

The effects of freestream turbulence on wind-induced responses of tall buildings

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ABSTRACT: The turbulence characteristics of natural winds are usually described by turbulence intensity, turbulence scale, and wind velocity spectra. Turbulence intensity reflects fluctuations of wind velocity, which is affected by the degree of surface roughness of the earth. One of the most widely used scales is the integral length scale which is a representation of the average size of the most energetic turbulent eddies. In this paper, three tall buildings with different heights and typical height/width ratios are chosen to investigate the effects of turbulence integral length scale on along-wind responses of the tall buildings. Discussions on the influences of turbulence intensity to the along-wind structural responses are also presented. The results of this study indicate that as turbulence integral length scale increases, the along-wind responses of the tall buildings decrease while the along-wind responses increase obviously with the growth of turbulence intensity.

KEYWORDS: turbulence characteristics; turbulence integral length scale; turbulence intensity; tall building; along-wind response; wind spectra

1. INTRODUCTION

Wind flow in the atmospheric boundary layer of the earth is highly turbulent. As a result, wind loads acting on buildings and structures are significantly influenced by turbulence characteristics. Turbulence integral length scale and turbulence intensity are two main parameters to describe the characteristics of natural wind. Turbulence integral length scale is the measure of average size of the vortices. For wind flows, there are three turbulence integral length scales in three directions (longitudinal, lateral and vertical directions), namely, L_u^x , L_u^y , L_u^z , and they are often expressed as $L_u^y \approx 0.3-0.4L_u^x$, $L_u^z \approx 0.5-0.6L_u^x$ (Counihan 1975). Turbulence intensity is the ratio of the standard deviation of fluctuating component to the mean value of wind velocity. It is related to the surface roughness of the ground. Turbulence integral length scale and turbulence intensity can be defined as follows.

$$L_u^x = \frac{1}{\sigma_u^2} \int_0^\infty R_{u_1 u_2}(x) dx \quad (1)$$

$$I_u = \sigma_u / \bar{U} \quad (2)$$

$R_{u_1 u_2}(x)$ is the cross-correlation function of fluctuating wind speed component u at two points. σ_u is the standard deviation of wind speed, and $\bar{U}$ is mean wind speed. In boundary layer wind tunnel testing, how to control the value of turbulence integral length scale is a difficult problem. Varshney and Poddar (2011) conducted an investigation on controlling turbulence integral length scale values in a wind tunnel and showed that the integral length scale can be controlled using different combinations of passive devices. However, it is difficult or impossible to generate wind

flows with sufficiently large values of turbulence integral length scale in wind tunnels, even active devices are adopted.

During the past several decades, many researchers have conducted wind tunnel studies on the effects of turbulence on bluff bodies. Lee (1975a) reported that addition of turbulence to the flow causes an increase of base pressure and reduction of the drag of a two-dimensional square cylinder. His experiments showed the strength of the vortex shedding reduces as the growth of turbulence intensity. Lee (1975b) also investigated the effects of turbulence integral length scale on mean forces of square prisms and indicated that the mean drag is sensitive to the variation of turbulence scale when it is around the body size. In addition, at high values of turbulence integral length scale the drag tends to a constant value greater than that at low values. Tieleman and Akins (1990) analyzed the effects of incident turbulence on pressure distributions on rectangular prisms. Their results showed that the pressure coefficients on the side and rear faces of the prisms vary primarily with the energy associated with the small scale turbulence in the incident flow. Laneville (1990) investigated the effect of turbulence scale ratio on pressure coefficients of two dimensional square cylinders, finding that when turbulence scale ratio is larger than three, the turbulence scale effect on mean drag is evident and the magnitude of this effect is about 12%. Nakamura (1993) pointed out that turbulence intensity and turbulence integral length scale have significant effects on pressure coefficients on bluff bodies.

Besides the above studies carried out by wind tunnel experiments, other methods such as full-scale measurements, CFD and structural dynamic analysis were also applied to investigate the wind effect on tall building. It has been recognized that the most reliable evaluations of wind effects are obtained from measurements of prototype buildings. Li et al. (1998, 2004a, 2004b, 2005, 2006), Campbell et al. (2005), among others, have carried out full-scale measurements of wind effects on tall buildings. These investigations provided important validation of design procedures as well as examined structural behavior of tall buildings under wind actions. On the other hand, CFD method becomes more and more attractive to study wind effects on tall buildings (Swaddiwudhipong and Khan 2002; Huang et al. 2007; Tominaga et al. 2008; Braun and Awruch 2009; Huang et al. 2011; Hang and Li 2012) because of low cost compared with wind tunnel testing. In fact, CFD and structural dynamic analysis can overcome the limitations of generating wind flows with sufficiently large values of turbulence integral length scale. Therefore, structural dynamic analysis method is adopted in this paper to investigate the effects of freestream turbulence on wind-induced responses of tall buildings.

2. RELEVANT FACTORS AFFECTED BY TURBULENCE CHARACTERISTICS

Nakamura (1993) indicated that turbulence intensity and integral scale have remarkable effect on pressure coefficients on bluff bodies and concluded that absolute value of base pressure increases with integral scale for 3D square rod, as shown in Fig.1. The effect of turbulence intensity on drag coefficients on bluff bodies has been investigated in the past. The relation of turbulence intensity and drag coefficients (Simiu and Scanlan, 1996), as shown in Fig. 2, is employed in this study. The relationship between base pressure coefficient and drag coefficient is expressed in Eq. (3) (Petty 1979; Laneville 1990).

$$C_D = 0.9 - 0.82C_p \quad (3)$$

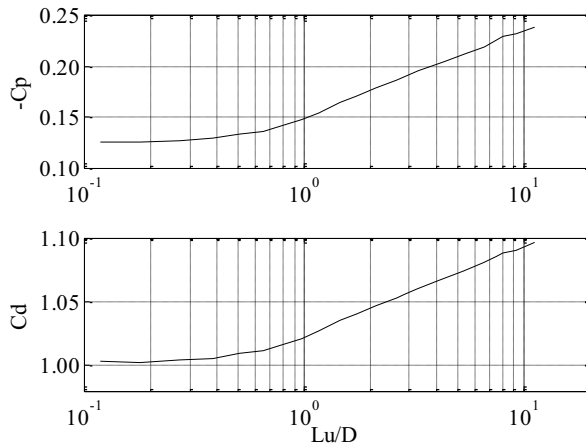


Figure 1. Pressure coefficient vs. turbulence integral scale

It can be seen from Fig. 1 that drag coefficient increases with turbulence integral scale significantly. The growth of drag coefficient will result in larger along-wind responses of

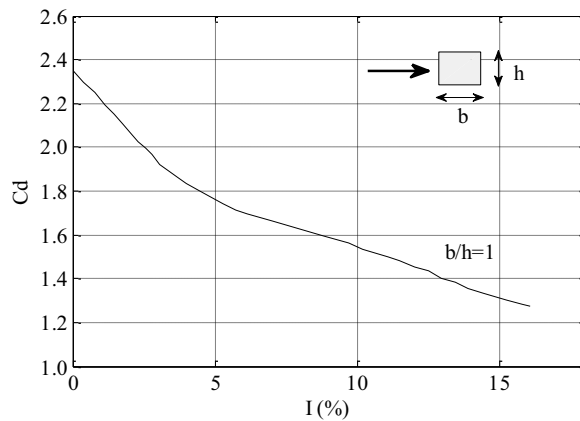


Figure 2. Drag coefficient vs. turbulence intensity (Simiu and Scanlan 1996)

tall buildings. Conversely, the increased turbulence intensity reduces the drag coefficient greatly, which will ultimately lead to the reduction of along-wind response of tall buildings.

In the computation of responses of long-span structures and high rise structures, spatial correlation of wind pressure cannot be ignored. For long-span structures, horizontal spatial correlation should be considered, and vertical spatial correlation can be neglected. On the contrary, for high rise structures, vertical spatial correlation must be taken into account, but horizontal spatial correlation may be ignored. Correlation coefficient ρ is the measurement of spatial correlation. Several empirical formulas for describing the correlation have been proposed. For example, Davenport (1967) presented a correlation function which is related to frequency n and distance between two points as follows:

$$\rho_{zz'}(z, z', n) = \exp\left(-C_z \frac{n|z - z'|}{\bar{v}_z}\right)$$

$$\rho_{xx'}(x, x', n) = \exp\left(-C_x \frac{n|x - x'|}{\bar{v}_x}\right)$$
(4)

where $C_z=7$, $C_x=8$. These two formulas have considered several factors, such as frequency n , distances of two points and average wind speeds, but without turbulence integral scale. The following formulas include the effect of turbulence integral scale on correlation coefficient (Zhang, 2006).

$$\begin{aligned}\rho_z(z, z') &= \exp\left(-\frac{|z - z'|}{L_z}\right) \\ \rho_x(x, x') &= \exp\left(-\frac{|x - x'|}{L_x}\right)\end{aligned}\quad (5)$$

where L_z and L_x are vertical and horizontal turbulence integral scale, respectively. The relationship between correlation coefficient of two points with distance of 50m and turbulence integral scale is shown in Figure 3.

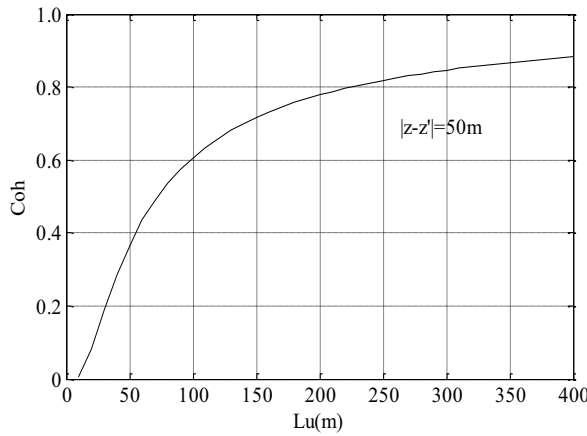


Figure 3. Correlation coefficient vs. turbulence integral scale

From Fig. 3, it can be seen that the correlation coefficient increases as turbulence integral scale increases. It is well known that the strengthening of correlation will lead to the increase of along-wind responses of tall buildings. In other words, an increase of turbulence integral scale may increase the along-wind responses.

Wind velocity spectrum varied with turbulence integral scale and turbulence intensity has significant effects on the wind-induced responses of tall buildings. There are many formulas that have been proposed to describe wind velocity spectrum. One of the widely-used wind velocity spectra was proposed by Von Karman, which is expressed as:

$$\frac{nS_u(n)}{\delta_u^2} = \frac{4 \frac{nL_u}{u}}{\left[1 + 70.8 \left(\frac{nL_u}{u}\right)^2\right]^{5/6}} \quad (6)$$

where n is the frequency; $S_u(n)$ is the power spectrum of wind velocity; δ_u is the standard deviation of fluctuating velocity; u is mean wind speed. L_u is the turbulence integral length scale. The variation of the wind velocity spectrum with turbulence integral length scale is presented in Fig. 4. In general, the fundamental frequencies of tall buildings arrange from 0.1 Hz to 2.0 Hz. Fig. 4 shows that the curves of the spectra shift to the left as turbulence integral scale increases, which means that the power of wind spectrum around fundamental frequencies reduces with the growth of integral scale. Thus, from this perspective, the increase of integral scale will result in the reduction of the along-wind responses of tall buildings.

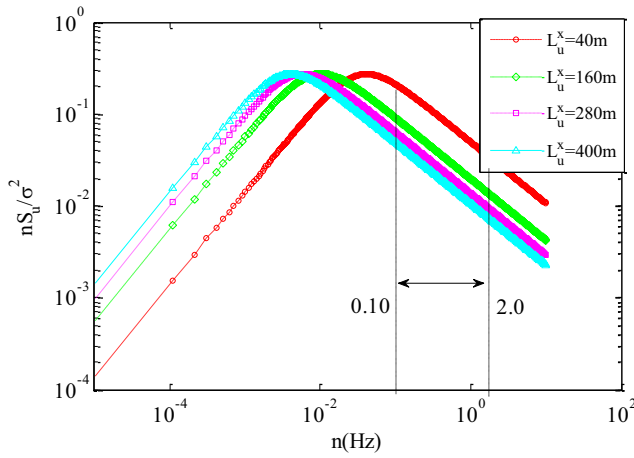


Figure 4. Von Karman spectra with different turbulence integral scales

Another form of Von Karman spectrum involved turbulence intensity is expressed as follow:

$$\frac{nS(z, n)}{v_*^2} = 0.475 \beta(z) \frac{x}{(1+x^2)^{5/6}} \quad (7)$$

$$x = \frac{nL_x}{v}, L_x = \frac{vS(z, 0)}{0.475\sigma_{vf}}, \sigma_{vf} = \beta(z)v_*^2, \beta(z) = \frac{(Iv)^2}{v_*^2}, v_* = K \overline{v_{10}^2}$$

where L_x is turbulence integral length scale, I is turbulence intensity. In order to consider the effect of turbulence intensity on wind velocity spectrum, L_x and v_{10} are assumed as constants. The wind spectra with different turbulence intensities are plotted in Fig. 5. As turbulence intensity increases, the wind velocity spectra shift up. This illustrates the increasing power of wind spectra. Therefore, the addition of turbulence intensity will result in the growth of the along-wind responses of tall buildings.

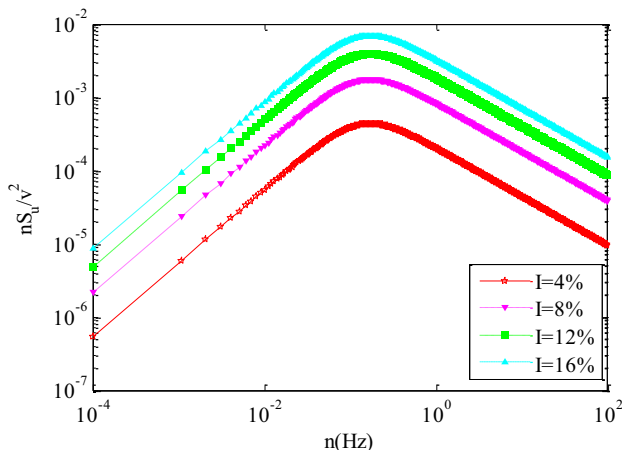


Figure 5. Von Karman spectra with different turbulence intensity

The effects of turbulence on drag coefficient, correlation coefficient and wind velocity spectrum have been discussed. The increase of turbulence integral length scale leads to the growth of drag coefficient and correlation coefficient, which will cause larger along-wind responses of tall buildings. Conversely, in the major frequency range of wind actions on tall

buildings (from 0.1 Hz to 2.0 Hz), the power of wind velocity spectrum reduces significantly as turbulence integral length scale increases, which will result in the reduction of the along-wind structural responses.

So, what on earth is the overall effect of turbulence integral length scale on the along-wind responses of tall buildings? This problem will be investigated in this paper through a detailed structural dynamic analysis. Similarly, the addition of turbulence intensity causes the decrease of drag coefficient but the increase of power of wind spectrum. The former will reduce the along-wind responses of tall building while the latter will increase the responses of tall buildings. This contradiction induces the uncertainty of the effect of turbulence intensity on the along-wind responses of tall buildings, which will also be investigated in this paper.

3. ALONG-WIND RESPONSES OF TALL BUILDINGS

A tall building can be simplified as a Multi-Degrees of Freedom (MDOF) System, the motion equation of a MDOF system subjected to random wind loads is:

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + [K]\{y\} = \{F(t)\} \quad (8)$$

where $[M]$, $[C]$ and $[K]$ are $N \times N$ order matrices of mass, damping and lateral condensed stiffness of the structure in along-wind direction. (N is the number of the total stories of a building). Since the order of the matrices defined in the above equation is high, the mode superposition method is used for evaluation of wind-induced response of a tall building. Assuming only the lowest N_k modes are considered in the computation, then the structural displacement vector $\{y\}$ is decomposed into

$$\{y\} = [\phi]\{q\} = \sum_{k=1}^{N_k} \{\phi_k\} q_k \quad (9)$$

where $[\phi]$ is the $N \times N_k$ mode shape matrix corresponding to the lowest N_k vibration modes. $\{q\}$ is the generalized displacement vector and q_k is the k -th component of vector $\{q\}$.

The power spectrum density (PSD) of the displacement responses at the location of the i -th floor (lumped mass) of the building would be

$$S_{yy}(y_i, \omega) = \sum_{j=1}^{N_k} \sum_{k=1}^{N_k} \phi_{ij} \phi_{ik} H_j^*(\omega) H_k(\omega) S_{f_j f_k}(\omega) \quad (10)$$

where

$$S_{f_j f_k}(\omega) = \frac{1}{M_j^* M_k^*} \sum_{i=1}^N \sum_{l=1}^N \phi_{ij} \phi_{lk} S_{F_i F_l}(\omega) \quad (11)$$

$S_{F_i F_l}(\omega)$ is the cross-PSD function of the local along-wind or across-wind load. The frequency response function $H_k(\omega)$ of the k -th vibration mode is

$$H_k(\omega) = (\omega_k^2 - \omega^2 + 2i\xi_k \omega \omega_k)^{-1}, i = \sqrt{-1} \quad (12)$$

For tall building structures, the damping ratio is relatively small and the frequency response function distributes sparsely in the frequency domain, therefore the cross-correlation terms in Eq. (10) are usually neglected, which leads to the following approximate expression of Eq. (10)

$$S_{yy}(y_i, \omega) = \sum_{k=1}^{N_k} \phi_{ik}^2 |H_k(\omega)|^2 \frac{1}{(M_k^*)^2} \sum_{j=1}^N \sum_{l=1}^N \phi_{jk} \phi_{lk} S_{F_j F_l}(\omega) \quad (13)$$

The PSD of the acceleration response $\ddot{y}_i$ at the i -th floor (lump mass) of the building would be

$$S_{\ddot{y}_i}(\ddot{y}_i, \omega) = \sum_{k=1}^{N_k} \omega_k^2 \phi_{ik}^2 |H_k(\omega)|^2 \frac{1}{(M_k^*)^2} \sum_{j=1}^N \sum_{l=1}^N \phi_{jk} \phi_{lk} S_{F_j F_l}(\omega) \quad (14)$$

The RMS values of displacement response and acceleration response of a building structure would be

$$\sigma_{y_i}^2 = \int_0^{\infty} S_{y_i}(y_i, \omega) d\omega \quad (15)$$

and

$$\sigma_{\ddot{y}_i}^2 = \int_0^{\infty} S_{\ddot{y}_i}(\ddot{y}_i, \omega) d\omega \quad (16)$$

The along-wind load on each lumped mass can be expressed as

$$S_{F_{xi} F_{xj}}(z_i, z_j, f) = (\rho C_D)^2 A_{z_i} A_{z_j} \bar{V}_{z_i} \bar{V}_{z_j} \sqrt{S_V(z_i, f) S_V(z_j, f) Coh(z_i, z_j, f)} \quad (17)$$

where $S_V(z_i, f)$ is the auto-power spectral density of the along-wind fluctuating wind speed, which can be represented by Von Karman spectrum.

4. VERIFICATION OF THE COMPUTATIONAL METHOD

For verification of the above method for calculating the along-wind responses of tall buildings, a typical rectangular building is chosen as a numerical example in this study. This rectangular tall building is a 30-storey steel structure with a cross-section area of $40m \times 40m$ and $120m$ height, and the average mass density is approximate $187.5kg/m^3$. Wind tunnel test was carried out for this building to determine the wind forces on the building using pressure measurement technique, and the along-wind, across-wind and torsional responses of the building were calculated based on the model test results (Yoshida et al. 1992). The analytical model of the building for the dynamic analysis was simplified as a cantilever shear column with five lumped masses; each lumped mass has two translational degrees of freedoms (DOFs) in horizontal directions (X and Y direction) and one rotational DOF in vertical (Z) direction, as shown Fig.6. The vertical distribution of the lumped mass of this building is shown in Fig.6 (Yoshida et al., 1992). The fundamental natural frequency of this building is 0.336 Hz in the two translational directions. Damping ratio was assumed to be 1% for all the vibration modes (Wu and Li, 2008).

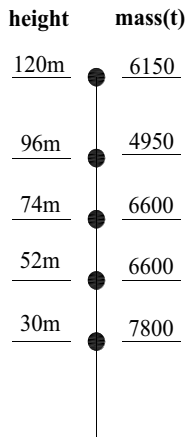


Figure 6. Simplified model of a tall building

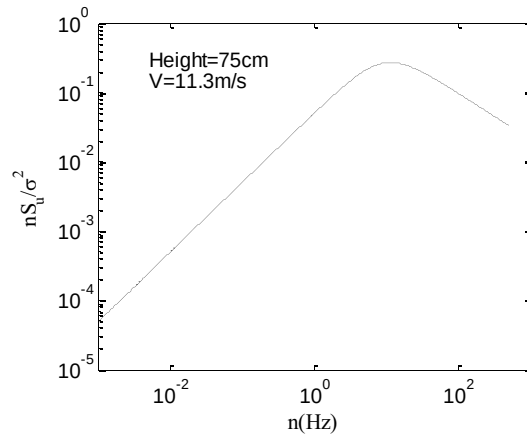


Figure 7. Power spectrum of wind speed in the wind tunnel testing

To examine the reliability of the computational method, two mean wind speeds atop the building, 20m/s and 30m/s, are chosen. The approaching wind direction is normal to one side of the square building. Comparison of the numerical predictions and wind tunnel test results are listed in table 1.

Table 1 Comparison between the numerical results and wind tunnel test results

Acceleration responses	$\sigma_{\ddot{y}}$ (gal)	
Wind speed	20m/s	30m/s
Numerical results	0.665	1.702
Wind tunnel results	0.620	1.913
Difference	7.26%	11.03%

As shown in table 1, the differences between the numerical results and wind tunnel test results are about 10%. Generally, such differences can be accepted in engineering practices, thus verifying the accuracy of the computational method.

5. EFFECTS OF TURBULENCE INTEGRAL LENGTH SCALE ON ALONG-WIND RESPONSES OF TALL BUILDINGS

To investigate the influences of turbulence integral length scale to the along-wind response of tall buildings, three square tall buildings with typical heights, 200m, 300m and 400m, are chosen as study objects, respectively. The models of the three tall buildings are simplified as cantilever shear columns with ten lumped masses; each lumped mass has two translational DOFs in horizontal directions and one rotational DOF in vertical direction. The average mass density is approximate 187.5kg/m^3 , and the vertical distributions of the lumped mass of the buildings are shown in Fig. 8.

The fundamental natural frequency and mode shapes of the tall buildings can be calculated by the empirical formulas stipulated in the Chinese Load Code for The Design of Building Structures (2001). Damping ratio was assumed to be 1% for all the vibration modes. The parameters of these three buildings are listed in table 2.

Table 2 Parameters of three tall buildings

Height (H)	200m	300m	400m
Width (D)	40m	60m	80m
Fundamental frequency (f_1) (Hz)	0.200	0.133	0.100

Ten different values of turbulence integral scales at height of 30m above ground are chosen for the calculation, while L_w/D arranges from 1 to 10. In the computation, the variation of turbulence integral length scale with height was described by the empirical formula of AIJ Recommendations for Loads on Buildings (AIJ 2005). This code recommends the following formula.

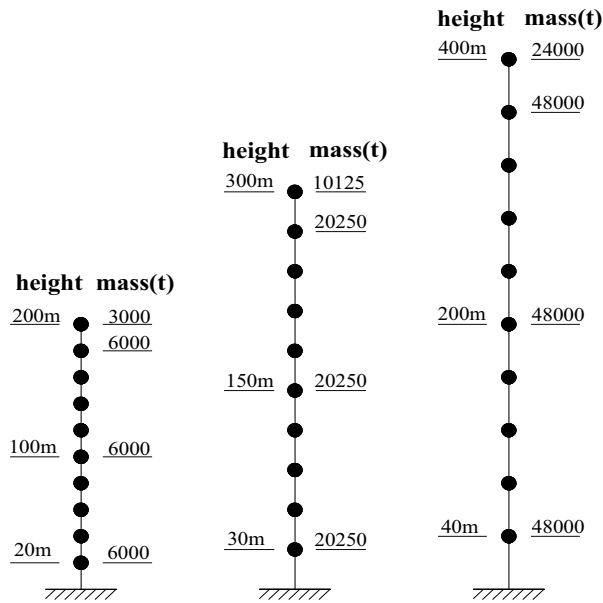


Figure 8. Three simplified models of the buildings

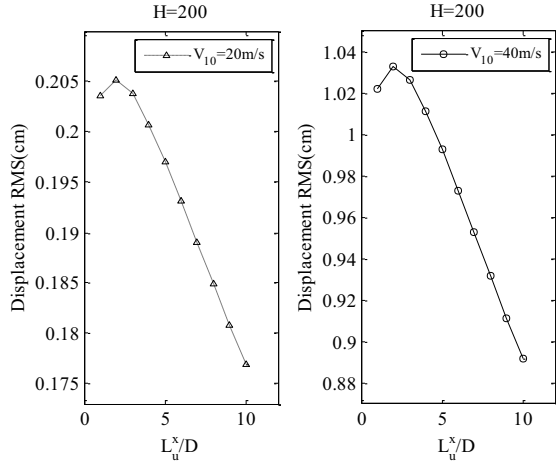
$$L_z = \begin{cases} 100 \left(\frac{Z}{30} \right)^{0.5} & 30m < Z \leq Z_G \\ 100 & Z \leq 30m \end{cases} \quad (18)$$

where Z (m) is height above ground; Z_G is a parameter determining the exposure factor. Turbulence integral length scale at one height calculated by this formula is a fixed value. However, the purpose of this paper is to discuss the variation of responses of tall buildings with various turbulence integral scales. So, different turbulence integral length scale profiles are required herein. In order to meet this requirement, the formula proposed by AIJ is modified as follows:

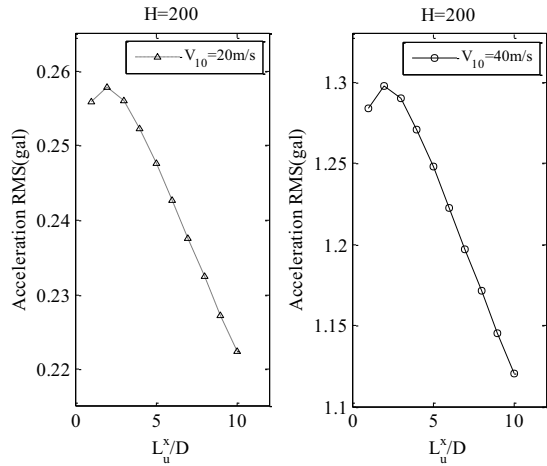
$$L_z = L_{30} \left(\frac{Z}{30} \right)^{0.5} \quad (19)$$

where L_{30} is turbulence integral length scale at 30m. In this study, the values of L_{30}/D were selected to vary between 1 and 10, and then the integral length scale at other heights can be

calculated by this formula easily. Mean wind speeds at 10m height are supposed to be 20m/s and 40m/s, respectively. Based on the computational procedure presented previously, the along-wind responses of these three tall buildings are calculated, as shown in the following figures.

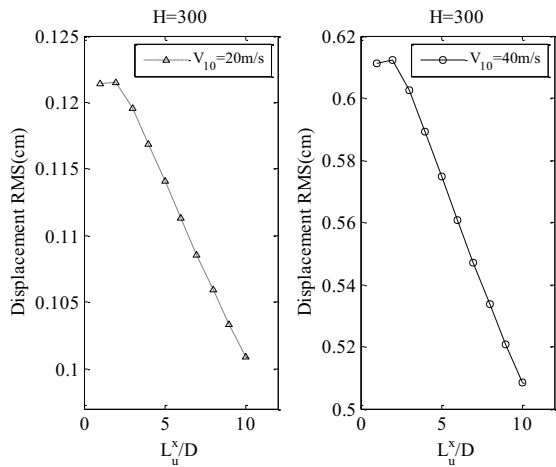


(a) Along-wind displacement responses

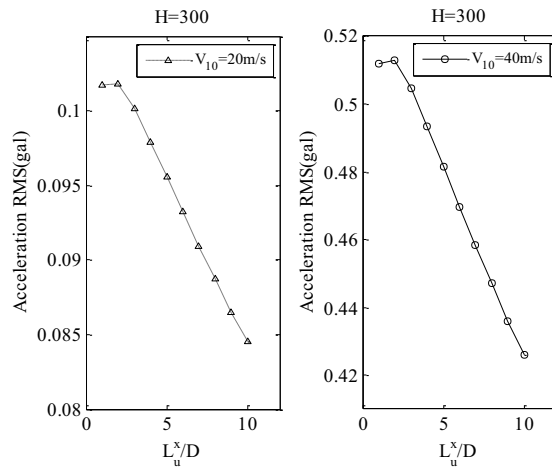


(b) Along-wind acceleration responses

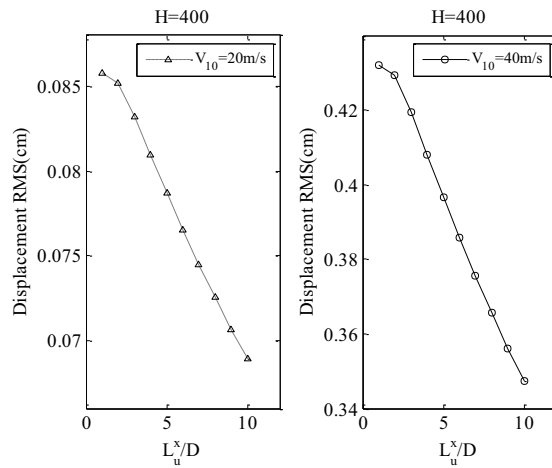
Figure 9. Along-wind responses of a building (200m)



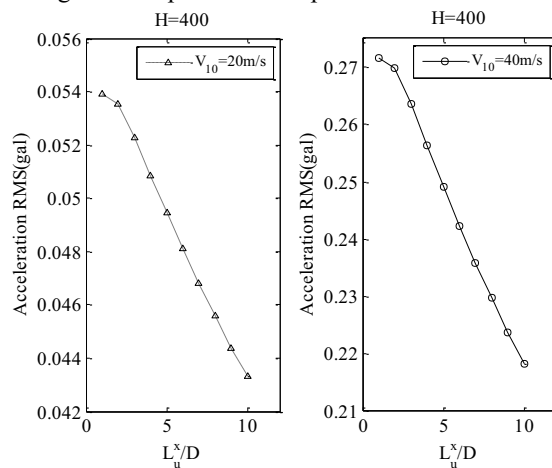
(a) Along-wind displacement responses



(b) Along-wind acceleration responses
Figure 10. Along-wind responses of a building (300m)



(a) Along-wind displacement responses



(b) Along-wind acceleration responses
Figure 11. Along-wind responses of a building (400m)

The above figures show the influences of turbulence integral length scale to the along-wind responses of three typical tall buildings with different heights under two wind speeds, namely,

20m/s and 40m/s. Fig. 9 presents the along-wind responses of a tall building where the building height is 200m. It can be seen from the figure that the along-wind responses increase with turbulence integral length scale when L_w/D is less than 2, then the responses reduce significantly with the increase of the integral scale when L_w/D is larger than 2. Similarly, Figs. 10-11 present the relationship between turbulence integral length scales and the along-wind responses of the tall buildings where the building heights are 300m and 400m, respectively. The effects of the integral scales on these two buildings are almost the same with those on the first building (200m). However, the uptrend of the structural responses when L_w/D is less than 2 becomes weaker gradually and eventually this uptrend is changed into downtrend as the building height increases. In conclusion, the along-wind displacement responses and acceleration responses decrease with the increase of turbulence integral length scale, although there are some uncertainties of small turbulence integral scales.

6. EFFECTS OF TURBULENCE INTENSITY ON ALONG-WIND RESPONSE OF TALL BUILDINGS

As discussed previously, the effects of turbulence intensity on drag coefficient and wind velocity spectrum are contradictory. Since these two factors have significant effects on the along-wind responses of tall buildings, it is necessary to examine the overall effects of turbulence intensity on the along-wind responses. Herein, turbulence intensities vary from 2% to 16%. Wind velocity spectrum employed in this study is Von Karman spectrum shown in Eq. (7). The relationship between turbulence intensity and drag coefficients is presented in Fig. 2. Based on the computational procedure given in section 3, the along-wind responses of the three tall buildings under wind actions with different turbulence intensities are shown in Figures 12-13 and Tables 3-4.

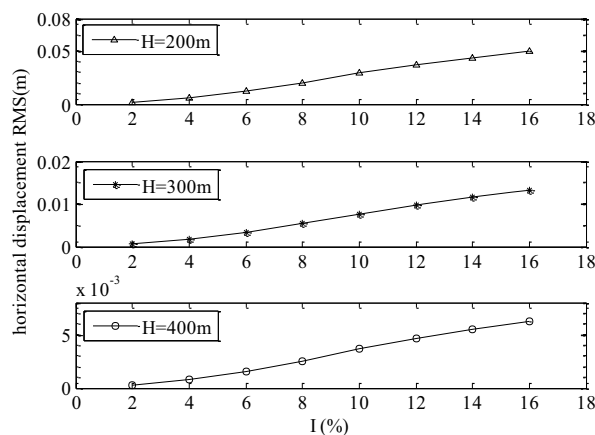


Figure 12. Along-wind displacements vs. turbulence intensities

Table 3 Along-wind displacements under different turbulence intensities

Along-wind displacements (cm)								
Height(m)	Turbulence intensities							
	2%	4%	6%	8%	10%	12%	14%	16%
200	0.2065	0.6385	1.2680	2.0230	2.8940	3.6470	4.3670	4.9740
300	0.0548	0.1694	0.3365	0.5369	0.7680	0.9679	1.1590	1.3200
400	0.0260	0.0804	0.1596	0.2547	0.3643	0.4591	0.5497	0.6261

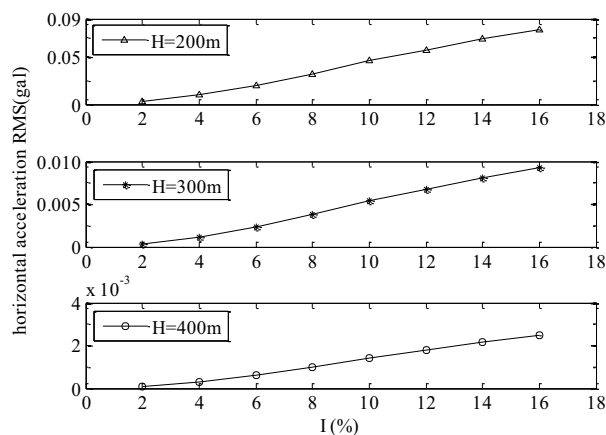


Figure 13. Along-wind accelerations vs. turbulence intensities

Table 4 Along-wind accelerations under different turbulence intensities

Height(m)	Along-wind acceleration (gal)							
	Turbulence intensities							
	2%	4%	6%	8%	10%	12%	14%	16%
200	0.003261	0.01008	0.02003	0.03195	0.04571	0.0576	0.06897	0.07856
300	0.000384	0.00119	0.00236	0.00377	0.00539	0.0068	0.00813	0.00926
400	0.000103	0.00032	0.00063	0.00101	0.00144	0.0018	0.00217	0.00247

Fig. 12 shows that the along-wind displacements increase evidently as the addition of turbulence intensity. For the along-wind acceleration responses, there is the same trend as shown in Fig. 13. When turbulence intensity increases from 2% to 16%, the displacement and acceleration responses of the tall buildings raise almost 24 times. So, it is concluded that turbulence intensity has significantly effects on the along-wind responses of tall buildings.

7. CONCLUSIONS

The effects of turbulence on the along-wind responses of tall buildings have been investigated. It was found that turbulence integral length scale and turbulence intensity have significant effects on the along-wind responses of tall buildings. Some conclusions from this study are summarized below.

- (1) Along-wind displacement responses and acceleration responses decrease with the increase of turbulence integral length scale, although there are some uncertainties of small turbulence integral scales.
- (2) Along-wind displacement and acceleration responses increase evidently as the addition of turbulence intensity. Such effects are so remarkable that the responses rise almost 24 times when turbulence intensity increases from 2% to 16%. Consequently, the effects of turbulence intensity cannot be ignored in the determination of along-wind responses of tall buildings.

8. ACKNOWLEDGEMENTS

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