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Analysis of Wind-Induced Vibration Response for a Long-Span Double-Arch-Support Steel Structure

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Abstract. As a new long-span double-arch-support steel structure system is applied to a stadium, it is necessary to study the wind-induced vibration response of the roof structure to meet the need of design. The modal analysis and the response analyses which include static wind response and wind-induced vibration response are calculated by ANSYS. The results show that the natural vibration frequency of structure is intensive (0.93 Hz~4.2 Hz). The most unfavorable wind direction angle of 135° is selected to study the wind-induced vibration response. And the wind-induced vibration coefficient calculated is satisfactory when compared with the wind tunnel test. It can be seen that it is feasible to use the stochastic simulation analysis method of wind-induced vibration response to get the wind-induced vibration coefficient.

Introduction

In modern society, long-span roofs are applied to all kinds of large public buildings to meet the requirements of architecture aesthetics and functions. However, the roofs can often be destroyed by the response of wind suction and fluctuating wind loads on the roof structure. So the wind-resistant performance of long-span structures becomes a concerned focus for designers and the select of wind vibration factors has been a key problem to solve [1]. In this paper, the wind-induced vibration response of a new long-span double-arch-support steel structure is studied to get its wind vibration factors and provide a reference for future design.

The new long-span double-arch-support steel structure is applied to a large stadium, which is combined with the upper tube arch and lower space arch (triangle truss). The span of the structural arch foots is 257m, and the maximum span of the radial main beam is 50m which doesn't include the cantilever parts. The roof structure is combined with tapered H-section steel beams, purlins and central counterbracings. Tapered H-section steel beams change gradually from the neighboring supports' section (H1000x600x16x34) to the lower space arch's section (H2000x600x16x34). Meanwhile the purlin's section type is H500x300x8x16 with alternative arrangement of 3 meters. And the section type of central counterbracing adopts ø350×10. As the both sides of structure are completely symmetrical, single side is taken as modal to be analyzed by ANSYS. The design sketch of double-arch-support steel structure is shown in Fig.1.

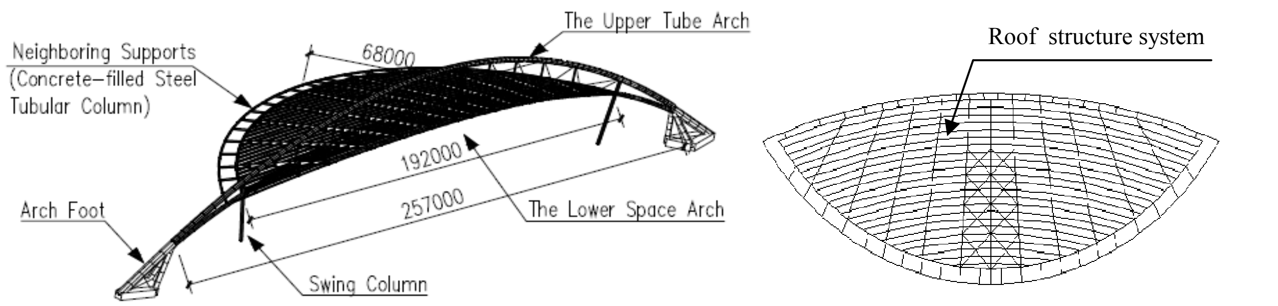


Fig.1 The design sketch of long-span double-arch-support steel structure

Modal Analysis

The structure modal is analyzed by the method of Block Lanczos in ANSYS [2]. And the contribution of cable pretension to the stiffness is taken into account in the analysis of each mode of the structure. The natural vibration frequency distribution of double-arch-support steel structure system is concentrated in the range of 0.93 Hz and 4.2 Hz in the first 200 orders. According to the load code for the design of building structures (GB50009-2012) [3], the first natural vibration period of the long span roof structure is 1.073s which is larger than 0.25s. Therefore, it is necessary to consider the effect of fluctuating wind pressure on the wind-induced vibration of structure. Meanwhile, the first three modals present overall vertical deformation which means the overall stiffness is better.

Static Wind Response Analysis

As the amount of wind-induced vibration response calculation is quite large, it's impossible to make an analysis of various directions of the wind [4]. So it's better to determine which direction controls the design of structure. The paper adopts the static wind response as a standard for judgment. Firstly, the wind loads of various working conditions are applied to the modal to calculate. Then the most unfavorable wind direction angle can be selected according to the maximum displacement response of node. There are nine wind direction angles (0º, 30º, 60º, 90º, 135º, 180º, 210º, 270º, 315º) to be selected with comprehensive consideration. The basic wind pressure of structure is 0.45kN/m^2 and the ground roughness is class B. The considered load includes dead weight, cable prestress and equivalent wind load standard values under all direction angles. The schematic diagram of wind direction angle in wind tunnel tests is shown as Fig.2. And this paper only shows the displacement deformation under the direction angle of 135 º in Fig.3 due to the limitation of space.

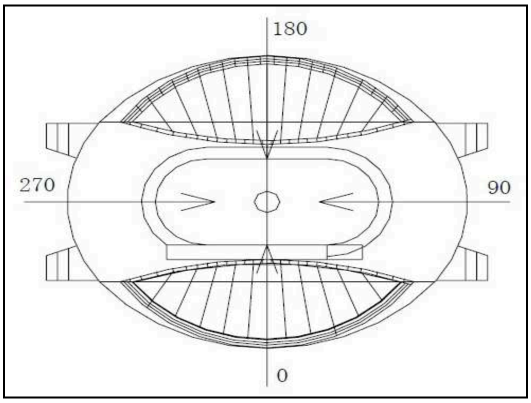


Fig.2 The schematic diagram of wind direction

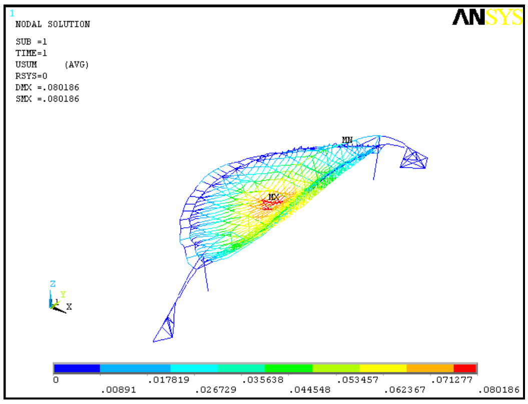


Fig.3 The displacement deformation (135º)

The results show that the main deformation of structure is dent, which means the equivalent wind load value of each direction angle is smaller than the weight of structure. The statistical results of total lift force (vertical upward), total downwind thrust of structure and the maximum displacement of each direction angle are listed in Table 1. It can be seen that the wind direction of 135º shows the maximum wind suction. Its total lift force is 5633KN and the minimum value of the maximum displacement is 80mm. It means that 135º is the most unfavorable wind direction and the wind loads in this direction should be regarded as the key consideration during the design.

Table 1 The statistical results under the action of each wind direction Angle

Wind direction angle	0 º	30 º	60 º	90 º	135 º	180 º	210 º	270 º	315 º
The total lift force (KN)	3904	3247	2405	1948	5633	3859	3862	1901	2821
The total downwind thrust (KN)	945	878	523	197	1421	936	1058	199	716
The max displacement (mm)	123	126	128	129	80	119	120	131	126

Wind-Induced Vibration Response Analysis

Calculation method. This wind-induced vibration response of structure is analyzed mainly based on the random simulation of fluctuating wind [5]. According to the statistical characteristics of wind loads, the stochastic simulation of fluctuating wind load time-history which adopts the linear filtering method is applied to the finite element modal. This paper adopts step-by-step integration method in time domain to solve structural dynamic differential equations with considering the influence of geometric nonlinearity. Then the samples of structural response are obtained and the law of wind-induced response can be summarized through the mean, mean square deviation and the corresponding frequency spectrum characteristics of wind vibration response. This time-history calculation uses the Newmark-β integration method to solve structural dynamic response [6]. The dynamic differential equation Eq.1 can be expressed as follows:

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=\{P(t)\} \tag{1}$$

where [M] and [C] are respectively lumped mass matrix and Rayleigh proportional damping, [K] is stiffness matrix and {P (t)} is wind load function.

Due to the equivalent static wind loads method, it shows the dynamic effect of wind loads can be replaced by the product of static load and wind-induced vibration coefficient β. Meanwhile the wind-induced vibration coefficient of displacement can be used to calculate the equivalent static wind load, this paper adopts the wind-induced vibration coefficient of displacement directly which is given as Eq.2.

$$\beta_z=\frac{\hat{D}_y}{\bar{D}_y}=1+g\frac{\sigma_y}{\bar{D}_y} \tag{2}$$

where $\bar{D}_y$ means the structure displacement response under the action of average wind, $\hat{D}_y$ means the overall wind vibration displacement response of structure which includs average wind response and fluctuating wind response, σ_y is the mean square deviation of displacement response and g is the peak factor[7]. And the value of g is 3.5 in this paper.

Key parameter selection. As the overall response of double-arch-support steel structure mainly focus on the first few natural frequencies, the twentieth of the maximum frequency (1.727Hz) is selected as the integral time step (0.029s). Meanwhile, this paper adopts Rayleigh damping [6] and the damping ratio of steel structure is 0.02 generally. And the first and fifth natural frequencies (f_1=0.9322Hz, f_5=1.727Hz) are selected to calculate the damping value. Besides, the statistical analysis of the time-history response can be carried out by the mean and mean square deviation of displacement.

In practice, since the vibration characteristics of structure vary greatly in different parts, it is reasonable to divide the structure to ensure the accuracy of result. So the roof is divided into six areas in this paper which is shown in Fig.3. Besides, it is necessary to know the shape coefficient of roof to calculate the wind load time-history. So the shape coefficients of roof under the wind direction angle of 135° are given by wind tunnel test report in Fig.4.

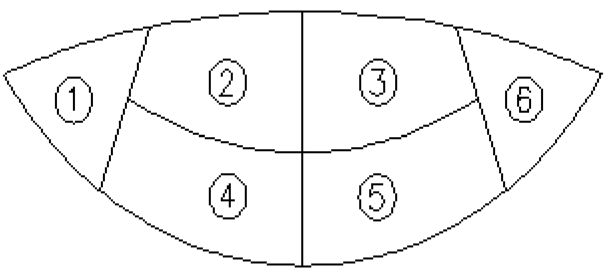


Fig.3 The partition of wind-induced vibration coefficient

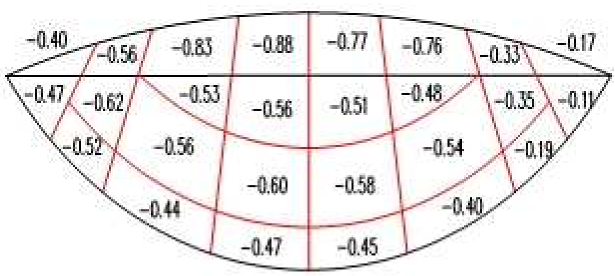
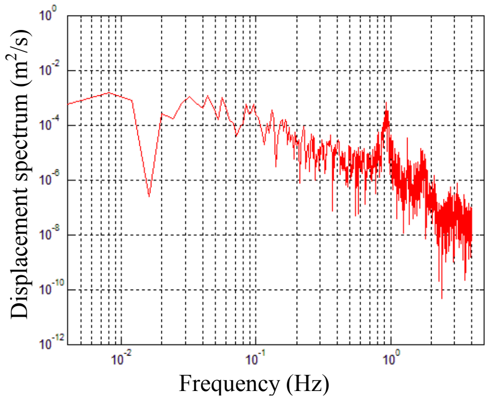
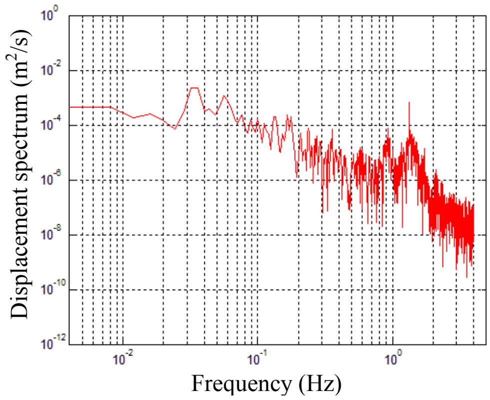


Fig.4 The shape coefficients of roof (135°)

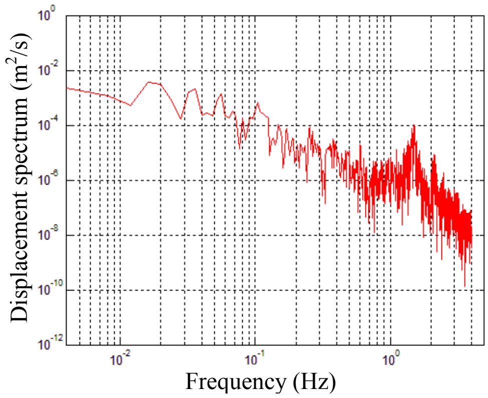
Analysis of calculated results. When the wind-induced vibration coefficients of displacement are collated on some nodes, the calculated values are extremely large and even beyond the normal range. But the values above are meaningless in practice. Therefore, the nodes of normal largest displacements in each area are taken into account to get the wind-induced vibration coefficients in this paper. At the same time, because there are lots of dense samples in the result, these valid data need to be transformed into the frequency domain in order to inspect the response of structure visually. The power spectrum reflects the distributions of the average energy in frequency domain under the fluctuating wind loads [8]. Figure.5 shows the representative four power spectrum curves of the structural displacement response.



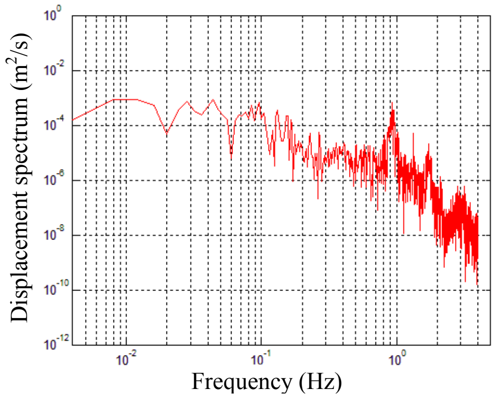
(a) Area 1



(b) Area 2



(c) Area 5



(d) Area 6

Fig.5 The displacement power spectrum of each area(135°)

It can be seen from Fig.5, the power spectrum curves of displacement are similar to the one of fluctuating wind speed, and the power response is mainly concentrated on the background response in low frequency. The low-frequency part below 0.9Hz is mainly the background response of wind. There are several peaks between 0.9 Hz and2.0 Hz, which are corresponding to the resonance of the first few frequencys respectively (f_1=0.9322Hz, f_2=1.358Hz, f_3=1.512Hz). It shows the wind-induced vibration response of the roof structure is mainly concentrated on vibration of low frequency and there is also along with a certain degree of resonance phenomenon. So the wind-induced vibration response is mainly affected by the background response and resonant response of the first few frequencies.

Comparison with wind tunnel test. In order to further verify the difference, it's necessary to make comparisons between the calculated wind-induced vibration coefficient based on stochastic simulation of fluctuating wind and the one of wind tunnel test [9]. The relevant data of the wind-induced vibration coefficient (135°) which include mean value, mean square deviation, the calculation values and experimental values of the wind-induced vibration coefficient are shown in Table.2. It shows that the calculation values are smaller than the experimental one in area 4 and 5, the error is about 12%.The calculation values are close to the experimental one in other areas.

Table.2 The relevant data of the wind-induced vibration coefficient (135º)

Partition number	1	2	3	4	5	6
mean value (mm)	23.30	34.74	32.92	48.38	48.06	18.53
mean square deviation (mm)	6.47	5.98	5.48	7.44	7.17	5.98
The calculation value	1.972	1.603	1.583	1.538	1.522	2.130
The experimental value of wind tunnel test	1.957	1.664	1.600	1.736	1.736	2.151
The error（%）	0.76	-3.69	-1.07	-11.38	-12.31	0.99

Thus it can be seen that the wind-induced vibration coefficient which is calculated through the stochastic simulation analysis method of wind vibration response reflects the wind-induced vibration characteristics of the structure to a large extent. The error of results is no more than 15%. So it is feasible to calculate the wind vibration coefficient through this method.

Conclusions

Through the modal analysis, the natural vibration frequency distribution of double-arch-support steel structure system is dense, and the first three modals of structure present the overall vertical deformation which means the overall stiffness is better. Meanwhile, 135º is the most unfavorable wind direction and the wind loads in this direction should be regarded as the key consideration during the design. And the wind-induced vibration response is mainly affected by the background response and resonant response from the first few frequencies. At last, it is feasible to use the stochastic simulation analysis method of wind-induced vibration response to calculate the wind-induced vibration coefficient through the comparison with wind tunnel test. And the calculated results of wind-induced vibration response can provide a reference for this kind of structure design.

References

[1] Feng Lu. Study of the wind-induced vibration response and wind vibration coefficient on long-span flat roof structure [D]. Hangzhou: Zhejiang University (2001). (In Chinese)

[2] Xinmin Wang. ANSYS numerical analysis of engineering structures [M]. Beijing: People's Communications Press (2011). (In Chinese)

[3] Load code for the design of building structures[S].GB50009-2012. (In Chinese)

[4] Junjie Luo, Dajian Han. Fast simulation method of stochastic fluctuating wind farm in long-span structures [J]. Beijing: Engineering Mechanics (2008). (In Chinese)

[5] Yuanqi Li, Shilin Dong. The simulation technology research and programming of long-span spatial structure wind load simulation technology research and programming [J]. Spatial Structures(2001). (In Chinese)

[6] Jingbo Liu, Xiuli Du. Structural Dynamics [M]. Beijing: China Machine Press(2005).(In Chinese)

[7] Yanlei Yu. The wind-induced response and parameter identification research of the spatial grid roof structure [D]. Harbin: Harbin institute of technology (2006). (In Chinese)

[8] Beibei Li. The effective tools of vibration analysis--power spectral density [J]. Packaging Engineering (2004). (In Chinese)

[9] Zhihong Wang. Simulation study of wind load [J]. Beijing: Journal of Building Structures (1994). (In Chinese)