Effect of Blockage on Spanwise Correlation in a Circular Cylinder Wake

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May 15, 2003

Summary

A short series of experiments was conducted with the aim of assessing the possible effect of tunnel blockage on spanwise correlation lengths measured in the near-wake of a circular cylinder. The results indicate that increasing blockage acts to increase spanwise correlation. This finding has important implications for the conduct and reporting of both physical and numerical experiments on bluff-body wake flows.

1 Introduction

The fact that flow confinement or tunnel blockage affects flows past both streamlined and bluff bodies has been recognised for many decades; for example, Richter & Naudascher (1976) showed that tunnel blockage could have a substantial effect on lift and drag forces exerted on a circular cylinder. Successful techniques for computing corrections to forces measured on streamlined bodies with attached flows have been evolved from potential theory, but there are as yet no truly effective techniques for dealing with separated flows in which there are large wake regions, especially when blockage is large.

The bluff-body flow which has received by far the most attention is that past circular a cylinder, due to both the technological importance and fascination of this fundamental flow. Recently, it has been realized that the flow past circular cylinders in wind tunnels can be sensitive to both the detail of the end treatment and the cylinder aspect ratio as well as blockage. While the average wake flow of a uniform circular cylinder is nominally two-dimensional, the time-varying flow shows substantial three-dimensionality at Reynolds numbers above a few hundred; typical small-scale "coherent structures" reported in the literature are arrays of counter-rotating streamwise rib vortices situated in the high-strain region between the main spanwise vortices (Wu *et al.* 1994). In addition, large-scale features such as slantwise vortex shedding and vortex dislocations (Williamson 1989, 1992) will also affect the three-dimensionality of the flow. Experiments which show the effect of cylinder

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aspect ratio on both sectional forces and spanwise correlation have been performed (e.g. Szepessy & Bearman 1992).

The possible effect of tunnel blockage on spanwise correlation has so far received little attention (although the effect of wall proximity in oscillatory flow was shown to have a substantial effect on correlation lengths by Kozakiewicz, Sumer & Fredsøe 1992). With this in mind, an exploratory experimental investigation of the effect of blockage on correlation was planned and carried out using a water tunnel with an adjustable-geometry working section.

2 Equipment

The experiments were performed in an open water channel that had a working section (width $\times$ depth) of 620×220 mm. A diagram of the working section is shown in figure 1. The floor and walls of the channel were made of glass, while the lid, cylinder end plates and movable walls were fabricated from Perspex. The movable walls could be repositioned in order to control the blockage, defined as the ratio of cylinder diameter to distance between the movable walls.

All measurements were obtained using the same circular cylinder, which had a diameter of 16 mm and a length of 220 mm. The cylinder was fabricated from polished PVC tubing and positioned with its axis vertical in the channel. Cylinder end plates, made to the dimensions recommended by Stansby (1974), were positioned on the cylinder at a distance of $1\,D$ from each end (figure 1), giving a resultant cylinder aspect ratio between the plates of 11.75:1. The cross-flow dimension of the end plates was $7\,D$, so that they did not touch the adjustable walls when the blockage was less than 1/7; for higher blockage ratios the plates were trimmed to fit between the walls.

Mean flow velocities were measured using a Pitot tube and an inclined manometer; maximum mean flow velocity was 0.25 m/s. The lower-wall boundary layer thickness was determined to be approximately 15 mm, so that the lower cylinder end plate was positioned above the channel boundary layer.

The cylinder had eight 1 mm diameter pressure tappings, laid out at a spacing of $1\,D$ along a generator of the cylinder which was positioned 120° from the leading generator, so that the tappings could be assumed to always lie downstream of the separation line. The tappings were connected by flexible capillary tubing to two Honeywell 163 pressure transducers. The tubes were adjusted to the same lengths, and were short enough (0.6 m) that the tubing system would have had insignificant dynamic interaction with pressure signals at the frequencies of interest. The natural frequency of the tubing–transducer system was not measured, but using measurements of diaphragm stiffness for these transducers published by Holmes & Lewis (1986), an estimated natural frequency of approximately 12 Hz was obtained using the method described by Doebelin (1975, ch. 6). This is substantially higher than the typical experimental Strouhal frequency of approximately 3 Hz. The tubes and transducers were filled with water, and the six tubes which were at any time unconnected to a transducer were capped.

Signals from the transducers were amplified and low-pass filtered with analogue equipment, then processed using a Data Precision DATA-6000 digital waveform analyser.

3 Results and Discussion

The maximum cylinder Reynolds number in unblocked flow was 4×10^3; in an effort to minimize Reynolds number effects the flow speed in the channel was reduced as blockage increased, so that the nominal Reynolds number in the gap between the cylinder and the side walls remained constant. Calculations based on conventional boundary-layer results indicate that the flow in the boundary layers of the cylinder end plates should have remained laminar, with a maximum thickness of 0.3 D for the highest-blockage case (40%), corresponding to the whole gap-width. The Reynolds number based on cylinder diameter and the flow speed far upstream varied between 4×10^3 and 2.4×10^3 as blockage increased from 5.6% to 40%.

The cross-correlation between two pressure signals p_1 and p_2 at different spanwise locations z_1 and z_2 was calculated as

$$\rho_{12} = \frac{\overline{p_1 p_2} - \overline{p_1}\,\overline{p_2}}{\sigma_{p_1}\sigma_{p_2}} \tag{1}$$

where σ_p represents pressure standard deviation and $\overline{p}$ a mean pressure. For each selected blockage ratio, the correlation coefficient was calculated for every combination of pressure tapping points. Since there were eight tappings, the correlation coefficients can be arranged in a symmetric 8×8 matrix where the row and column numbers represent numbers assigned to the tappings. Such a matrix has unity as its leading diagonal and if the process which produces the pressure signals is homogeneous in the spanwise direction, the upper and lower diagonals are uniform, i.e., the correlation coefficient depends only on the spacing of the pressure tappings. It was found that this was approximately the case and accordingly the values of ρ presented here (figure 2) are average values for a given dimensionless spanwise separation $\lambda = |z_1 - z_2|/D$.

It can be seen in figure 2 that increasing blockage had the effect of substantially increasing the spanwise correlation of the pressure signals. In order to quantify the effect, one-parameter curves of the form

$$\rho(\lambda) = \frac{1}{1 + \left(\frac{\pi}{2\Lambda}\right)^2 \lambda^2} \tag{2}$$

were fitted "by eye" to the curves in figure 2. The fitted parameter Λ can be interpreted as a dimensionless correlation length since

$$\Lambda = \int_0^\infty \rho(\lambda)\, d\lambda. \tag{3}$$

While the results of such a fit are necessarily crude (particularly as some of the results obtained are much greater than the length of cylinder used in the experiments), they do produce numerical values for further comparison and computation. Values obtained by curve fitting are summarized in table 1.

In addition to the implications these results hold for comparisons of spanwise correlation length in physical and numerical experiments, the effect of spanwise correlation must be considered when measurements of fluctuating forces are presented. Often, due to the nature of the physical set-up, measurements of fluctuating forces on bluff bodies are obtained using some finite length of body and then reduced and presented as sectional fluctuating values. This adds to the difficulty of comparing values between experiments and doubtless

Blockage	5.6%	20%	40%
Λ	7	13	20

Table 1: Dimensionless correlation lengths (Λ) obtained by fitting curves of the form (3) to the results of figure 2.

contributes to the wide variability of measurements of fluctuating quantities such as lift and drag.

It is possible to convert values of fluctuating lift or drag obtained with a finite length of cylinder to sectional values under the presumption of spanwise homogeneity and a knowledge of the spanwise correlation length; the method has been previously described by Howell and Novak (1979). Assuming a correlation function of the form (3) can be applied to the correlation of lift forces at different points along the span, the ratio of standard deviation of a fluctuating force obtained with a finite length of cylinder and reduced to an equivalent sectional value F'_{avg} to that obtained with a true sectional measurement F' is

$$\frac{F'_{\text{avg}}}{F'} = \left(\frac{4\Lambda_L}{\pi} \left\{ \arctan \frac{\pi}{2\Lambda_L} - \frac{\Lambda_L}{\pi} \ln \left[1 + \left(\frac{\pi}{2\Lambda_L} \right)^2 \right] \right\} \right)^{1/2}, \tag{4}$$

where $\Lambda_L = \Lambda D/L$ expresses the correlation length as a proportion of the active length of cylinder on which forces are measured rather than diameter. The ratio expressed by (4) is plotted in figure 3.

As an example of the use of (4), consider the possibility that fluctuating lift forces had been measured on the 11.75 D length of cylinder between end plates in the present experiment and reduced to equivalent sectional values (i.e. divided by dynamic pressure times projected area of cylinder). For the case of 5.6% blockage, the correlation length Λ was approximately 7 D (table 1), making $\Lambda_L = 7/11.75 = 0.596$. Using (4), $F'_{\text{avg}}/F' = 0.786$. Therefore to convert values of equivalent sectional values to sectional values under the assumption of spanwise homogeneity, divide by 0.786. This makes the true sectional values approximately 27% higher than the equivalent sectional values. The amount of correction needed increases as Λ_L drops; see figure 3. A better solution to the problem is to use either a force transducer with a very short length or to use some form of sectional measurement obtained using pressure transducers, however both methods present practical difficulties (see e.g. Blackburn 1992; Szepessy & Bearman 1992 respectively for discussions of the two methods).

While the above method may be used to estimate true sectional values of fluctuating force coefficients from the more commonly presented equivalent sectional values, perhaps it is more important in the longer term (and during design of experiments) to recognize that blockage can affect spanwise correlation. For example, the experiments of Richter and Naudascher (1976), designed specifically to study the effects of blockage on fluctuating forces showed that increased blockage did act to substantially increase fluctuating lift and drag forces experienced by a circular cylinder. When designing their experiment they were careful to be able to vary the blockage without changing cylinder aspect ratio or surface roughness by using a working section of adjustable geometry. However, since they obtained measurements of forces using a cylinder with active length of 6.6 D, presented values of equivalent sectional forces *but did not present measurements of wake correlation length*, it is very difficult to estimate the true values of sectional fluctuating force coefficients from their results. Likewise it is difficult to generalize their results to different lengths of cylinder when attempting, perhaps in a design situation, to estimate fluctuating forces in a different geometry.

4 Conclusions

While recognizing the limitations of the exploratory experiments described here, the results presented indicate that there is a further, previously unrecognized effect of blockage on three-dimensional flows past bluff bodies; increased blockage acts to increase spanwise length-scales of such flows.

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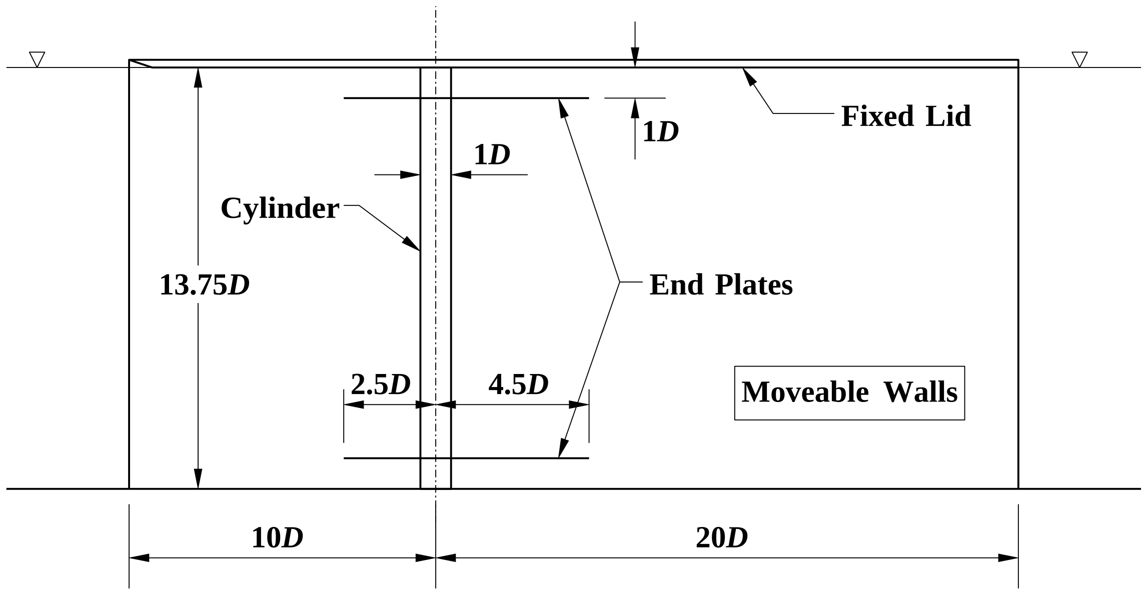

Figure 1: View of cylinder model in adjustable-geometry insertable working section. End-plates had a cross-flow width of 7 D at blockages of less than 14% (1/7); for higher blockages the width was reduced to fit distance between the movable walls.

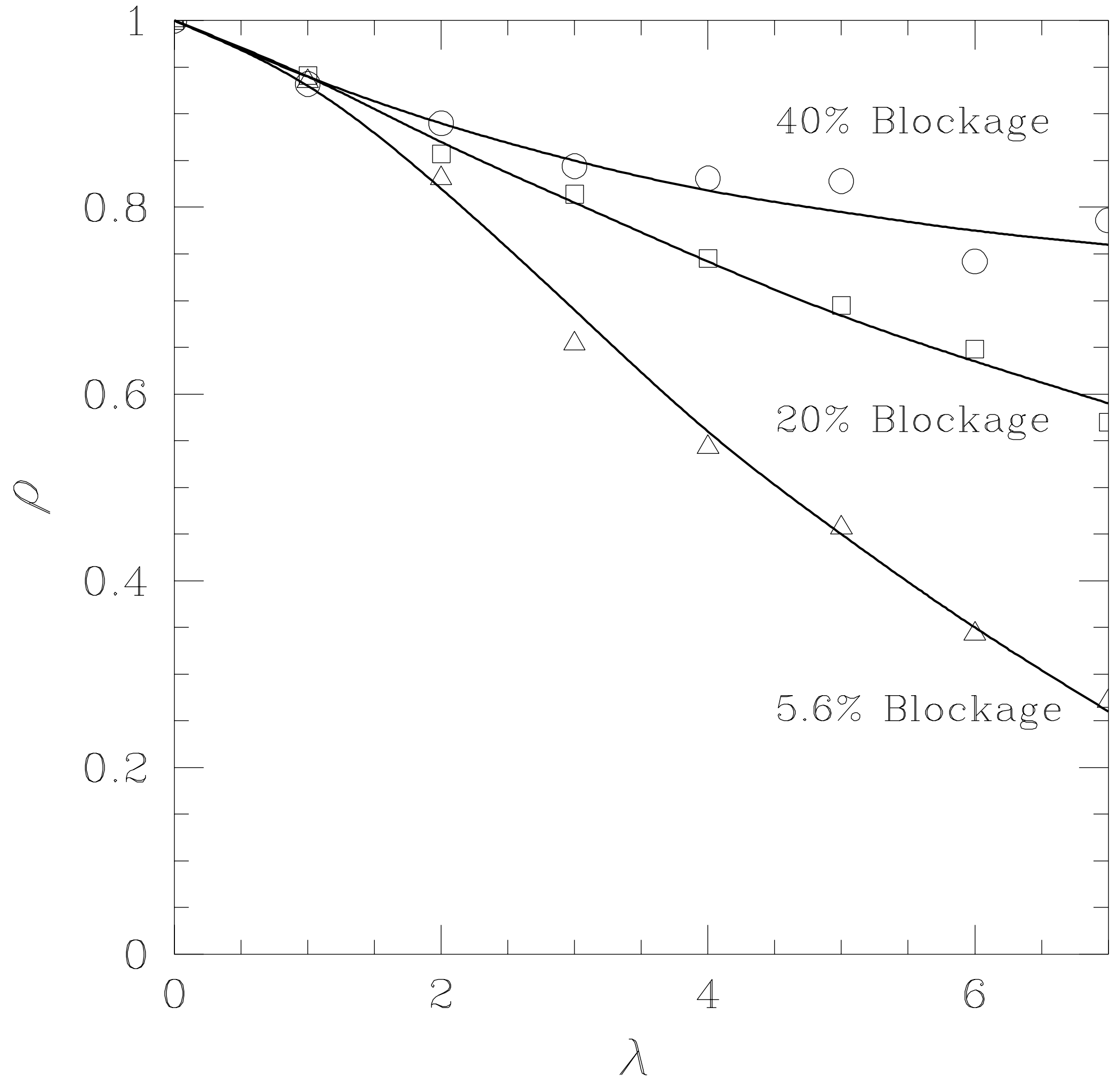

Figure 2: Plot showing correlation coefficient of surface pressure fluctuations, ρ, as a function of spanwise separation, λ.

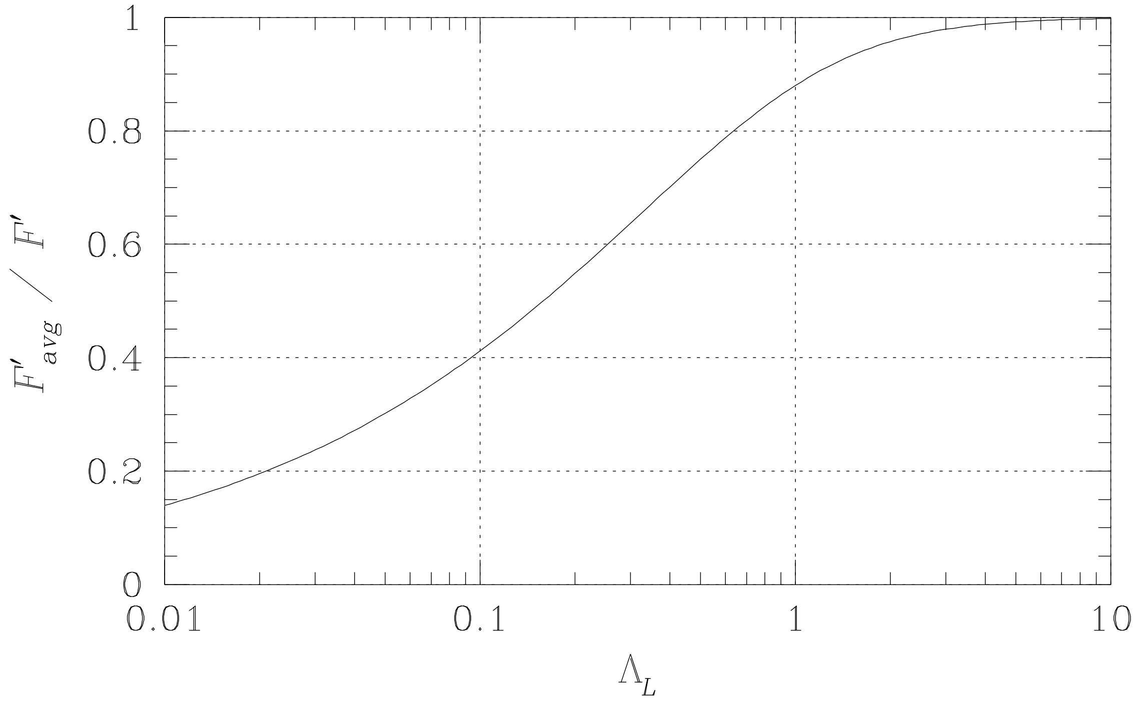

Figure 3: The ratio $F'_{\rm avg}/F'$ (equation 4) as a function of the ratio of correlation length to span Λ_L for the correlation function (2).