

# **The simplified method of along-wind response of lattice transmission tower based on field test**

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## **Abstract**

Lattice transmission tower is an important lifeline project. This kind of structure is sensitive to wind load. The wind load is the main lateral load. The scholars in the world mainly research on the along-wind response of the structure based on strip theory and quasi-stability theory. However, the force spectrum based on quasi-stability theory is different from that obtained by the field test and the wind tunnel test, which make large discrepancy on the along-wind response result.

In this paper, a simplified method to model the along-wind response of a structure based on field test results is discussed. The simplified method is based on the fundamental mode generalized force spectrum (FMGFS) model and the frequency-domain method. The MATLAB soft is available to calculate the root-mean-square (RMS) of acceleration. It is concluded that the RMS value from the simplified method is very approached to that obtained by the field test. The deviation is controlled in 5%, which means the simplified method is an effective method.

**Keywords:** Lattice transmission line, along-wind response, fundamental mode generalized force spectrum, root-mean-square of acceleration, frequency-domain method.

## **1. Introduction**

Lattice transmission line is a typical slender structure, which has the characters of light weight, highness and low-damp. This kind of structure is sensitive to wind load. The scholars in the world mainly research on the along-wind response of the structure which is based on strip theory and quasi-stability theory.

The quasi-stability theory was proposed by Davenport firstly [1]. According to the theory, the cross-spectral density of along-wind fluctuating wind pressure was

simulated by fluctuating wind speed spectrum and coherence function. Then, the mode-superposition method was used to calculate the along-wind response of the structure. Davenport also advanced that dynamic wind loading was separated into background (quasi-static) and resonant components based on their frequency content. This theory has been used widely in the world. Based on this theory, many scholars such as Vellozzi [2], Vickery [3] and Simiu [4] deduced the response by numerical calculation method, which established the fundamental framework of along-wind response analysis.

The gust response factor (GRF) approach, introduced by Davenport [5] for along-wind excited buildings, has been used worldwide in building code and standards. Holmes [6-8] researched on the wind response and the equivalent static wind loads (ESWLs). He proposed that the equivalent pressure distribution associated with the background response can be derived by the load-response correlation method. And the distribution for the resonant response in the first mode can be represented as a distribution of inertial forces over the height of the tower. These two distributions were combined by the “root sum of squares” rule. This method has been a standard method to calculate the ESWLs.

The wind force on the structure can be qualified through the multiple-point synchronous scanning of pressures (MPSSP) on a structure model surface in a wind tunnel, or by high frequency force balance (HFFB) method. However, the wind force on the lattice tower is difficult to be measured in detail with MPSSP method because of its high hollowness rate. HFFB method has been used widely because the model is simple and the data is easy to dispose.

The field test utilizes the fluctuating wind and the fluctuating ground vibration as the input to measure the dynamic character. It is assumed that the input is white noise process, the frequencies of the structure are spaced widely and the fluctuation behavior is ergodic process. The test result is used to analyze the structure’s internal force and displacement. Momomura [10] and Okamura [11] clarified the characteristics of wind and wind-induced vibration of an electrical transmission tower installed on a mountainous area, based on full-scale data obtained at wind speed of less than 25m/s. They proposed that the vibration characteristics of the tower with conductors were strongly influenced by the behavior of the conductors. The aerodynamic damping of the conductors played an important role in their total damping. Chinese scholars Renle Ma and Minjuan He [12-14] obtained the full-scale dates from a broadcast tower in Hei Longjiang, a self-support transmission tower and a guyed tower in Jiangyin. The dynamic parameters were derived from these tests. They also tested two adjacent straight towers in Hebei [15] simultaneously. They deduced the dynamic characteristics of the two towers coupled with the lines. The frequencies of the insulator were also obtained by the tests.

Based on the quasi-static theory, the influence of aerodynamic admittance on the structure is ignored and the along-wind force spectrum is deduced from the wind speed function straightly. However, as the force spectrum based on this theory is discrepant

with that derived from the test, the response of the structure has a large wipe between these two methods. Hence, it is meaningful to study the along-wind force spectrum based on the wind test to calculate the structure's response.

Shuguo Liang [16] has deduced the FMGFS of the lattice tower by HFFB test, which take into account the aerodynamic admittance. In this paper, this FMGFS is used to simulate the acceleration of the structure and the frequency-domain method is employed. The response of this method is compared with the result derived from the Hebei field test [15] as refer to verify the accuracy of the method.

## 2. Method

### 2.1. Fundamental mode generalized force spectrum on along-wind direction

HFFB technique has evolved to be the most versatile and widely used method. In this technique, a lightweight rigid model of the structure is mounted on a very stiff base balance capable of measuring aerodynamic loads over a range of incidence angles of the approaching wind. A major advantage of this approach is that wind force spectrum can be measured directly when the structure is exposed to the wind buffeting caused by surrounding buildings or the terrain. Once the wind force spectrum derived from the HFFB technique is obtained, they can be used to predict the lateral drift and acceleration response analytically by the random vibration theory. Shuguo Liang et al. [9,16] did a number of HFFB tests in TJ-1 wind tunnel in Tongji University and obtained the empirical formula of the FMGFS.

The empirical formula of along-wind FMGFS is expressed as follows:

$$S_{F_1^*}(f) = \frac{\sigma^2}{f} \cdot \frac{a(fB/V_H)^{1.05}}{[1 + b(fB/V_H)^2]^{1.5}} \quad (1)$$

$$\sigma = \frac{1}{2} C_M \rho V_H^2 AR \quad (2)$$

in which,  $S_{F_1^*}(f)$  refers to the FMGFS,  $\sigma$  is root mean square(RMS) of fundamental mode generalized force,  $\rho$  means the density of air, A is the contour area in the flow direction, R refers to the ratio between actual area and contour area,  $V_H$  denotes mean wind speed on the top of the structure, f is frequency, a, b and  $C_M$  are the fitting indexes, which are respectively 14.6,113.5 and 0.088 in turn, B refers to Bottom-width of the tower in the direction of approaching flow.

### 2.2. frequency-domain method

The frequency-domain method is employed to model the along-wind response of the transmission line. The vibrate formulation of multi-degree-of-freedom system can be given by:

$$M\ddot{y}(t) + C\dot{y}(t) + Ky(t) = P(t) \quad (3)$$

According to the mode-superposition method, the displacement can be expressed as:

$$y(t) = \phi q(t) \quad (4)$$

Substituting Eq. (4) into Eq. (3), and left multiplying  $\phi^T$ ,

$$\ddot{q}_j(t) + 2\xi_j\omega_j\dot{q}_j(t) + \omega_j^2q_j(t) = F_j(t) \quad (5)$$

in which,  $q(t)$ ,  $M^*$ ,  $C^*$ ,  $K^*$  and  $F_j(t)$  are generalized displacement, mass, damping, stiff and force in turn,  $\xi_j$ ,  $\omega_j$  are the ratio of damping and the circle frequency of the jth mode.

### 2.3. The acceleration RMS

According to the random vibration theory, the displacement power spectrum of the jth-mass point can be written as follows:

$$S_{y_j}(\omega) = \int_{-\infty}^{+\infty} R_{y_j}(\tau) e^{-i\omega\tau} d\tau = \sum_a \sum_b \phi_{ja} \phi_{jb} H_a(-i\omega) H_b(i\omega) S_{F_a F_b}(\omega) \quad (6)$$

Where,  $S_{F_a F_b}(\omega)$  is the cross-power spectral density of  $F_a(t)$  and  $F_b(t)$ ,  $H_a(i\omega)$  is frequency response function.

Taking into account the small damping and discrete natural frequencies of the lattice tower, the cross terms in Eq. (6) can be neglected. Then, Eq. (6) is approximated as:

$$S_{y_j}(\omega) = \sum_a \phi_{ja}^2 |H_a(i\omega)|^2 S_{F_a}(\omega) \quad (7)$$

Where,  $S_{F_a}(\omega)$  refers to the power spectral density of  $F_a(t)$ .

According to random vibration theory, the power spectral density of the acceleration of the jth-mass point refers as:

$$S_{a_j}(\omega) = \omega^4 S_{y_j}(\omega) \quad (8)$$

And the acceleration RMS value of the jth-mass point is expressed by:

$$\sigma_{a_j}^2 = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{a_j}(\omega) d\omega = \sum_a \phi_{ja}^2 \frac{1}{(M_{aa}^*)^2} \int_{-\infty}^{+\infty} (2\pi f)^4 |H_a(if)|^2 S_{P_a^*}(f) df \quad (9)$$

The acceleration of the structure is composed of the background response and the resonant part. The background pressure distribution is the quasi-static loading produced by the fluctuations due to turbulence, but with frequencies too low to excite resonant response. The resonant part is approximately as a narrow-band white noise with the

range of  $\Delta = \pi f_a \xi_a$ . The RMS of acceleration background response of the  $j$ th-mass can be estimated as:

$$\sigma_{a_{jb}}^2 = \sum_a \phi_{ja}^2 \frac{1}{\omega_a^4 (M_{aa}^*)^2} \int_{-\infty}^{+\infty} (2\pi f)^4 S_{P_a^*}(f) df = \sum_a \phi_{ja}^2 \frac{1}{(K_{aa}^*)^2} \int_{-\infty}^{+\infty} (2\pi f)^4 S_{P_a^*}(f) df \quad (10)$$

The RMS of the resonant response of the  $j$ th-mass is given by:

$$\sigma_{a_{jr}}^2 = \sum_a \phi_{ja}^2 \frac{1}{(M_{aa}^*)^2 \omega_a^4 (2\xi_a)^2} (2\pi f_a)^4 S_{P_a^*}(f_a) \Delta_a = \sum_a \phi_{ja}^2 \frac{\pi f_a}{4(M_{aa}^*)^2 \xi_a} S_{P_a^*}(f_a) \quad (11)$$

Then, the Eq. (9) can be expressed as:

$$\sigma_{a_j}^2 = \sigma_{a_{jb}}^2 + \sigma_{a_{jr}}^2 = \sum_a \phi_{ja}^2 \left[ \frac{1}{(K_{aa}^*)^2} \int_{-\infty}^{+\infty} (2\pi f)^4 S_{P_a^*}(f) df + \frac{\pi f_a}{4(M_{aa}^*)^2 \xi_a} S_{P_a^*}(f_a) \right] \quad (12)$$

The background acceleration is generally negligibly small as compared to the resonant component. So, when only the resonant component is considered, the RMS of the acceleration of the  $j$ th-mass can be estimated as follow

$$\sigma_{a_j}^2 = \sigma_{a_{jr}}^2 = \frac{\phi_{j1}^2 \sigma^2}{(M_{11}^*)^2} \cdot \frac{\pi a (fB / V_H)^{1.05}}{4\xi_1 [1 + b(fB / V_H)^2]^{1.5}} \quad (13)$$

### 3. Model

In this paper, a 500kV suspension-type tower sited at Hebei province is studied. This steel angle tower has a height of 48.5m. The main structure members such as columns are made of Q345 steel with others of Q235. The profile of the structure is as shown in Figure 1.

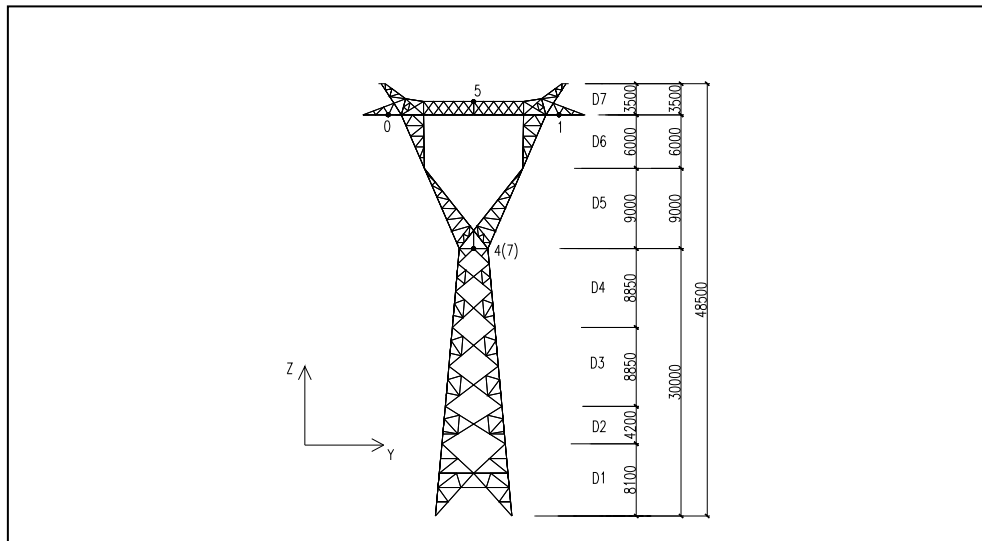


Figure 1: the profile of the structure and the test points

In this study, the wind-induced results of the adjacent self-support towers are obtained from the field tests on the bi-direction simultaneously. The acceleration values are measured by the acceleration sensors. The along-line direction is named as x-direction, while y-direction is perpendicular to the lines and z- is the vertical direction. SVSA soft is used to collect the data, which also can analyze the data. There are only 5 points in single tower with 3 points in x-direction and 2 in y-direction. Point 0, 1, 4 are in x-direction with 5, 7 in y-direction. All of the points can be seen in Figure1.

By the using of the SVSA soft, the fundamental frequencies and the ratio of the damping are derived from the acceleration results of the test. Figure 2 summarizes these parameters of the structure.

	x- translation	y- translation	torsion
Fundamental frequency ( Hz)	1.765	1.774	2.325
Ratio of damping ( % )	1.874	1.8356	1.7966

Figure 2: The parameters of the structure derived from the field test

The model simplified as the lumped mass model is suitable to the frequency-domain method. The simplified model and the fundamental mode of x-direction can be seen in Figure3. Figure 4 shows the masses and the mode of the structure. Then, the MATLAB soft is available to calculate the acceleration RMS value of the structure at the basis of

the parameters in Figures 2, 4.

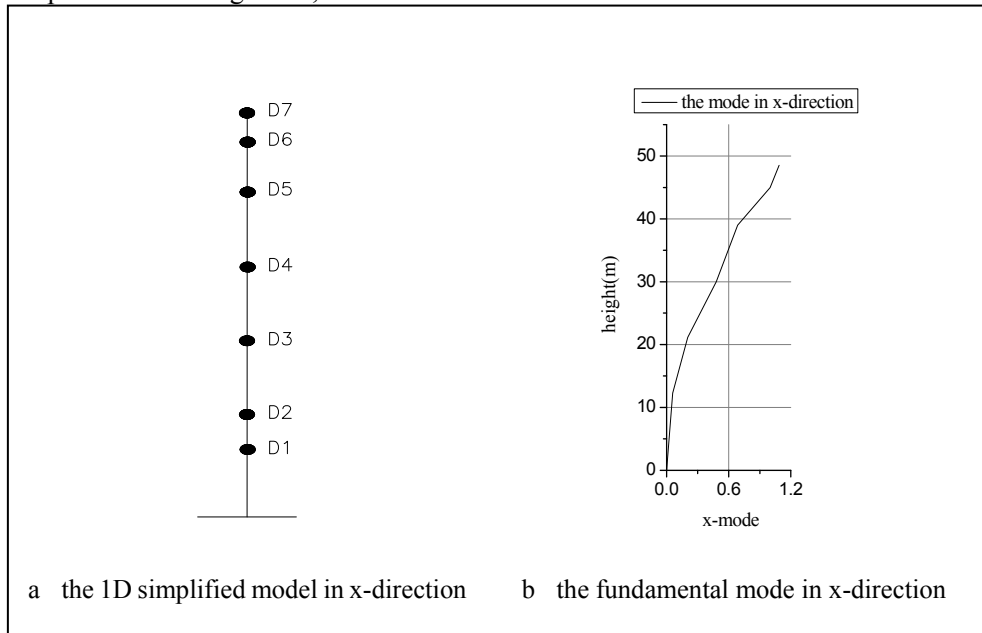


Figure 3: the 1D simplified model and the fundamental mode in x-direction

Height(m)	8.1	12.3	21.15	30	39	45	48.5
Mass(kg)	2996.6	1147.2	2129.4	2024.5	2274.2	834	2659.5
mode	0.039	0.059	0.205	0.408	0.687	1	1.088

Figure 4: The characteristics of the structure

#### 4. Result

The mean wind speed at the tower's top is less than 10m/s. 31-group data are collected. There are 9 groups which measure the ground pulsation synchronously. The sampling interval of the acceleration time history is 0.01s, and total 32768 data are recorded during the time duration of about 328s. 7 set of representative data are compared in this article. The 60s x-direction acceleration of the point at the height of 45m and 30m can be shown in Figure 5 and Figure 6 respectively. It is observed that the acceleration values periodically fluctuate at  $0.02 \sim 0.02 \text{ m/s}^2$ ,  $0.006 \sim 0.006 \text{ m/s}^2$ , respectively.

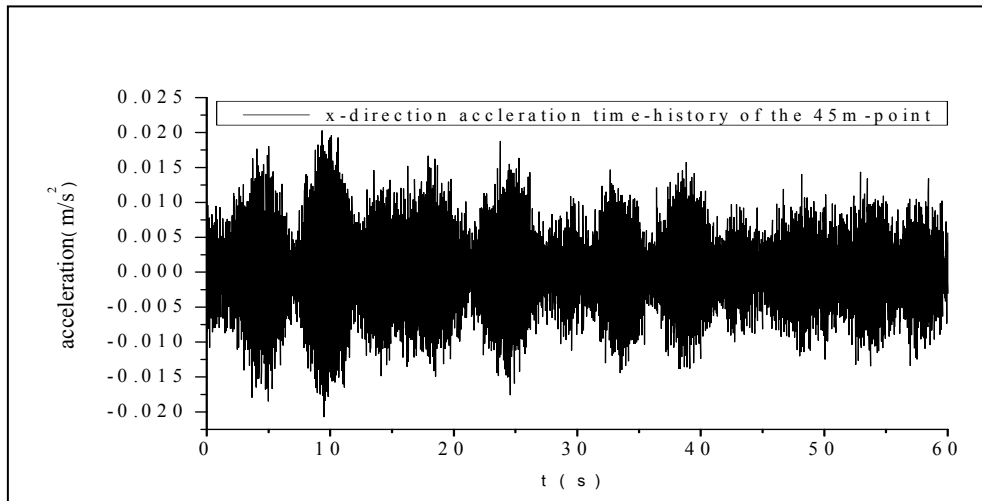


Figure 5: The x-direction acceleration time-history line of 45m-mass point

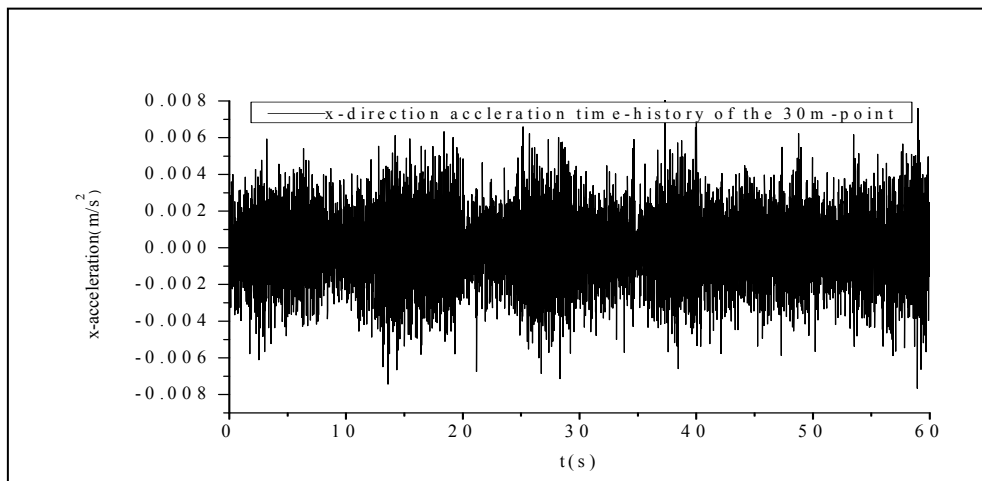


Figure 6: The x-direction acceleration time-history line of 30m-mass point

#### 4.1. The influence of ground vibration

The test response is induced by the wind and ground fluctuating. So the influence of the ground fluctuation on the structure must be considered firstly. The response of the structure can be simulated by SAP2000 soft with the known ground vibration. Take the 9th group as example, the acceleration values of the ground vibration are shown in Figures 7, 8. It is noted that the values in x- and y-direction fluctuate at the range of  $-5 \times 10^{-4} \sim 5 \times 10^{-4} \text{ m/s}^2$ ,  $-2 \times 10^{-5} \sim 2 \times 10^{-5} \text{ m/s}^2$ , respectively. According to the probability



statistics theory, the RMS of these two directions are  $2.60 \times 10^{-3} \text{m/s}^2$  and  $1.15 \times 10^{-4} \text{m/s}^2$ .

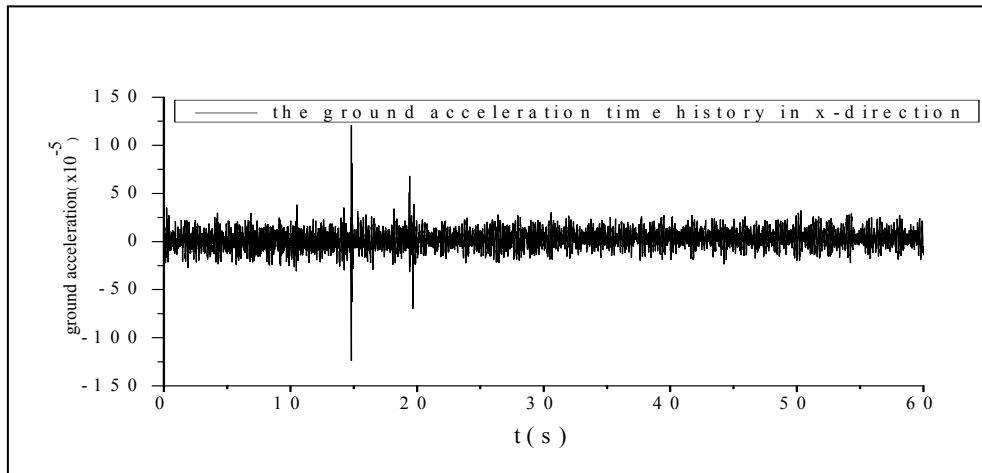


Figure 7: the ground acceleration time history in x-direction

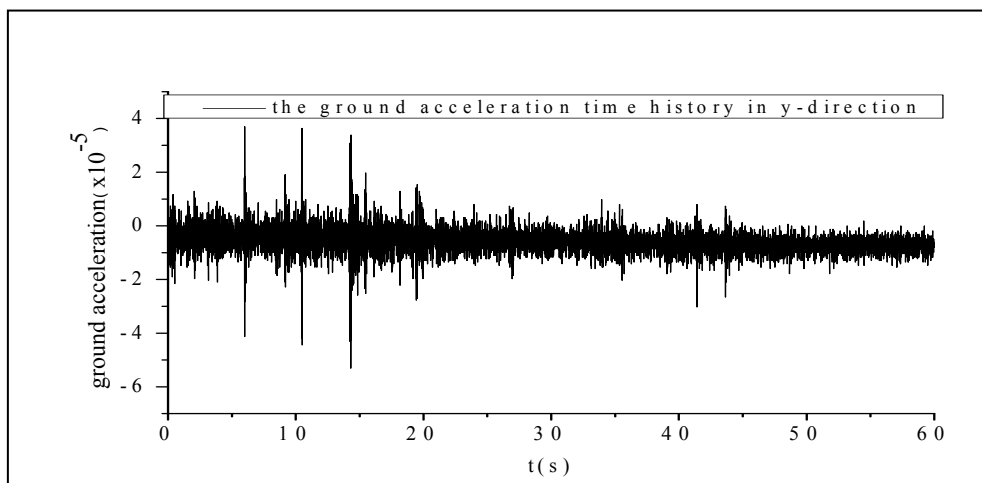


Figure 8: the ground acceleration time history in y-direction

The acceleration RMS values of 45m-point in x-direction are presented in Figure 9. In this Figure, the acceleration induced by the ground vibration is approximately  $1.3 \times 10^{-4} \text{m/s}^2$ . It is noteworthy that when RMS of the acceleration response is low, the proportion of the response induced by the ground vibration is large to 10%. However, when the result achieves  $3 \times 10^{-3} \text{m/s}^2$ , the proportion is less than 5%. It is clear that

with the increase in wind speed, the influence of the ground vibration decreases and the ground-induced response can be neglected.

term	1	2	3	4	5	6	7	8	9
Ground-induced RMS ( $10^{-4}$ )	1.36	1.10	1.18	1.36	1.66	1.16	1.06	1.24	1.20
Test RMS( $10^{-3}$ )	1.11	1.74	2.29	2.49	2.58	3.68	2.42	3.26	6.69
Ratio (%)	12.28	6.34	5.15	5.48	6.44	3.15	4.39	3.80	1.79

Figure 9: The acceleration RMS induced by ground vibration and the ratio in x-direction

#### 4.2. Result deduced by the simplified method

The acceleration RMS values of the mass points are deduced by the simplified method. The results of 45m-point and 30m-point are presented in Figures 10, 11. These figures demonstrate that when the wind-speed is less than 7m/s, the RMS of the 45m-point is less than  $2 \times 10^{-3} \text{ m/s}^2$  with an error of about 10%. Compared the result with Figure 9, it is deduced that when the wind is about 4m/s, the proportion of ground-induced response is approximately 10%. Hence, the error is caused by the neglected ground response not the method. It is notable that when the wind-speed is near 7 m/s, the error is less than 5%, which is consistent with the Figure 9. It is concluded that the method is suitable to simulate the along-wind response with a high accuracy.

Wind speed in x-direction (m/s)	Acceleration RMS at the top point( $10^{-3} \text{ m/s}^2$ )		Absolute error( $10^{-3}$ $\text{m/s}^2$ )	Relative error
	Test result	Calculated result		
4.0224	1.15	1.25	0.10	8.67%
4.1306	1.35	1.28	-0.07	-5.40%
4.1633	1.39	1.28	-0.11	-7.76%
4.3061	1.53	1.42	-0.11	-7.46%
4.398	1.63	1.53	-0.11	-6.51%
7.0857	6.73	7.01	0.28	4.11%
7.0878	6.74	6.68	-0.06	-0.86%

Figure 10: the acceleration RMS on the 45m-mass point

Wind speed in x-direction (m/s)	Acceleration RMS at the top point ( $10^{-4}$ m/s <sup>2</sup> )		Absolute error ( $10^{-4}$ m/s <sup>2</sup> )	Relative error
	Test result	Calculated result		
4.0224	5.72	5.11	-0.61	-10.70%
4.1306	5.52	5.89	0.36	6.53%
4.1633	5.66	6.29	0.63	11.15%
4.3061	6.25	6.92	0.66	10.60%
4.398	6.66	7.25	0.59	8.87%
7.0857	27.47	26.48	-0.99	-3.62%
7.0878	27.49	27.82	0.32	1.18%

Figure 11: the acceleration RMS on the 30m-mass point

## 5. Conclusion

The analysis of the along-wind induced response established on the full-scale test and the simplified method are presented. In this context, the influence of ground-vibration on acceleration is discussed. With the increasing of the wind speed, the effect of the ground vibration decreases. When the mean wind speed at the tower's top is greater than 7m/s, it is reasonable to neglect the ground-vibration with the proportion of 2%. Meanwhile, the simplified method presented in this paper is proved to be high precise with the error of 5%.

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