EFFECT OF SQUARE CELLS IN IMPROVING WIND TUNNEL FLOW QUALITY

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ABSTRACT

The effects of square cells with different length and width sizes in improving flow quality were studied in the course of building a new small open loop wind tunnel. The cobra probe was used to measure the fluctuating flow components. The focus of this study was put on the effects of the square cells in attenuating the total turbulence intensity including the free-turbulence carried by the incoming flow and the turbulence generated by the square cells itself. The change tendency of the mean wind velocity and the total turbulence characteristics in the decay area have been studied by varying the length to cell size ratio L/D, and ratio of distance between the square cells and the measuring position to cell size X/D.

KEYWORDS: WIND TUNNEL, FLOW QUALITY, HONEYCOMBS

Introduction

As one of most effective facilities in investigating wind engineering problems, wind tunnels have been used extensively for the model tests and fluid flow research purposes in the field of engineering, meteorology and aerodynamics. Till now, many types of wind tunnel have been built, even with the rapid development of the computing capabilities and computational fluid dynamics technology. A wind tunnel is still an essential facility either in research work or practical applications. When the strong effect of free-stream turbulence on the shear layers was realized in 1930s, high flow quality has become desirable when a wind tunnel is under construction. High flow quality becomes more important for sensitive experiment requiring extremely smooth flow. One of the most important aspects of flow in a wind tunnel is the level of turbulence intensity. During the design of a wind tunnel, lots of work will be devoted to ensure that the flow in test section can have low level turbulence and steadiness. The main methods adopted in the flow straightening and turbulence reduction system include the use of wire-mesh screens, honeycomb and contractions. According to widely accepted views, the screens and contractions reduce the longitudinal components of turbulence or mean-velocity variation to a greater extent than the lateral components. Honeycombs exhibit greatest importance in straightening out the flow, reducing the lateral component of the mean wind and the larger turbulent eddies. Honeycomb, operating with screens and contractions, are often found in many wind tunnels. No matter in previous designs of wind tunnel or the modern ones, honeycomb seems to be absolutely essential in producing high quality flows in wind tunnels [1, 2].

Since honeycombs not only suppress the incoming free-turbulence but also produces some turbulence referred as self-turbulence simultaneously, it is normally accepted that the most effective method to reduce turbulence intensity is the reducing wire mesh screens. Many
research works have been done about the effect of the turbulence-reducing screens [3-6]. While in some cases of water tunnels they are used both to support the operations of the tunnels and to conduct independent fluid dynamics research. Turbulence-reducing screens popular in wind tunnels were not suitable in water because they are susceptible to hydro elastic interactions which, under some situations, may lead to large screen oscillations and deformation. Then honeycomb was preferred to reduce turbulence intensity in the water tunnel [7, 8]. Not many tests have actually been done to investigate the function of honeycomb in suppressing the turbulence intensity in spite of the fact they have been used for a long time. Some work had been done by Lumley [9] and Loehrke and Nagib [10] studying the generation of self-turbulence and the balance condition for the suppression and generation effect of the honeycomb. Also Mikhailova, etc. [11], using different lengths honeycomb with different sizes of cells, had studied more comprehensively about the process of self-turbulence. They focused on the relation between L/D ratio, which is defined as the length of the honeycomb to the diameter of the cells, and the generation, development and decay of the self-turbulence behind the honeycomb. Although those previous studies have uncovered some mechanisms of the effects of honeycomb in improving flow quality, most of those researches were conducted in the well built wind tunnel and free-turbulence in the incoming flow were generated by some passive apparatus. While honeycomb are normally used in building new wind tunnels, the incoming flow before the honeycomb will absolutely have not only swirl but also angularity. Then the performance of honeycomb under such condition may have some different characters.

At present, a new large wind tunnel is proposed in the School of Mechanical engineering, University of Adelaide. Before it is put into practice, a model wind tunnel was built. So in the process of building the model wind tunnel, the work presented here was carried out to investigate the effects of square cells, in lieu of the honeycombs, in improving the quality of the wind tunnel flow.

Experimental arrangement

Although the proposed new wind tunnel is a vertical close-loop circuit one, the preliminary stage of an open circuit model tunnel with work section of 500mm* 500mm *2000mm was adopted for this present study. Since square cells are a lot simpler to fabricate than honeycombs, the present investigation will use square cells for all tests. Similar to the honeycomb, square cells of different sizes and lengths were made. Because of the limited material for this preliminary stage, 3mm thick plywood was used to fabricate the square cells. For the acquisition of experimental data, a cobra probe was used to measure the fluctuating wind speed in the wind tunnel. Figure 1 shows the cobra probe and one of the square cells used in these tests. According to the research result in the previous literatures [10, 11], when the ratio of distance between honeycomb and anemometer to the cell size which hereafter referred as X/D is higher than 10, the self-turbulence of honeycomb begins to decay. As the objective of the present study was to find out the total effect of the square cells in improving the flow quality, all square cell configurations were installed at the inlet of the working section, keeping the distance from the square cells to the cobra probe fixed at 1.3m which is long enough for most cell sizes except the 2-cells situation to keep the X/D ratio higher than 10. The different types of the square cell configurations were identified by the number of square cells in one row, hereafter was referred as 8-cells, 16-cells and so on. The ratios L/D of the length to cell sizes of the different types of the square cells were listed in the Table 1.
Results and analyses

3.1 Lateral fluctuating wind characteristics

Due to the angularity of the incoming flow from the fan, the original flow in the working section was not always parallel to the center line of work section. Limited by the cobra probe’s physical shape, it was hard to make sure that the head of probe parallel to the center line. Hence the measurements of the incoming flow angles were not used for the analyses. The measurement coordinate system of the cobra probe is shown in Figure 2 [12]. Although the angle measurement of the incoming flow may be influenced by the initial installation condition, the mean longitudinal velocity of the incoming flow can be generated by the appropriate formulation as long as the probe was kept vertical in the cross section of the wind tunnel. So we can estimate the effect of the square cells in attenuating flow angularity by the lateral distribution of the longitudinal mean wind velocity.

Suppose that \( \bar{u}(t) \), \( \bar{v}(t) \) and \( \bar{w}(t) \) denote the three components of the fluctuating wind speeds measured by the probe respectively, and the mean wind speeds of the three directions represented by \( \bar{U}_1, \bar{U}_2 \) and \( \bar{U}_3 \), then the direction cosines of the three directions can be obtained by the following formulations.
The longitudinal, lateral and vertical fluctuating components of the incoming flow can be obtained by the following formulations:

\[

cos \alpha_u, cos \beta_u, cos \gamma_u = (U_1, U_2, U_3) / U \tag{2.1}
\]

\[

cos \alpha_v, cos \beta_v, cos \gamma_v = \frac{(0, 0, 1) 	imes (cos \alpha_u, cos \beta_u, cos \gamma_u)}{\sqrt{cos^2 \alpha_u + cos^2 \beta_u}} \tag{2.2}
\]

\[

cos \alpha_w, cos \beta_w, cos \gamma_w = \frac{(cos \alpha_u, cos \beta_u, cos \gamma_u) 	imes (cos \alpha_v, cos \beta_v, cos \gamma_v)}{\sqrt{cos^2 \alpha_u + cos^2 \beta_u}} \tag{2.3}
\]

Then, the longitudinal, lateral and vertical fluctuating components of the incoming flow can be obtained by the following formulations:

\[

t(t) = \bar{u}(t) \ cos \alpha_u + \bar{v}(t) \ cos \beta_u + \bar{w}(t) \ cos \gamma_u \tag{3.1}
\]

\[
	n(t) = \bar{u}(t) \ cos \alpha_v + \bar{v}(t) \ cos \beta_v + \bar{w}(t) \ cos \gamma_v \tag{3.2}
\]

\[
	n(t) = \bar{u}(t) \ cos \alpha_w + \bar{v}(t) \ cos \beta_w + \bar{w}(t) \ cos \gamma_w \tag{3.3}
\]

The lateral distribution of the longitudinal mean wind velocity at the mid height of the working section with and without the application of different cell sizes of 120mm length square cells are shown in the Figure 3. Figure 4 exhibits the change of the standard deviation of the wind velocity as a function of the L/D ratios. As can be seen from Figure 4, the uniformity of the wind field in the working section was greatly improved with the increase of L/D ratios. Deducing from the drop tendency of Figure 4, satisfying the lateral uniformity would be obtained if an L/D ratio of 9 were used. As the performance of the square cells are also influenced by the thickness of the material used for testing, considering the material used for the square cells was 3mm plywood, the ideal L/D ratio will decrease if thinner material were used for the fabrication of the square cells. This ratio range seems to be lower than the value of 8-12, as proposed by N.P. Mikhailova, etc. [11] at which the honeycomb suppresses the free-turbulence most efficiently.
Besides the lateral distribution of the longitudinal mean wind velocity, the effects of the square cells in attenuating lateral component of mean wind and larger turbulent eddies can also been exhibited by the improvement of lateral fluctuating turbulence intensity. Figure 5 shows the lateral fluctuating turbulence intensity measured with different square cells configurations. As shown by the decay curve in Figure 5, when keeping the length L fixed and changing the size of the cells, the effect of L/D ratio on reducing the lateral turbulence intensity measured at the position of cobra probe which is 1300mm downstream from the fixed position of the square cells showed slight difference. If the decay curves are fitted by a power law function, the exponents are 0.54, 0.27, and 0.34 for L=12cm, 24cm, 36cm respectively. So if fixing the distance between the square cells and the measurement position, it shows that the longer length of the square cells becomes less effective for the same L/D ratios. If the turbulence intensities are plotted against the ratio of X/D, as shown in Figure 6, the three curves collapse onto the same power law decay curve with an exponent of 0.05.

![Figure 5](image1)  ![Figure 6](image2)

Figure 5  The decay curve of lateral turbulence intensity $I_w$ against L/D ratio

Figure 6  The decay curve of lateral turbulence intensity $I_w$ against X/D ratio

### 3.2 Longitudinal fluctuating wind characteristics

Although honeycomb works as an operator which not only suppresses the incoming free-turbulence but also generate significant self-turbulence, its function as attenuating longitudinal flow turbulence is still shown to be quite useful, especially in some water tunnels where wire mesh screens are not suitable. Unlike previous works [9-11] putting most part of their attention on the generation and development of the self-turbulence immediately after the honeycomb, our objective mainly focused on the total effect of the square cells in attenuating the turbulence of the wind tunnel flow. The longitudinal mean wind velocity and fluctuating turbulence intensity were measured by the cobra probe fixed in the decaying region of the self-turbulence. The measuring position of the cobra probe was fixed at the mid height of the working section along the center line of the wind tunnel. With the distance between the cobra probe and the square cells keeping constant, the total effect of the square cells on the mean wind velocity $U$ and the longitudinal turbulence intensity $I_u$ are shown in Figures 7 and 8.

Figures 7 and 8 show that for the same L/D ratio, the longer square cells are seen to produce more mean wind velocity reduction. On the other hand, the shorter square cells with the same L/D ratio were more effective in attenuating the longitudinal turbulence. For the mean wind velocity, the decay curve drops along a nearly linear style in spite of the difference in the square cells length. However the longitudinal turbulence intensity decay curve exhibits a power law tendency with an exponent of around 0.2.
The measured mean wind velocity and turbulence intensity are plotted against the X/D ratio in Figures 9 and 10. As can be seen from Figure 9, the $U$ versus X/D curve have similar trend as with $U$ versus L/D situation, at same X/D ratio, the longer square cells caused more velocity drop, but different decay curves have nearly the same downtrend slope. As compared with the $I_w$ versus X/D curves, the $I_u$ versus X/D curves are more scattered. If using the empirical formulation in Equation (4) as proposed by Lumley etc. [8] to fit the $I_u$ versus X/D curve, it is obvious that different length of the square cells have different exponents, since the Equation (4) does not consider the effect of the square cells length. These results agree with literature [11]. But the fitted exponents, around 0.2 here, do not agree with their results. It may be caused by the thick plywood used for making the square cells in this test.

$$\varepsilon = 10(X / D)^{0.5}$$  \hspace{1cm} (4)

As is known, honeycomb attenuates the free-stream turbulence intensity by reducing the large scale eddies into smaller scales and then leads to their rapid decay in the downstream flow. Thus the function of honeycombs can also be manifested by the change of turbulence scale in the downstream flow. For the longitudinal turbulence flow, the widely accepted Kaimal power spectrum Equation (5) was used to fit the turbulence integrate scales.
Figure 11 shows the change tendency of the longitudinal turbulence length scale $L_u$ under different types of square cells tested and Figure 12 shows the relation between the longitudinal turbulence length scale and the X/D ratio. The two figures exhibit similar tendency for the longitudinal turbulence length scale under the same L/D ratios or same X/D ratios. The longer square cells generate smaller turbulence length scale. This tendency is in agreement with the $I_{uu}$ versus X/D tendency in Figure 10. In the contrary, it does not agree with the $I_{uu}$ versus L/D tendency in Figure 8, with the fixed distance between the square cells and the measuring position. The longer square cells cause higher turbulence intensity at the same L/D ratio. This may be caused by the relatively low mean wind speed of the longer square cells as compared with the shorter ones.

\[
\frac{nS_{uu}(n)}{\sigma^2_u} = \frac{4*(nL_u/U)}{[1+70.7(nL_u/U)^2]^{3/6}} \quad (5)
\]

Conclusions

From this preliminary investigation during the construction of a new wind tunnel, some conclusions can be drawn. For the flow straightening function, square cells with L/D ratio around 7 will have satisfying performance, like honeycombs. In the downstream area where self-turbulence also begins to decay, the power law decay tendency of the total turbulence intensity in the downstream flow is influenced by the length of the square cells. When judged by the X/D ratio, the longer square cells are more effective in attenuating the turbulence at the same X/D ratio, and the longitudinal turbulence length scales also becomes smaller.
Reference
