An Experimental Investigation of the effects of Surface Roughness and Free-Stream Turbulence on the fluctuating pressures on a Circular Cylinder

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Abstract

This paper outlines an investigation of the effects of free-stream turbulence and surface roughness on the fluctuating pressures on a circular cylinder at Reynolds numbers above 10^5. The investigation is currently testing at Reynolds numbers between 1×10^5 and 3×10^5 with a smooth cylinder to determine the performance of a pressure measurement system. Fluctuating forces are being determined by integrating the surface pressures around the centre of the cylinder. The focus is on the aerodynamic parameters of base pressure coefficient, fluctuating lift spectra, Strouhal number and specifically spanwise correlation of forces and pressures. An important result has indicated that it is possible to measure the correlation by using spanwise pressures at the 90-degree generator instead of using the fluctuating lift forces. The other results have shown disagreement with published data for the Reynolds number range indicating a possible problem with the flow or the surface finish of the cylinder.

Introduction

The circular cylinder is an interesting shape aerodynamically. As the Reynolds number increases the flow characteristics around the cylinder change, particularly the mean drag and vortex shedding. These characteristics are influenced by a number of factors such as, free-stream turbulence intensity and scale, surface roughness, and aspect ratio.

There have been numerous tests on smooth and rough circular cylinders in both low and high turbulence flows to determine the mechanisms that occur in the flow as the Reynolds number increases. The majority of the tests, such as Basu (1985), have focused on a Reynolds number range below 10^6 because of interest in the abrupt transition that occurs around the cylinder and the lack of research facilities to obtain Reynolds numbers above this value.

Investigations that have achieved high Reynolds numbers of order 10^7 have been performed in aerodynamic wind tunnel where there is low turbulence (<1%) (Shih *et al* 1993) and the cylinder surface is smooth. The Reynolds numbers attained are close to high full-scale values of 10^7 to 10^8, but the flow conditions and cylinder are different to full-scale wind conditions of high turbulence intensity and a rough surface finish of the structure. Experiments on cylinders at lower Reynolds numbers have shown that turbulence and surface roughness have a significant effect on the aerodynamics of a cylinder (Niemann and Holscher 1990).

Investigation

An experimental program is in progress at Monash University to investigate the flow characteristics around a circular cylinder for Reynolds numbers up to 3×10^6. The investigation includes determination of the effects of surface roughness and free stream turbulence on the cylinder's mean pressure distribution, fluctuating lift, mean drag, vortex shedding frequency and circumferential and spanwise correlation. The Reynolds number experiments in the region of 10^6 will use the 1MW wind tunnel at Monash University. Measurements taken of the instantaneous pressures on the cylinder surface are integrated to calculate the forces on the cylinder. The benefit of this technique over the direct force measurement is that the measurement system is independent of the mechanical response of the cylinder. This is a limitation with direct force measurement methods because as the natural frequency of the system is approached the force data is increasingly contaminated by the response of the system.

The partial results being reported in the paper are part of the preliminary investigation using the Monash University 450kW wind tunnel to determine the performance of the pressure system using the smooth cylinder. Particular interest is in the correlation of spanwise pressures/fluctuating lift force on the cylinder.

Experimental Method

This part of the investigation of the fluctuating pressure on the surface of a circular cylinder was performed in the 450kW Wind Tunnel at Monash University. The working section uses an insertable section that reduces the 2x2m working section to 2x1m allowing Reynolds number up to 3 x 10^5 to be achieved. A turbulence grid was used upstream of the test section to generate homogeneous turbulence of varying intensity and longitudinal length scale. Table 1 gives the turbulence intensities and scale for the different grid positions.

Table 1: Turbulence intensities and length scales

Position	I_u (%)	L_x (mm)
Bare Tunnel (no grid)	2.4	110
Grid at x = 3.55 from cylinder centreline	16	150
Grid at x = 4.6 m	14	150
Grid at x = 5.6 m	12	140
Grid at x = 7.2 m	8	130
Grid at x = 9.6 m	6	130

Four 100mm-diameter cylinders of varying surface roughness have been pressure tapped using 1mm taps. Figure 1 shows the pressure tap layout for all the cylinders. There are tappings in the centre then at 0.25D, 0.5D, 1D, 2D and 3D in each direction from the centre. The centre of the cylinder has a complete ring of taps and there is a partial ring at two diameters to the left of centre for analysing the correlation of pressures and fluctuating lift forces. Other locations have tappings at ±90 degrees and tappings for stagnation and base pressures. The pressure tappings in the rough cylinders were installed after the sandpaper was attached to avoid the need for clearance holes. This enabled the tappings to be inserted level with the backing paper of the sandpaper and be completely surrounded by roughness elements.

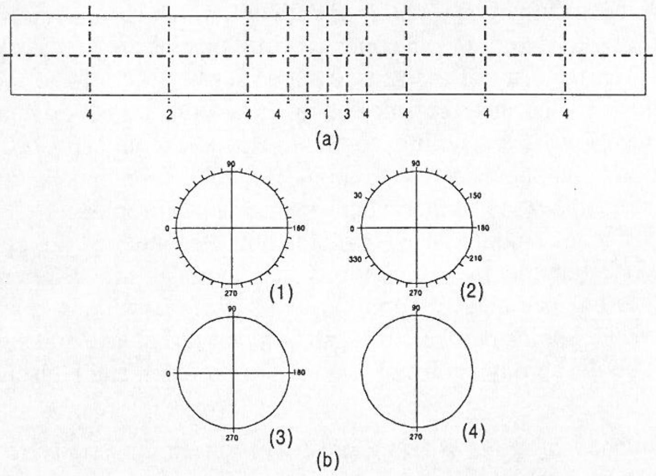

Figure 1: Pressure tapping locations (a) axially (numbers indicate tapping type given in (b)), and (b) circumferentially

Table 2 shows the relative roughnesses of the surface for the four cylinders. The smooth cylinder surface was finished by lightly sanding with emery paper to remove any large manufacturing imperfections. The relative roughnesses for the sandpapers were determined from the manufacturer's data on average particle size and spreading density.

Table 2: Cylinder surface relative roughness

Cylinder Code	Sandpaper Grade	$^{k}/_{D}$ x 10^{-3}
Smooth		0.02
Rough 1	P180	0.74
Rough 2	P60	2.48
Rough 3	P40	4.22

Each cylinder had in total 86 pressure taps along and around the surface. To measure all these points simultaneously a Scanivalve ZOC-16 pressure transducer system was used. This system measures 96 pressure channels simultaneously at sampling frequencies up to 1000Hz. Time histories were sampled at either 500 or 1000Hz for periods up to 40 seconds giving between 20000 to 40000 samples. Long time histories are required in order to achieve a reasonable resolution in the sprectra calculations.

The position of the pressure transducer unit beside the working section required the use of 1500mm long tubing to connect each transducer to a pressure tap. The long tube length had a dynamic response that would affect the measurement of fluctuating pressures. The data are corrected for tubing dynamic response using the Inverse Transfer Function method outlined by Irwin (1979). This method uses a the transfer function measured prior to testing of the tubing combined with the pressure transducer for the range of frequencies up to the Nyquist frequency. The pressure time histories are then corrected in the frequency domain. The benefit of using this method rather than restrictors or leak tubes is that it corrects for both the phase and amplitude responses of the tubing.

The collected data was analysed using Matlab™ for simplicity. Since the value of blockage was small, 5%, no correction was made on the data for blockage.

Results and Discussion

Figure 2 shows the spanwise correlation coefficients measured on the cylinder. For comparison data from Cheung (1983) has been reproduced. It is obvious that the spanwise correlation measured in the current experiments is considerable higher than measured by Cheung for a similar Reynolds number and free stream turbulence. This gives a correlation length of 3D, which is the trend at precritical Reynolds numbers.

The single point plotted on Figure 2 is the result of correlating the fluctuating forces on the centre of the cylinder and the partially completed ring two diameters to the left of centre. This point shows good agreement with the correlation of pressures at 90 degrees from stagnation. Although this is only a single point it indicates that it is possible to infer the spanwise correlation from a single pressure taps along the 90-degree generator. This is useful as it shows that it not necessary to have a large number of complete tapping rings along the cylinder to measure the fluctuating lift forces and hence determine the spanwise correlation.

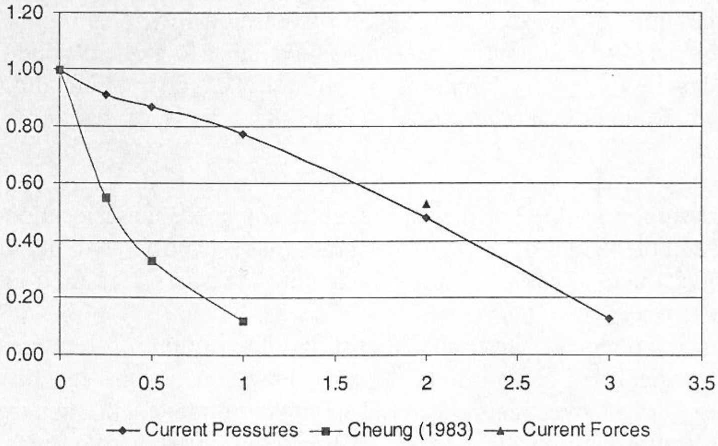

Figure 2: Spanwise correlation coefficients for the smooth circular cylinder

The shedding frequency from the power spectra of the fluctuating lift was 67Hz giving a Strouhal number of 0.2. The presence of regular shedding indicates the flow conditions are either precritical or supercritical because in the critical regime the shedding peak becomes broad banded. The base pressure coefficient was –1.02, which is again particular to the precritical regime (Blackburn 1992). The section drag coefficient calculated from the integrated mean pressure distribution was 0.33 which is indicative of the supercritical regime after the drag coefficient decrease during critical transition.

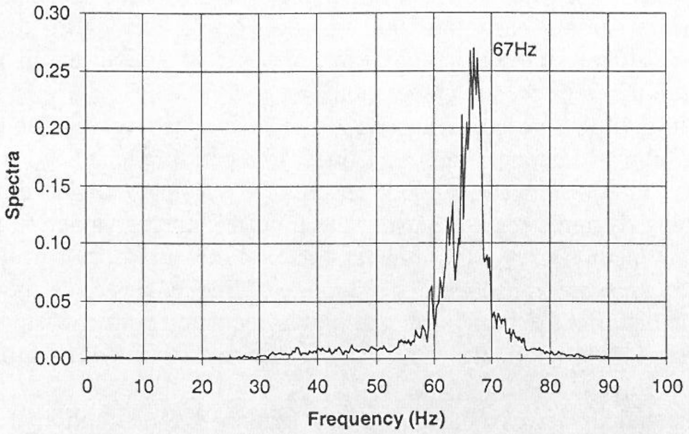

Figure 3: Power spectra of the fluctuating lift coefficient

These results were not expected because the tunnel had a moderate amount of free-stream turbulence that was expected to cause the flow around the cylinder to be in the supercritical regime. In this regime the spanwise correlation length decreases to approximately 1.5D (King 1977), the base pressure increases to a moderate value of –0.5, along with the drag coefficient and a return to regular vortex shedding. Even though the cylinder surface was a sanded finish the roughness level was small. Roughness improves the spanwise correlation of the forces by making the separation line along the cylinder more even, but was not expected to make as much difference to the correlation as indicated in Figure 2.

The lack of agreement in the results with publish data indicates there may be problems with the flow in the wind tunnel or with the surface finish of the cylinder. Further experiments are planned to determine the causes of this variation before any experiments proceed in the larger wind tunnel.

Conclusions

The limitations of research facilities to obtain high Reynolds number data for circular cylinders has restricted the amount of data that is available to explain wind induced motion of circular structures in full scale. Facilities at Monash University will allow new data to be collected at high Reynolds numbers that include the effects of free-stream turbulence and surface roughness.

Correlation between the fluctuating forces at two locations on the cylinder and similarly between the pressures measured at the 90 degree tappings for these locations has shown good agreement between the values obtained. This shows that it is possible to determine the spanwise correlations of the fluctuating forces from fluctuating pressures measured along the 90-degree generator of the cylinder.

The results obtained have an interesting distribution of the measured parameters between the precritical and supercritical regimes. Few conclusions can be drawn from these results other than further investigation is required to determine whether the trends are due to the wind tunnel and flow conditions or an effect of the non-uniform surface finish of the cylinder.

References

Basu, R. I., 1985. *Aerodynamic Forces on Structures of Circular Cross-Section. Part 1. Model-Scale Data Obtained Under Two-Dimensional Conditions in Low-Turbulence Streams*, J. Wind Engng Indust. Aerodyn., **21**, 273-294

Blackburn, H. M. 1992. *Lift on an Oscillating Cylinder in Smooth and Turbulent Flows.* PhD Thesis, Department of Mechanical Engineering, Monash University, Australia.

Cheung, C. K. 1983. *Effect of Turbulence on the Aerodynamics and Response of a Circular Structure in Wind Flow.* PhD Thesis, Department of Mechanical Engineering, Monash University, Australia.

Irwin, H. P. A. H., Cooper, K. R., Girard, R. 1979. *Correction of distortion effects caused by tubing systems in measurements of fluctuating pressures.* J. Wind Engng Indust. Aerodyn., **40**, 93-107

King, R. 1977. *A Review of Vortex Shedding Research and its Application*, Journal of Ocean Engineering, **4**, 141-172

Niemann, H. J., Holscher, N., 1990. *A review of Recent Experiments on the Flow Past Circular Cylinders*, J. Wind Engng Indust. Aerodyn., **33**, 197-209

Shih, W. C. L., Wang, M., Coles, D., Roshko, A., 1993. *Experiments on Flow Past rough circular cylinders at large Reynolds Numbers*, J. Wind Engng Indust. Aerodyn., **49**, 351-368