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Turbulence effects on surface pressures of rectangular cylinders

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Abstract. This paper presents the effects of free-stream turbulence on streamwise surface pressure fluctuations on two-dimensional rectangular cylinders. Particular attention is given to possible effects of turbulence integral scale on fluctuating and peak pressures. The mean, standard deviation, peak pressure coefficients, spectra and cross-correlation of fluctuating pressures were measured to investigate the nature of the separation and reattachment phenomenon in turbulent flows over a wide range of turbulence intensity and integral scale.

Key words: bluff body aerodynamics; turbulence effects; surface pressures; wind tunnel testing.

1. Introduction

There have been a number of investigations carried out to study the effects of free-stream turbulence on surface pressure fields on rectangular cylinders over the last three decades. However, most of the previous studies have involved extensive measurements in the near wake for base pressures or in the reattachment zone where the maximum fluctuating pressure occurs and the maximum free-stream turbulence intensity used in these studies was about 15%. However, the main interest for wind engineering application involves much higher turbulence intensities and the generation of very low peak pressures.

Although the generation of large negative pressure fluctuations near leading edges and corners of buildings and structures is a major cause of damage during windstorms, this phenomenon has received relatively little attention. Saathoff (1988), Saathoff and Melbourne (1989) focused their investigation on the generations of peak pressures which occur in the forward part of the separation bubble and which are of primary concern in wind engineering. But the largest ratio of turbulence integral scale to model thickness in their studies was less than 2.0, which is smaller than the typical values of the turbulence scale ratio in the natural

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wind around buildings and structures. The models used in their experiments were a blunt flat plate and a square cylinder only. Nakamura and Ozono (1984) investigated the effects of turbulence on streamwise pressures of two-dimensional rectangular cylinders. They have studied the mean flow field, but no attention gives to the unsteady surface pressures. Their results have shown that the effects of free-stream turbulence on mean pressure fields depend on the chord/thickness ratio (H/D) of a rectangular cylinder. Several studies (e.g., Bearman and Truman 1972) have indicated that flow around rectangular cylinders (H/D<3) is strongly dependent on the model afterbody length. Meanwhile, the effects of free-stream turbulence on streamwise fluctuating and peak surface pressures of rectangular cylinders are less clear, partly due to a lack of experimental data. More work is thus required to investigate the turbulence effects on streamwise pressure fluctuations in separated and reattaching flows over the various chord/thickness ratios of rectangular cylinders in various turbulent flows. Hence, the effects of free-stream turbulence on pressure fluctuations around two-dimensional cylinders with different H/D have been investigated by the authors. Wind flow over a rectangular cylinder is dependent on the chord/thickness ratio, therefore measurements on models with long afterbodies will be discussed separately from models with short afterbodies. The observations on cylinders with longer afterbodies (H/D>1) are presented in this paper.

The present paper is concerned mainly with measurements of fluctuating pressures and very low peak pressures in the regions near the leading edges in grid-generated turbulent flows and smooth flow. The main purpose is to examine the effects of turbulence intensity and integral scale on pressure fluctuations in separated and reattaching flows, attention gives to pressure fluctuations in various turbulent flows over a larger range of turbulence integral scales and turbulence intensities of relevance to the wind engineering field.

2. Experimental arrangements

The experiments were carried out in the wind tunnel laboratory at Monash University. With the construction of the new 1 MW environment wind tunnel at Monash University with its large working section of 6 m $\times$ 12 m cross-section and 40 m long, a much larger turbulence integral scale than those obtained by previous studies can be generated in this facility. This wind tunnel allows us to study the bluff body aerodynamics over a larger range of turbulence intensity and scale of relevance to the wind engineering field. In order to generate various turbulent flows with a wider range of turbulence intensity and integral scale, free-stream turbulence was generated by using bi-planar wooden grids. Eight different grids were used, which had bar widths of 16 mm, 25 mm, 35 mm, 37 mm, 70 mm, 100 mm, 300 mm and 500 mm, respectively. The ratio of mesh size to bar width was approximately 4.0 for each grid. The experiments were carried out over a wide range of the ratio of the free-stream longitudinal turbulence integral scale (L_x) to the model thickness (D), $L_x/D = 0.35$ to 15. The latter value is much higher than usually produced in previous wind tunnel studies for the separation bubble. At the same time, the free-stream longitudinal turbulence intensity, $I_u = \sigma_u / u$, varied from 0.8% to 25%. The smooth flow had a turbulence intensity of 0.8%. Turbulence measurements were made with a TSI constant temperature hot wire anemometer. The longitudinal turbulence integral scale, L_x, was estimated by fitting the Harris-von Karman spectrum to the measured longitudinal velocity spectra.

This paper describes an experimental study of two rectangular cylinders, which had a thickness, D, of 50 mm and a depth/thickness ratio, H/D, of 2 and 4, respectively. The spanwise dimension is 1.6 m, giving a aspect ratio of 32. The models were mounted horizontally between the endplates, and with the front face normal to the approaching flow. The Reynolds number based on the model thickness was approximately in the range of 2.5×10^4-5.0×10^4 throughout the present experiments. According to Li's study (1996), the Reynolds number was considered as high enough to ensure that the pressure data were no longer sensitive to variations in the Reynolds number.

Streamwise pressure distributions were measured using a row of tapping on the centreline of the bottom surface on the models. A spanwise row of tappings located near the leading edge on the bottom surface of each model was used to measure lateral cross-correlations of fluctuating pressure. Pressure data were collected using Honeywell 163 pc transducers connected to pressure tapping with 60 mm lengths of PVC tubing. Restrictors placed in the tubing provided a flat frequency response within 10% up to 250 Hz.

3. Experiment results

In the present experiments, pressure data were low-pass filtered at 400 Hz, then recorded and analyzed by using a Perkin-Elmer computer. The sampling frequency was 1000 Hz. Mean, standard deviation and peak pressure coefficients are defined, respectively, as :

$$C_p = \frac{\bar{p}-p_0}{\frac{1}{2}\rho u^2} \tag{1}$$

$$C_{\sigma_p} = \frac{\sigma_p}{\frac{1}{2}\rho u^2} \tag{2}$$

$$C_{\breve{p}} = \frac{\breve{p}-p_0}{\frac{1}{2}\rho u^2} \tag{3}$$

where $\bar{p}$ is the time mean pressure, σ_p is the standard deviation of the pressure, $\breve{p}$ is the peak pressure, p_0 is the static pressure at the model location, u is the mean wind velocity at the model location, ρ is the density of air.

Values of C_p (mean pressure coefficient), $C_{\sigma p}$ (standard deviation pressure coefficient), were ensemble averages from 400 seconds of data collection. The $C_{\breve{p}}$ (negative peak pressure coefficient) was the average of 100 peak measurements from consecutive 4 second samples.

Fig. 1 shows the mean pressure distributions measured on the model with H/D = 2. The mean pressure data obtained from the model with H/D = 4 are presented in Figs. 2 and 3 to study the effects of free-stream turbulence intensity and scale on streamwise mean pressure distributions. Figs. 1-3 show the distributions of the mean pressure coefficient, C_p, in turbulent flows which have four values of turbulence intensity, I_u, of about 8%, 12%, 15% and 20%, and the ratio of turbulence integral scale to the model thickness, L_x/D, is in the range of 0.8 to 15.0.

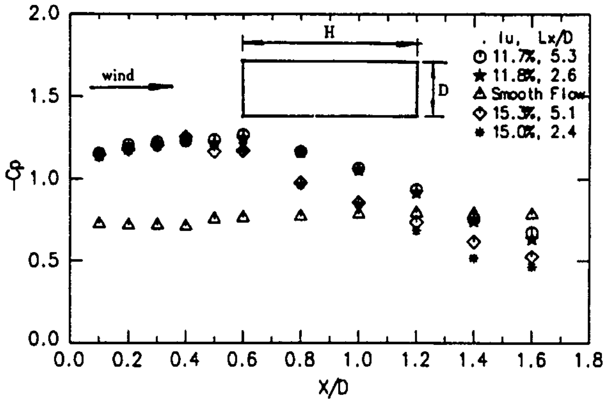

Fig. 1 Distributions of mean pressure coefficient in turbulent and smooth flows (H/D = 2)

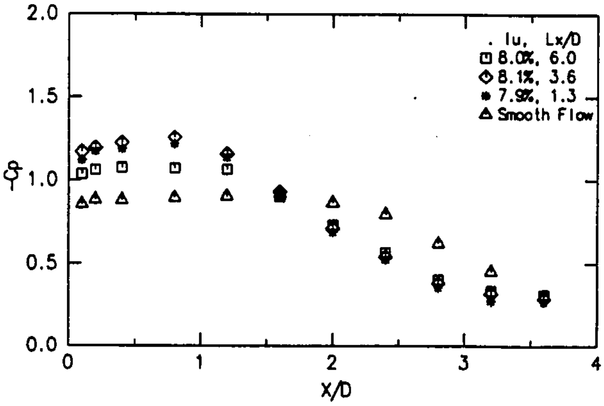

Fig. 2 Distributions of mean pressure coefficient on the model (H/D = 4) in turbulent flows

It can be seen from the data presented in Fig. 1 that the higher turbulence levels lead to greater pressure recovery, and an increase in free-stream turbulence intensity reduces the size of the separation bubble. This is due to an increase in curvature of the shear layer, as noted by previous researchers (e.g., Lee 1975). As shown in Fig. 1, the pressure distribution measured in smooth flow is rather flat, indicating that wind flow is separated throughout. The data presented in Fig. 1 show little effect of turbulence scale on the mean pressure distributions for $L_x/D < 5.3$ in the tests. However, as shown in Fig. 2, with further increasing turbulence scale to $L_x/D = 6.0$, what is the most interesting is the presence of the effect of turbulence scale on C_p. It is clear that turbulence scale has a significant effect on the mean pressure distribution in the leading edge region. The mean pressure coefficients that were measured near the leading edge in larger scale turbulent flow are close to the values of C_p obtained in smooth flow. Fig. 3 also demonstrates that there is a considerable effect of turbulence scale on the distributions of C_p, and an increase in turbulence scale ratio to a large value reduces the magnitude of C_p measured near separation, but increases the magnitudes of C_p in other regions. This suggests that large scale turbulence increases the mean reattachment length. It is worth noting that, as shown in Fig. 4, the mean pressure distribution obtained in turbulent flow with higher turbulence intensity and larger turbulence scale

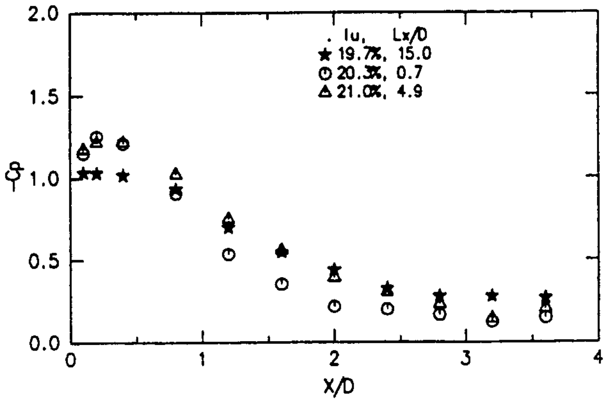

Fig. 3 Distributions of mean pressure coefficient on the model (H/D = 4) in turbulent flows

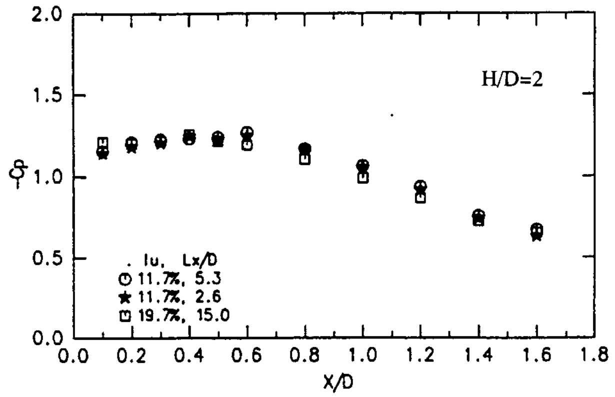

Fig. 4 Distributions of mean pressure coefficient in turbulent and smooth flows

(I_u = 19.7%, L_x/D = 15.0) is in good agreement with those measured in wind flows with lower values of I_u and smaller values of L_x/D (I_u = 15.0%, L_x/D = 2.6 and 5.3). This suggests that for streamwise mean pressure distribution, larger L_x/D causes less pressure recovery, and an increase in free-stream turbulence scale ratio to a large value is equivalent to reduce free-stream turbulence intensity.

Fig. 5 shows mean pressure coefficients at two representative positions of X/D = 0.2 and 3.2 on the cylinder with H/D = 4 plotted as a function against turbulence scale for turbulence intensity I_u = 20%, indicating that with further increase in turbulence scale ratio to a large value (e.g., L_x/D = 15.0), the magnitudes of C_p measured near the leading edge and in the reattachment zone are asymptoting towards corresponding smooth flow values. This suggests that when $L_x >> D$, the flow approximates to a slow quasi-steady variation of the direction and magnitude of the approaching velocity (Bearman 1972), hence, it can no longer affect the mean flow around bluff bodies effectively. This is in agreement with Nakamura and Ozono's (1987) observation for a blunt flat plate.

Previous experimental results (Li and Melbourne 1995a, 1995b, 1995c) showed that mean pressure distributions obtained with a square cylinder were scale-dependent as $L_x/D < 5.3$, however, as discussed above, little scale effect on mean pressure was evident for rectangular

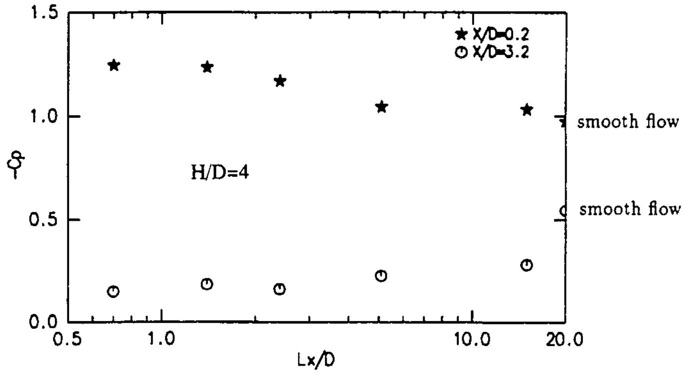

Fig. 5 Mean pressure coefficient at x/D = 0.2 & 3.2 as a function of the turbulence scale (with $I_u = 20\%$)

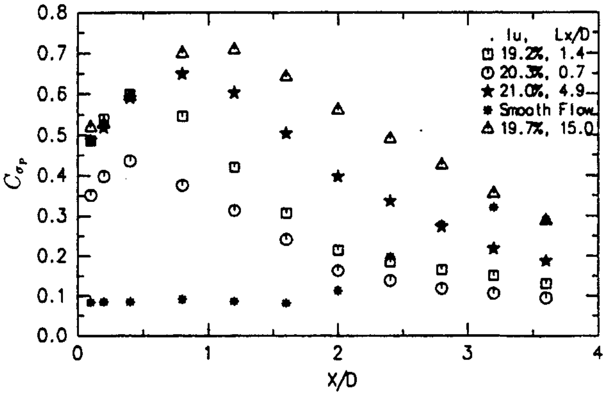

Fig. 6 Distributions of fluctuating pressure coefficient on the model (H/D = 4) in turbulent flows

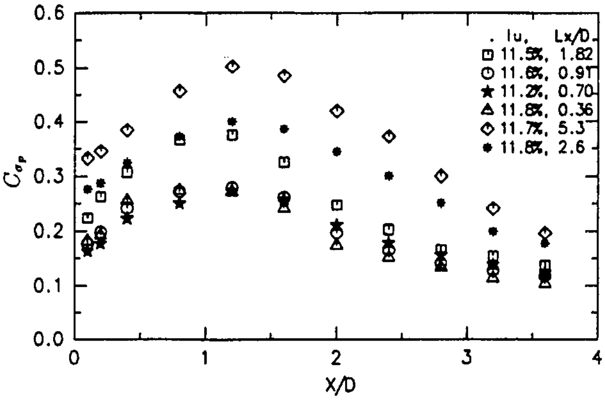

Fig. 7 Distributions of R.M.S. pressure coefficient on the cylinder with H/D = 4 in turbulent flows

cylinders with H/D≥2 in the same range of L_x/D. This suggests that turbulence scale has less effect on C_p for long rectangular cylinders than that for short cylinders as $L_x/D < 5.3$.

Streamwise distributions of standard deviation pressure coefficient, C_{σ_p}, measured on the model with H/D = 4 are shown in Figs. 6 and 7. It can be seen from these figures that the distributions of C_{σ_p} are strongly dependent on both turbulence intensity and scale. An increase in turbulence intensity and scale causes fluctuating pressures to increase and the location of maximum C_{σ_p} to move further forward and downstream, respectively. For example, an increase in turbulence intensity from 11.5% to 19.2% moves the position of maximum C_{σ_p} upstream from 1.2D to 0.5D, and as shown in Fig. 6, an increase in turbulence scale ratio from 1.4 to 15 moves the position of maximum C_{σ_p} downstream from 0.5D to 1.2D. As discussed by previous researchers (e.g., Hiller and Cherry 1981), the position of flow reattachment is located just upstream of the position of maximum C_{σ_p}. This illustrates again that increasing turbulence scale causes the reattachment length to become larger. In other words, small scale turbulence reduces the reattachment length. Nakamura and Ohya (1983) indicated that small scale turbulence can cause earlier reattachment of the shear layer onto the streamwise side through increased mixing in the shear layer. It has been reported by many researchers (e.g., Hunt 1981, Nakamura and Ohya 1983) that small scale turbulence (the order of shear layer thickness) is responsible for the modification of the shear layer structure. If the value of L_x is much larger than this, represents a reduction in the energy at high frequencies and an increase in turbulence integral scale causes a thinner shear layer and less reattachment.

Streamwise profiles of C_{σ_p} obtained on the model with H/D = 2 are presented in Fig. 8. Again here the effect of increasing turbulence scale is clearly to increase the values of C_{σ_p} progressively. The values of C_{σ_p} measured in smooth flow are considerable lower than those obtained in turbulent flows.

The maximum fluctuating pressure coefficients which occur in the reattachment zone are plotted in Fig. 9 for the model with H/D = 4. The measured C_{σ_p} near the leading edge on the same model plotted as a function of turbulence intensity are presented in Fig. 10, and the values of L_x/D are shown next to each data point in the two figures. The effects of both turbulence intensity and scale on C_{σ_p} in the region of flow separation and reattachment can be clearly seen. The data presented in these two figures indicate that the effect of turbulence scale on C_{σ_p} in the region of flow separation and reattachment becomes greater as turbulence intensity increases.

Streamwise distributions of negative peak pressure coefficient $C_{\check{p}}$ measured on the cylinder with H/D = 2 are shown in Fig. 11 and Fig. 12. The peak pressure coefficients also show a

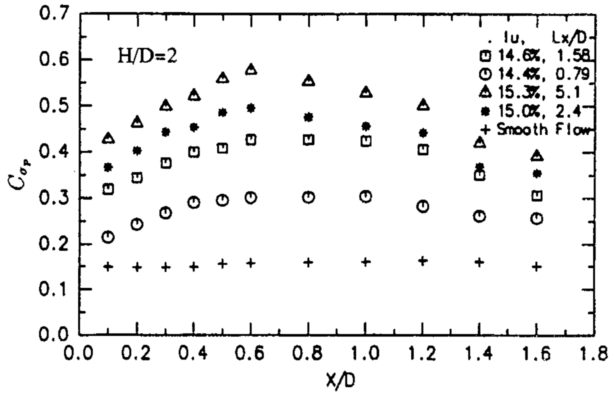

Fig. 8 Distributions of R.M.S. pressure coefficient in turbulent flows

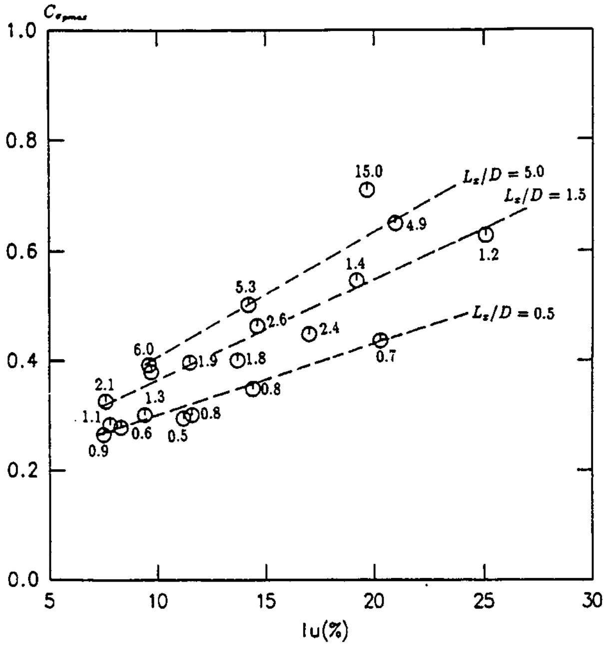

Fig. 9 Maximum fluctuating pressure coefficient as a function of the turbulence intensity (H/D = 4)

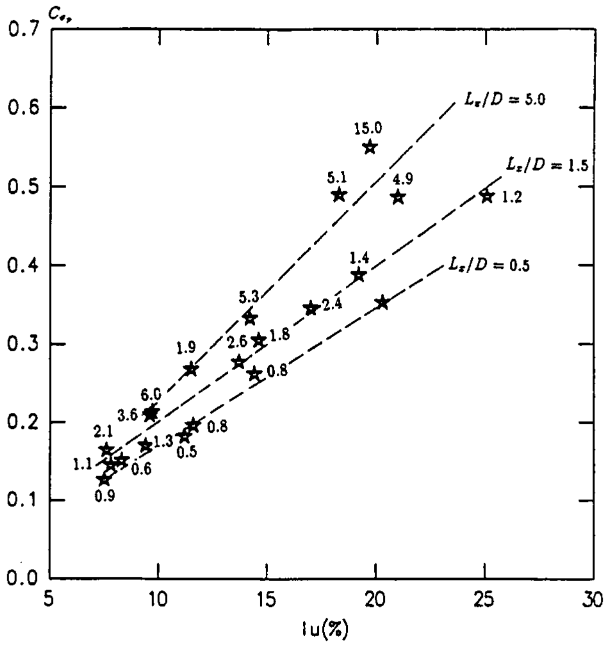

Fig. 10 Fluctuating pressure coefficient near separation as a function of the turbulence intensity (H/D = 4)

dependence on turbulence intensity. The scale effect on the values of $C_{\tilde{p}}$ is not significant as $L_x/D < 0.92$ as shown in Fig. 11. However, with a further increase in the values of L_x/D, the

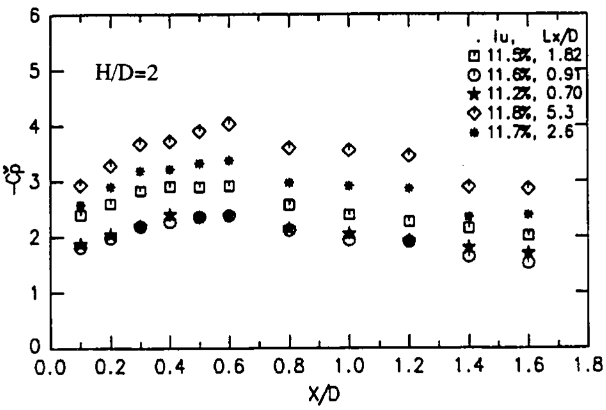

Fig. 11 Distributions of peak pressure coefficient in turbulent flows

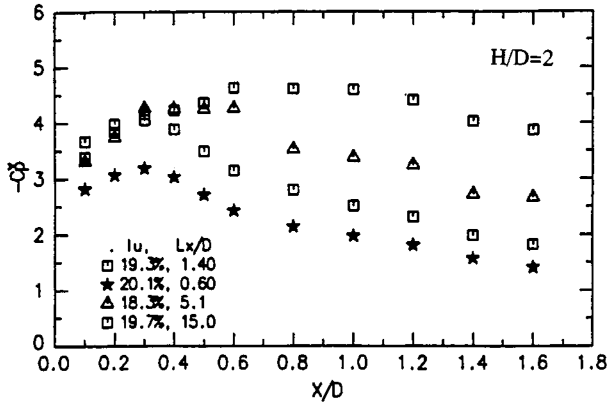

Fig. 12 Distributions of peak pressure coefficient in turbulent & smooth flows

peak pressure coefficients show a dependence on both turbulence intensity and scale. It can be seen in Fig. 11 that a 5.9:1 increase in turbulence scale is associated with a 67% increase in the maximum value of $|C_{\breve{p}}|$. As shown in Fig. 12, with a further increase in the values of turbulence scale ratio to 15.0 at high turbulence intensity ($I_u = 20\%$), the values of $|C_{\breve{p}}|$ measured near the trailing edge are significantly increased while the magnitudes of $C_{\breve{p}}$ near the leading edge are similar to those measured in relatively smaller scale turbulent flows.

It has been shown that both turbulence intensity and scale have significant effects on streamwise peak pressure distributions. In an attempt to combine the effects of turbulence intensity and scale into a single parameter, the negative peak pressure coefficients with the largest magnitude measured on the streamwise surface on the two models, were initially plotted as a function of L_x/D on log-log format and found that they are approximately proportional to $(L_x/D)^{0.40}$. Fig. 13 and Fig. 14 show that the minimum peak pressures measured on the models with H/D = 2 and 4 are plotted as a function of $(\sigma_u/u)(L_x/D)^{0.40}$, respectively. As shown in these two figures, the minimum peak pressures correlate reasonably well with the parameter $(\sigma_u/u)(L_x/D)^{0.40}$. The empirical equations decided by the best least squares fit for the models with H/D = 2 and 4 are proposed to give a reasonable estimation for the minimum peak pressure coefficient by

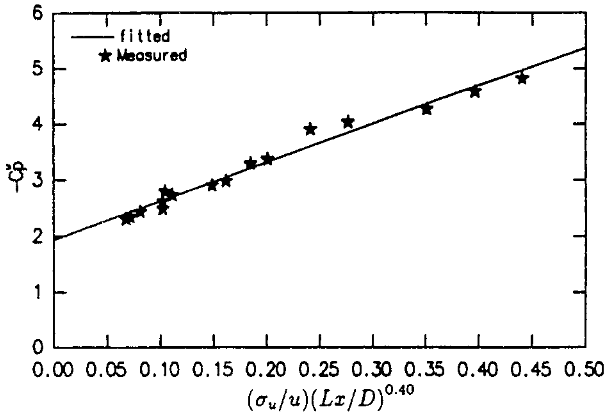

Fig. 13 Minimum negative peak pressure coefficient as a function of the turbulence parameter (H/D = 2)

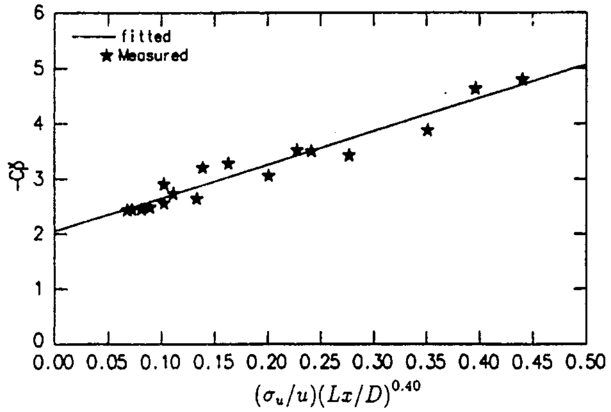

Fig. 14 Minimum negative pressure coefficient as a function of the turbulence parameter (H/D = 4)

the following two equations, respectively.

$$C_{\breve{p}} = -6.8640(\sigma_u / u)(L_x / D)^{0.40}-1.9381 \tag{4}$$

$$C_{\breve{p}} = -6.0148(\sigma_u / u)(L_x / D)^{0.40}-2.0473 \tag{5}$$

The design of cladding for buildings requires knowledge of the properties of the peak pressures which a building may experience during its project time. The effects of turbulence on the cumulative distributions of extreme peak pressures are discussed below.

The cumulative distributions of $C_{\breve{p}}$ measured on the cylinder with H/D = 2 at X/D = 0.1 are shown in Fig. 15. Fifty peaks were extracted from a record of 50 samples. Each sample contains 4096 collected pressure data and the point with the largest magnitude was chosen for calculation of $C_{\breve{p}}$. The peak pressure coefficients are plotted as a function of the reduced variate, $\tilde{x}$, defined as :

$$\tilde{x} = - \ln [- \ln (i - 0.44) / (N + 0.12)] \tag{6}$$

where i is the rank order and N is the sample size (i.e., 50).

It was suggested by Holmes (1984) that this plotting method provides a good

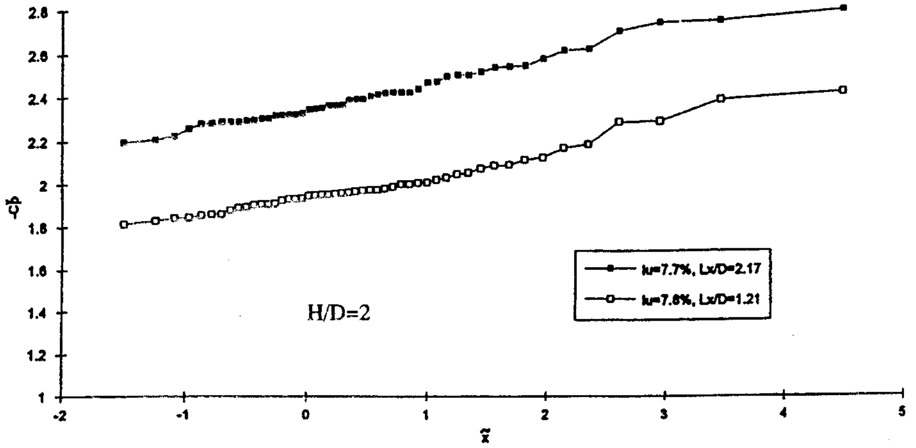

Fig. 15 Cumulative distributions of peak pressure coefficients

approximation to an unbaised plotting formula for the Type I extreme-value distribution. $C_{\tilde{p}}$ can be expressed as follows :

$$C_{\tilde{p}} = U_c + (1/a)\tilde{x} \tag{7}$$

The effect of turbulence scale on peak pressure data is shown very well in Fig. 15. An increase in L_x/D by a factor of two increases the value of U_c by approximately 20% while the values of -(1/a) are approximately the same for turbulence flows having different scale ratios but with approximately the same turbulence intensities.

Knowledge of the frequency content of fluctuating pressures is very useful in understanding their origin. Pressure spectra measured on the model with H/D = 2 at X/D = 0.2 are displayed in Fig. 16 for smooth flow and three turbulent flows with about the same turbulence intensity (I_u = 7.7%), but different scale ratios. A high-amplitude spike in the pressure spectrum corresponding to the Strouhal frequency in a narrow band is evident in the case of smooth flow, which suggests that pressure fluctuations in smooth flow are dominated by vortex shedding at the Strouhal frequency for this cylinder. The addition of turbulence to the flow causes the peaks of spectra to become smaller and shift to lower frequency with a wider frequency

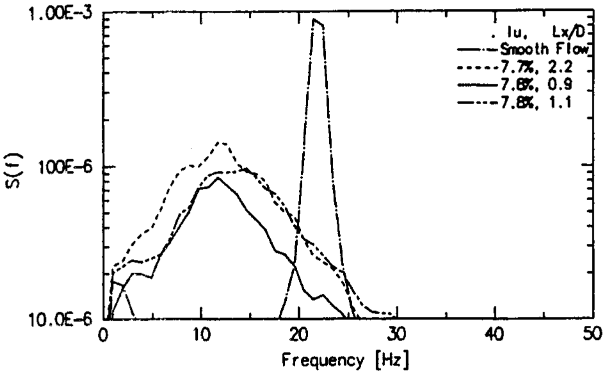

Fig. 16 Pressure spectra measured on the model H/D = 2 at X/D = 0.2

bandwidth. Meanwhile, the distributions of the pressure spectra obtained in different scale flows are similar, but the magnitude of the spectral peak is higher in larger scale flow than that in smaller scale turbulent flow. As a result, the values of C_{σ_p} measured in larger scale turbulent flow ($L_x/D = 2.17$) are larger than those obtained in smaller scale turbulent flow ($L_x/D = 0.5$), which was described previously.

The determination of wind loading acting on a building and the calculation of the overall

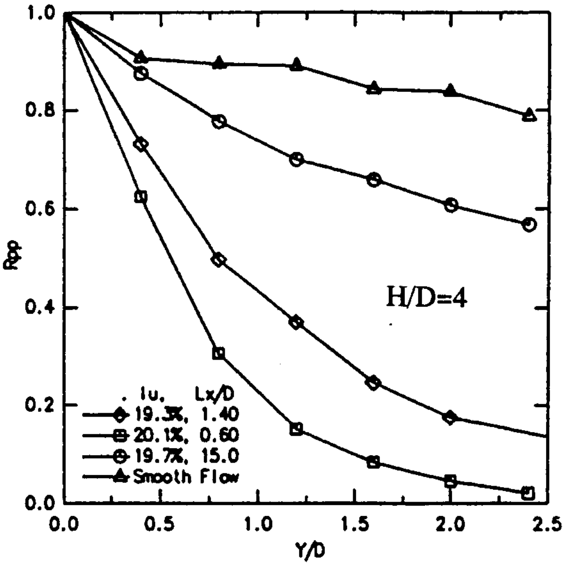

Fig. 17 Cross-correlation of fluctuating pressure as a function of lateral displacement

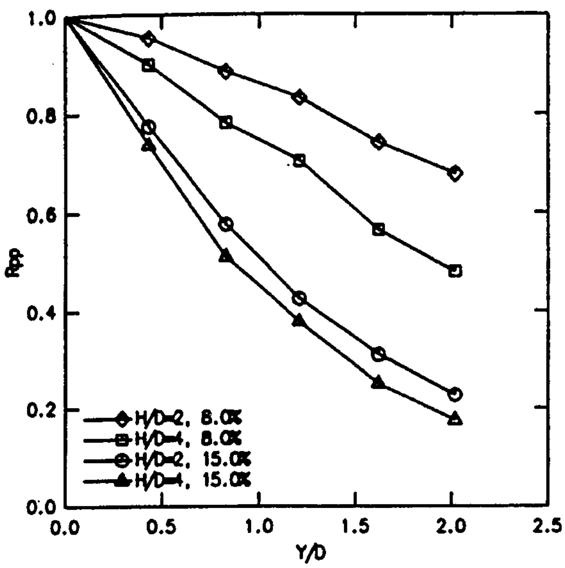

Fig. 18 Cross-correlation of fluctuating pressure measured on the cylinder with H/D = 2.4

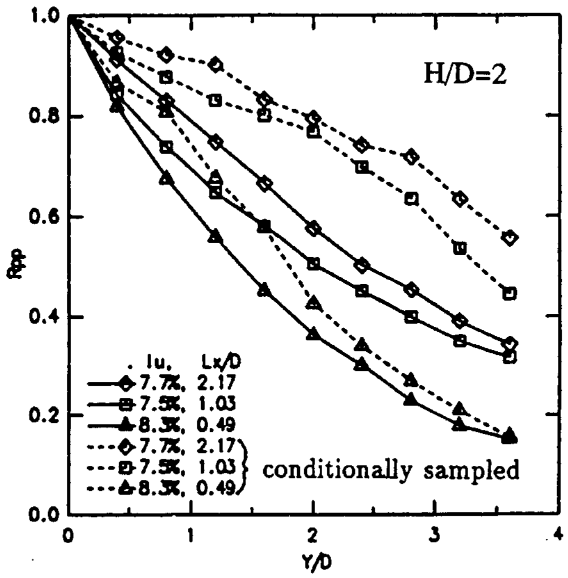

Fig. 19 Cross-correlation of fluctuating pressure as a function of lateral displacement

response of a structure to fluctuating pressures require a knowledge of the relationship between the pressure fluctuations at different locations on the building and structure. This relationship can be described in terms of a cross-correlation coefficient.

The time averaging lateral cross-correlation of fluctuating pressures at zero time lag near separation (at X/D = 0.2) as a function of lateral displacement are presented through Fig. 17 to Fig. 19 for the two models. The cross-correlation coefficient R_{pp} gives an indication of the spanwise extent of vortices in the separation bubble. It can be seen that for the data presented in Fig. 17, the turbulence scale dominates the distributions of the lateral cross-correlation of fluctuating pressures. An increase in turbulence scale causes the cross-correlation to increase progressively. The effect of chord/thickness ratio on the lateral pressure correlation can be seen in Fig. 18 by comparing the data measured at the same turbulence configurations for the models with different afterbody lengths. The spanwise correlation measured near separation on the bluff 2:1 section is higher than those obtained on the slender 4:1 section. Addition of turbulence intensity causes a decrease in spanwise correlation as also shown in Fig. 18.

As the primary interest in the present study is in peak pressure structure, in order to study how well the peak pressures are correlated across the span, conditionally-cross correlation (R^*_{pp}) was measured in the manner suggested by Saathoff (1988) to obtain a quantitative estimate of the spanwise correlation of peak pressures. A sample size of 100 peaks was used to calculate R^*_{pp}. The condition is triggered whenever the pressure single falls 3 standard deviations below the mean.

Fig. 19 compares the normal and conditional spanwise cross correlation measured near separation, at zero time delay. The peak suction pressures are much better correlated than the time averaged pressure fluctuations. Furthermore, the correlation of the peak suction pressures also increases as the turbulence scale ratio becomes larger. This illustrates the importance of correctly simulating the free-stream turbulence scale to estimate the response of large span bridges and canopy structures in wind tunnel tests.

4. Conclusions

The measured results presented above have shown that the streamwise surface pressure distributions can be affected significantly by the approaching turbulence, and they are strongly dependent on both turbulence intensity and scale. Several conclusions are evident from this study concerning the surface pressure fields on the two-dimensional rectangular cylinders with long afterbodies (H/D = 2 and 4).

Experimental data have indicated that mean pressure distributions on the rectangular cylinders with H/D=2 and 4 are strongly dependent on free-stream turbulence intensity but are not significantly affected by turbulence scale over a range of turbulence scale ratio from 0.4 to 5.3 in the present experiment. However, with a further increasing turbulence scale to L_x/D = 6.0, turbulence scale starts to have a significant effect on the mean pressure distribution. The mean pressure coefficients which were measured near the leading edges in larger scale turbulent flow are close to the corresponding values of C_p obtained in smooth flow. On the other hand, fluctuating pressures are dependent on both turbulence intensity and scale. The magnitudes of the standard deviation of pressure and negative pressure coefficients increase with turbulence intensity and scale. The effect of turbulence scale on fluctuating pressure coefficients and negative peak pressure coefficients becomes greater as turbulence intensity increases. In other words, the larger the turbulence intensity is, the stronger effect the turbulence scale has, in the range of I_u and L_x/D tested in the present work for the two cylinders. It has been found that the minimum peak pressures measured on the two models all show good correlation with $(\sigma_u/u)(L_x/D)^{0.40}$. The lateral cross-correlation of fluctuating pressures near separation is significantly affected by the free-stream turbulence scale. An increase in turbulence scale causes the lateral cross-correlation of time averaged fluctuating pressures and peak pressures to become greater. Peak pressures in the region near the leading edges are better correlated than time averaged fluctuations.

It is clear that correct modeling of both turbulence intensity and integral scale is necessary when endeavoring to estimate the highest magnitude of design pressures on buildings and structures having a rectangular cylindrical shape.

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