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Fluctuating wind field analysis based on random Fourier spectrum for wind induced response of high-rise structures

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Abstract. An accurate calculation of the stochastic wind field is the foundation for analyzing wind-induced structure response and reliability. In this research, the spatial correlation of structural wind field was considered based on the time domain method. A method for calculating the stochastic wind field based on cross stochastic Fourier spectrum was proposed. A flowchart of the proposed methodology is also presented in this study to represent the algorithm and workflow. Along with the analysis of regional wind speed distribution, the wind speed time history sample was calculated, and the efficiency can therefore be verified. Results show that the proposed method and programs could provide an efficient simulation for the wind-induced structure response analysis, and help determine the related parameters easily.

Keywords: stochastic wind field; cross stochastic Fourier spectrum; wind speed time history; time domain method; fluctuating wind field; structure wind induced respond

1. Introduction

The main purpose of wind-resistant research is the analysis of structural response and its dynamic reliability under wind load. For a building structure, the wind velocity of a spatial point could be described by a stochastic process. However, for a long-span or high-rise building, the correlation of wind speeds at various heights should be considered. In this situation, the spatial wind speed should be regarded as a stochastic speed field. Therefore, how to systemically model the reasonable time-domain speed field is the basis to analyze stochastic response and the reliability of wind-induced structures.

In the definite structure system, the typical stochastic vibration was used for the wind resistant analysis, which includes frequency domain method and time domain method. Frequency domain method is more efficient in estimating structural fluctuating response based upon the wind speed spectrum (Li *et al*. 2015). However, frequency domain method is only applicable to linear structure, which affects the accuracy of the structural response analysis. Time domain method could be used to directly calculate the maximum value in the time history of structure stress and displacement. It is not necessary for the time domain methods to simplify the structural model; however, its computation is time-consuming. Nevertheless, the time domain analysis is more straightforward and universal as compared with the domain analysis. In this paper, a methodology for simulating stochastic fluctuating wind field was proposed using the random Fourier spectrum and a flowchart of this methodology was presented. Random Fourier spectrum analysis method was also used in a case study, and the fluctuating wind speed time history and its power spectrums were generated to analyze the response spectrum of a high-rise building.

2. Mutual stochastic Fourier spectral fluctuating wind field modeling method and its programming

2.1 Stochastic characters

Stochastic characters include annual 10 minutes average maximum wind speed U_{10}, roughness length Z_0, and spectral coherence functions γ_{ij} (C_1,C_x,C_y,C_z).

The annual 10 minutes average maximum wind speed U_{10} should be analyzed based on the original wind data history. The distribution and its parameters could be easily determined by the generalized unified probability plotting (GUPP) method (Lin *et al*. 2015a).

According to the *Chinese Load Code for the Design of Building Structures*, the roughness length can be quantitatively decided according to the geometrically condition (Lin *et al*. 2014). Considering the uncertainty of roughness of the ground, the gradient wind velocity can be tested in the specific locations. Then sample data of the real ground roughness z_0 can be calculated based on the widely applied gradient distributions, such as exponential and logarithmic distributions (Zhi *et al*. 2015). Based on the

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distribution analysis, the parameters and distribution type can be determined; the mean and standard error can therefore be obtained as well. Applying the stochastic modeling method, the probability distribution density can be obtained. The value of z_0 can be subsequently determined through the comparison with traditional statistic methods and hypothesis testing.

Spectral coherence function γ_{ij} (C_1,C_x,C_y,C_z) is related to the coefficients of C_1, C_2, C_3 and C_4. Based on the statistical analysis of tested gradient wind speed, the distribution of related parameters C_1, C_2, C_3, and C_4 can be determined by the correlation of experiential equation $S(z, n)$ of fluctuating wind spectrum, Fourier spectrum and power spectrum.

2.2 Stochastic wind field modeling

Stochastic wind speed V_s, is assumed to be a random stationary field, which can be separated into a mean value component $\bar{V}(z)$ and a zero mean value fluctuation component $V(x,y,z,t)$ described by Zhang (1990), as shown below

$$V_s(x,y,z,t)=\bar{V}(z)+V(x,y,z,t) \tag{1}$$

2.2.1 Mean wind speed

Mean value component $\bar{V}(z)$ is described by the wind speed profile function, which is the function of average wind speed in different altitudes. The Logarithmic and exponential law function are two most common wind speed profile functions as described by Huang and Xu (2013). The logarithmic wind speed profile is used in this study as

$$\bar{V}(z)=\frac{1}{k}u_* \ln(z/z_0) \tag{2}$$

where, k is Von Karman constant, which can be taken as 0.4, z_0 is ground roughness length (m), u_* is shear velocity, which is defined by

$$u_*=\sqrt{\frac{\tau_0}{\rho}} \tag{3}$$

In this function, τ_0 is ground shear force and ρ is air density.

Actually, τ_0 is hard to obtain, so u_* is calculated using the wind speed $\bar{V}(z')$ on the specific height z', which can be 10 meters.

$$u_*=\frac{k\bar{V}(z')}{\ln(z'/z_0)} \tag{4}$$

Therefore, the function of wind speed profile can be represented as

$$\bar{V}(z)=\bar{V}(z_{10})\cdot\frac{\ln(z/z_0)}{\ln(10/z_0)} \tag{5}$$

2.2.2 Power spectrum of fluctuating wind field

There are many mathematical forms that are in use to express the power spectral density of longitudinal wind velocity-e.g., Von Karman Spectrum, Davenport Spectrum, Simiu Spectrum etc. The spectrum expression proposed by Davenport (1961) is applied in the current Chinese Building Code (Ministry of Housing and Urban-Rural Development of PRC 2012). This expression does not account for the influence of height

$$\frac{nS(z,n)}{u_*^2}=\frac{4f^2}{(1+f^2)^{4/3}} \tag{6}$$

in which, $f=\frac{1200n}{U_{10}}$, where n is the frequency, U_{10} (m/s) is the average wind speed of 10 meters' height.

Based on this, the unilateral spectrum function can be defined as

$$S(z,n)=\frac{4f^2u_*^2}{n(1+f^2)^{4/3}} \tag{7}$$

At the height of z=10 m, and circular frequency $\omega=2\pi n$, Eq. (7) becomes as follows

$$S(\omega)=\frac{460800\,\omega}{\pi\left[\ln\left(\frac{10}{z_{10}}\right)\right]^2\left[1+\left(\frac{600\,\omega}{\pi U_{10}}\right)^2\right]^{4/3}} \tag{8}$$

Then two sided auto spectral density function should be

$$S(z,n)=\frac{4f^2u_*^2}{2n(1+f^2)^{4/3}} \tag{9}$$

2.2.3 Cross stochastic Fourier spectrum of fluctuating wind field

Stochastic wind speed field is spatially continuous (Ke *et al* 2016). However, the discrete wind load is used for the actual analysis. For the specific spatial point (x_j,y_j,z_j), j=1, 2, 3…, n, stochastic process $V_j(t)$ is the wind speed time history of the j point as studied by Shinozuka and Deodatis (1991, 1996)

$$V_j(t)=V_j(x_j,y_j,z_j,t) \tag{10}$$

Therefore, there are n stochastic processes of the spatial points to form n directions wind speed stochastic vectors as $\{V_1(t), V_2(t), \ldots, V_n(t)\}$.

The cross spectral density matrix of multiple zero mean value stochastic processes is

$$F(z_0,U_{10},n)=\begin{bmatrix} F_{11}(z_0,U_{10},n) & F_{12}(z_0,U_{10},n) & \cdots & F_{1n}(z_0,U_{10},n) \\ F_{21}(z_0,U_{10},n) & F_{22}(z_0,U_{10},n) & \cdots & F_{2n}(z_0,U_{10},n) \\ \vdots & \cdots & \ddots & \vdots \\ F_{n1}(z_0,U_{10},n) & F_{n2}(z_0,U_{10},n) & \cdots & F_{nn}(z_0,U_{10},n) \end{bmatrix} \tag{11}$$

Diagonal elements $F_{ii}(z_0,U_{10},n)$ are composed by auto-spectrum

$$F_{ii}(z_0,U_{10},n)=F_{V_i}(z_0,U_{10},n)^2, i=1,\ldots,n \tag{12}$$

The off-diagonal elements $F_{ii}(z_0,U_{10},n)$ are composed by cross-spectral density function between V_i and V_j

$$F_{ij}(z_0,U_{10},n)=F_{V_i}(z_0,U_{10},n)F_{V_j}(z_0,U_{10},n)\gamma_{ij}(z_0,U_{10},C_1,C_x,C_y,C_z,n) \tag{13}$$

where i, j=1, 2,..n

U_{10} (m/s) is the average wind speed of 10 meters' height, z_0(m) is ground roughness length, and n(Hz) is the frequency, C_1, C_x, C_y, and C_z are the attenuation coefficients of correlation functions. For sake of simplification, C_1, C_x, C_y, and C_z are all taken as 1 in the following simulation section. For a specific construction site and the 10 meters' height wind speed conditions, the elements of the mutual stochastic Fourier matrix are the variables with respect to the variable n.

$$F_{ii}(n) = F_{V_i}(n)^2, i = 1,...,n \tag{14}$$

$$F_{ij}(n) = F_{V_i}(n) F_{V_j}(n) \gamma_{ij}(n), i = 1,...,n \tag{15}$$

Self-power spectrum density function is a real value even function of n, as

$$\begin{cases} F_{ij}^0(z_0, U_{10}, n) = F_{ij}^0(z_0, U_{10}, -n) \\ F_{ij}^0(z_0, U_{10}, n) = F_{ji}^0(z_0, U_{10}, n) \end{cases} \tag{16}$$

Then, the matrix for calculating stochastic Fourier spectrum is symmetric.

2.2.4 FFT technique for wind speed spectral

FFT technique can be used to reduce the cost of wind speed spectral. Cross stochastic Fourier spectrum $F(z_0,U_{10},n)$ could be resolved by Cholsky method as follow.

$$F(z_0, U_{10}, n) = I(z_0, U_{10}, n) I^T(z_0, U_{10}, n) \tag{17}$$

where, $I(n)$ is the lower triangular matrix

$$I(z_0, U_{10}, n) = \begin{bmatrix} I_{11}(z_0, U_{10}, n) & 0 & 0 & 0 \\ I_{21}(z_0, U_{10}, n) & I_{12}(z_0, U_{10}, n) & 0 & 0 \\ \vdots & \cdots & \ddots & 0 \\ I_{n1}(z_0, U_{10}, n) & I_{n2}(z_0, U_{10}, n) & \cdots & I_{nn}(z_0, U_{10}, n) \end{bmatrix} \tag{18}$$

To distinguish to the power n, the nn is used to describe the special dimensions of the discrete wind history. The wind speed history of each dimension is as follows

$$V_j(t) = \sqrt{2}\sqrt{2\pi} \sum_{m=1}^{j} \sum_{l=1}^{N} I_{jm}(\omega_{ml}) \sqrt{\Delta n} \cos\left[2\pi n_{ml} t - \theta_{jm}(\omega_{ml}) + \phi_{ml}\right], \quad j = 1, 2, \ldots, nn \tag{19}$$

which is unilateral power spectrum

$$V_j(t) = \sqrt{2\Delta\omega} \sum_{m=1}^{j} \sum_{l=1}^{N} I_{jm}(\omega_{ml}) \cos\left[\omega_{ml} t - \theta_{jm}(\omega_{ml}) + \phi_{ml}\right], \quad j = 1, 2, \ldots, nn \tag{20}$$

If it is a two-sided power spectrum, the coefficient should be $2\sqrt{2\pi}$, and then the wind speed history is as follow

$$V_j(t) = 2\sqrt{2\pi} \sum_{m=1}^{j} \sum_{l=1}^{N} I_{jm}(\omega_{ml}) \sqrt{\Delta n} \cos\left[2\pi n_{ml} t - \theta_{jm}(\omega_{ml}) + \phi_{ml}\right], \quad j = 1, 2, \ldots, nn \tag{21}$$

which is

$$V_j(t) = 2\sqrt{\Delta\omega} \sum_{m=1}^{j} \sum_{l=1}^{N} I_{jm}(\omega_{ml}) \cos\left[\omega_{ml} t - \theta_{jm}(\omega_{ml}) + \phi_{ml}\right], \quad j = 1, 2, \ldots, nn \tag{22}$$

In this paper, single-side spectrum is considered.

The fluctuating wind speed time history can now be rewritten as

$$V_j(p\Delta t) = \mathrm{Re}\left\{ \sum_{m=1}^{j} G_{jm}(q\Delta t) \exp\left[i\left(\frac{2\pi m \Delta n}{nn} (p-1)\Delta t \right) \right] \right\}, \quad P = 1, \ldots, M \times nn, \; j = 1, \ldots, nn \tag{23}$$

where, $\Delta t = 2\pi/(M\Delta\omega)$, $\Delta\omega = \omega_u/N$.

In order to avoid aliasing, the time step Δt has to obey the condition: $\Delta t \leq 2\pi/2\omega_u$.

The following condition was established between N and M (Popescu *et al*. 1998): $M \geq 2N$.

Furthermore, q was taken as the remainder of p/M, q=1,…,M.

$$G_{jm}(q\Delta t) = \sum_{l=1}^{M} B_{jm}(2\pi l \Delta n)(i(2\pi(l-1)\Delta n)((q-1)\Delta t)) \tag{24}$$

in which

$$B_{jm}(2\pi l \Delta n) = B_{jm}(l\Delta\omega) = \begin{cases} \sqrt{2\Delta\omega} I_{jm}\left(2\pi(l-1)\Delta n - \frac{m\Delta n}{nn}\right) \exp(i\phi_{ml}), 1 \leq l \leq N \\ 0, N \leq l \leq M \end{cases} \tag{25}$$

define

$$ml = \omega_{ml} = 2\pi(l-1)\Delta n + \frac{m\Delta n}{nn} \tag{26}$$

in which, as described by Bracewell (1986)

$$I_{jm}(\omega_{ml}) = \left| I_{jm}(\omega_{ml}) \right| \exp\left(i\theta_{jm}(\omega_{ml})\right) \tag{27}$$

where

$$\theta_{jm}(\omega_{ml}) = \arctan\left\{ \frac{\mathrm{Im}\left[I_{jm}(\omega_{ml})\right]}{\mathrm{Re}\left[I_{jm}(\omega_{ml})\right]} \right\}, \quad j = 1, \ldots, nn; m = 1, \ldots, j \tag{28}$$

However, I is the real matrix, then I_m is zero.

$$\theta_{jm}(\omega_{ml}) = 0; \exp\left(i\theta_{jm}(\omega_{ml})\right) = 1 \tag{29}$$

$$I_{jm}(\omega_{ml}) = \left| I_{jm}(\omega_{ml}) \right| \tag{30}$$

$$B_{jm}(2\pi l \Delta n) = B_{jm}(l\Delta\omega) = \begin{cases} \sqrt{2\Delta\omega} \left| I_{jm}\left(2\pi(l-1)\Delta n - \frac{m\Delta n}{nn}\right) \right| \exp(i\phi_{ml}), 1 \leq l \leq N \\ 0, N \leq l \leq M \end{cases} \tag{31}$$

Based on Eq. (31), Eq. (24) was transformed into

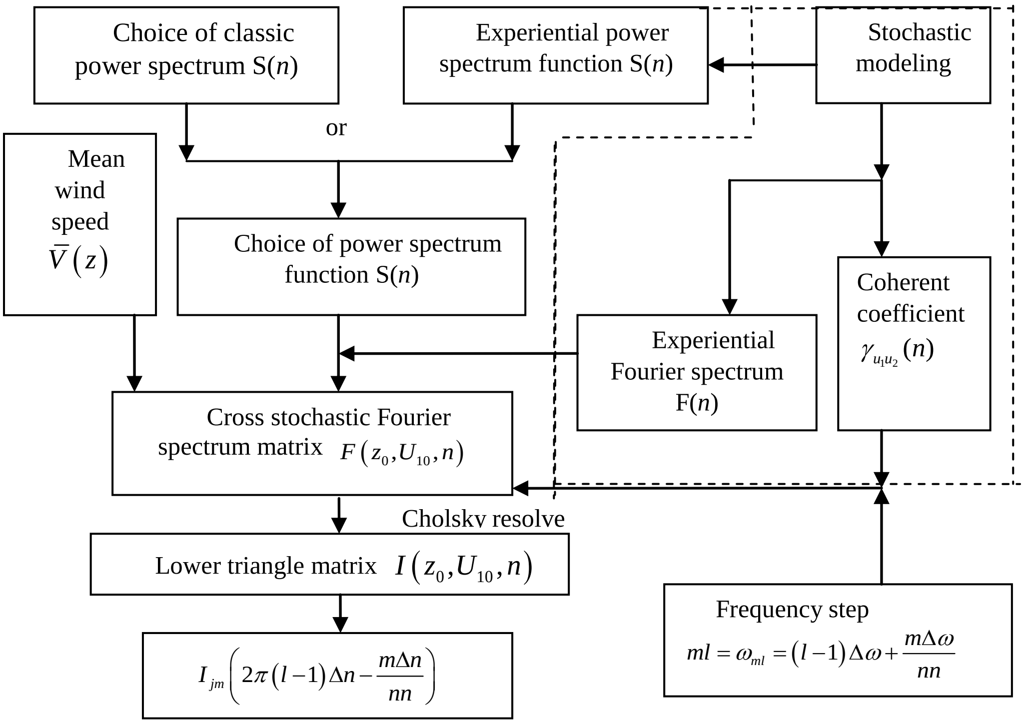


Fig. 1 Cross stochastic Fourier spectrum and its resolve

$$G_{jm}^{(q)}=\sum_{l=1}^{m}B_{jm}^{(l)}\exp\left(\frac{2\pi i(l-1)(q-1)}{M}\right) \tag{32}$$

where, $G_{jm}^{(q)}$ is the discrete Fourier transform of $B_{jm}^{(l)}$.
in which

$$B_{jm}^{(l)}=B_{jm}(2\pi l\Delta n)=B_{jm}(l\Delta\omega) \tag{33}$$

$$G_{jm}^{(q)}=G_{jm}(q\Delta t) \tag{34}$$

In those functions, nn is the wind speed spectrum dimension, n_u is the upper cut-off frequency beyond which the power spectral density function may be assumed to be zero for either mathematical or physical reasons. The measure unit of n_u is H_Z. The energy scaling which is to describe the number of n_u can be defined as

$$p=\frac{\int_0^{n_u}S(n)dn}{\int_0^{\infty}S(n)dn}\times 100\% \tag{35}$$

where, p is required to be 1, according to the research $n_u\geq 3$, the energy cover 95%.
where, ml is the sample value of angular frequency, shown as

$$\begin{aligned}ml=\omega_{jl}&=2\pi(l-1)\Delta n+\frac{m2\pi\Delta n}{nn}\\&=(l-1)\Delta\omega+\frac{m\Delta\omega}{nn}\end{aligned} \tag{36}$$

to satisfy the ergodicity, j=1~nn, and l=1~M for ω_{ji}.

It is worth to be mentioned that, as investigated in the existing references, the wind speeds and structural response all exhibited non-Gaussian features (Shields *et al*. 2013, Peng *et al*. 2014, Kareem *et al*. 1994, Yang *et al*. 2015, Grigoriu *et al*. 2003). Therefore, in this research, the Gaussian process of the wind speed is taken into consideration in the following sections.

The period T_0 of the V_j, which is

$$V_j(t)=V_j(p\Delta t) \tag{37}$$

defined as

$$T_0=p\Delta t=nn\times M\times\Delta t\,,\quad p=1,2,\ldots,nn\cdot M \tag{38}$$

2.2.5 Programming of fluctuating wind speed simulation

The program of the fluctuating wind speed field sample includes two parts: one is cross stochastic Fourier spectrum program, and the other one is wind speed field sample program. Cross stochastic Fourier spectrum program was made to help generate the cross stochastic Fourier spectrum and resolving it. Wind speed field sample program helps generate the wind speed field sample, which includes the *nn* direction fluctuating wind speed time history.

In this paper, two programs were coded by MATLAB software, and the programming flow chart can be seen in Fig. 1 to Fig. 2.

3. High rise building case study

3.1 Simulation of wind speed time histories

A high-rise building with 52 stories and 167.5 m height constructed on the sea side of Xiamen was taken as a case

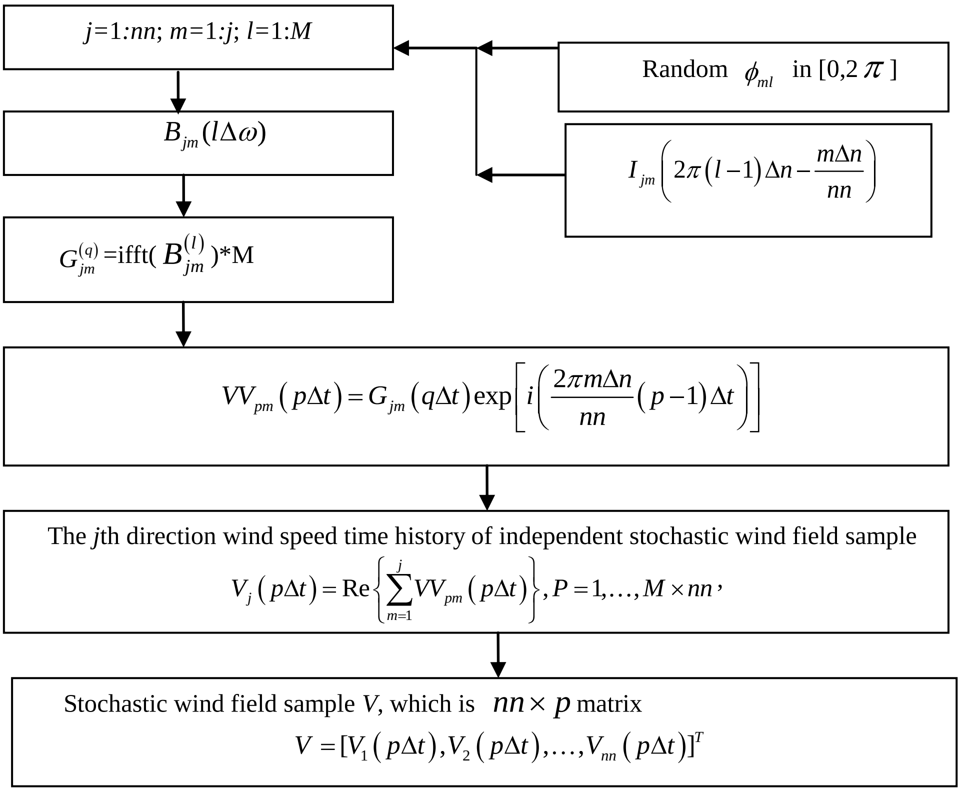


Fig. 2 Wind speed field program

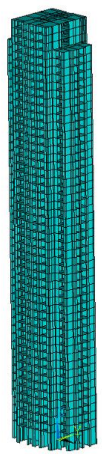
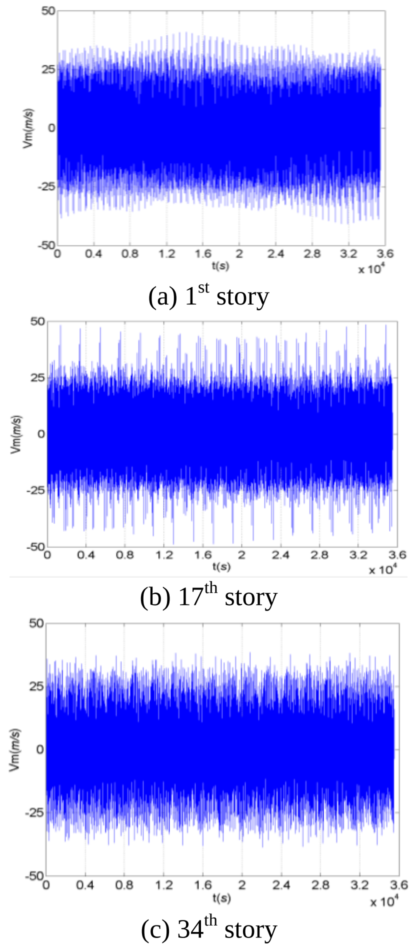


Fig. 3 Structure model

to study. Natural frequency of the building is 0.328 Hz. Finite element analysis software ANSYS was applied to model the building. Beams and columns were modeled as Beam 188 element in the software Moreover, the boundary condition of bottom was regarded as fixed without considering the ground interaction. The model of the building is shown in Fig. 3.

Based on the program of wind speed field, fluctuating wind speed power spectrum and time history data are calculated. The main parameters of the analysis include dimension nn, ground roughness length z_0, upper cut-off frequency n_u, modeling time M, and annual maximum wind speed recorded every 10 minutes on 10 meter height U_{10}. Based on the research of the annual maximum wind speed recorded every 10 minutes in south east of China, the

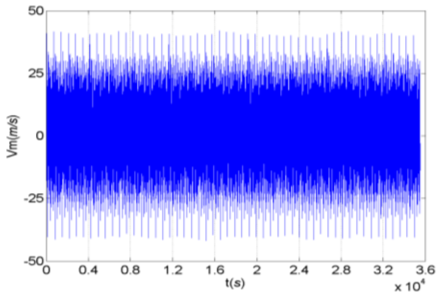


(a) 1st story

(b) 17th story

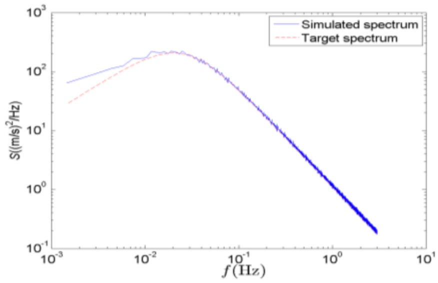
(c) 34th story

Fig. 4 Fluctuating wind speed time history at various heights

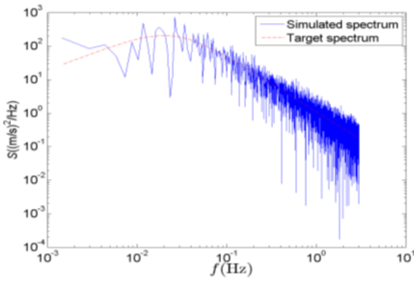


(d) 52nd story

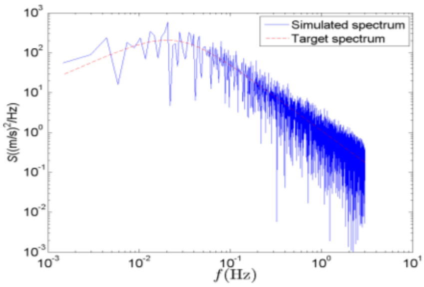
Fig. 4 Continued



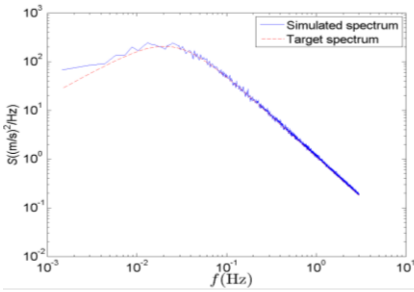
(a) 1st story



(b) 17th story



(c) 34th story

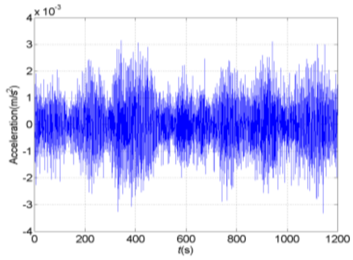


(d) 52nd story

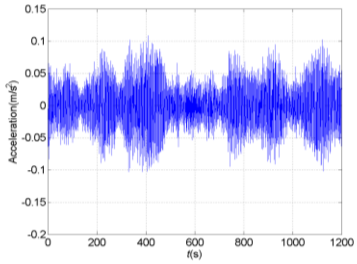
Fig. 5 Fluctuating wind power spectrum

distribution should be Pearson-III. Therefore, U_{10} was considered as the maximum wind speed depends on 50 years return period, which is 31 m/s (Lin *et al*. 2015b).

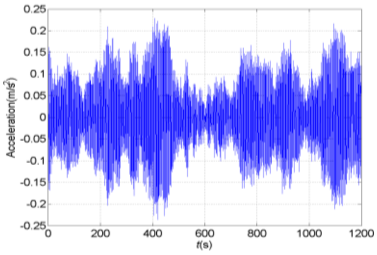
Fig. 6 Nephogram of acceleration



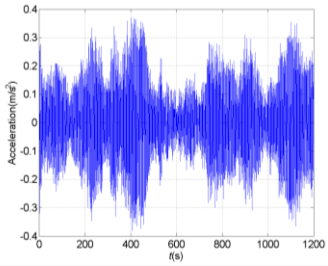
(a) 1st story



(b) 17th story

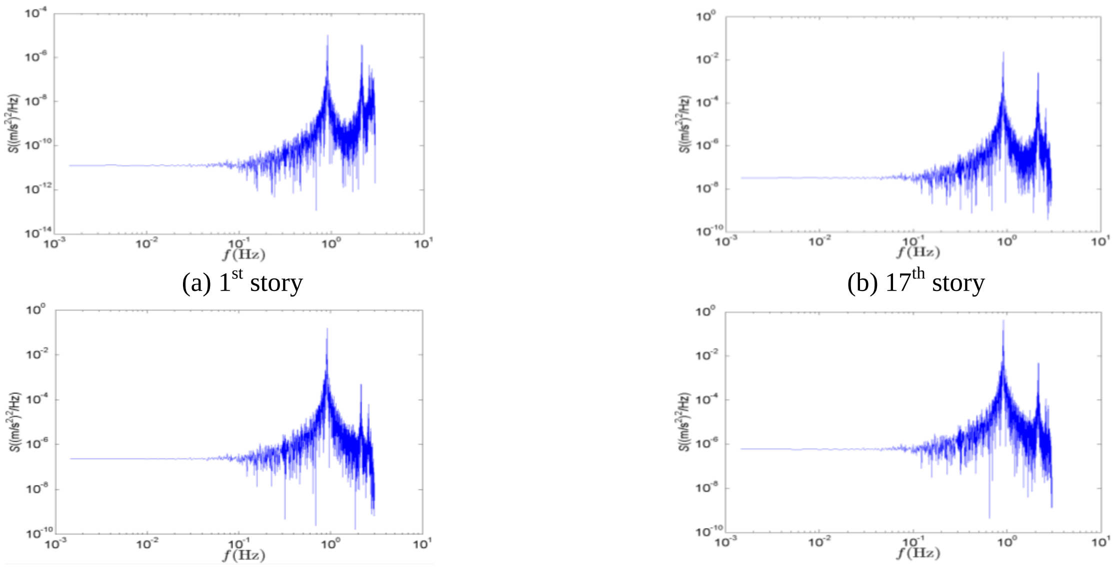


(c) 34th story



(d) 52nd story

Fig. 7 Acceleration time history of the structure



(a) 1st story

(b) 17th story

(c) 34th story

(d) 52nd story

Fig. 8 Acceleration power spectrum of the structure

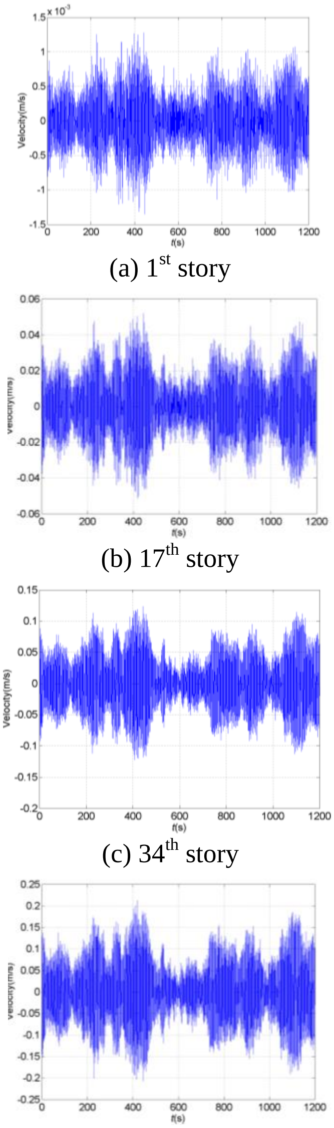
Fig. 9 Nephogram of velocity

In this case, the nn=52, z_0=0.01 m, n_u=3 Hz, M=4096. The results of the wind speed time history and power spectrum can be seen in the Fig. 4 and Fig. 5. For the sake of analysis, the 1st, 17th, 34th and 52nd stories were selected to be simulated.

Fig. 4 indicates the fluctuating wind speed time history. To verify the accuracy of results, the corresponding wind speed power spectrums in logarithm coordinate can be seen in Fig. 5. The blue line indicates the simulated spectrum while the red dashed line represents the target spectrum, which is Davenport spectrum in the paper. It can be seen that the simulated and target spectra match reasonably well, indicating the effectiveness of the proposed methodology.

3.2 Structure responds simulation under the fluctuating wind field

The structure modeling is simulated by ANSYS. Some



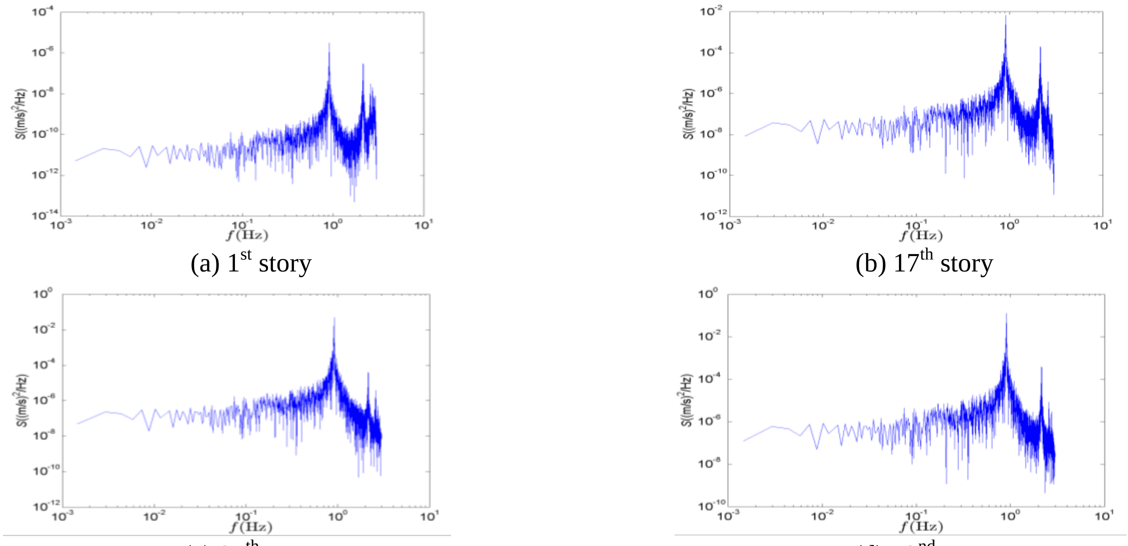
(a) 1st story

(b) 17th story

(c) 34th story

(d) 52nd story

Fig. 10 Velocity time history of the structure



(a) 1st story (b) 17th story

(c) 34th story (d) 52nd story

Fig. 11 Velocity power spectrum of the structure

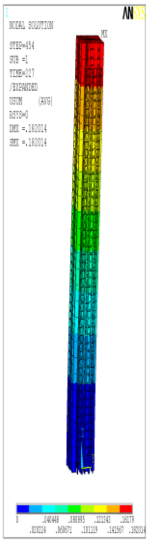
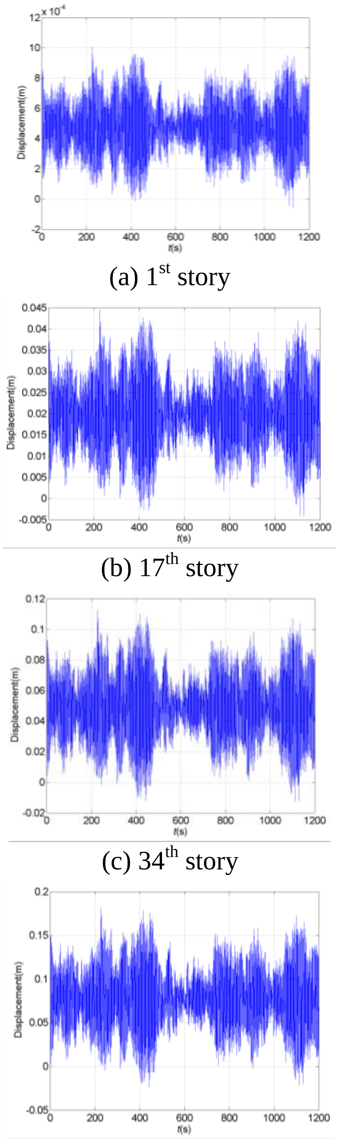


Fig. 12 Nephogram of displacement



(a) 1st story

(b) 17th story

(c) 34th story

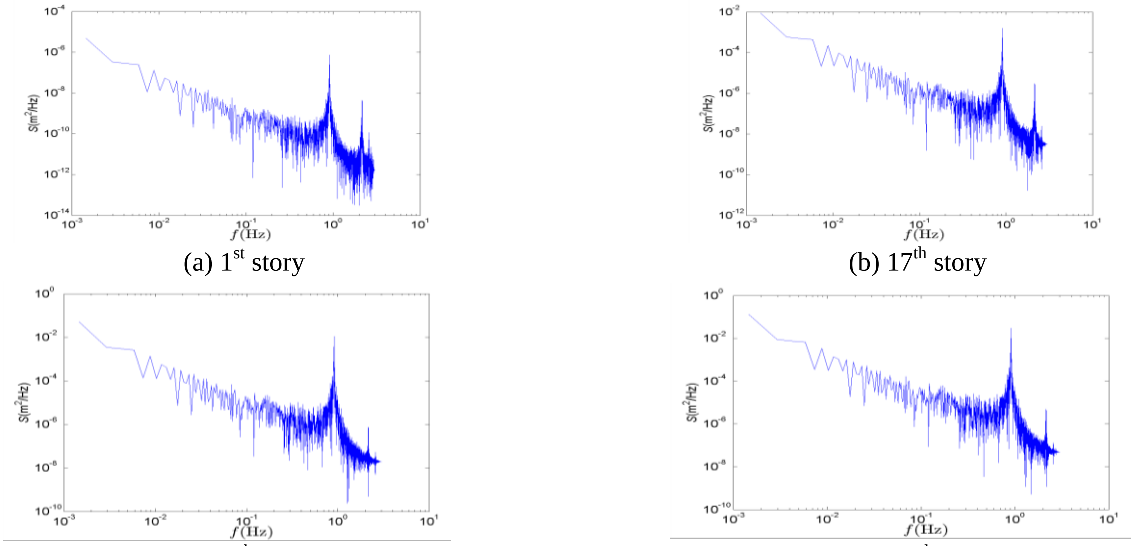
(d) 52nd story

Fig. 13 Displacement time history of the structure

of the stories (1st, 17th, 34th and 52nd) were selected to show the dynamic characteristics of the model. Fig. 6 shows the nephogram of acceleration of the structure and Fig. 7 indicates the acceleration time history of the model. As it can be observed in the figures, the acceleration reaches the highest in the top story. Fig. 8 represents the acceleration power spectrum of the model, which can be concluded that the accelerations are mainly dominated by the high frequency dynamic despite the stories.

Analogously, Fig. 9 shows the nephogram of velocity while Fig. 10 represents the velocity time history indicating that the higher velocity appears on the top stories. According to Fig. 11, the high frequency dynamic also plays an important role to the structure vibration.

Fig. 12 indicates the nephogram of displacement and Fig. 13 indicates the displacement time history of the selected stories. The displacement of the 52nd story is around two hundred times that of the 1st story. The power



(a) 1st story (b) 17th story

(c) 34th story (d) 52nd story

Fig. 14 Displacement power spectrum of the structure

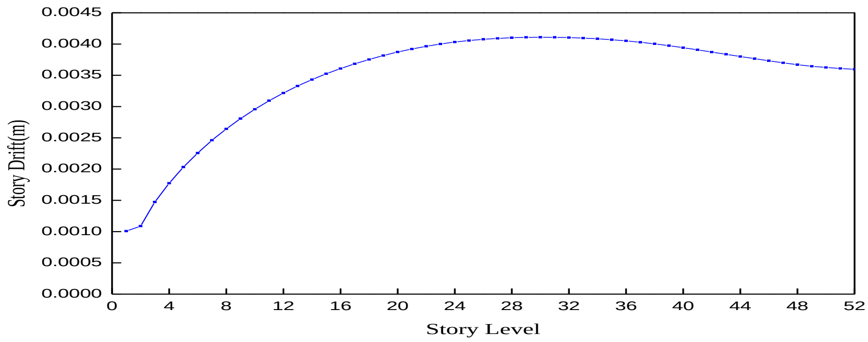


Fig. 15 Story drift of the structure

spectrum and the displacements are also dominated by the high frequency.

Fig. 15 shows the variation of story drift of the structure with building elevations. The story drift is defined as the difference in lateral deflection between two adjacent stories. It is found that the story drift reaches to the maximum neither at the bottom story nor at the top story, but at the middle part of the building.

4. Conclusions

A reasonable wind field time history is of great significance for the analysis of stochastic wind field-induced structural response and reliability. Based on the cross stochastic Fourier spectrum, a calculation method for stochastic wind field was proposed in the paper. The detailed derivation of equations and programming were introduced in the paper as well. Using the numerical software MATLAB, the simulation results were presented. A 52-story high-rise building was taken as a study case. Simulation of the fluctuating wind field was programmed and ANSYS software was employed to calculate the response of the structure. Results are shown as below:

• Based on the simulation by cross stochastic Fourier spectrum and wind speed field program, the simulated spectrums fitted target spectrums very well. The comparisons of the fluctuating wind power spectrums indicated the efficiency of the proposed calculation method.

• According to the model analysis by ANSYS software, the largest acceleration occurred at the top of the structure. Moreover, the largest displacement and velocity appear on top story of the structure as well. Considering the three responses, there is large difference between the maximum and the minimum values, which could be more than one hundred times.

• The largest story drift occurred at the middle part of the building, which was almost four times that of the smallest one on the bottom of the building.

• Power spectrum analysis of acceleration, velocity and displacement showed that the high frequency dynamics played a significant part in the structural vibration, and it should be received attention in further structural analysis.

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