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Effects of turbulence integral length scale on a Smooth Cylinder's axial correlation length at Critical and Supercritical Reynolds numbers

M. Eaddy, W.H. Melbourne and J. Sheridan

Department of Mechanical Engineering
Monash University, Clayton, Victoria, AUSTRALIA

ABSTRACT

Measurements have been made of the axial correlation length on a smooth circular cylinder in low and high turbulent flow conditions. For the high turbulence flow the integral length scales were varied between 0.7D and 2D. The results for the low turbulence and high turbulence with integral scales smaller than the cylinder diameter agree well with published results. At the higher turbulence conditions with integral scales larger than the cylinder diameter it was found that the axial correlation length increased with turbulence intensity, peaking at values of approximately 3 diameters. It is postulated that this increase is caused by interaction between the transverse component of the turbulence vortices and the vortices being shed from the cylinder.

1. INTRODUCTION

The critical regime for a smooth circular cylinder is identified by a pronounced decrease in the mean drag coefficient from approximately 1.2 at Re~1.5×10^5 to 0.25 at Re~4×10^5. The Reynolds number at which the mean drag attains a minimum value is termed the critical Reynolds number and indicates the beginning of the supercritical regime (Roshko, 1961). The axial correlation length undergoes a similar decrease in value over this Reynolds number range, dropping from 3-6 diameters to ~1 diameter at the critical Reynolds number and maintaining this value in the supercritical regime (King, 1977). Zdravkovich (1997) describes the mechanism that causes this transition as a reduction in the stability of the wake region as the separation point moves rearwards and the separating shear layers become more and more aligned with the free stream, until eventually the transition to turbulence point reaches the separation point at the critical Reynolds number.

It is well known that the effect of free stream turbulence can be seen as an effective increase in Reynolds number, resulting in the critical transition and the decrease in axial correlation length to occur at lower Reynolds numbers (Cheung, 1983). Unfortunately, in order to obtain data at these Reynolds numbers the diameter of the cylinder needs to be large because of velocity limits of wind/water tunnel facilities. This causes the ratio of turbulence integral scale to cylinder diameter to reduce below unity, typically 0.5D. Experimental data obtained in these conditions have shown little effect of turbulence scale on the axial correlation length, results typically giving values of 1 diameter in the critical/supercritical regimes (Bruun and Davies, 1975; Blackburn, 1992). Due to these results it is currently understood that free stream turbulence affects the Reynolds number when transition is initiated and the magnitude of the pressure fluctuations around the cylinder. Results from experiments that have used turbulence of longitudinal integral scale (L_x/D) larger than the diameter of the cylinder are reported, Surry (1972) and Mulcahy (1984), but either have not investigated Reynolds numbers in the critical regime or have not measured the axial correlation length.

In this paper we present results from experiments in which the turbulence integral scale was varied from 0.7D to 2D with turbulence intensities between 2 and 12 %, for a Reynolds number range of 7×10^4 to 3.3×10^5. The results in low and high turbulence flow with an L_x/D smaller than the cylinder diameter are presented to show agreement with published data. These results are then extended with new data from experiments with L_x/D larger than the cylinder diameter.

2. EXPERIMENTAL METHOD

2.1 CYLINDER MODEL

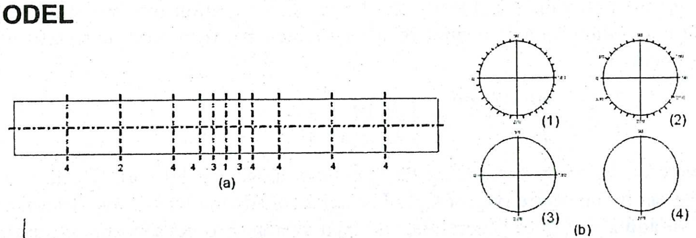

Figure 1: Location of pressure taps (a) axially with number relating to (b) circumferential position

The circular cylinder model was constructed from diameter 100mm aluminium tube. This cylinder was pressure tapped as shown in Figure 1 with a complete ring of taps at 10 degree intervals in the centre and taps along the 90 and 270 degree generators (0 degrees being the front stagnation line) at ratios of the cylinder diameter. Each tapping consisted of a 1mmID x 20mm stainless steel tube inserted in the cylinder wall with a 1500mm long P.V.C tube connecting it to a pressure transducer. The P.V.C tubing was closed with no restrictors or leaks to reduce the resonant response of the tubing. The cylinder used was classified a nominally smooth with a roughness ratio ($^k/_D$) of 0.02×10^{-3}. This was achieved by sanding the cylinder surface with fine emery paper to remove any major surface imperfections.

2.2 WIND TUNNELS

The experiments were performed in the 450kW and 1MW wind tunnels at Monash University. The use of these two tunnels allowed Reynolds numbers from 7 x 10^4 to 3.3 x 10^5 to be obtained with different turbulence intensities and integral scales. The cylinder was installed in the 2x1m section of the 450kW tunnel horizontally at mid height between end plates, resulting in an aspect ratio of 9.0:1 and a blockage of 5 %. The cylinder was clamped in place when aligned to the flow and can be classified as a stationary cylinder. In the 5x4m working section of the 1MW tunnel a platform was used to mount the cylinder vertically between end plates so the aspect ratio remained identical to the 450kW tunnel. Blockage in this tunnel was reduced to 2.5%. The cylinder was mounted vertically for easy connection of the pressure taps to the pressure transducers.

Alignment of the cylinder with the onset flow was achieved by rotating the cylinder until the stagnation pressure at the zero degree pressure tap was maximised and the pressure taps on either side (10 and 350 degrees) had similar mean pressures.

2.3 TURBULENCE GENERATION

Homogeneous free stream turbulence of different intensity and scale was generated in the 450kW tunnel using grids placed at four or five positions upstream of the cylinder. The turbulence characteristics at each position were measured using an end flow crossed hot wire anemometer connected to a TSI constant temperature anemometer bridge. The three turbulence components were obtained by rotating the cross wire 90 degrees, first measuring the u,w and then the u,v components.

The integral length scales were determined by fitting the Von Kärman turbulence spectra to the spectrum of turbulence measured in the wind tunnel. Tables 1 and 2 present the turbulence intensities and integral length scales for the three (u,v,w) components of turbulence with 'x' being the distance from the cylinder centreline to the centreline of the turbulence grid.

Table 1: Grid 1 turbulence intensities and integral length scales in 450kW Wind Tunnel

Position	I_u (%)	I_v (%)	I_w (%)	L_{ux}/D	L_{uy}/D	L_{uz}/D
Bare Tunnel	0.6	0.6	0.6			
1. x = 4.6m	12	12	12	1.4	0.8	0.8
2. x = 5.6m	10	10	10	1.4	0.9	0.9
3. x = 7.2m	7	7	7	1.4	1.2	1.2
4. x = 9.6m	5	5	5	1.4	1.4	1.4

Table 2: Grid 2 turbulence intensities and integral length scales in 450kW Wind Tunnel

Position	I_u (%)	I_v (%)	I_w (%)	L_{ux}/D	L_{uy}/D	L_{uz}/D
1. x = 3.55m	7	7	7	0.7	0.7	0.7
2. x = 4.6m	5.3	5.3	5.3	0.7	0.7	0.7
3. x = 5.6m	4	4	4	0.7	0.7	0.7
4. x = 7.2m	3	3	3	0.7	0.7	0.7
5. x = 9.6m	2	2	2	0.7	0.7	0.7

The turbulence conditions in the 1MW wind tunnel with no grid was I_u=3.5%, I_v=3.5% , I_w=3.5%, L_{ux}/D=2, L_{uy}/D=1.2, and L_{uz}/D=2.

2.4 DATA ACQUISITION AND PROCESSING

The instantaneous pressures from the 88 pressure taps on the cylinder were sampled using an electronic Scanivalve system at a frequency of 1000hz for 35 seconds.

The initial processing of the pressure data involved correcting the data for the resonant response of the P.V.C tubing and the small time lag caused by the multiplexers in the Scanivalve. The correction of the resonant response was done using the technique presented by Irwin *et al* (1979) in the frequency domain. The resonant response and phase lag of the 1500mm P.V.C. tubing at frequencies up to 500hz had been previously measured. Convolution of inverse of this response with the Fourier transformed pressure data corrected the data for the resonant and phase lag effects. In the frequency convolving the data with an inverted phase shift and an amplitude response of one corrected for domain the time lag imposed by the multiplexer. The data was then inverse Fourier Transformed to give the corrected pressure signal for each tapping.

The axial correlation length is determined by integrating the correlation coefficients as a function of the axial separation from a reference point, as given in Equation (1). Ideally the limits of integration are zero and infinity but due to the constraints of experiments the correlation length integral is approximated between zero and point where the correlation coefficient curve first becomes negative.

$$\lambda_z = \int_0^{\rho_{xz}(x/D)=0} \rho_{xz}\left(\frac{x}{D}\right) d\left(\frac{x}{D}\right) \qquad (1)$$

The correlation coefficients were obtained by correlating the pressures along the 90 and 270 degree generators with the pressure at the 90 or 270 degree tap in the centre ring of taps. The axial correlation length was determined four times, to the left and right of centre on the 90 and 270 degree generators, and then averaged to get the axial correlation length quoted in this paper. This approach was taken because the vortex shedding in the critical and supercritical regimes is three dimensional along the cylinder axis. Therefore, the centre reference point may not be exactly in the centre of a vortex cell and shorter or longer correlation lengths may be measured to the left and right of the centreline.

3. RESULTS

The axial correlation length measured on the smooth cylinder in low turbulence flow is presented in Figure 2 with published data from three authors are included for comparison. This figure illustrates how the axial correlation length decreases dramatically when the cylinder undergoes critical transition. In the high subcritical regime (Re< 2x10^5) the axial correlation length is between 3.5 to 4 diameters and then suddenly drops to approximately 1 diameter in the supercritical regime. Excluding Batham's (1973) data all the other data undergoes transition at a Reynolds number, although Bruun and Davies

(1975) have only managed to capture the initial part of the transition process. Agreement between Blackburn and Melbourne (1993) and current data is good, as both experiments were performed in the same wind tunnel.

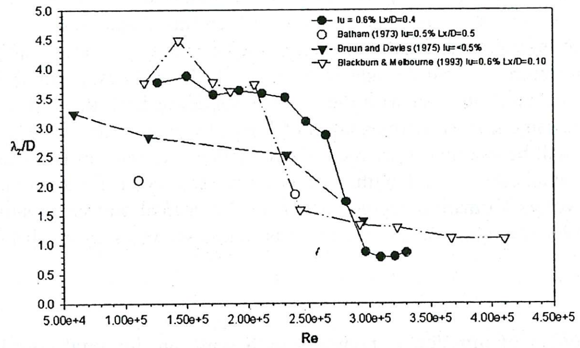

Figure 2: Axial Correlation Length for a Smooth Cylinder in low turbulence flow as a function of Reynolds Number

Figure 3 (a) and (b) present the axial correlation length measured for the L_x/D ratios used in these experiments. Figure 3(a) is the data obtained for the flow conditions where the L_x/D was less than unity. The effect of the turbulence is to promote earlier critical transition on the cylinder, as shown by a measured axial correlation length of one for almost all cases. This agrees well with the experimental data from Blackburn and Melbourne (1993) for their lower turbulence intensities. However, at their highest intensity there is a noticeable increase in the axial correlation length indicating an increase in vortex shedding organisation. Batham's (1973) indicates a considerably shorter axial correlation length in turbulent flow, approximately 0.5D. One point in the current data does stand out, the lowest Reynolds number at an intensity of 2% where an axial correlation length of three diameters was recorded. Comparison with correlation lengths in Figure 2 indicates at this turbulence intensity critical transition is occurring between the two lowest Reynolds numbers.

Figure 3(b) presents the five turbulence configurations where the L_x/D ratio was greater than unity. The effect of the larger integral turbulence on the axial correlation length is significant when figures (a) and (b) are compared. The axial correlation length increases with turbulence intensity reaching values near three diameters at the highest turbulence intensity. This correlation length is similar to those measured in the high subcritical regime for the smooth cylinder in low turbulence flow (Figure 2). Unfortunately, the velocity range available in the 450kW wind tunnel with the grids installed limited the lowest Reynolds number attainable; hence we were not able to take measurements in these turbulence configurations that included the critical transition Reynolds number.

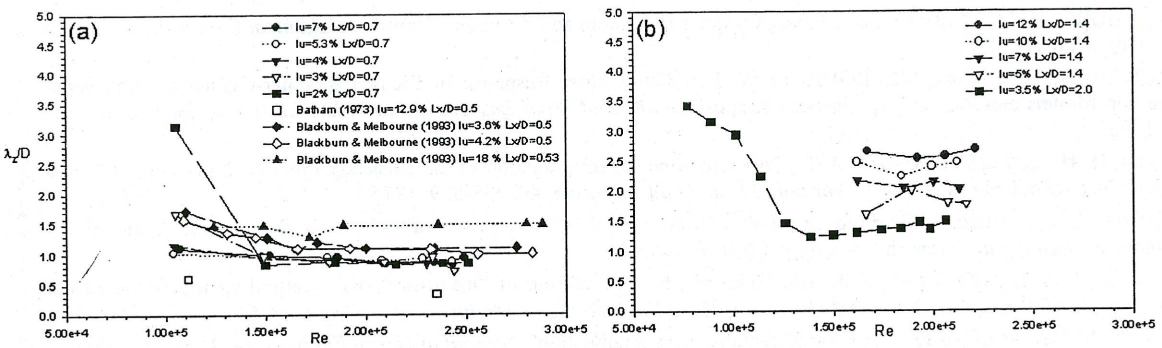

Figure 3: Axial Correlation Length for a Smooth Cylinder in turbulent flow with (a) $L_{ux}/D < 1$, and (b) $L_{ux}/D > 1$, as a function of Reynolds number

4. DISCUSSION

The axial correlation length measured on the smooth cylinder in low turbulence flow showed good agreement with previously published data. The axial correlation length decreased from 3-4 diameters to one diameter during critical transition, which is the accepted value for smooth circular cylinders in low turbulence flow in the critical regime (King, 1977).

As described by Batham (1973), Cheung (1983) and Blackburn and Melbourne (1993) the introduction of free stream turbulence results in an effective increase in the Reynolds number. This is apparent in the current set of results for turbulence with a longitudinal L_x/D less than unity, with an axial correlation length of 1 diameter measured in the turbulent flow. These values are consistent with those obtained by researchers who have tested smooth circular cylinders in turbulent flow and was expected because the majority of the published axial correlation length data for a smooth cylinder in turbulent flow has been taken with turbulence with this L_x/D. This scale ratio is the result of the unfortunate compromise between obtaining high Reynolds numbers of the critical and supercritical regimes vs. maintaining a high integral scale to diameter ratio. The effect of small-scale turbulence was to promote earlier critical transition, which has been described by Batham (1973) as an effective increase in Reynolds number. Turbulence of this scale may be successful at promoting this transition because it can interact with the separation shear layers causing the point of turbulence transition to occur closer or at the point of separation.

The axial correlation lengths measured in the turbulent flow with a longitudinal L_x/D greater than unity showed a significant increase in the vortex shedding organisation that increased with turbulence intensity, peaking at values of three diameters at the highest intensity. Blackburn and Melbourne (1993) postulated that this might occur in turbulent flows with large integral scales. Their results, which are replotted in Figure 3(a), showed that at high turbulence intensity, although the integral scale was 0.5D, the axial correlation length is increased. Further investigation is required to determine the mechanisms that cause this increased vortex shedding organisation. Current thought is the larger L_x/D vortices, particularly the traverse component (perpendicular to the flow and cylinder axis), interact with the vortices shedding from the cylinder prompting them to shed over larger span of the cylinder at the same instant. Investigation of L_x/D effects on a flat plate by Li and Melbourne (1999) showed that a quasi steady situation will be eventually reached where further increases in L_x/D are seen as a slowly varying mean flow and have no effect on the axial correlation length. This is expected to occur for a circular cylinder and may have a relationship with the length of the vortex formation region, which in the critical and early supercritical regimes is 2.7D (Roshko, 1993). The L_x/D required for this quasi-steady situation is unknown and may be difficult to generate in a wind tunnel due to facility limitations.

5. CONCLUSIONS

This research has investigated the effect of turbulence integral length scale on the axial correlation length on a smooth cylinder in the critical and supercritical regimes. Comparison with published axial correlation lengths for smooth cylinders in low turbulence flow has found good agreement.

Axial correlation lengths measured for the smooth cylinder in turbulence flow with the L_x/D less than unity were found to agree with current expected values of one diameter. The turbulence caused an effective increase in the Reynolds number, with critical transition occurring at considerably lower Reynolds numbers than the low turbulence case. Turbulence of this integral scale is able to interact with the separating shear layers promoting the turbulent transition and reducing the axial uniformity of the vortex shedding, hence the decrease in axial correlation length.

The axial correlation length was found to increase with turbulence intensity for L_x/D greater than unity. Peak values of approximately three diameters were measured on the cylinder for turbulence intensities of 12%, which are similar to those measured in the high subcritical regime. Further investigation is required to determine the mechanism that causes this increase in vortex shedding organisation. Current thought is the larger scale turbulent vortices, especially the traverse component, are able to interact with the shedding vortex and cause the vortex to shed along the axis of the cylinder at the same instant. Based on results for a flat plate, it is expected that the effect of the turbulence integral scale will eventually reach a quasi-steady situation and this may be related to the formation length of the vortices shedding from the cylinder.

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