TURBULENCE EFFECTS ON PRESSURE FLUCTUATIONS IN SEPARATED AND REATTACHING FLOWS I. MEAN AND FLUCTUATING PRESSURE DISTRIBUTIONS

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1.INTRODUCTION

There have been a number of wind tunnel studies carried out to investigate the effects of turbulence intensity and scale on surface pressure fields on flat plates and rectangular cylinders over the last three decades. However, much of these previous studies have involved extensive measurements in the reattchment zone where the maximum r.m.s. pressure occurs. Saathoff and Melbourne(1989) thus concentrated their investigation on the generation of peak pressures which occur in the forward part of the bubble and which are of primary concern in wind engineering, as fluctuating pressures in this region have been recognized as a major cause of roof failure on low-rise buildings and of cladding failure on tall buildings. But the largest ratio of turbulence integral scale to the model thickness in their study was less than 2.1, which is smaller than the typical values of the turbulence scale ratio in the natural wind around buildings. More work is needed over a much larger range of turbulence scale to be relevant to the wind engineering field. Although Nakamura and Ozono (1987) investigated the effects of turbulence on streamwise pressures over a large turbulence scale range, only mean pressures were measured in their study. Flow visualization experiments by Cherry et al. (1984) and Saathoff (1988) have shown that the instantaneous flow field in a separation bubble is significantly different from that obtained by mean flow measurements.

Wind tunnel experiments were conducted to study the effects of the intensity and scale of turbulence on streamwise surface pressures of two-dimensional blunt flat plate and rectangular cylinders with different afterbody lengths exposed to grid turbulence over a large range of turbulence scale by focussing attention on the fluctuating and very low peak pressures measured near separation. This paper presents some of the results regarding the effects of turbulence on streamwise mean and fluctuating pressure distributions. Turbulence effects on the generation of peak pressures are discussed in the accompanying paper.

2.EXPERIMENTAL ARRANGEMENTS

The experiments were conducted in a 450kw wind tunnel with a working section of 2.0m square and 15m long at Monash University. The desired free-stream turbulence was generated by using bi-planar wooden grids. Seven different grids were used. The ratio of mesh size to bar width was approximately 4.0 for each grid. The intensity and scale of free-stream turbulence could be altered by changing the grids or the distance from the grids to the model. The experiments were carried out over a wide range of the ratio of turbulence integral scale to the model thickness, L_x/D = 0.35 to 8.22 for an approximately constant turbulence intensity, while the turbulence intensity varied from 8% to 25%. Smooth flow has a turbulence intensity of 0.8%. Figure 1 shows a typical example of longitudinal velocity spectra for different grid configurations. The spectra of the two turbulent flows which have approximately the same turbulence intensity but different scales are presented in Figure 1. For the small scale turbulence the grid is very close to the model. The difference in turbulence energy distributions in the frequency domain in large and small scale turbulent flows can be seen.

A blunt flat plate with a rectangular cross-section, a square cylinder and two rectangular cylinders with depth/thickness ratio,H/D, of 2 and 4, respectively, were used as experimental models which had the same thickness, D, of 50mm. The spanwise dimension was the same, 1.6m. The models were mounted horizontally between endplates located 200mm from each side wall of the tunnel to ensure the uniformity of the flow around the models. The Reynolds number based on the thickness of models was kept approximately at 4.5×10^4. Cherry et al. (1984) found that the mean pressure distribution on a blunt flat in smooth flow is Reynolds number independent in the range of $3.0 \times 10^4 < Re < 6.0 \times 10^4$. Nakamura et al. (1984) also drew a similar conclusion for various sizes of afterbody rectangular cylinders.

Pressure data on the models were collected using Honeywell 163pc transducers connected to pressure tappings with 60mm lengths of PVC tubing with an internal diameter of 1.5mm. Restrictors placed in the tubing provided a flat frequency response within 10% up to 250Hz. Streamwise pressure distributions were measured using a row of tappings on the centreline of the bottom surface of each model. 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. All the measurements presented in the two papers were made at zero incidence.

3.EXPERIMENTAL RESULTS

Mean, standard deviation and peak pressure coefficients in the data presentation are defined, respectively, as:

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

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

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

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

In the experiments, pressure data were recorded and analyzed by using a Perkin-Elmer computer. The sampling frequency was 1000 Hz. A large amount of data were recorded to ensure that random nature of the data can be statistically estimated. Values of C_p and C_{σ_p} are ensemble averages from 400 seconds of data collection. The $C_{\check{p}}$ is the average of 100 peak measurements from consecutive 4 second samples. 65536 data points were recorded for spectral analysis.

3.1 Streamwise Pressure Distributions

Distributions of the mean pressure coefficient, C_p, on the flat plate in turbulent flows with approximately the same intensity (8.0%) but different turbulence scales are presented in Fig.2. The data presented in Fig.2 show little effect of turbulence scale on mean pressure distributions up to L_x/D=4.86. However, with further increase in turbulence scale ratio to L_x/D=8.22, it can be seen that the mean pressure coefficients, which were measured near the leading edge in particular, are scale-dependent. Fig.3, Fig.4 and Fig.5 show the mean pressure distributions on the rectangular cylinders with depth/thickness ratio of 4, 2 and 1, respectively. The results obtained on models with $H/D = 2, 4$ indicate that as turbulence scale ratio changes from 1.03 to 2.17, little scale effect on mean pressure distribution is evident. With further increase in turbulence ratio to 4.86, the values of C_p become more negative. However, when the scale ratio reaches to 8.22, the magnitudes of C_p are becoming smaller. As can be seen in Fig.3, the mean pressure coefficients measured near the leading edge in a very large scale turbulent flow ($L_x/D = 8.22$) are close to the values of C_p obtained in smooth flow. This is in agreement with Nakamura and Ozono's conclusion (1987) which suggested that turbulence of very large scale is equivalent to a flow with slowly fluctuating velocity, and hence it can no longer influence the bluff body mean flow effectively. The measured mean pressure coefficients on the square cylinder model shown in Fig.5 are apparently changing with turbulence scale in all the ranges of turbulence scale tested. The values of Cp measured at $L_x/D = 4.86$ are more negative than data obtained at $L_x/D = 1.12$. With further increasing turbulence scale ratio to 8.22, it was found that the magnitude of mean pressure coefficients decreased approximately 18% and 10% compared with those obtained at $L_x/D = 4.86$ and 1.12, respectively. The distributions of C_p on the four models tested for a given turbulent flow are shown in Fig.6. It can be seen that the mean pressure coefficients measured near separation for rectangular cylinders with $H/D > 1$ demonstrate a similar distribution while the values of C_p obtained on the square cylinder are more negative.

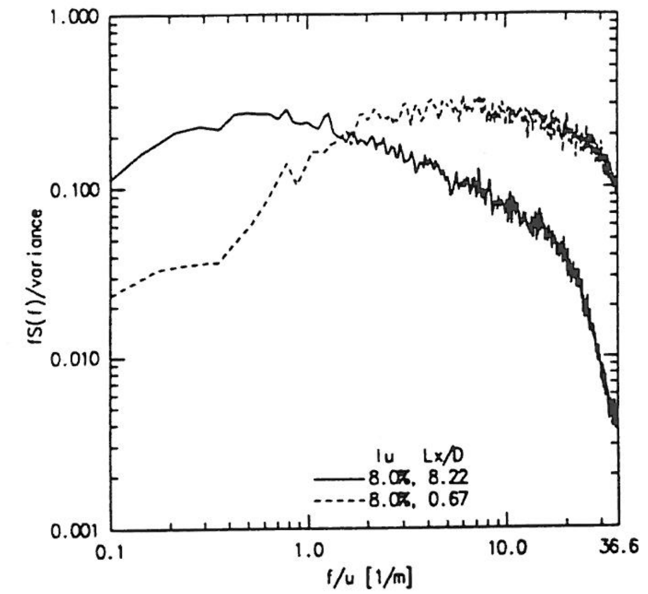

Figure 1. Longitudinal Velocity Power Spectra Obtained at Model Position For Different Grid Configurations.

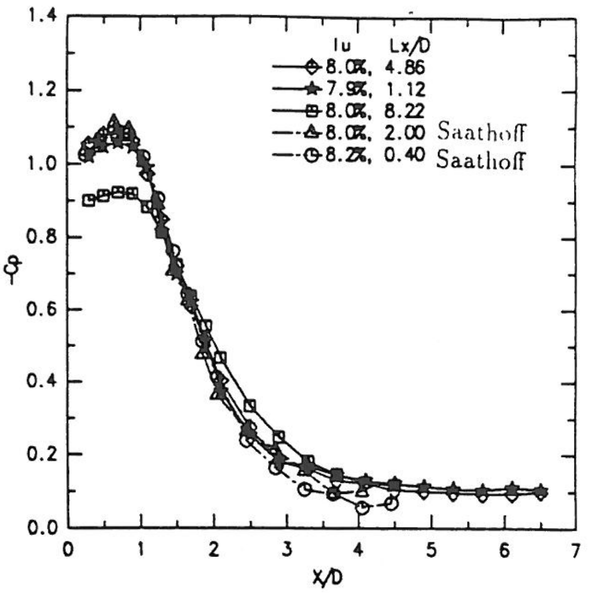

Figure 2. Streamwise Mean Pressure Distributions On The Blunt Flat Plate In Turbulent Flows

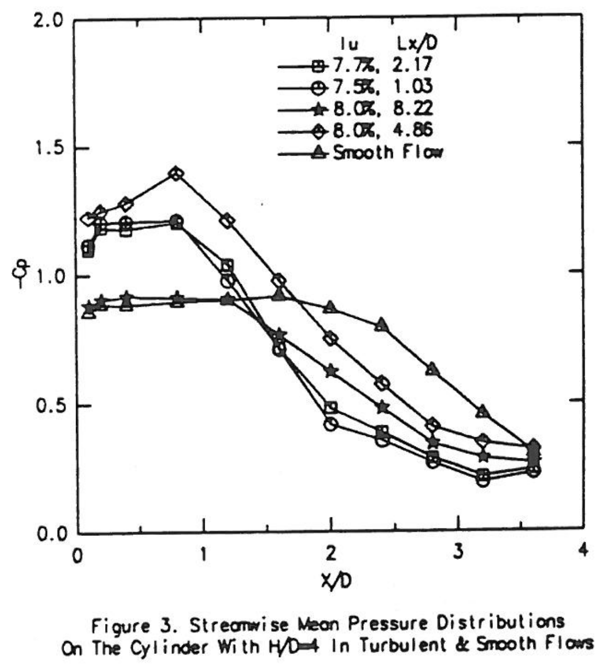

Figure 3. Streamwise Mean Pressure Distributions On The Cylinder With H/D=4 In Turbulent & Smooth Flows

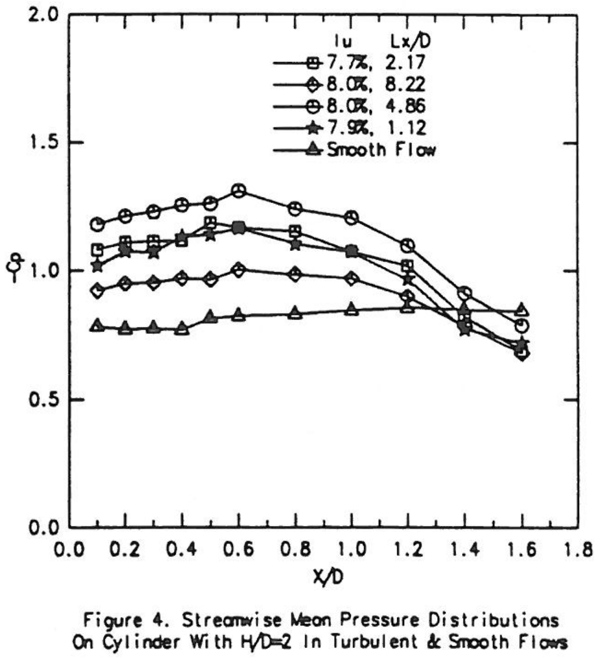

Figure 4. Streamwise Mean Pressure Distributions On Cylinder With H/D=2 In Turbulent & Smooth Flows

Streamwise distributions of r.m.s. fluctuating pressure, C_{σ_p}, on the flat plate are presented in Fig.7. An increase in turbulence intensity causes fluctuating pressures to increase and the location of maximum C_{σ_p} to move closer to the leading edge. An increase in turbulence intensity from 8% to 15% moves the position of maximums C_{σ_p} upstream from 1.5D to 0.7D. As shown in Fig.7, C_{σ_p} increases with increasing scale from 0.40 to 4.86. The magnitude of this effect in this case is about 100%. With further increase in turbulence scale ratio to 8.22, the maximum value of C_{σ_p} does not keep increasing and are about the same as measured at L_x/D=4.86. It can be seen in Fig.8 and Fig.9 that the profiles of C_{σ_p} measured on the cylinders with $H/D = 2$ and 4 are not sensitive to changing turbulence scale for $0.36 < L_x/D < 0.91$. However, with further increase in scale ratio to 1.82, turbulence scale has a significant effect on the distributions of C_{σ_p}. The distributions of C_{σ_p} in turbulent and smooth

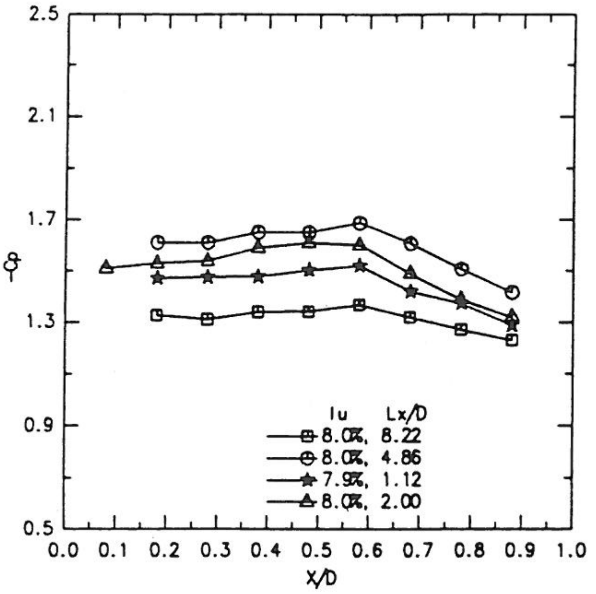

Figure 5. Streamwise Distributions of Mean Pressure Coefficient On The Square Cylinder In Turbulent Flows

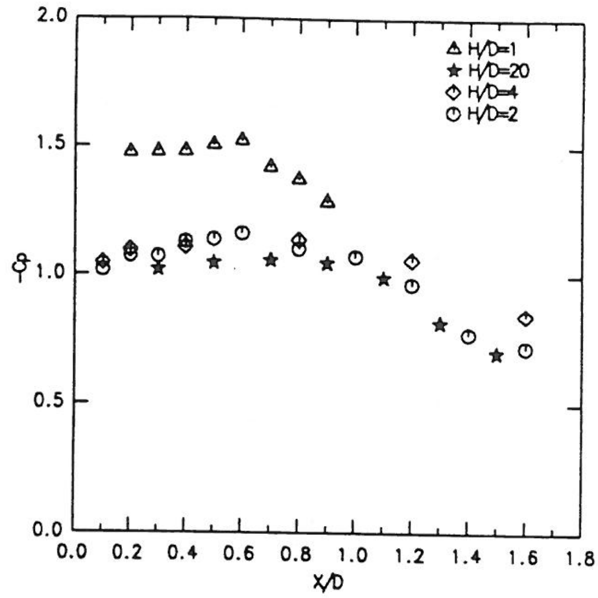

Figure 6. Distributions of Mean Pressure Coefficient On The Four Models In Turbulent Flows(Iu=8%,Lx/D=1.12)

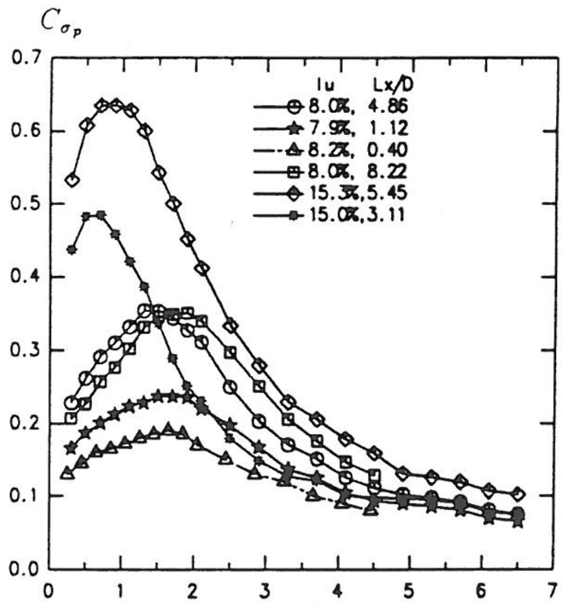

Figure 7. Distributions of Fluctuating Pressure Coefficient On The Blunt Flat Plate In Turbulent Flows

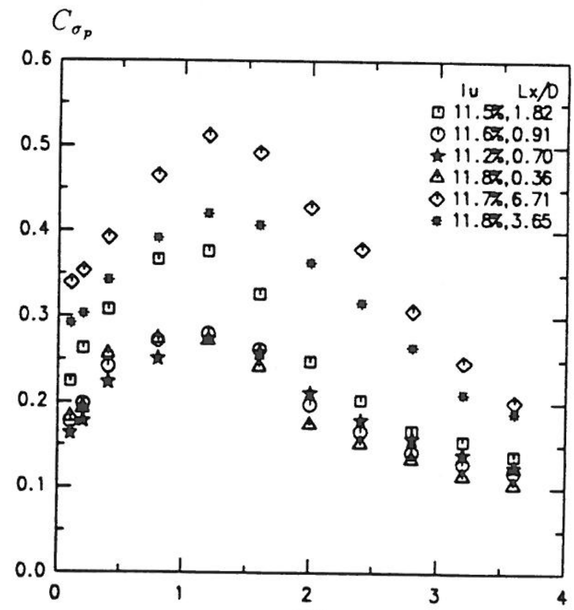

Figure 8. Distributions of R.M.S. Pressure Coefficient On The Cylinder With H/D=4 In Turbulent Flows

flows measured on the square cylinder are presented in Fig.10. The fluctuating pressures at all points on the streamwise surface are larger in the absence of free-stream turbulence than those obtained in turbulent flows. Fig.10 shows that in relatively smaller and larger scale turbulent flows ($L_x/D = 1.12$ and 8.22), little scale effect on C_{σ_p} is evident. However, turbulence scale has a significant effect on C_{σ_p} at $L_x/D = 4.86$. Fig.11 also demonstrates the similarity among the profiles of C_{σ_p} obtained on the cylinders with $H/D = 2, 4$ and 20 in a turbulent flow, which implies that the source of pressure fluctuations may be the same for the three cases. However, for the same turbulent flow, the values of C_{σ_p} measured on the square cylinder are much larger, in particular in the region near the leading edge. Fig.12 shows the measured C_{σ_p} near the leading edge on the cylinder with $H/D = 2$ as a function of turbulence intensity. The data clearly indicate that the effect of tuebulence scale on C_{σ_p} becomes greater as turbulence intensity increases.

The conclusions and the references of this paper are presented in the companion paper in this proceedings.

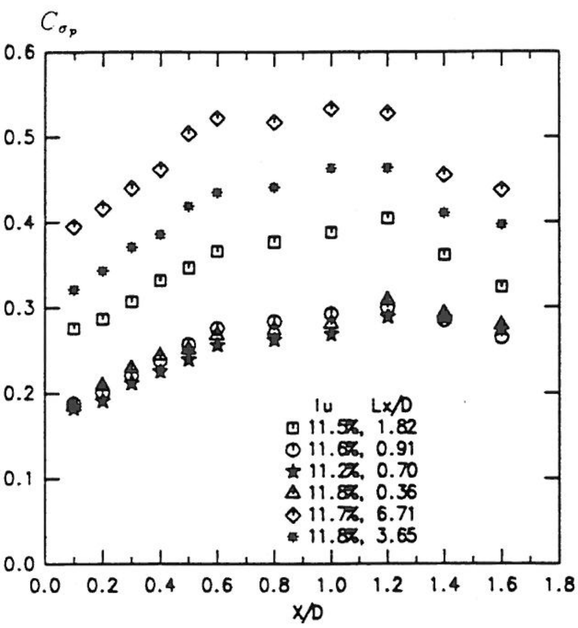

Figure 9. Distributions of R.M.S. Pressure Coefficient On The Cylinder With H/D=2 In Turbulent Flows

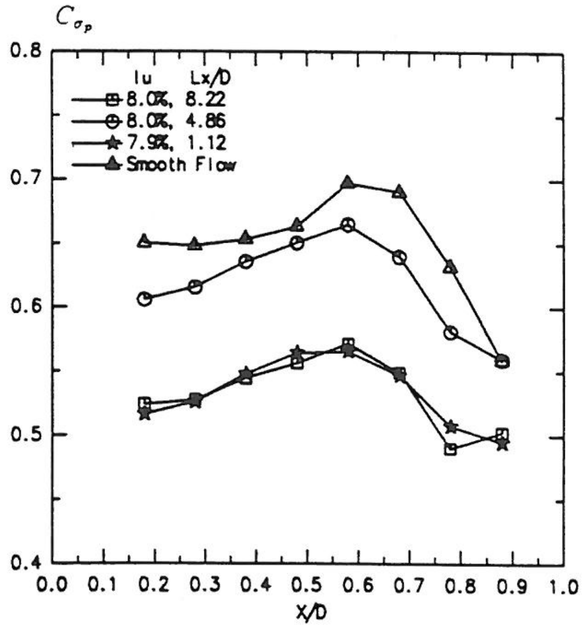

Figure 10. Distributions of Fluctuating Pressure Coefficient On The Square Cylinder In Turbulent and Smooth Flows

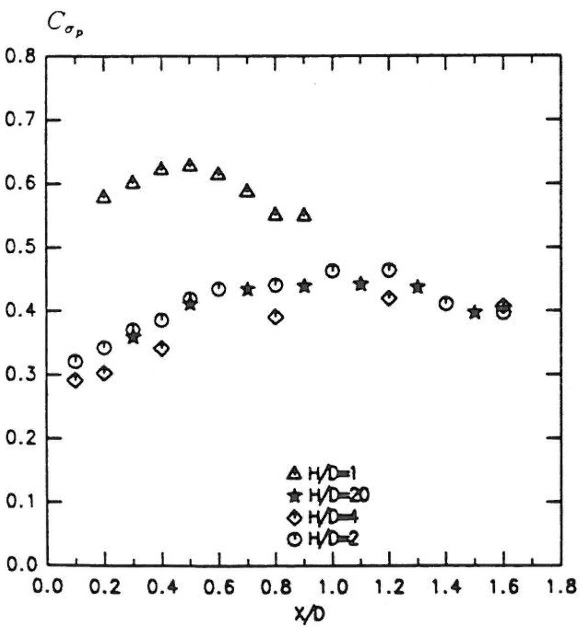

Figure 11. Distributions of Fluctuating Pressure Coefficient On The Four Models In Turbulent Flows(Iu=8%,Lx/D=1.12)

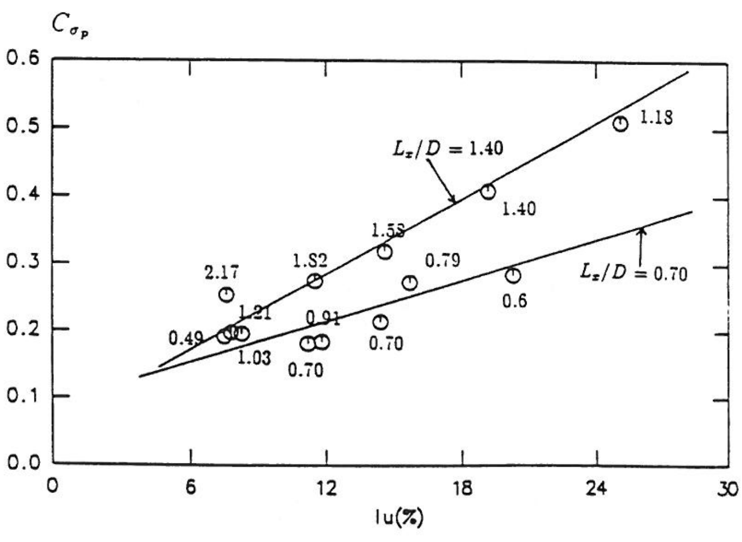

Figure 12. Fluctuating Pressure Coefficient Near The Leading Edge (Values of Lx/D Are Shown Next to Each Data Point).