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Effect of Turbulence Characteristics on Fluctuating Pressure Characteristics around Circular Cylinders and Cooling towers with Various Reynolds Numbers

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Abstract

Flow phenomena around a circular cylinder belong to basic issues in fluid mechanics. Many investigations have been conducted successfully. However, studies concerning turbulence characteristics (turbulence intensity, turbulence integral scale and spectrum characteristics) on fluctuating pressure characteristics are still few. In this paper, combined with field measurement results of a cooling tower, pressure experiments have been carried out using both active wind tunnel and passive wind tunnel in Tongji University. The effect of turbulence characteristics on fluctuating pressure characteristics with various Reynolds numbers has been investigated. The present results show the fluctuating pressure distribution is mainly determined by the Reynolds number. The turbulence intensity influences the fluctuating pressure distribution, especially in the windward region for higher Reynolds number. The fluctuating pressure coefficient decreases with the increasing turbulence integral scale, while the effect of wind spectrum is not evident.

Introduction

Flow phenomena around a circular cylinder belong to basic issues in fluid mechanics. Many investigations have been conducted successfully. Aerodynamic force characteristics in different Reynolds number regime have been investigated and reviewed by Roshko [12], Achenbach [1], Schewe [15], Zdravkovich [18] and so on. Till now, one of the interest areas is the characteristics of fluctuating wind pressures. Fluctuating wind pressures on cylinders are influenced by oncoming turbulence and signature turbulence. Nishimura and Taniike [10] investigated the characteristic of the fluctuating pressures induced by Karman vortex at a subcritical Reynolds number. Gu [7] studied the fluctuating pressure distribution for a bare cylinder and cylinder with rotatable splitter plates in a range of Reynolds number from 3E4 to 6E10. However, the effect of turbulence characteristics and the Reynolds number, especially higher Reynolds number, on the fluctuating pressure around circular cylinders has yet to be supplemented with more focuses.

The mathematical modeling about characteristics and mechanics of the cylinder flow field are useful to engineering application, such as marine engineering, buildings, bridges, tubes and so on. With the development of economy, the maximum height of circular buildings or other similar modern buildings and large-roof structures has continuously exceeded the world records. Cooling towers are one kind of circular section buildings, and show sensitivity to wind-induced effects under strong wind excitation. It is well-known that surface wind loading distribution of cooling towers is the dominant parameter for wind-resistance design. The on-the-spot measurement data of stochastic wind pressure for the large cooling tower at high Reynolds number is insufficient, and especially the relationship between flow turbulence characteristics and surface fluctuating wind pressure eigenvalue distribution is not explicit.

This study aims to fill the vacancy of the studies on the turbulence characteristics and the Reynolds number, especially higher Reynolds number, on the fluctuating pressure of circular cylinders. It is also the supplement to the basic investigation of flow around circular cylinders, and can provide design foundation for large-scale cooling towers and similar circular cross section structures.

Turbulence intensity, turbulence integral scale and spectrum characteristics are three decisive parameters for turbulent flow. In this paper, the field measurement data have been compared with earlier researcher's results. And wind tunnel experiments concentrating on the fluctuating pressure distributions around the circular cylinders considering the effect of turbulence intensity, turbulence integral scale and spectrum characteristics, have been carried out.

Dynamic wind pressure measurement

Field measurement layout

There are also some basic observation reports [2,8,9,11,13,14] that considered surface fluctuating wind pressure characteristics of cooling towers at supercritical Reynolds number conditions (Re⩾ 10E7). Some of the research results have been adopted by relevant specifications [5,6,17]. In Simiu and Scanlan [16], a simple comparison between fluctuating pressure measurement of prototype cooling towers from Ruscheweyh [13] and Sageau [14] and wind tunnel tests of a reduced-scale model by Davenport [4] in the monograph "Wind Effect of Structure" was made. It was noted that there were some obvious differences about fluctuating wind pressure distribution observation around the prototype cooling towers, and possible influencing factors have been ignored.

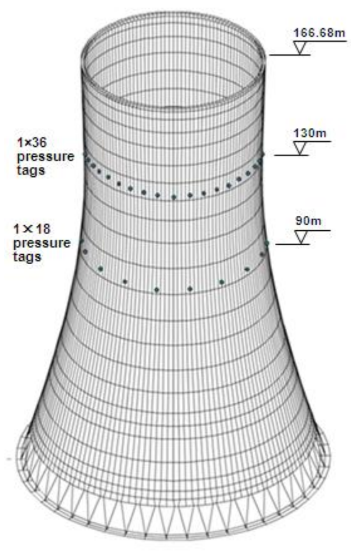

Figure 1. Layout of measured cooling tower

Since 2009, in-situ measurements on a 166.68m-high full-scale cooling tower located in Pengcheng Power Plant in Xuzhou of

Jiangsu province has been carried out, making a comparative analysis of actual measurements and wind tunnel experiments on the external surface fluctuating wind pressure distribution and subsequently establishing a relation pattern between inflow turbulence intensity and fluctuating wind pressure. The layout of the measured cooling tower is shown in Fig.1.

Field measurement result

Six strong wind events have been recorded ranging between 11m/s and 17m/s at a height of 130m, and the incoming wind direction from ENE to NNW can avoid the interference of surrounding buildings. Fig. 4 shows the fitted curve of fluctuating pressure coefficient, defined as the standard deviation of wind pressure coefficient considering possible pressure variations. Some previously measured results of fluctuating pressure are also compared. The circumferential fluctuating pressure distribution can be roughly divided into three areas: upwind area (0°~40°), crosswind area (40°~120°), and leeside area (120°~180°), in which the upwind area has a maximal fluctuating wind pressure at the 0° angle point, and reaches a minimum value near 30°. The maximum value of circumferential fluctuating pressure is in the range of crosswind area 80°~90°, and then the fluctuating wind pressure is reduced dramatically; 110°~120° is the transition area of crosswind area and wake region and inflow deviates in this region; wind pressure fluctuation in the leeside area is stable and maintains small values from 140°~180°.

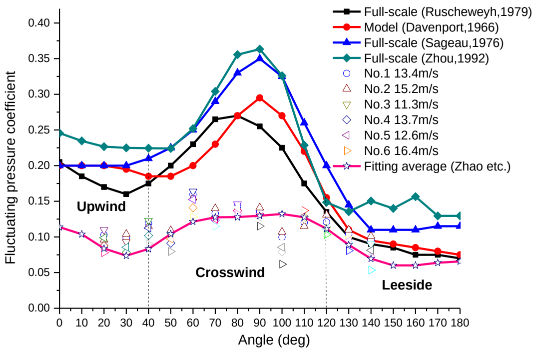

Fig. 2 Circumferential fluctuating pressure distribution

Although the Reynolds numbers of previous actual fluctuating wind pressure measurements are all above 10E7, the circumferential fluctuation values of different measured results vary greatly in the above three regions, and is especially obvious in the upwind and crosswind areas. Taking into account the different heights and surrounding areas for earlier observation, the inflow turbulence intensity would be quite different. It's necessary to recheck the influence of turbulence on fluctuating pressure. Thus in the following, the effects of inflow turbulence intensity on the circumferential fluctuating wind pressure distribution are discussed for in-situ measurements and wind tunnel tests.

Wind tunnel experiment

This experiment investigated the effect of turbulence characteristics (including turbulence intensity, turbulence integral scale and spectrum characteristics) on the fluctuating pressure of cooling towers and circular cylinders. The circumferential fluctuating pressure has been measured through synchronous pressure tests by the Scanivalve system.

The experiments on models of the cooling tower and the cylinder have been carried out in the multiple-fans active wind tunnel TJ-5 and passive wind tunnel TJ-2 and TJ-3.

Active wind tunnels have multiple identical fans, and each one can be adjusted individually. Cao [3] used another active wind tunnel in Japan and studied the effects of velocity shear on vortex shedding and aerodynamic forces on a cylinder with its axis normal to the plane of the shear profile. And other turbulent flow field with high turbulence intensity, large turbulence integral scale and narrow-band spectrum characteristics can also be generated in active wind tunnels.

Active wind tunnel TJ-5 is 1.8m high and 1.5m wide. As shown in Fig.3, the wind tunnel has 120 identical fans, as shown in Fig.3, and the maximum turbulence integral scale can even exceed 100.0 m.

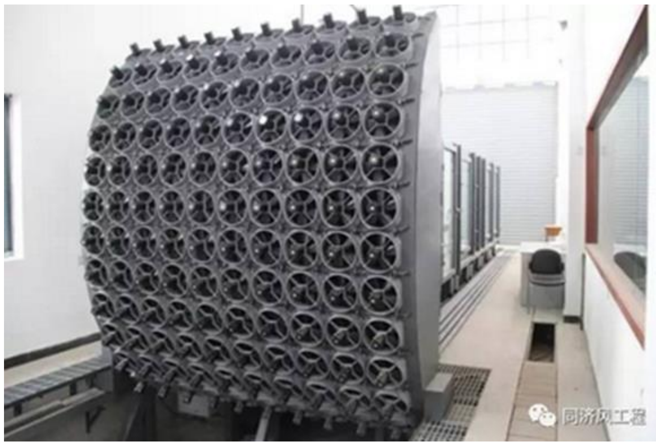

Figure 3. Layout of fans in active wind tunnel TJ-5

Multi-scale cylinder models were designed to ensure that the turbulence integral scale to cylinder diameter ration λ (=L/D) can be continuously adjusted in a specific range. The experiment also aims to investigate effect of two different spectrum characteristics, the wide band and the narrow band, on the RMS of fluctuating pressure coefficients. Therefore, the test case for effect of turbulence integral scale on fluctuating pressure is shown in Table 1.

Wind tunnel	**Cylinder diameter D (m)**	**Spectrum**	**Turbulence integral scale L (m)**	**λ(L/D)**
TJ-3	0.75	Wide band	0.3	0.4
			0.4	0.53
			0.5	0.67
	0.4		0.3	0.75
			0.4	1
			0.5	1.25
TJ-2	0.15	Wide band	0.3	2
			0.4	2.67
			0.5	3.33
	0.075		0.3	4
			0.4	5.33
			0.5	6.67
	0.05		0.3	6
			0.4	8
			0.5	10
TJ-5	0.075	Wide band / Narrow band	1	13.33
			2	26.67
			5	66.67
			10	133.33
			……	

Table 1. Test case for effect of turbulence integral scale on fluctuating pressure

In TJ-2 tests with the 0.15m diameter cylinder model, the blockage ratio is 5%, and the attainable maximum Reynolds number is 3.02E5, in the critical region. And in TJ-3 tests with the 0.75m diameter cylinder model, the blockage ratio is 5%, and the attainable maximum Reynolds number is 7.54E+05 in the supercritical region. Therefore, effect of turbulence characteristics on the fluctuating pressure of circular cylinders at high Reynolds number can be investigated in wind tunnel TJ-2 or TJ-3.

All the models were manufactured by organic glass, and set vertically in the wind tunnels with connectors on the bottom of the models. Regardless of spanwise correlation, only one set of wind pressure distribution in the middle of the model will be measured. 36 pressure taps were set in the measurement section with an interval of 10°.

Experiment Results

Effect of Turbulence Characteristics for the cooling tower

According to the experiment carried out in TJ-3 with the cooling tower model, inflow turbulence directly influences the value of fluctuating wind pressure coefficient for the stagnation point, as shown in Fig.4. The experimental relationship can be fitted using a linear fit as Eq. (1).

$$P_u = 1.6 \times I_u \tag{1}$$

in which P_u is fluctuating pressure coefficient on stagnation point and I_u is incoming turbulence intensity with unit %.

With the least square method, the distribution relationship under different inflow turbulence intensities can be fitted using fitting formula of RMS distribution of wind pressure coefficient around the circumference as follows:

$$C_p'(\theta) = \sum_{k=0}^{m} \alpha_k cosk\theta \tag{2}$$

in which C_p' is the RMS value of wind pressure, m=7, θ is the angle from the incoming flow direction, a_k is the fitting parameter. Then, the fitted fluctuating pressure curves with different turbulence intensities are obtained, as illustrated in Fig.5.

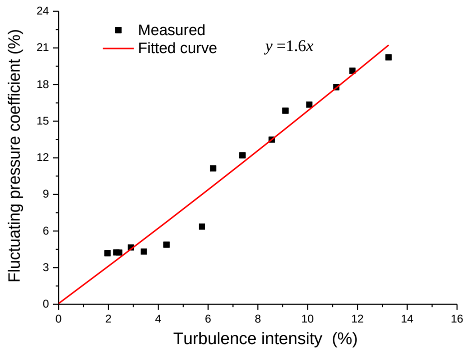

Fig. 4 Fitting curve between RMS of pressure coefficient on stagnation point and turbulence intensity at the same height

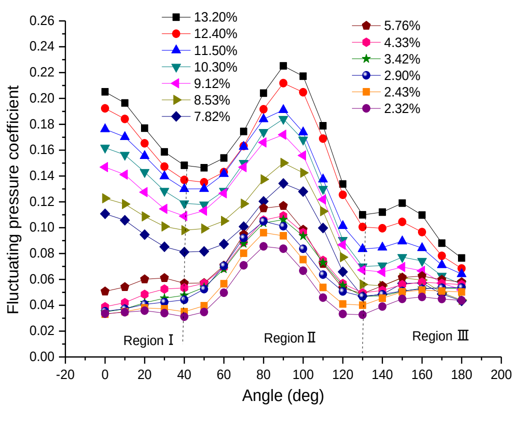

Figure 5. The fitted fluctuating pressure curves with different turbulence intensities (Re=3.85E5)

According to Fig.5, fluctuating pressure distribution characteristics with high turbulence intensities (higher than 7.82%) are not as same as those with low turbulence intensities (lower than 5.76%). The former ones have two maximums. One maximum appears at the stagnation point, and another one appears at angle around 90°. The windward fluctuating pressure coefficients are considerably larger than wake flow ones, while the later ones only have one maximum appearing at angle around 90°, and the fluctuating pressure coefficients of windward side are relatively close to those of wake flow.

Therefore, it can be assumed that, the turbulence intensity has evident effects on the windward fluctuating pressure. So the discrepancies in several actual measurements of the fluctuating wind pressure distribution (Fig. 2) may result from turbulence intensity difference, and it is essential to establish the relationship of the surface fluctuating pressure distribution to the incoming turbulence intensity.

Effect for Turbulence Characteristics for cylinder models

The experiment for 7.5cm-diameter cylinder model has been carried out in wind tunnel TJ-5. The effects of turbulence characteristics on fluctuating pressure characteristics around the cylinder are identified as followed.

As shown in Fig.6, the fluctuating pressure curves move up as turbulence intensity increases, which is consistent with the results of the cooling tower experiment. However, the distribution characteristics are not exactly the same with the cooling tower model. For the cylinder model, values in upwind region are relatively lower, while the wake region ones are relatively higher. One reason for this discrepancy is the different Reynolds number. For the cylinder model, the Reynolds number is in sub-critical region, while the Reynolds number for the cooling tower is in critical region and super critical region. In other words, flow patterns change with the Reynolds number, resulting in different fluctuating pressure distributions.

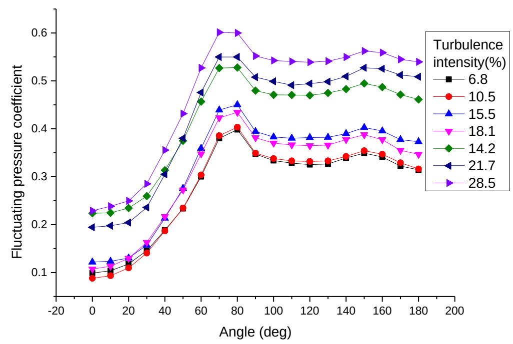

Figure 6. The fluctuating pressure curves with different turbulence intensities (Re=3E4, L≈2m.)

When turbulence intensity is identical, different turbulence integral scale also affects the value of the fluctuating pressure as shown in Fig.7. The fluctuating pressure coefficient decreases with the increasing turbulence integral scale.

The results mentioned above were all obtained under wide band spectrum. Narrow band spectrum, especially unidirectional sinusoidal flow cases with wide range of turbulence intensities and turbulence integral scale were carried out as well. The results are nearly the same with the cases under wide band spectrum.

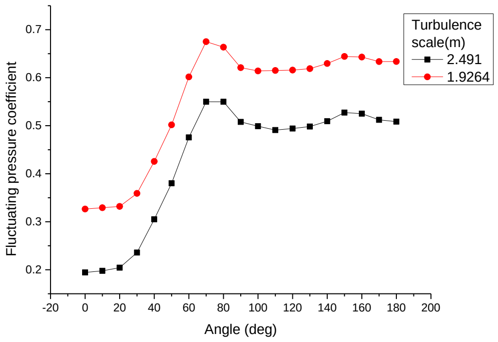

Figure 7. The fluctuating pressure curves with different turbulence integral scale (Re=3E4, Iu≈23%)

Because of short time, the experiment results for cylinder models in passive wind tunnel will be added later. Expected experiment results involve several distributions about Root-Mean-Square (RMS), extreme value and circumferential distribution pattern of fluctuating pressure coefficients of cylinder surface under different turbulence intensity, turbulence integral scale and spectrum characteristics for large scope of Reynolds numbers.

Conclusion

Through field measurement of a cooling tower and wind tunnel experiments of both cooling tower and cylinder, some meaningful conclusions about the effect of turbulence characteristics on fluctuating pressure are drawn as followed. The new understanding about fluctuating pressure distribution under the influence of Reynolds number effect and flow parameters provides design guidance for cooling towers and similar structures.

Compared with earlier researcher's field measurement data, the results of Pengcheng cooling tower shows the circumferential fluctuating pressure distribution can be roughly divided into three areas: upwind area (0°~40°), crosswind area (40°~120°), and leeside area (120°~180°), and each area has its own fluctuating pressure characteristics. On the other hand, the mean value of fluctuating pressure of our results is much lower than previous work.

According to the experiment results in wind tunnel TJ-3 and active wind tunnel TJ-5, fluctuating pressure distributions are mainly determined by the Reynolds number. For smaller Reynolds number, the fluctuating pressure coefficient is lower in upwind region and higher in wake region. Turbulence intensity has evident effects on the fluctuating pressure coefficient, especially upwind fluctuating pressure in higher Reynolds number region. Thus, the variations in inflow turbulence intensity are the main reason for discrepancies in several actual measurements of the fluctuating wind pressure distribution as shown in Fig.2.

Combined with present results, the effects of turbulence characteristics on fluctuating pressure have been identified and summarized with the help of active wind tunnel techniques. Fluctuating pressure coefficients will increase with increasing turbulence intensity and decreasing turbulence integral scale, while the effect of wind spectrum is not evident.

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