the National

Building Code of Canada: statistics of loads and load effects", *Can. J. Civil Eng.*, **30**(2), 429-439.
Bashor, R., Kijewski-Correa, T. and Kareem, A. (2005), "On the wind-induced response of tall buildings: The effect of uncertainties in dynamic properties and human comfort thresholds", *Proceedings of the Americas Conference on Wind Engineering*, Baton Rouge, LA, May.
Burton, M.D. (2006), "Effects of low frequency wind-induced building motion on occupant comfort", Ph.D. Dissertation, Civil Engineering Department, The Hong Kong University of Science and Technology, Hong Kong.
Burton, M.D., Kwok, K.C.S., Hitchcock, P.A. and Denoon, R.O. (2006), "Frequency dependence of human response to wind-induced building motion." *J. Struct. Eng. - ASCE*, **132**(2), 296-303.
CFE. (2008), *Manual de diseño de obras civiles: Diseño por viento*, Mexico City, Mexico.
Chen, P.W. and Robertson, L.E. (1972), "Human perception thresholds of horizontal motion" *J. Struct. Div. - ASCE*, **98**(8), 1681-1695.
Commision of the European Communities. (1994), *Basis for design and actions on structures, Eurocode No. 1*, Brussels, Belgium.
Davenport, A.G. (1981), "Some attributes of the wind load requirements of the National Building Code of Canada", *Proceedings of the 3rd Canadian Workshop on Wind Engineering*, Vancouver, April; Toronto, Ontario, May,
Davenport, A.G. (2000), "A comparison of seismic and windstorm hazards", *Proceedings of the 6th Environmental Specialty Conference of the Canadian Society for Civil Engineering*, London, Ontario, June.
Denoon, R.O. and Kwok, K.C.S. (2011), "Implications of full-scale building motion experience for serviceability design", *Wind Struct.*, **14**(6), 537-557.
Ellingwood, B.R. and Tekie, P.B. (1999), "Wind load statistics for probability-based structural design", *J. Struct. Eng.*, **125**(4), 453-464.
Ellingwood, B.R., Galambos, T.V., MacGregor, J.G. and Cornell, C.A. (1980), *Development of a probability based load criterion for American National Standard A58*, NBS Special Publication 577, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C.
Goto, T. (1975), "Research on vibration criteria from the viewpoint of people living in high-rise buildings. (Part 1) Various responses of humans to motion", *Transactions of the Architectural Institute of Japan*, **237**(11), 109-118.
Goto, T. (1983), "Studies on wind-induced motion of tall buildings based on occupants' reaction", *J. Wind Eng. Ind. Aerod.*, **13**, 241-252.
Huang, G. and Chen, X. (2007), "Wind load effects and equivalent static wind loads of tall buildings based on synchronous pressure measurements", *Eng. Struct.*, **29**(10), 2641-2653.
Huang, M.F., Chang, C.M. and Kwok, K.C.S. (2011), "Occupant comfort evaluation and wind-induced serviceability design optimization of tall buildings", *Wind Struct.*, **14**(6), 559-582.
Irwin, A.W. (1979), "Human response to dynamic motion of structures", *The Structural Engineer*, **56**(9), 237-244.
Isyumov, N. (1993), "Criteria for acceptable wind-induced motion of tall buildings", *Proceedings of the International Conference on Tall Buildings*, CTBUH, Rio de Janeiro, Brazil.
Isyumov, N. and Kilpatrick, J. (1996), "Full-scale experience with wind-induced motions of tall buildings", *Proceedings of the 67th regional conference council on Tall Buildings and Urban Habitat*, Chicago, IL.
Kim, Y.C. and Kanda, J. (2008), "Wind response characteristics for habitability of tall buildings in Japan", *Struct. Des. Tall Spec. Build.*, **17**, 683-718.
Kwok, K.C.C., Burton, M.D. and Abdelrazaq, A.K. (2015), "Wind-Induced Motion of Tall Buildings: Designing for Habitability", *ASCE*, USA.
Lamb, S., Kwok, K.C.S. and Walton, D. (2013), "Occupant comfort in wind-excited tall buildings: Motion sickness, compensatory behaviours and complaint", *J. Wind Eng. Ind. Aerod.*, **119**, 1-12.
Lamb, S., Kwok, K.C.S. and Walton, D. (2014), "A longitudinal field study of the effects of wind-induced building motion on occupant well-being and work performance", *J. Wind Eng. Ind. Aerod.*, **133**, 39-51.
López-Ibarra, A. (2016), "Acceleration in tall buildings due to wind", Master thesis dissertation, Universidad Nacional Autónoma de México, Mexico.
Melbourne, W.H. and Cheung, J.C.K. (1988), "Designing for serviceable accelerations in tall buildings", *Proceedings of the 4th International Conference on Tall Buildings*, Hong Kong and Shanghai.
Michaels, M.N., Kwok, K.C.S. and Tung, Y.K. (2013), "Exploratory analyses and modelling of parameters influencing occupant behaviour due to low-frequency random building motion", *J. Wind Eng. Ind. Aerod.*, **115**, 82-92.
NBCC. (2005), *National Building Code of Canada*, Part 4 Structural Design, Commentary 1, Wind Load Effects.
Pozos-Estrada, A. (2009), "Reliability of wind-sensitive buildings: a serviceability design consideration", Ph.D. Dissertation, The University of Western Ontario, London, Ontario, Canada.
Pozos-Estrada, A., Hong, H.P. and Galsworthy, J.K. (2010), "Serviceability design factors for wind-sensitive structures", *Can. J. Civil Eng.*, **37**(5), 728-738.
Reed, J.W. (1971), *Wind induced motion and human discomfort in tall buildings*, Research Report No. 71 – 42, M. I. T., Cambridge, Mass., USA.
Solari, G. (1993), "Gust Buffeting II: dynamic alongwind response", *J. Struct. Eng. – ASCE*, **119**(2), 383-398.
Tamura, Y. (2003), "Wind resistant design of tall buildings in Japan", *Proceedings of the 11th International Conference on Wind Engineering*, **1**, Lubbock, Texas, USA,
Tamura, Y., Kawana, S., Nakamura, O., Kanda, J. and Nakata, S. (2006), "Evaluation perception of wind-induced vibration in buildings", *Proceedings of the Institution of Civil Engineers, Structures & Buildings* 159, October.
Walton, D., Lamb, S. and Kwok, K.C.S. (2011), "A review of two theories of motion sickness and their implications for tall building motion sway", *Wind Struct.*, **14**(6), 499-515.
Zhi, L., Li, Q.S., Wu, J.R. and Li, N.I. (2011), "Field monitoring of wind effects on a super-tall building during typhoons", *Wind Struct.*, **14**(3), 253-283.

AD