

Simulation of Fluctuating Wind Pressure for Heliostat by Autoregressive Model Method

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Abstract: Through statistical analyzing existed wind tunnel tests' time interval data of fluctuating wind speed by heliostat's entrance and fluctuating wind pressure on its surface, various spatial nodes' fluctuating wind pressure's relevant characteristics are obtained. Basing on wind speed spectrum which alters accordingly with height, random sequence of different nodes' corresponding fluctuating wind pressure time interval is simulated by using AR method. The simulation result tallies well with the tentative data.

Key words: Wind pressure power spectrum, Wind pressure time series, Numerical simulation, AR method, Heliostat

0. Introduction

It's generally & internationally acknowledged that solar energy plays an important role in renewable energies for its incomparable merits including cleanliness, safety, easy availability, long life, freedom from maintenance and so on. It's spacious in countryside area where sunshine is also sufficient, as is suitable to develop solar energy electricity generation technologies to alleviate tough problem of electricity using. Heliostat group is the main part of tower-typed solar energy power plant's heat collecting system. The so-called tower-typed solar energy power plant occupies bigger area and does demand to its peripheral environment. So generally it's located away from urban area, while commodious places like outskirts or village areas are good candidates. The landform of such places is comparatively smooth & flat, the ground roughness is lower, as decides wind load's larger energy and stronger wind effect on heliostat. Heliostat set is a kind of flexible structure that is extremely sensitive to wind load. Therefore, research on heliostat's working under wind load and how to improve its wind-resistance appear significant in designing.

Wind load includes mean wind load whose period is long and fluctuating wind load whose period is short. The mean wind load is usually dealt with as static one, while research methods on fluctuating wind load's effects on the structure are mainly divided into two kinds: time domain analytic method and frequency domain analytic method. The so-called frequency domain analytic method is to convert existed wind speed spectrum or that transformed from time interval by tests to wind pressure spectrum, to obtain response spectrum through power transmission coefficient, then to obtain structure power responsive value through integrating response spectrum according to random theory. The time domain analytic method is to directly utilize wind pressure time interval from wind tunnel tests or computer simulated onto the structure, to obtain the structure's power response directly through power computation. The time domain analytic method can not only obtain relationship between natural wind & structure power response it produces and time, but also cover the structure's non-linear influences, as confirms its vital significance in wind engineering research. When there's no wind-tunnel test data, it's an effective method to seek wind load time interval by using numerical value simulation.

1. Fluctuating wind speed and wind pressure power spectrum

Wind speed vector at any time is constituted by mean component and fluctuating component:

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

Mean wind velocity is only related with height, could be calculated by logarithm ratio or index ratio. Here index ratio is adopted in the computation formula:

$$\bar{v}(z) = \bar{v}(10)(z/10)^\alpha \quad (2)$$

z is height of measured point, α is index of ground roughness.

Fluctuating wind is stochastic and changes with time and spatial variation, as is usually considered steady Gauss stochastic process with zero average value. Fluctuating wind speed could be described through its power spectrum. Fluctuating wind speed power spectrum mainly reflects intensity of energy distribution each frequency segment corresponding to in fluctuating wind, describing process statistical characteristics' digital features from frequency point of view.

Fluctuating wind speed spectrum is to be obtained by processing strong wind observation record. Common wind speed spectrum includes: Davenport spectrum disregarding onflow's integral length scale's alteration with height, Harris spectrum, VonKarman spectrum with onflow's integral length scale's alteration with height taken into account, Simiu spectrum and so on.

Karman spectrum and Simiu spectrum have taken altitudinal influence into account. Its function form is:

$$\frac{fS(f)}{\sigma^2} = \frac{4fL/\bar{v}}{[1 + 70.8(fL/\bar{v})^2]^{5/6}} \quad (3)$$

$$\frac{fS(f)}{\sigma^2} = \frac{200zf/\bar{v}}{[1 + 50(zf/\bar{v})^2]^{5/3}} \quad (4)$$

f is frequency of fluctuating wind velocity, \bar{v} is the mean wind velocity at altitude of z , L is onflow integral length scale.

Relationship of wind pressure and wind velocity is $w = rv^2/2g$. Power spectrum of fluctuating wind pressure could be gained according to fluctuating wind velocity's power spectrum. That is:

$$S_w(y, z, f) = 4\bar{w}^{-2} S_v(f)/\bar{v}^2 \quad (5)$$

f is frequency of fluctuating wind velocity, $S_v(f)$ is function of fluctuating wind velocity's power spectrum, $S_w(f)$ is function of fluctuating wind pressure's power spectrum, \bar{w} is the mean wind pressure at altitude of z .

Existed wind-tunnel test data are based to calculate the mirror's fluctuating wind pressure at wind direction angles ranging from 0° to 180° and elevation angles ranging from 0° to 90° . Its 0-dimensional coordinates power spectrum curves are drawn up and compared with that obtained through Karman and Simiu wind velocity conversion. It could be seen that the actual value and the computed value fit well in certain range of elevation angle and wind angle. Here one point should be made clear, that is when the mirror is vertical to wind direction, the fluctuating wind pressure is mainly caused by vortex shedding, and its alteration rules deviate from predicted values.

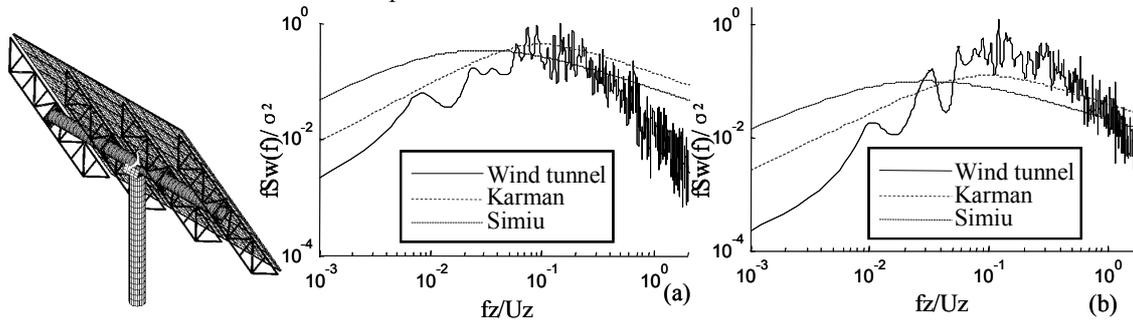


Fig.1 Structure of heliostat

Fig.2 Comparison of Wind Tunnel's Wind Pressure Spectrum from Tests and Computed One (a) Wind Direction Angle 0° , Elevation Angle 0° (b) Wind Direction Angle 45° , Elevation Angle 70°

2. Fluctuating wind pressure space coherence function and correlation function

Each space point's fluctuating wind pressure is mutually interactive, whose space relevance could be expressed by Coherence Function. Here the frequency domain correlation coefficient formula suggested by Davenport is adopted, and is extended to degree of three-dimension.

$$\rho(f) = \exp \left\{ \frac{-f \left[C_x^2 (x - x')^2 + C_y^2 (y - y')^2 + C_z^2 (z - z')^2 \right]^{\frac{1}{2}}}{\frac{1}{2} [\bar{v}_z + \bar{v}'_z]} \right\} \quad (6)$$

C_x , C_y & C_z are respectively two space points' attenuation coefficients at all angles; x , y , z and x' , y' , z' are respectively two space points' coordinates; \bar{v}_z and \bar{v}'_z are the mean wind velocity at altitudes of z and z' ; f is fluctuating wind's frequency.

The n-dimensional fluctuating wind pressure's power spectral density function could be directly deduced from wind pressure power spectral density function. The mutual power spectral density function should take the two space points' relevance into account. With i & j 's spectrum density - S_{ii} & S_{jj} given, the formula below could be computation's ground:

$$S_{ij}(f) = \sqrt{S_{ii}(f)S_{jj}(f)} \cdot \rho_{ij}(f) \quad (7)$$

The correlation function could be computed by using Wiener-Khintchine Formula:

$$R_{ij}(\tau) = \int_0^\infty S_{ij}(f) \cos(2\pi f \tau) df, \quad i, j = 1, \dots, n \quad (8)$$

3. Simulation of wind pressure time interval

Among wind load's numerical value simulation methods, the steady Gauss stochastic process simulation methods could fall into two kinds: superposed harmonious wave method and linear wave filtering method. Superposed harmonious wave method is to sum basing on trigonometric series, as is also called frequency spectrum denotation method including CAWS method, WAWS method, etc. Linear wave filtering method is also called time series method, which is the stochastic process disposing white noise random sequence with mean zero value through filter and makes it output assigned spectrum features basing on linear filtering technology. Auto Regressive Method (AR), Moving Average Method (MA), Auto Regressive Moving Average Method (ARMA) and so on are included. Among them, AR Method computes little while its speed is high, so it's widely applied in stochastic vibration analysis.

The fluctuating wind pressure vector could be expressed by the formula below:

$$w(t) = Cu(t) \quad (9)$$

C is Cholesky decomposed lower triangular matrix of n-dimensional fluctuating wind pressure time interval's correlation function matrix R_N ; $u(t)$ is extended self-regressive model of n irrelevant Gauss stochastic process vectors provided according to Iwatani. N stochastic processes could be produced via it;

$$R_N = CC^T \quad (10)$$

$$u(t) = \sum_{k=1}^p \Psi_k u(t - k\Delta t) + N(t) \quad (11)$$

P is the AR model's step number; Δt is minimum time interval. According to mutual correlation matrix covering time lag and Yule-Walker equation, it could be obtained that:

$$R(k\Delta t) = \sum_{k=1}^p \Psi_k R[(m-k)\Delta t] \quad m = 1, \dots, p \quad (12)$$

To get the parameters by using Gaussian Elimination Method:

$$\begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \vdots \\ \Psi_p \end{bmatrix} = \begin{bmatrix} R(0) & R(\Delta t) & \cdots & R[(p-1)\Delta t] \\ R(\Delta t) & R(0) & \cdots & R[(p-2)\Delta t] \\ \vdots & \vdots & \cdots & \vdots \\ R[(p-1)\Delta t] & R[(p-2)\Delta t] & \cdots & R(0) \end{bmatrix}^{-1} \begin{bmatrix} R(\Delta t) \\ R(2\Delta t) \\ \vdots \\ R(p\Delta t) \end{bmatrix} \quad (13)$$

R_N could be determined according to Formula (14). To Cholesky decompose R_N , the following lower triangular matrix could be obtained.

$$R(0) = \sum_{k=1}^p \Psi_k R(k\Delta t) + R_N \quad (14)$$

$$N(t) = C \cdot n(t) \quad (15)$$

$n(t)$ is a group of stochastic series mutually independent whose mean value and unit square deviation are both zero.

4. Simulation of heliostat's structure wind load

The above elaborated methods are accorded in Matlab programming to compute heliostat's surface fluctuating wind pressure. The heliostat's mirror straddles on a combination cell whose arrangement is accorded to divide the board into 24 blocks, and each block's geometrical center is granted as a simulated spot. The simulated spot's coordinates vary with alteration of heliostat's elevation angle and azimuth angle. The mean wind velocity 14m/s at altitude of 10m is adopted. Chinese Load Standard divides landforms into four kinds, among which 'field, village, jungle, knoll as well as house-sparse village or town and suburb' belongs to B-class. B-class landform's ground roughness index $\alpha = 0.16$; Sampling frequency is 50 Hz; Simulation period is 120s; Time-gap is 0.2s; 4 is taken to be The AR's step number.

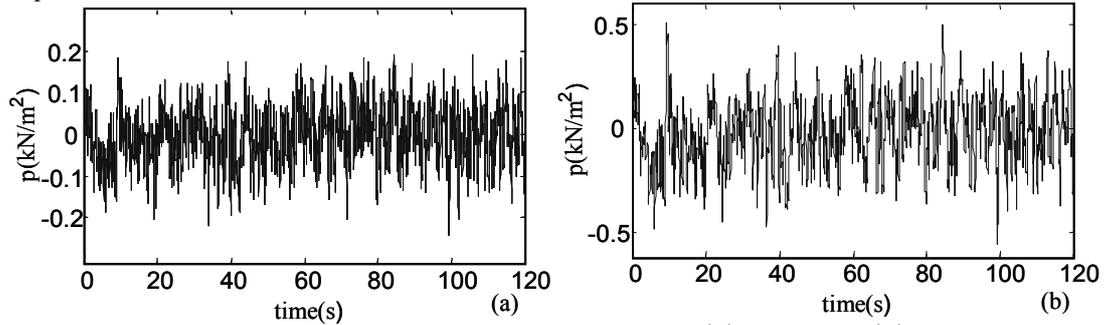


Fig.3 Curve of Simulated Wind Pressure Time Interval (a) Block A1, (b) Block C8

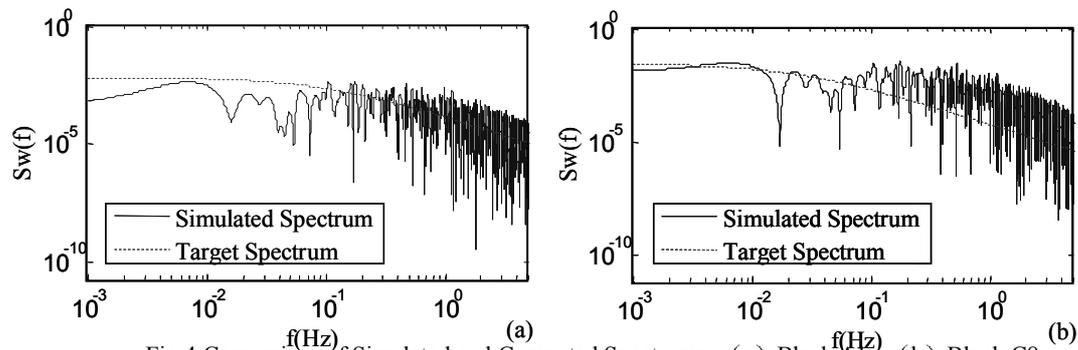


Fig.4 Comparison of Simulated and Computed Spectrums (a) Block A1, (b) Block C8

Fig. 3 shows curves of lower right block A1 and upper left block C8's fluctuating wind pressure time intervals separately. Fluctuating wind pressure is a stochastic process whose accuracy needs verification through statistical examination. The commonly used verification method is to seek the produced time interval sequence's power spectrum, and compare it with target power spectrum. Fig. 4 demonstrates that the simulated wind pressure time interval's power spectrum fits with the target spectrum extremely well. Since this case uses power spectrum altering with different altitudes, target power spectrums of A1 and C8 are not the same.

5. Conclusions

According to this paper, the AR method could effectively simulate stochastic wind load process, compute quickly and precisely, and accommodate more spots' simultaneous simulation with their space correlation characteristics taken into account. But structure in wind field is to be affected by onflow and vortex shedding. When the mirror is against the wind, frequency of load power spectrum's peak value is basically consistent with that of approaching longitudinal wind spectrum's. Load power spectrum has obvious feature of falling off swirl which perplexes the situation when it's crosswind. So this method brings bigger errors. Statistic data of tests indicates that logical results would be obtained at elevation angle varying from 0° ~ 70° and wind angle varying from 0° ~ 60° .

Numerous parameters are involved when simulating wind pressure time interval. Whether they're reasonable or not counts for much. Some of them could be selected according to specific project. Some other parameters like sampling frequency, time-gap, step number of AR computation and so on are not so direct-viewing. But these parameters usually do influence computation speed, simulation precision, etc., or even sometimes decide whether the simulation process could carry on or not. Generally speaking, the higher sampling frequency is, the more precise simulation is. But the price is expanded computation work. Value of minimum time-gap Δt shouldn't be too small. Suggestion is no smaller than 0.1s, otherwise mistake emerges. The AR computation step number should be the one by which square sum of two neighboring models' residual errors changes little, generally between 4 and 6. Segmentation unit of frequency computation is better not to be overlarge, especially when high-frequency contains less energy. Research indicates that when upper limit of segmented frequency is 3, total energy's over 95% could have been covered. Thus it's unnecessary to enlarge it.

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