# RESEARCH ON WIND PRESSURE AND WIND-INDUCED VIBRATION CHARACTERISTICS OF EXPO AXIS CABLE-MEMBRANE STRUCTURE BY FIELD MEASUREMENT

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**Key words:** Cable-Membrane Structure, Field Measurement Research, Wind Pressure Characteristics, Wind-Induced Response, Damping Ratio.

**Summary.** In order to deeply investigate the wind pressure characteristics and the wind-induced vibration characteristics of cable-membrane structure, a monitoring study on the Expo Axis cable-membrane structure was carried out. The wind speed, wind pressure and wind-induced response were measured simultaneously. The wind pressure characteristics, the structure's dynamic characteristics and the damping ratio were analyzed based on the monitoring data. The probability density distribution of wind pressure has some non-Gauss property. With the change of wind direction wind pressure coefficient by field measurement and wind tunnel test has the same trend. The acceleration RMS and power spectral density vary with the wind direction. The acceleration RMS increases with the increase of mean wind speed. Damping ratio decreases with the increase of natural frequency.

## 1 INTRODUCTION

Cable-membrane structure is a new type of structure developed in recent decades. It has been widely used in large span spatial structures. It has the advantages of novel appearance, excellent mechanical property, better flexibility and unique aesthetic compared to traditional structures. Also it has the characteristics of light weight, small stiffness, low and dense natural frequency. It belongs to the wind-induced sensitivity structure, and wind load is the control load[1, 2]. The damping ratio of cable-membrane structures is always a difficult parameter to determine.

The research methods of the wind resistance of cable membrane structures are mainly focused on numerical wind tunnel method, random vibration analysis method and wind tunnel test method. Field measurement is the most direct and reliable method to study the characteristics of wind load and wind-induced response on structures. However, field measurement has the characteristics of long cycle, high difficulty and high cost, the lack of field measurement research has become an important factor in the study of wind resistance.

Some scholars, such as Li[3, 4] have carried out a series of field measurement research on low rise buildings and high-rise buildings. However, there are few studies on the wind pressure characteristics of cable-membrane structures. Kim[5] carried out a long term monitoring study on the dynamic response of the membrane structure of the World Cup Stadium in Jeju Island.

Expo Axis' roof in Expo 2010 Shanghai China is composed of two parts, the cable-membrane structure and Sun Valleys. The cable-membrane structure is open structure with a total length of about 840m, the maximum span of 97m, the maximum height of 38m, an area of about 64000 $m^2$. The cable-membrane structure roof comprises two parts of the supporting system and the membrane surface system. PTFE membrane material was used as membrane surface. It locates in Shanghai Pudong New Area in China and adjacent to Huangpu River, wind speed is large all year round, and in the summer and autumn it is easily affected by the typhoon. It is necessary to study wind pressure characteristics and dynamic characteristics of such structures.

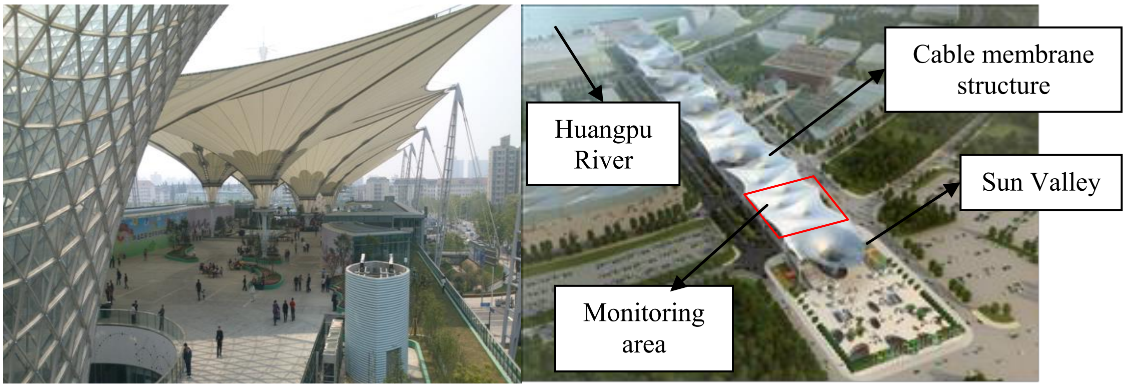



Figure 1: Expo Axis' roof in Expo 2010 Shanghai China

## 2 MONITORING SYSTEM

A long term monitoring system of Expo Axis' roof in Expo 2010 Shanghai China which consists of 5 main parts: the sensor system, the automatic collection system, the central database subsystem, the structural health warning assessment system and IoT monitoring system was built.

A 3-axis ultrasonic anemometers of Model 81000 produced by R.M. YOUNG COMPANY was used to measure the wind speed and the wind direction. For wind speed, its range is from 0 to 40m/s, the resolution is 0.01m/s and the accuracy is ±1% rms ±0.05 m/s (0 to 30 m/s) or ±3% rms (30 to 40 m/s). For wind direction, its range is from 0° to 359.9°, the resolution is 0.1° and the accuracy is ±2° (1 to 30 m/s) or ±5° (30 to 40 m/s). It was arranged at the top of the mast in the main measuring area.

22 micro differential pressure sensors were placed on membrane surface and for each measuring point there were two sensors arranged symmetrically top and bottom membrane surface. The measuring range is 0 ~ 1000Pa and the precision is ±1%.

8 acceleration sensors were placed on membrane surface to monitor the wind effect. The acceleration ranges from 0 to 0.5g (1g=9.8m/s$^2$) and the sampling frequency ranges from 0.05 to 300Hz, the voltage sensitivity is 10V/g.

The collection and processing system was specifically designed and developed according to the characteristics of the project. 5 dynamic acquisition instruments of 8 channels were used and were connected to the master station in main control room through optical fiber. The data was thransfered to a proprietary database by internet.

Table 1: Measuring points of sensors

| Point location | Main measuring area | | | | | | | | Secondary measuring area | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Pressure sensors (top) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Pressure sensors (bottom) | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| Acceleration sensors | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | | | |

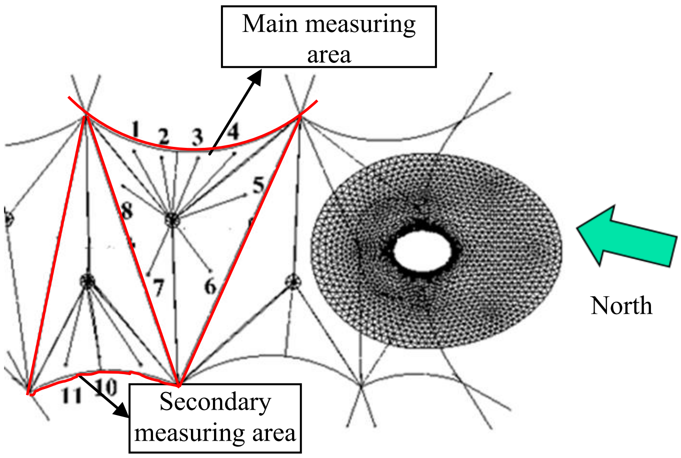



Figure 2: Measuring point layout

## 3 WIND PRESSURE CHARACTERISTICS

Similar to the probability density distribution of wind speed, the probability density distribution of wind pressure is analyzed by using higher order statistics analysis method. Table 2 shows the Mean values of skewness and kurtosis of fluctuating wind pressure of Measuring point 4, 9 and 15. Skewness is larger than 0 and kurtosis is larger than 3. It indicates that fluctuating wind pressure has some non-Gaussian characteristics. It is thought that the reason should be that wind pressure characteristics is not only affected by oncoming flow, but also by the signature turbulence of the structure. What's more the vibration of the structure can also affect the wind pressure characteristics.

Table 2: Mean values of skewness and kurtosis of fluctuating wind pressure

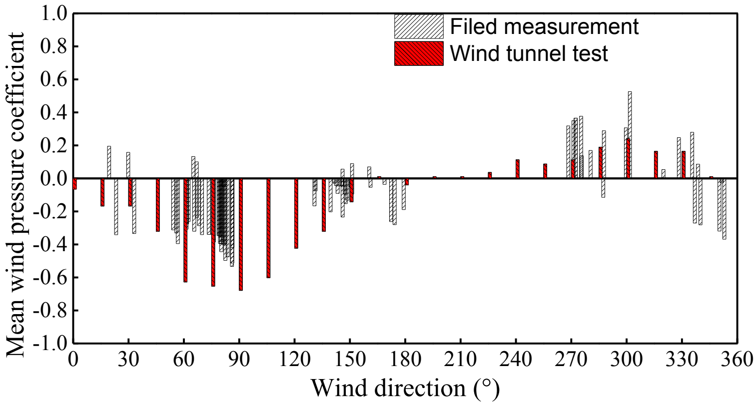
| Measuring point | 4 | 9 | 15 |
|---|---|---|---|
| skewness | 0.502 | 0.577 | 0.355 |
| kurtosis | 3.378 | 4.615 | 5.058 |

Mean wind pressure coefficient $C_{Pmean}$, Maximum wind pressure coefficient $C_{Pmax}$, Minimum wind pressure coefficient $C_{Pmin}$ can be calculated as:

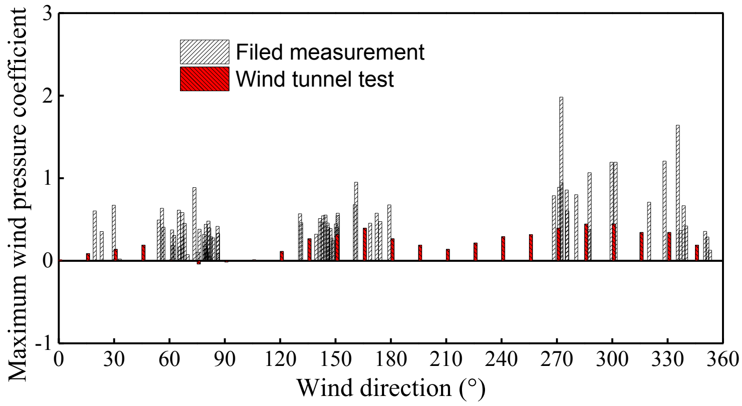
$$C_{Pmean} = \frac{P_{mean}}{\frac{1}{2}\rho U^2} \quad C_{Pmax} = \frac{P_{max}}{\frac{1}{2}\rho U^2} \quad C_{Pmin} = \frac{P_{min}}{\frac{1}{2}\rho U^2} \tag{1}$$

In Formula (2), $P_{mean}$, $P_{max}$, $P_{min}$ are the mean value, maximum value, minimum value of wind pressure in 10 minutes, for membrane, wind pressure can be obtained by making the difference between pressure measured by the wind pressure sensors top and bottom membrane surface at the same place. $U$ is the 10min mean wind speed, for comparison, it is chosen as the gradient wind speed, which can be calculated according to the measured mean wind speed.

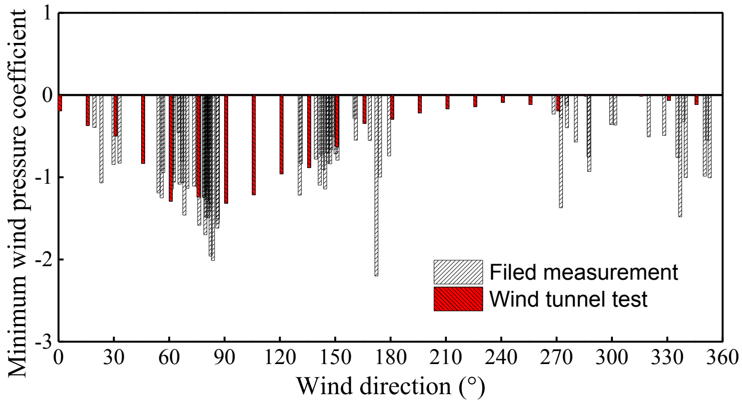
Some wind tunnel tests of rigid model of Expo Axis' roof have been conducted. Figure 3 shows the mean, maximum and minimum wind pressure coefficient of Measuring point 1 by field measurement and wind tunnel test. The results show that with the change of wind direction, wind pressure coefficient by field measurement and wind tunnel test has the same trend. however maximum and minimum wind pressure coefficient by field measurement is greater. the difference may be due to the difference of wind filed simulation and the neglect of structural vibration in wind tunnel tests.




a) Mean wind pressure coefficient




b) Maximum wind pressure coefficient




c) Minimum wind pressure coefficient

Figure 3: Comparison of Wind pressure coefficients of Measuring point 1 obtained by field measurement and wind tunnel test

## 4 WIND-INDUCED VIBRATION

Vibration strength of the structure can be represented by the root mean square of acceleration. The mean wind speed of 8 m/s was chosen, the acceleration RMS values changing with wind direction were shown in Figure 4. The root mean square value of acceleration response varies regularly with the direction of the wind, when the mean wind direction angle is near 0° and 90° , the acceleration RMS is larger, and the RMS is smaller when the mean wind direction angle is near 45° .

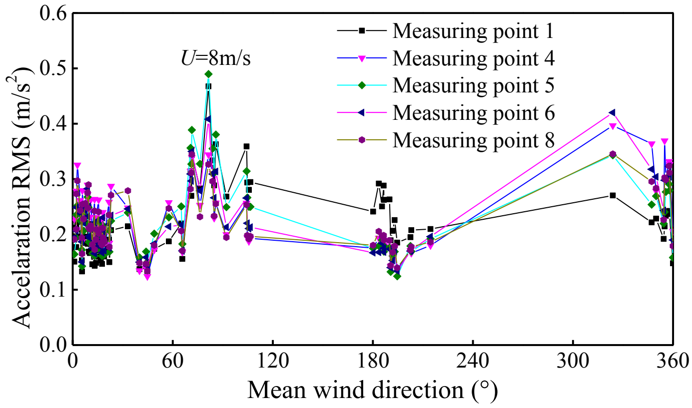



Figure 4: Acceleration rms versus wind direction

Figure 5 shows the power spectral density of measuring point 1 with mean wind speed of 8 m/s changing with wind direction. From the graph, when the wind direction angle is 2°, 23° and 45°, the power spectral density is small, especially at 45°, while at 65°, 81° and 106°, the power spectral is relatively large.

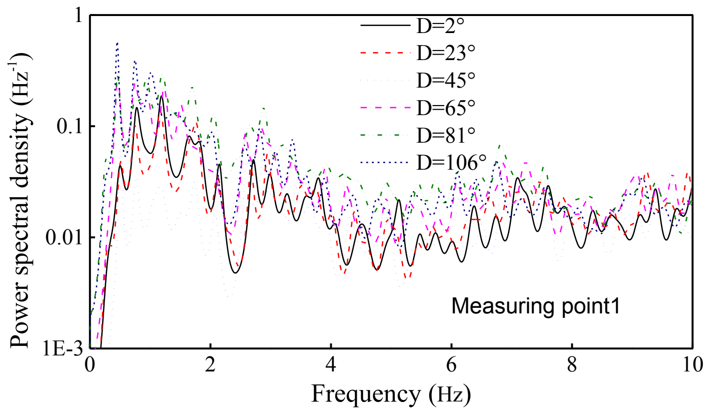
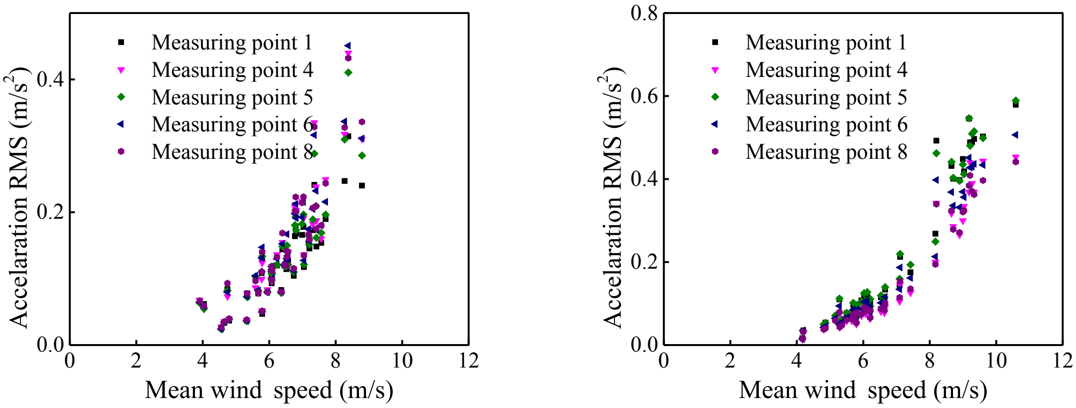



Figure 5: Power spectral density of Measuring point 1 versus wind direction

Figure 6 shows the relationship between acceleration RMS and mean wind speed, the acceleration RMS increases with the increase of mean wind speed, and the increase rate and the dispersion are also increasing.




a) Wind direction of 0° b) Wind direction of 90°

Figure 6: Acceleration RMS versus mean wind speed

## 5 NATURAL FREQUENCY AND DAMPING RATIO

Measuring point 1, 5 and 6 were chosen to analyze the structural natural frequency and the damping ratio. Peak picking method (PP), Hilbert-Huang Transform method (HHT) and Stochastic Subspace Identification method (SSI) were adopted.

Table 3 shows the natural frequency results calculated by PP, HHT and SSI. The results were mean values by several measurements. It is easy to see the first order frequencies were very close.

Table 3: Natural frequencies calculated by PP, HHT and SSI

| Frequency (Hz) | Method | | |
|---|---|---|---|
| | PP | HHT | SSI |
| 1st order | 2.86 | 2.85 | 2.70 |
| 2nd order | 13.08 | 14.66 | 12.17 |
| 3rd order | 24.72 | 24.50 | 15.15 |
| 4th order | | | 18.94 |
| 5th order | | | 25.12 |

Some pieces of 10 minutes data ware selected at different time to analyze the damping ratio. Figure 7 shows the damping ratio results calculated by SSI using different data. It indicates that damping ratio decreases with the increase of frequency.

The damping form of the cable-membrane structure is assumed to conforms to Rayleigh damping. The damping ratio formation of i-th order can be described as:

$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{\beta}{2}\omega_i \tag{2}$$

where $\alpha$ , $\beta$ are fitting parameters, $\omega_i$ is the i-th order frequency. $\alpha = 0.4084$ , $\beta = 0.0007$ , based on least square method. Figure 8 shows the mean value of damping ratio by SSI and the fitting curve based on Formula (2).

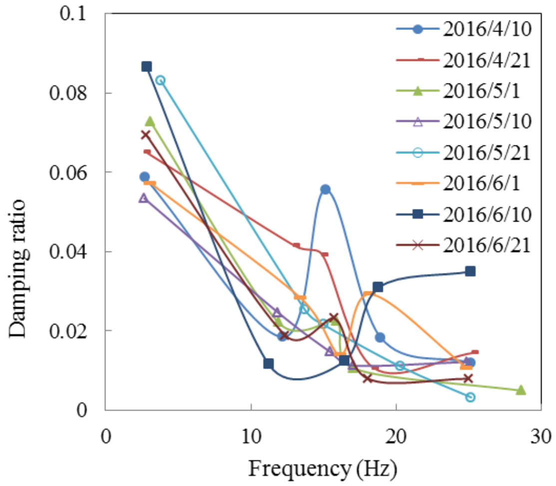



Figure 7: Damping ratio calculated by SSI

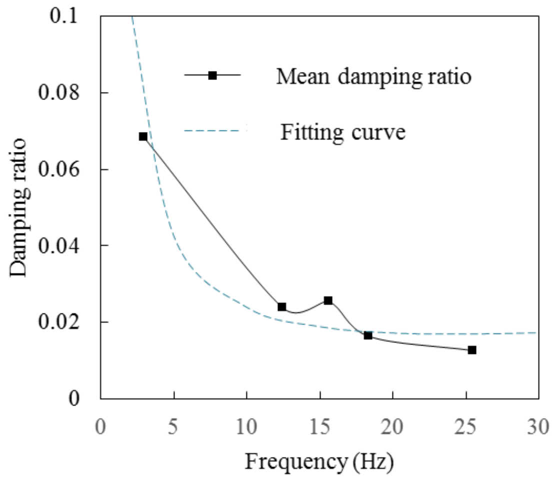



Figure 8: Mean value of damping ratio calculated by SSI and the fitting curve based on Formula (2)

## 6 CONCLUSIONS

This paper introduces the field measurement of Expo Axis' roof in Expo 2010 Shanghai China and shows wind pressure and the wind-induced vibration characteristics of the cable-membrane structure. The main conclusions are as follows:

- Obtaining the wind field, wind pressure and the structure's wind-induced response by field measurement is the most effective means to study the wind effects of cable-membrane structure.
- Fluctuating wind pressure has some non-Gaussian characteristics. With the change of wind direction wind pressure coefficient by field measurement and wind tunnel test has the same trend.

- The acceleration RMS and power spectral density vary with the wind direction. The acceleration RMS increases with the increase of mean wind speed and the increase rate and the dispersion are also increasing.
- Damping ratio decreases with the increase of natural frequency and it can be fitted in the Rayleigh damping form in this case.

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