Crosswind forces on circular cylinders at high Reynolds numbers

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Abstract

An investigation in to the effects of surface roughness and free stream turbulence on the fluctuating crosswind forces for a circular cylinder has been completed. A Reynolds number range from 2×10^5 to 8×10^5 has been investigated. High fluctuating crosswind forces have been measured on rough cylinders in turbulent flows. It was found that the high values were caused by a combination of surface roughness increasing the lift axial correlation length and free stream turbulence increasing the sectional fluctuating lift coefficients.

Introduction

In many engineering applications of circular cylinders the surfaces of the cylinders have a degree of roughness due to manufacturing process or environmental conditions. Additionally, the external flows these bodies are exposed to are turbulent. At high Reynolds numbers, *Re*, above 10^5, Fage and Warsap (1929) showed that the mean drag coefficient and Szechenyi (1975) the fluctuating lift coefficient were significantly influenced by these factors.

A number of investigations have been completed at Monash University into the effects of surface roughness and turbulence on the crosswind forces, notably Cheung (1983), Zhang (1993), and Palmer (1994). The three investigations observed similar increases in the fluctuating lift coefficient for rough cylinder in turbulent flow. However, measurements were taken of the total fluctuating lift coefficient, $\sigma_{cl}(l)$, which gives a span averaged force on a finite length cylinder. The approach made it difficult to separate the effects of surface roughness and turbulence on the crosswind forces. As a result two explanations for the high crosswind forces were proposed; Cheung suggested the high values were caused by the effect of surface roughness, and Zhang and Palmer suggesting the high values were caused by the effect of free stream turbulence.

In this investigation a different measurement approach has been adopted. Instantaneous measurements of the sectional fluctuating lift coefficient, $\sigma_{cl}(0)$, and the axial correlation length of the lift forces, λ_c, have been made. The $\sigma_{cl}(0)$ and λ_c are related to $\sigma_{cl}(l)$ using Equation (1) proposed by Kacker *et al.* (1974).

$$\sigma_{cl}(l) = \sigma_{cl}(0) \times \frac{\sqrt{2\lambda_c}}{l}, \ where\ \lambda_c = \int_0^l (l-s)R_f(s)ds,$$
$$R_f(s) = \frac{\overline{E(y_1,t)E(y_2,t)}}{E^2}, \ and\ \mathrm{s} = (\mathrm{y}_1 - y_2). \tag{1}$$

where y_1 and y_2 are points along the generators of the cylinder.

Experimental Method

The investigation was carried out in the 5m high x 4m wide working section of the 1MW wind tunnel at Monash University. The experiment comprised a smooth circular cylinder; 400mm in diameter, which spanned the tunnel's working section. The cylinder was instrumented with multiple pressure tappings as shown in Figure 1. The tapping arrangement consisted of a complete ring at the centre of the cylinder and tappings at ratios of the diameter along the 90 and 270 degree generators (0 degrees is the front stagnation line).

The relative roughness, *k/D*, of the cylinder was of the order 10^5. A range of surface roughness was achieved by wrapping the cylinder in sandpaper of various grain sizes. The experiments were performed for two *k/D* of 0.8×10^{-3} and 2.5×10^{-3}.

Free stream turbulence was generated using symmetric grids positioned in the 5m high x 12m wide section approximately 10 m upstream of the cylinder centreline. Three flow configurations were used, an empty tunnel with a turbulence intensity of $I_u = 4\%$, a grid with a panel width of 300mm giving I_u

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= 7%, and a 600mm panel giving I_u = 12%. The longitudinal integral length scale for the three flow configurations was approximately 0.3 m. A series of instantaneous pressure measurements were taken using an electronic Scanivalve system at 200 Hz as the Reynolds number was varied between 2 x 10^5 and 9 x 10^5.

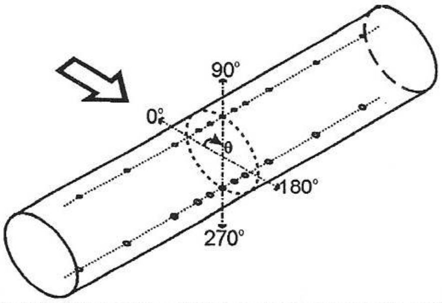

Figure 1: Schematic of the pressure tapping locations

The $\sigma_{cl}(0)$'s were calculated by integrating the instantaneous pressure distributions around the central ring. The λ_c's presented were determined using the correlation of pressures along the 90 and 270 degree generators. The pressures along the generators were correlated with the corresponding pressure tap in the central ring. This approach was adopted because of the demand for complex instrumentation to measure the sectional forces at numerous locations along the span of the cylinder. Ribeiro (1991), in a review of published correlation coefficient data, concluded that the correlation on the 90 degree (or 270 degree) generator was a reasonable approximation of the force correlation.

Results and Discussion

The investigation examines the effects of surface roughness and free stream turbulence on the $\sigma_{cl}(0)$ and λ_c experienced by a circular cylinder. Figures 2(a) and (b) show the variation of $\sigma_{cl}(0)$ and λ_c with *Re* for a range of I_u's for the smooth cylinder. The $\sigma_{cl}(0)$ is observed to increase with I_u, while there is a small variation of λ_c, but remains short (~0.8D) indicating poor coherence of the lift force along the span of the cylinder.

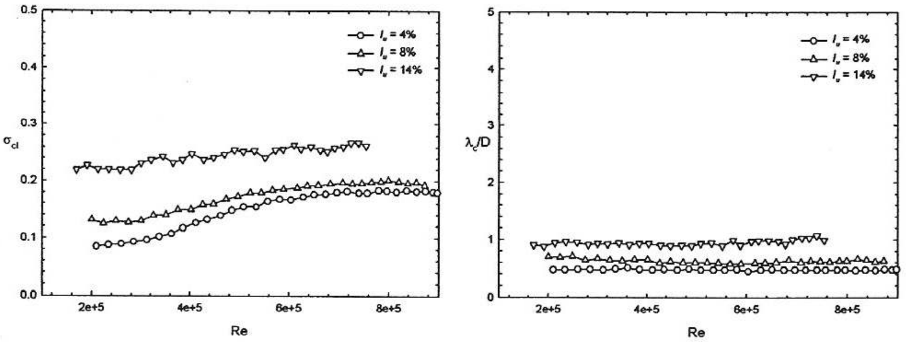

Figure 2: (a) $\sigma_{cl}(0)$ and (b) λ_c/D for a nominally smooth cylinder as a function of *Re* for various I_u

Figure 3(a) and (b) show the variation of $\sigma_{cl}(0)$ and λ_c with *Re* for a range of *k/D* for I_u = 4%. The addition of surface roughness has resulted in an increase in magnitude of $\sigma_{cl}(0)$ and λ_c compared to the smooth cylinder case. The increase of $\sigma_{cl}(0)$ suggests that the presence of surface roughness enhances the effect of free stream turbulence as well as significantly improving the lift force correlation along the cylinder span. During these experiments strong crosswind vibration of the cylinder was observed.

The final case presented in Figures 4(a) and (b) are where Cheung (1983), Zhang (1993) and Palmer (1994) observed their highest values of $\sigma_{cl}(l)$. At the high values of *k/D* and I_u the $\sigma_{cl}(0)$ has increased to values greater than 0.40 for the *Re* range investigated. The increase of I_u has caused a decrease of λ_c

compared to the I_u = 4% case, but the value is still an order of two larger than the smooth cylinder in the same turbulent flow.

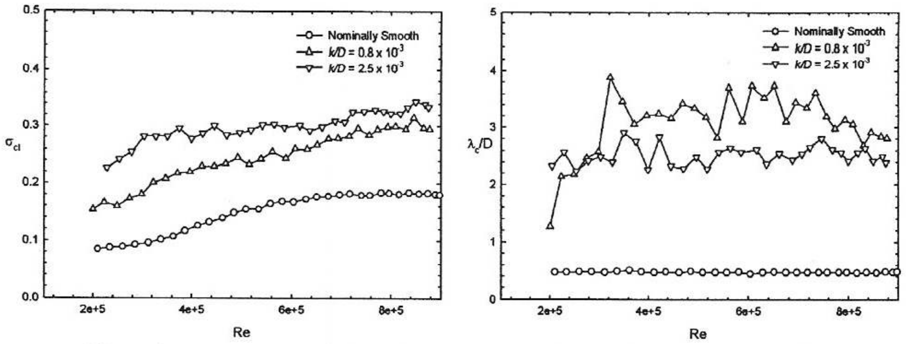

Figure 3: (a) $\sigma_{cl}(0)$ and (b) λ_c/D for various k/D with I_u=4% as a function of *Re*

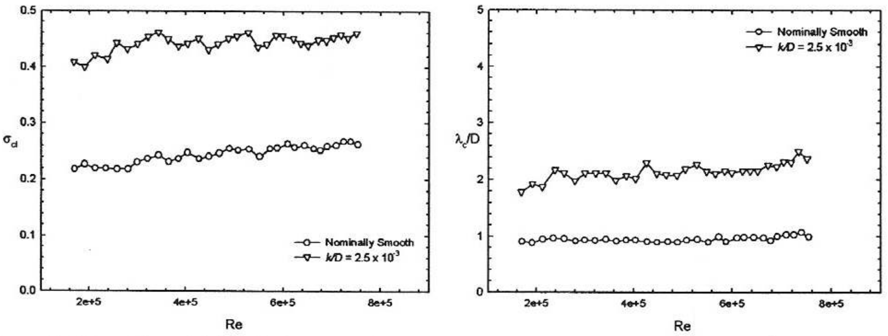

Figure 4: (a) $\sigma_{cl}(0)$ and (b) λ_c/D for a nominally smooth cylinder and $k/D = 2.5 \times 10^{-3}$ with I_u=14% as a function of *Re*

The $\sigma_{cl}(0)$ spectrum at a $Re = 6.51 \times 10^5$ for the rough cylinder case in Figure 4(a) shown in Figure 5. The presence of free stream turbulence has not caused significant broad banding of the spectrum commonly found for a smooth cylinder, instead the majority of the energy is centred on the vortex shedding reduced frequency of 0.2. Therefore, the high values of $\sigma_{cl}(0)$ presented in Figure 4(a) calculated from an unfiltered time series, do represent an increased fluctuating crosswind force due to enhanced vortex shedding.

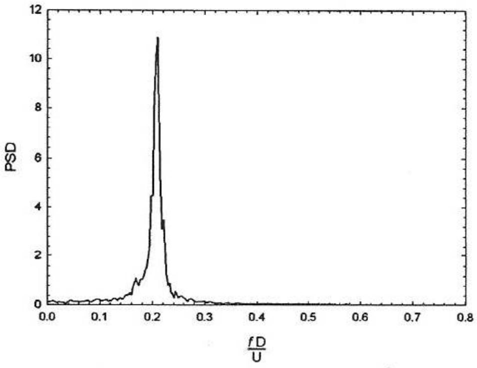

Figure 5: Sectional fluctuating lift spectrum for $k/D = 2.5 \times 10^{-3}$ at $Re = 6.51 \times 10^5$ and I_u = 12%

The data presented in Figures 2 to 5 have shown that $\sigma_{cl}(0)$ is primarily influenced by I_u and that λ_c is primarily influenced by k/D. However, the significant effect of turbulence on $\sigma_{cl}(0)$ is realised only if the surface of the cylinder has a degree of surface roughness. The results have shown high values of $\sigma_{cl}(0)$ and λ_c for rough cylinders in turbulent flow, however for completeness Equation 1 was used to relate the sectional values and the correlation to the $\sigma_{cl}(l)$ for a finite length cylinder. Table 1 presents the results of the calculation for a rough cylinder in turbulent flow for $Re = 6.51 \times 10^5$.

Table 1: Calculation of $\sigma_{cl}(l)$ from experimental results at $Re = 6.51 \times 10^5$ for $l = 1.8$m, where D = 0.4m

Case	$\sigma_{cl}(0)$	λ_c (m)	$\sigma_{cl}(l)$
Smooth $I_u = 4\%$	0.16	0.3	0.08
Smooth $I_u = 12\%$	0.26	0.4	0.13
$k/D = 2.5 \times 10^{-3}$ $I_u = 4\%$	0.30	1.2	0.26
$k/D = 2.5 \times 10^{-3}$ $I_u = 12\%$	0.45	0.96	0.35

The data presented in Table 1 shows the same trends reported previously by Cheung, Zhang and Palmer, with the largest $\sigma_{cl}(l)$ occurring for the rough cylinder in turbulent flow. Although, for the rough cylinder in turbulent flow, the inherent three-dimensionality of the turbulence has caused a reduction of λ_c, the decrease is offset by an increase in magnitude of $\sigma_{cl}(0)$. These results show that the high crosswind forces are caused by the complimentary effects of surface roughness and free stream turbulence, rather than the effects of roughness or turbulence individually as suggested previously.

Additionally, it has been shown the use of surface roughness in the wind tunnel to trip the boundary layer of the cylinder to 'simulate' higher Reynolds number regimes will result in significantly higher total crosswind forces. The opposite of this, the use of smooth cylinders in the wind tunnel to model full scale cylinders in the environment, will under estimate the crosswind forces, due to the lack of correct surface roughness modelling.

Conclusions

An investigation of the effects of surface roughness and free stream turbulence on the crosswind forces has been completed for a Reynolds number range from 2×10^5 to 8×10^5. The high total fluctuating crosswind forces reported by Cheung (1983), Zhang (1993) and Palmer (1994) have been shown to be caused by the combined effects of surface roughness and free stream turbulence. Surface roughness increases the axial correlation length of the lift forces, while free stream turbulence increases the sectional fluctuating lift coefficient.

The use of surface roughness in the wind tunnel should be considered carefully, as the fluctuating crosswind forces for circular cylinders may be under or over predicted depending of the selection of the model surface conditions.

References

Cheung, C. K. (1983). *Effect of turbulence on the aerodynamics and response of a circular structure in wind flow*. Mechanical Engineering. Clayton, Monash University.

Fage, A. and J. H. Warsap (1929). *The effects of turbulence and surface roughness on the drag of a circular cylinder*. London, Aeronautical Research Council: 7.

Kacker, S. C., B. Pennington, et al. (1974). "Fluctuating Lift Coefficient for a Circular Cylinder in Cross Flow." Journal of Mechanical Engineering Science **16**(4): 215-224.

Palmer, T. R. (1994). *The Effect of Turbulence and Surface Roughness on the Aerodynamics of a Two-Dimensional Circular Cylinder*. Mechanical Engineering. Clayton, Monash University.

Ribeiro, J. L. D. (1991). "Effects of surface roughness on the two-dimensional flow past circular cylinders II: fluctuating forces and pressures." Journal of Wind Engineering and Industrial Aerodynamics **37**: 311-326.

Szechenyi, E. (1975). "Supercritical Reynolds number simulation for two-dimensional flow over circular cylinders." Journal of Fluid Mechanics **70**(3): 1975.

Zhang, H. (1993). *Flow interference between two circular cylinders in turbulent flow*. Mechanical Engineering. Melbourne, Monash University.