Research for Suction Control on Roof Wind Pressure of Low-rise Building

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***Abstract*—With the application of boundary layer theory, the N-S equation in the boundary layer of the wall is simplified in this research. Combined with the boundary conditions, the relationship between the wall pressure gradient and the velocity gradient near the wall is obtained, therefore the roof pressure characteristics and the location of the separation point are analyzed. The rigid model of low-rise building with flat roof was fabricated. The combination of wind tunnel test and theory is utilized to analyze the distribution characteristics of roof pressure. The suction device is designed to complete the wind tunnel pressure test of the low-rise building model under active suction. The influence of the suction position on the roof wind pressure is studied, and the mechanism of the suction-to-wall turbulence control is proposed. Research results show that the arrangement of the suction device in the separation bubble area has a significant influence on the average wind pressure coefficient of the roof, which can greatly reduce the suction of the roof.**

***Index Terms*—Low-rise building, boundary layer theory, wind tunnel test, turbulence control, suction**

I. INTRODUCTION

Low-rise buildings, which is the most common form of building structure, has been widely used in most housing, public facilities and industrial plants in rural areas and cities, of which the safety is the most important for people [1]. A large number of investigations have shown that wind-induced damage on low-rise buildings is one of the main factors of casualties and property losses during windstorms [2]. For example, more than 90% of the industrial sheds in Tong'an Industrial area in Xiamen were destroyed and some factories were even blown away [3], caused by the typhoon "Moranti", which landed in Fujian Province, China, in September 2016.

The wind-resistance research on the roof of low-rise buildings has attracted attentions by researchers for a long time. Experimental methods were applied to fully understand the wind pressure characteristics of the roof and also the corresponding mechanism of the characteristics. With the usage of flow field visualization test and numerical simulations, it has been concluded that, when the wind direction is perpendicular to the eaves toward the low-rise buildings, the incoming flow will separate through the roof, during which the vortex formed and will attache to the roof as a separation area surrounded by a shear layer to form a separation bubble [4,5]. When the wind direction is at a certain angle to the eaves, the flow separation and a cone vortex which is similar to airplanes' delta wing will be produced, forming the discrete vortexes in the separation layer, falling off into the wake behind the roof[6]. The discovery of coherent structure changed the knowledge of turbulence, and proved that turbulent fluctuation is not completely random, but includes an orderly side in disorder, and this ordered movement dominates the transmission of momentum and energy in shear turbulence. It has been proved in modern aerodynamics that there are multi-scale coherent structures for fluid motion in the near-solid region [7]. In Robinson's [8] research, vortex and strip are the basic elements of near-wall turbulence and are closely related in spatial locations.

Since the influence of wall turbulence on the resistance of moving objects is significant, the research on the control of wall turbulence mainly focuses on the drag reduction technology. Control methods have been applied including grooved surface method, open hole method, transverse rib method, suction method and large vortex breaking method [9]. Some methods have also attracted the attention of structural wind engineering researchers. Choi et al. [10] studied the influence of controlling of splitter plate, bottom plate exhausting and three-dimensional spanning perturbation technology on the control the flow around a bluff body. Vedat et al. [11] reviewed the research results of tail vortex control in a circular flow around a cylinder. Zhang et al. [12] effectively suppressed the vortex-induced resonance of the bridge by arranging the suction holes in the bridge segment model to effectively avoid the tail vortex shedding.

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In this research, the influence of local aspiration disturbance on the turbulence of the roof wall is investigated based on the wall turbulence intensity control theory and wind tunnel test. Results show that the suction force can be significantly reduced with small amount of suction when properly arrange the suction holes. The suction control in wind resistance of low-rise buildings and the feasibility of their implementation are discussed based on the wind tunnel test results in this research, which can be referenced in the wind-resist design of low-rise building.

II. THEORETIC ANALYSIS

Due to the viscosity of the air, the air flowing through the roof of the low-rise building is attached to the wall surface, forming a low-speed layer near the roof. In the low-speed layer, along the vertical direction of the wall, the velocity decreases rapidly from the outer U to zero on the wall surface, forming a viscous shear layer, as shown in Fig. 1. The shear layer near the wall is called viscous boundary layer by Prandt, referred as boundary layer[13]. The external velocity U decreases to zero along the vertical direction of the wall, which results in the velocity gradient. The velocity gradient in the vertical wall direction in the boundary layer is large, therefore the viscous shear stress can not be negligible [14].

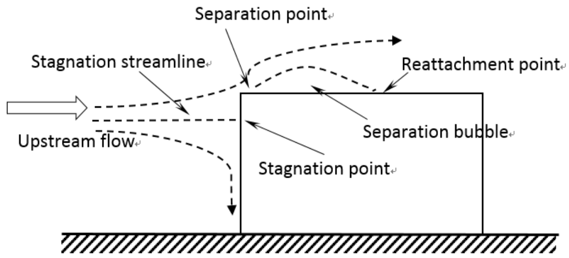

Figure 1. Schematic diagram of the roof air flow boundary layer

According to the Prandtl boundary layer theory, the flow of boundary layer of the wall follows the N-S equation. When the boundary layer thickness d/l<<1, the N-S equation can be simplified to obtain the mathematical describing the flow of laminar boundary layer. Due to the thinness of boundary layer, the influence of gravity can be ignored. Assuming the external pressure distribution as *p* (x,y), the 2-dimensional for of N-S equation at x and y direction can be as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\frac{\partial^2 u}{\partial y^2} \quad (2)$$

$$\frac{\partial p}{\partial y}=0 \quad (3)$$

The boundary condition can be:

$$y=0:\ u=c=0;\ y=\infty: u=U(x) \quad (4)$$

In which, the u and v are the velocity components in x and y direction respectively, p is the pressure distribution function, ρ is the density of air, and μ indicates the air viscosity constant.

The expression can also be suitable for the unsteady filed when the equation (2) is expressed as:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\frac{\partial^2 u}{\partial y^2} \quad (5)$$

The boundary is changed as:

$$y=0:\ u=c=0;\ y=\infty: u=U(x,\ t) \quad (6)$$

It can be seen from Equation (3), the pressure remains constant in the *y* direction in the boundary layer, indicating that the external pressure of boundary layer can act on the wall through the boundary layer. The pressure distribution on the wall is completely determined by the external potential flow. Therefore, the pressure function and speed function on the wall should satisfy:

$$\frac{\partial p}{\partial x}=\mu\frac{\partial^2 u}{\partial y^2} \quad (7)$$

It can be indicated from the above equation that the second derivative of the velocity profile on the wall has the same sign with pressure gradient in the x direction. According to the sign of pressure gradient, the turbulence of the wall can be divided into three regions:1 along the pressure gradient region; 2. the minimal pressure point *C*; 3. the adverse pressure gradient region, in which the velocity profile is concave and the the curvature in the flow direction increases and the inflection point rises. After going through the minimum pressure, the air flow will enter the adverse pressure gradient region, there will be a separation point *S* which satisfy $\partial u/\partial y=0$, where the velocity profile is tangent to y direction. After the S-point, the velocity profile continues to be concave and the speed become negative, indicating the appearance of reverse flow and separation bubble.

It can be concluded by the above analysis, the roof pressure analysis can be used to determine the location of the separation point and to study the effect of the suction position on the roof pressure.

III. DESIGN OF MODELS AND WIND TUNNEL TEST

A. *Model Design*

To investigate the influence of suction disturbance on roof wind pressure, two wind tunnel text models are designed. The dimension of the model are 48cm length, 72cm width and 24cm height, as shown in Fig. 2:

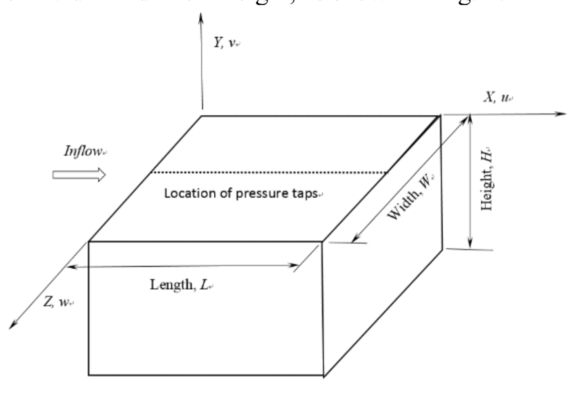

Figure 2. Schematic diagram of the model

230 measurement points are arranged along the mid-line of the model, as shown in Fig. 2 with all the parameters indicated. The incoming wind direction in perpendicular to the eave in the test. The purpose of the wind tunnel tests is to investigate the characteristics of the boundary layer of the two-dimensional bluff body around the wall, estimate the location of the separation point by the surface pressure distribution and the pressure distribution gradient along the wind speed direction and study the influence of the position of the separation point on the roof pressure based on the characteristics of pressure distribution and the judgment of the position of the separation point.

The wind tunnel tests are conducted in the low-speed test section of the wind tunnel laboratory of the Wind Engineering Research Center of Xiamen University of Technology. The wind tunnel lab of Xiamen University of Technology is a series of double-test section and direct-reflow convertible boundary layer wind tunnel. The dimension of low-speed test section is 25m length, 6m width and 3.6m height with highest test wind speed 30m/s. The dimension of high-speed test section is 8m length, 2.6m width and 2.8m height with maximum test wind speed 90m/s.

The wind tunnel test model is made of 4mm acrylic sheets with sufficient stiffness and strength as shown in Figure 3. The DTC Initium electronic pressure scanning system produced by American PSI Company is applied for wind pressure measurement. DTC Initium integrates advanced modular circuit design with PSI's Digital Temperature Compensation (DTC) technology to maintain optimum accuracy without calibrating pressure sensors online. DTC Initium can connect up to eight 64-channel DTC Series ESP sensors, providing up to 512 pressure measurement channels. DTC Initium includes software triggering and hardware-triggered packet capture, and the engineering unit throughput transmitted to the host is up to 1200 Hz per channel. In this experiment, the data acquisition time of each group is 180 seconds, and the sampling frequency is 330 Hz. The cobra fluctuating anemometer is used to monitor the wind speed and turbulence intensity at the reference model height in real time. The suction control device is mainly composed of an adjustable micro-pump pump with maximum inspiratory volume 1.8 L/min.

Figure 3. Model of wind tunnel test

B. Boundary Layer Simulation and Turbulence Generation

Due to the complexity of the environment, the topographical features are various at different locations. The certain devices need to be installed in the wind tunnel lab simulate the topographical features in the wind tunnel test. For example, the carpets are applied to simulate the suburban grassland, and the wind tunnel roughness elements can be applied to simulate the wind filed in urban area. However, in many cases, the boundary layer can not sufficiently developed with only roughness elements, therefore, some auxiliary devices such as wedges are often placed at the entrance, as shown in Fig. 4 and Fig. 5.

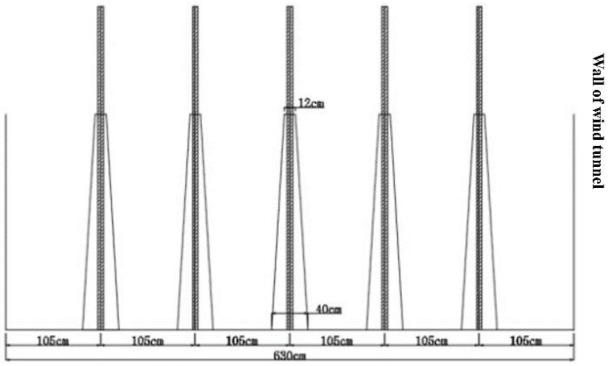

Figure 4. Wedge in the wind tunnel lab

Figure 5. Wedge roughness elements in the wind tunnel lab

IV. RESULT ANALYSIS OF WIND TUNNEL TEST

A. Data Collection and Analysis

In structural wind engineering, the wind pressure on the surface of obstacles can be expressed by a dimensionless wind pressure coefficient as shown in the following equation:

$$C_{pi} = \frac{p_i - p_0}{\rho U_0^2/2} \tag{8}$$

In which, U_0 is the average wind speed at the roof surface, p_i is the measured pressure of the ith point, p_0 represents the pressure of the reference roof surface, ρ is the density of air which is ρ=1.29kg/m^3 .

Considering the random process of the wind pressure coefficient collected by the measuring points, the statistical parameters such as mean, variance and skewness are of great significance in the study of roof wind load. Therefore, in the analysis, the statistical methods of stochastic processes are used to obtain the parameters [13].

$$\bar{C}_{pi} = \frac{1}{N}\sum_{j=1}^{N} C_{pij} \tag{9}$$

$$\sigma_{C_{pi}} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(C_{pij} - \bar{C}_{pi}\right)^2} \tag{10}$$

$$C_{si} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_{pij}-\bar{C}_{pi}}{\sigma_{C_{pi}}}\right)^3 \tag{11}$$

In which, C_{pij} is the calculated wind pressure coefficient by jth measured data of ith measure points based on Eq.(1), $\bar{C}_{pi}$ is the average wind pressure coefficient calculated by the data acquisition data of ith point over a period of time, $\sigma_{C_{pi}}$is the mean square error of the ith measuring point, which indicates the deviation from the mean value, C_{si} is the skewness of the wind pressure coefficient which can be applied to study the non-Gaussian characteristics of random variables.

B. Suction Control Design

According to the Prandtl boundary layer theory, the wall pressure gradient along the airflow direction needs to have a process from positive to negative before the separation, that is, it will not be separated at the top of the windward wall, but be slightly behind. Based on the wall boundary layer theory, the separation point is near the wall pressure gradient ∂p/∂x=0.

In this section, the suction pump is connected to the piezometer to perform suction control. In order to study the influence of the suction position on the roof wind pressure, the suction pump power remain constant in each working condition, and the inhalation position is defined as:

$$\xi = \frac{x_s}{L} \tag{12}$$

Where x_s is the distance from the suction hole to the leading edge of the eaves, L is the length of the building, ξ is a dimensionless parameter, indicating the relative position of the separation point on the roof.

The influence of different suction positions on the roof pressure are shown in Fig. 6-Fig.8. It can be seen from Fig. 6-Fig.8: (1) The suction has a significant influence on the mean value and mean square error of the roof wind pressure, while has little effect on the skewness of the roof wind pressure. Indicating that it does not change the non-Gaussian characteristics of wind pressure; (2) when the suction position near $\xi = 0.15$, the influence is significant.

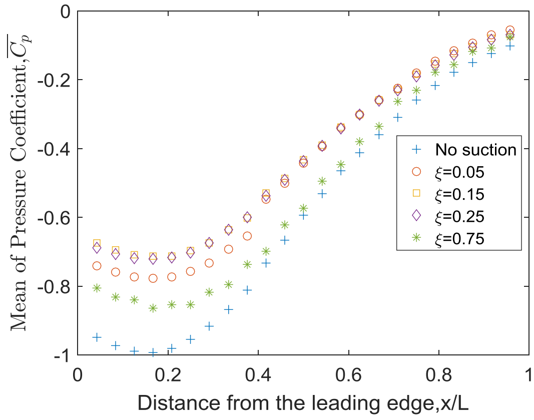

Figure 6. Influence of suction position on mean wind pressure coefficient

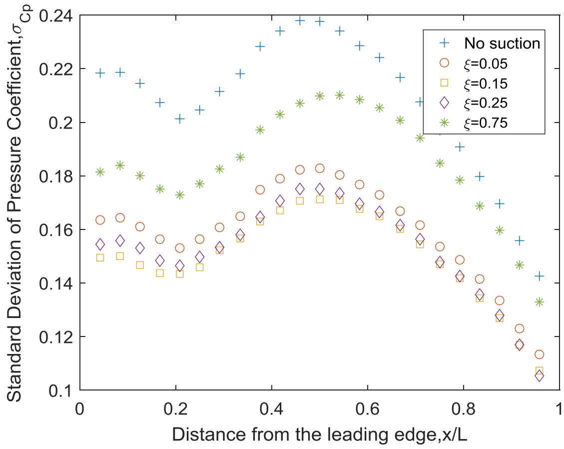

Figure 7. Influence of suction position on standard deviation of wind pressure coefficient

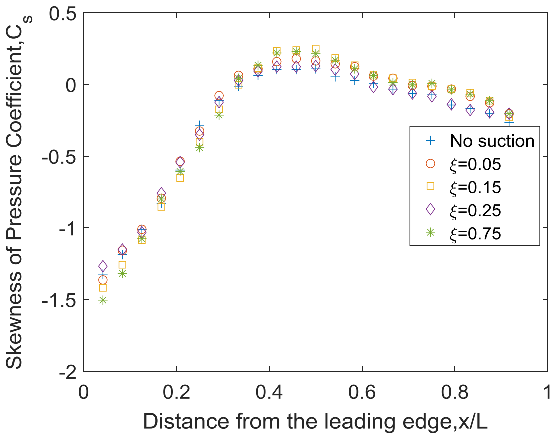

Figure 8. Influence of suction position on skewness of wind pressure coefficient

V. Conclusions

In this research, the wind pressure distribution law of low-rise building roof is firstly analyzed based on the boundary layer theory and wind tunnel test. By inhaling at different positions of the low-rise building roof, the wind pressure coefficients of the roof are measured and compared, and the influence of the suction position on the roof pressure control is obtained. And the mechanism of the suction control of roof wind pressure is also studied by applying the wall turbulence control theory and time averaging technology. The main conclusions of this research are:

(1) When the wind direction is perpendicular to the roof surface, the separation point occurs near the front side eaves when the wind pressure reaches to minimum.

(2) The suction on the low-rise building roof has a disturbing effect on the wind field of the roof, which can change the wind pressure distribution of the roof, and also the smaller amount of inhalation can change wind pressure of the roof.

(3) The suction position has a great influence on changing the wind pressure of the roof. When the suction hole is near the separation point or in the upstream area of the separation point, it has a significant influence on the average wind pressure coefficient near the separation point, which can effectively suppress the maximum suction of the roof; when the suction hole is far from the separation point of the flow, it has little effect on the average wind pressure and cannot effectively suppress the maximum suction.

Conflict of Interest

The authors declared no conflicts of interest.

Author Contributions

Changzhao Qian and Changping Chen contributed to the conception of the study; Haitao Hu and Zhujun Li performed the experiment; Changzhao Qian performed the data analyses and wrote the manuscript, Dandan Xia and Bifeng Liu helped perform the analysis with constructive discussions; all authors had approved the final version.

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