J. Fluid Mech. (1965), *vol.* 22, *part* 1, *pp.* 187–196
Printed in Great Britain

A disturbance-sensitive Reynolds number range of the flow past a circular cylinder

By J. H. GERRARD
Mechanics of Fluids Department, Manchester University

(Received 17 August 1964)

The change by an order of magnitude of the oscillating properties of the flow past a circular cylinder in the Reynolds number range 2×10^3 to 5×10^4 is demonstrated experimentally. It is shown that in this range these properties are highly susceptible to small disturbances of the frequency of the transition waves which precede turbulence in the shear layers just downstream of the cylinder. It is suggested that this susceptibility is responsible for the different lift coefficient values measured by various workers.

The effect of disturbances on the mean flow properties is also described.

The frequency-determining mechanism and the characteristic length of the oscillating flow are discussed.

Introduction

As long ago as 1933 Schiller & Linke discovered that large changes took place in the flow close behind a circular cylinder in the Reynolds number† range between approximately 10^3 and 10^4. They found first that what we now call the formation region of the wake was considerably reduced in size as the Reynolds number increased through this range. Secondly, they were also able to demonstrate that this change was attended by a movement of the position of transition to turbulence towards the cylinder. A fuller investigation of this effect made at this laboratory has recently been published by Mrs Bloor (1964). The present paper will show the importance and fundamental nature of the two conclusions of the work by Schiller & Linke. The paper also explains the discrepancy in the published measurements of oscillating lift coefficient, C_L, in this range of Reynolds number. The C_L measurements of the author published in 1961 show a large change as Reynolds number changes. The publication by Keefe (1961) cast doubts on these measurements. With the added contribution by Bishop & Hassan (1963) which seemed to confirm Keefe's work I began to consider seriously whether my measurements were subject to some systematic error of alarming proportions. At this juncture I discovered a similar variation with Reynolds number in a property of the flow which is much easier to measure, namely the fluctuating velocity at the side of the cylinder. By means of these measurements the reason for the discrepancy between the two sets of published values of oscillating lift coefficient will be demonstrated and other flow quantities will be discussed in the light of this.

† Based on the cylinder diameter and the free stream velocity.

Wind tunnel and models

The most significant quality of the experimental apparatus is the extremely low level of turbulence that is achieved in the wind tunnel 20 in. × 20 in. working section. The level is presumably as low as can be obtained without removing the turbulent boundary layers from the working section walls. The distribution of

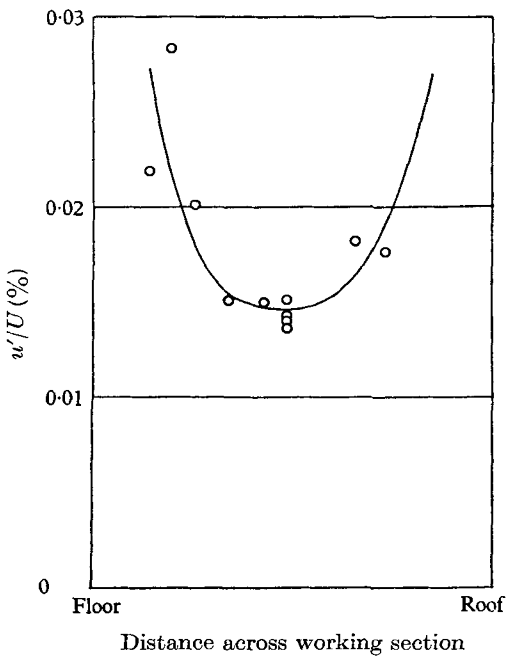

FIGURE 1. Axial component of free stream turbulence intensity at the model position.

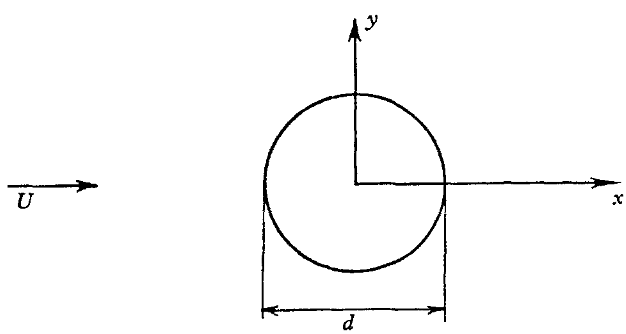

FIGURE 2

the axial component of turbulence intensity at the model position is shown in figure 1. The shape of the distribution leads one to suppose that the fluctuations are in fact due to the presence of the turbulent boundary layers which are about 1·5 in. thick at this position. The low level is attributed to a well-designed fan section, the use of many screens, a long settling chamber following the last screen, a contraction ratio of about 20 and the fact that the tunnel is sealed except at one position just downstream of the working section. The tunnel is described by Collis (1952).

The models used were brass circular cylinders, smooth, but not especially so. These spanned the working section centrally in the position of the traverse of figure 1. Axes were taken as shown in figure 2.

Measurements were made with a constant temperature hot-wire anemometer of the type designed by Somerville & Turnbull (1963).

The basic measurements

The effect to be described was discovered whilst investigating the fluctuating velocity just outside the boundary layer at the shoulder of the cylinder ($x = 0$). Figure 3 shows the results of traverses along the line $x = 0$ well separated in the Reynolds number range we are considering. Two properties are immediately apparent: a wide range of u'_s/U is covered as the Reynolds number is varied; the velocity fluctuation distribution appears not to be simply a function of Reynolds number and y/d within a diameter of the surface: u'_s is the r.m.s. velocity at $x = 0$ and U is the free stream speed. The relevant characteristic length will be discussed below. When the hot-wire was moved into the separated boundary layer the fluctuating velocity intensity rose sharply presumably due to the oscillation in position of the layer. The velocity fluctuation does not vary very greatly in level with y close to the surface outside the boundary layer. It should perhaps be remarked that the oscillations in velocity were almost entirely confined to the fundamental shedding frequency but the levels recorded were measured with a wave analyser having a Q of 10 ($Q = f/\delta f$, where f is the centre frequency and δf is the width of the filter where the gain is 3dB below the maximum).

A series of measurements were made at $x = 0$ and $y = 0{\cdot}6d$ covering the whole range of Reynolds number with three cylinders of diameters 1 in., $\frac{1}{4}$ in. and $\frac{1}{8}$ in. The results are shown in figure 4 where the logarithm of the percentage velocity fluctuation is plotted against Reynolds number. Also shown on the same graph are the r.m.s. lift coefficients, C'_L, measured by Gerrard (1961), Keefe (1961) and Bishop & Hassan (1963). There is a striking similarity between the u'_s/U and C'_L values measured by the author in the same low turbulence wind tunnel. Also shown are u'_s/U values obtained with a turbulence-producing grid of 1 in. mesh size placed at the beginning of the working section 60 in. upstream of the model. This produced a turbulent intensity of 1 % at the model position. In the Reynolds number range in which C'_L and u'_s/U increase with Reynolds number it is seen that increased turbulence raises u'_s/U by a factor of 4 or 5. The values of u'_s/U obtained in the turbulent stream are in fair agreement with the C_L values of Keefe which seems to show that the different C_L values obtained experimentally reflect the turbulence level in the tunnel used. Keefe's wind tunnel almost certainly has a much higher turbulence level than the one used by the author. In the Canadian wind tunnel the contraction is almost immediately preceded by a corner, that is, there is no settling chamber. Bishop & Hassan's measurements were made in a water channel of which we have no details.

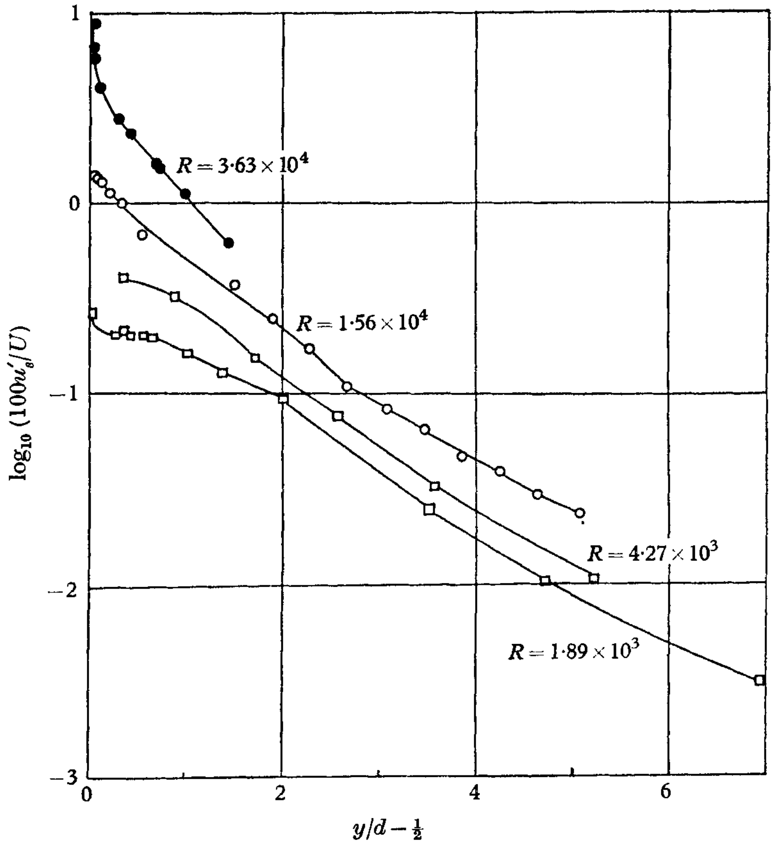

FIGURE 3. Intensity of velocity fluctuation at fundamental frequency as a function of distance in diameters from the surface of the cylinder at $x = 0$. ●, ○, $d = 1$ in.; □, $d = \frac{1}{8}$ in.

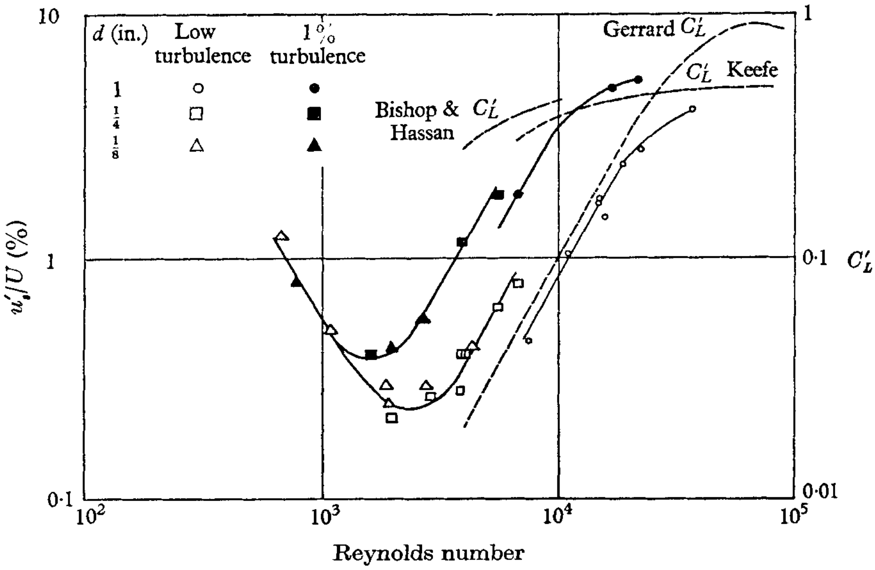

FIGURE 4. The effect of turbulence on the magnitude of the oscillating velocity at the side of the cylinder and a comparison of the variation with Reynolds number of the oscillating velocity and the oscillating lift coefficient.

To say that the increases in the two oscillating quantities considered are produced by a turbulent intensity of 1 % without reference to the turbulent spectrum leaves the description incomplete. It had been discovered previously that the flow was sensitive to acoustic radiation and so a loud speaker was placed in the working section and the frequency of excitation varied. The transition waves preceding turbulence in the shear layer springing from the side of the cylinder (Bloor 1964) are sensitive to sound radiation as Sato (1956) shows. Their frequency is altered to that of the sound radiation when the frequency of the sound and that of the undisturbed transition waves are not too different. As

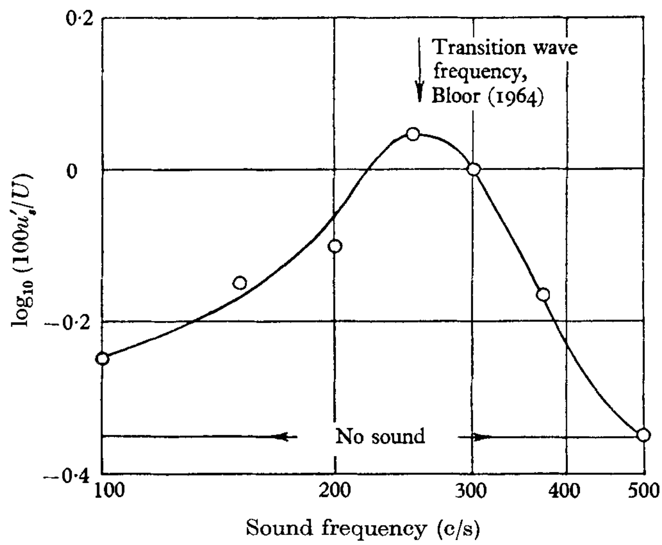

FIGURE 5. The effect of excitation by sound waves having $u'/U = 0{\cdot}01$ % at a Reynolds number of 6900.

can be seen from figure 5 the fluctuating velocity at the shoulder of the cylinder can be increased $2\frac{1}{2}$-fold when the sound frequency is the same as the transition wave frequency. The sound level corresponded to a u'/U of 0·01 %. A 2-fold increase in sound level produced only slight changes in figure 5. Whether the greater increase found with disturbances produced by the grid turbulence was due to a band of frequencies surrounding the transition wave frequency or due to quite different frequencies was not investigated.

Discussion of the basic mechanisms of the flow and further experiments

Returning to figure 3 and the fact that the oscillating velocity field near the cylinder appears not to be simply a function of Reynolds number and y/d we can, taking into account the experimental results above, make some observations on the basic mechanism of the oscillating flow. If the oscillating field is determined by y/L, where L is a characteristic length which is not the cylinder diameter we must consider which are the other lengths in the problem. That the basic characteristic length of oscillating wake flow is that of the vortex configuration and not of the body producing it follows Roshko's (1954) ideas. The length U/N, where N

is the fundamental vortex frequency, determines the longitudinal length scale of the wake some distance downstream of the cylinder: but U/N changes by a factor of about 8 between the two cylinders used in figure 3. Another length scale of the wake is the length of the formation region (Bloor 1964, figure 9). It seems reason-

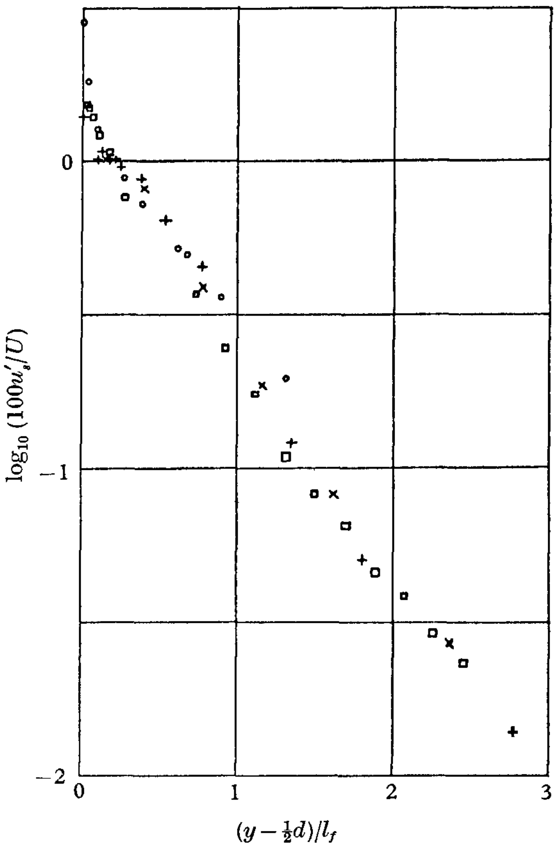

FIGURE 6. The points of figure 1 displaced to pass through the point (0, 0·2), when non-dimensionalized with the length of the formation region l_f. ○, $R = 3{\cdot}63\times10^4$; ×, $R = 1{\cdot}56\times10^4$; □, $R = 4{\cdot}27\times10^3$; +, $R = 1{\cdot}89\times10^3$.

able that the oscillating velocity field close to the cylinder should possess a characteristic length equal to the distance behind the cylinder at which vortices are formed. To test this hypothesis the measurements of figure 3 were plotted as a function of the distance from the cylinder surface divided by the length of the formation region taken from Bloor (1964). The fluctuating velocity distributions now became the same shape. In figure 6 the distributions are shown displaced so that they all pass through the point $\log 100u_s'/U = 0$ at $(y-\frac{1}{2}d)/l_f = 0{\cdot}2$: l_f is the length of the formation region. The points almost collapse onto a single curve.

When the disturbance level is increased the fluctuating quantities u_s/U and C_L increase to values corresponding to a higher Reynolds number. Presumably transition to turbulence moves closer to the cylinder to the position corresponding to the Reynolds number of the increased fluctuating quantities. This, however, is not a complete description because the fundamental frequency N remains almost unaltered. To change N either U or d must be altered. The increased level of disturbance affects the transition waves and this somewhat drastically. The frequency of the disturbed transition waves is that of the sound and so their frequency is altered by as much as a factor of two. The fact that N remains the same leads us to conclude that the basic determining characteristic behind the length scale U/N is not the transition waves. The Strouhal number Nd/U is altered by the insertion of a splitter plate (Roshko 1954): the splitter plate has a profound effect upon the shedding of circulation by the oscillating reversed flow at the rear of the cylinder. Work not yet published shows that, at least at high Reynolds numbers, the *oscillating* reversed flow shedding of circulation is of the same order of magnitude as the *oscillating* component of the shedding of circulation from the boundary-layer separation point. A fundamental problem of the oscillating wake flow is the explanation of what determines the Strouhal number. Put another way: as a vortex grows from one side of the cylinder what determines the point at which circulation ceases to be fed into this vortex and the next one begins to grow? It seems an attractive possibility that the reversed flow shedding of circulation, which is of opposite sign to that shed from the boundary-layer separation point, builds up to that value which causes the separated layer to develop a curvature which grows into the separation of the two vortices.

The explanation of the variation of u_s/U with Reynolds number is somewhat difficult. One notices from Bloor's figure 9 (1964) that when the turbulent length of the unrolled-up shear layer is biggest then u_s/U is smallest. The longest length of turbulent shear layer presumably produces the largest velocities at the rear of the cylinder due to enhanced entrainment. This one would expect to be attended by maximum Nd/U and minimum vortex strength. It is not possible at this stage to explain in detail the relative orders of magnitude.

The effect of disturbances on some mean flow properties

The mean velocity at the shoulder of the cylinder ($x = 0$, $y = 0{\cdot}6d$) also changes when the flow is disturbed. This velocity we denote by $\overline{u}_s$ and will compare it with the quantity which Roshko (1954) defines as $\overline{u}_s$ but which in his case is the speed just outside the boundary layer at the separation point. This confusion of the terms is thought to have no significant effect. Free-streamline theory relates base pressure coefficient to the speed $\overline{u}_s$; in fact,

$$C_p = 1-(\overline{u}_s/U)^2. \quad (1)$$

Figure 7 shows experimental values of the surface pressure coefficient at the rear of the cylinder ($y = 0$). Again the values obtained in the low-turbulence wind tunnel are significantly different from values obtained with higher turbulence levels. The same decrease in C_p is observed when grids of $\frac{1}{2}$ in. and 1 in. mesh size are inserted at the beginning of the working section. These decreased values also agree with some measurements of other workers and our own measurements in a tunnel of high turbulence level ($> 1\%$ intensity).

Values of mean velocity $\overline{u}_s$ calculated from figure 7 using (1) are included with direct measurements of $\overline{u}_s$ in figure 8. There is excellent agreement between $\overline{u}_s$

found in these two ways when the turbulence level is low: behind a turbulence producing grid however direct measurement of the mean velocity shows no change, whereas the measurements derived from pressure coefficients are markedly increased. This discrepancy is unexplained.

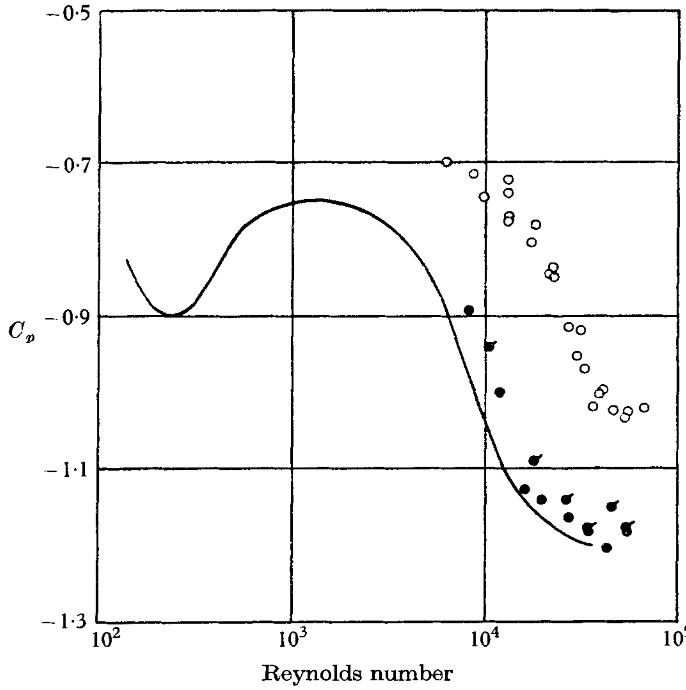

FIGURE 7. Cylinder base pressure coefficient as a function of Reynolds number. ○, d = 1 in. low turbulence level; ●, d = 1 in. behind ½ in. mesh turbulence grid; ●́, d = 1 in. behind 1 in. mesh turbulence grid; —, measurements in an open circuit wind tunnel of high turbulence level.

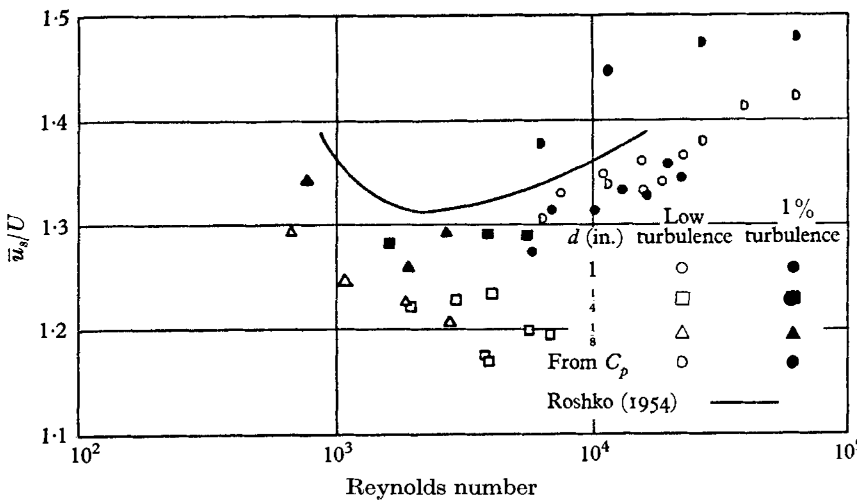

FIGURE 8. Mean velocity at the side of the cylinder as a function of Reynolds number and the effect of free stream turbulence level on this.

All the measurements were made at or near the centre of the wind tunnel. There is a variation of the mean surface pressure coefficient, C_p at $y = 0$, along the span: C_p has a minimum at the tunnel centre. This spanwise variation cannot therefore be attributed to the variation in the free-stream turbulence level across the span which one would expect to produce a maximum C_p at the centre if the variation at this low level could be expected to have any effect at all. It has been demonstrated by attaching end-plates to the cylinder that the spanwise variation is sensitive to end conditions.

Conclusions

It is found that provided the level of disturbance is low there is a large increase in the fluctuating lift coefficient and in the fluctuating velocity at the side of the cylinder as the Reynolds number increases from 2×10^3 to about 5×10^4. If the flow contains disturbances of the frequency of the transition waves which precede the turbulent flow in the shear layers shed from the cylinder the range of Reynolds number over which the quantities show this large increase is shifted to lower Reynolds number. Thus the discrepancy between some measured values of C_L can be explained in terms of the turbulence level of the free stream.

The characteristic length of the oscillating properties of the flow is found to be proportional to the length of the formation region.

The changes observed cannot be explained simply in terms of an effective change in Reynolds number. By a closer examination of the changes which take place it is demonstrated that the mechanism which governs the frequency of vortex shedding is not the transition waves but could be connected with the fundamental frequency component of the shedding of circulation by the reversed flow at the rear of the cylinder.

The effect of disturbances is also observed on the mean properties of the flow. It is well known that the base pressure coefficient and the Strouhal number show a relatively small change with Reynolds number in this range. It is shown that the base pressure and the mean velocity outside the boundary layer at the shoulder of the cylinder are susceptible to disturbances in the same way as the fluctuating quantities. The Strouhal number behaves like a mean rather than an oscillating quantity presumably because the strengths of the vortices depend most strongly upon the mean rate of shedding of circulation, as work as yet unpublished will show. It seems logical also that if the mechanism which determines the frequency is the shedding of circulation at fundamental frequency by the reversed flow at the rear of the cylinder then this should be correlated with the vortex strength.

The author expresses his grateful acknowledgement to Mrs Susan Bloor who assisted with most of the experimental work.

REFERENCES

BISHOP, R. E. D. & HASSAN, A. Y. 1963 The lift and drag forces on a circular cylinder in a flowing fluid. *Proc. Roy. Soc.* A, **277**, 32.

BLOOR, M. S. 1964 The transition to turbulence in the wake of a circular cylinder. *J. Fluid Mech.* **19**, 290.

COLLIS, D. C. 1952 The dust problem in hot-wire anemometry. *Aero. Quart.* **4**, 93.

GERRARD, J. H. 1961 An experimental investigation of the oscillating lift and drag of a circular cylinder shedding turbulent vortices. *J. Fluid Mech.* **11**, 244.

KEEFE, R. T. 1961 An investigation of the fluctuating forces acting on a stationary circular cylinder in a subsonic stream and of the associated sound field. *Univ. Toronto Inst. Aerophys. Rep.* no. 76.

ROSHKO, A. 1954 On the drag and shedding frequency of two-dimensional bluff bodies. *N.A.C.A. Tech. Note,* no. 3169.

SATO, H. 1956 Experimental investigation on the transition of laminar separated layer. *J. Phys. Soc. Japan,* **11**, 702.

SCHILLER, L. & LINKE, W. 1933 *Z. Flugtech. Motorluft,* **24**, 193.

SOMERVILLE, M. J. & TURNBULL, G. F. 1963 Self-generating high frequency carrier feed-back anemometer. *Proc. I.E.E.* **110**, 1905.