J. Fluid Mech. (1973), *vol.* 61, *part* 3, *pp.* 499–511
Printed in Great Britain

The interaction between a pair of circular cylinders normal to a stream

By P. W. BEARMAN AND A. J. WADCOCK†
Department of Aeronautics, Imperial College, London

(Received 4 July 1973)

This paper describes how the flows around two circular cylinders, displaced in a plane normal to the free stream, interact as the two bodies are brought close together. Surface pressure measurements at a Reynolds number of $2{\cdot}5 \times 10^4$, based on the diameter of a single cylinder, show the presence of a mean repulsive force between the cylinders. An instability of the flow was found when the gap between the cylinders was in the range between one diameter and about 0·1 of a diameter. Correlation measurements of hot-wire outputs indicate how mutual interference influences the formation of vortex streets from the two cylinders. Spanwise correlation measurements show that the correlation length doubles as the cylinders are brought into contact.

1. Introduction

One approach to the problem of predicting the flow around buildings in close proximity is to develop an understanding of interactions between flows by experiments on relatively simple arrangements of bluff bodies. The present paper describes an experimental investigation of the flow about a pair of circular cylinders separated in a plane normal to the free stream. The principal aim was to study the way in which the flow past the cylinders changed, as their separation was reduced, from that past two independent cylinders to that past a single body. The flow about an isolated circular cylinder, placed normal to a stream, has been the subject of extensive investigation (Morkovin 1964). By comparison little work has been carried out on the problem of the mutual interference between cylinders.

Force measurements on a circular-cylinder pair have been made by Bierman & Herrnstein (1933) in the Reynolds number range $5{\cdot}5 \times 10^4$–$1{\cdot}4 \times 10^5$, the Reynolds number being based on the diameter of a single cylinder. They found that for a cylinder gap of four diameters or more there was practically no interference. For spacings less than four diameters the interference drag, defined as the difference between the drag of the cylinders in combination and the sum of the drags of the cylinders measured in isolation, could be either positive or negative depending on both the Reynolds number and the cylinder gap.

Hori (1959) measured the pressure distribution on one cylinder of a cylinder pair with separations of 0·2, 1 and 2 cylinder diameters, at a Reynolds number of

† Present address: Aeronautics Department, California Institute of Technology, Pasadena.

8×10^3. He deduced that the drag of the cylinder pair was greater than that of the two cylinders in isolation and that at all the gaps he investigated there was a repulsive force acting between the cylinders. He also observed, for gaps of 0·2 and 1·0 diameters, that the base pressure could take on one of several values. Bierman & Herrnstein and Hori drew their conclusions from measurements on only one of the cylinders assuming the flow to be symmetric about the pair.

Spivak (1946) carried out a very detailed hot-wire investigation of the predominant frequencies in the flow field behind a pair of cylinders over a Reynolds number range from about $1{\cdot}5 \times 10^4$ to $9{\cdot}3 \times 10^4$. He discovered three fairly distinct regimes of flow; for gaps greater than one diameter the frequency of vortex shedding was the same as that for a single body, whereas for gaps of less than 0·5 diameters the shedding frequency appeared to be associated with a body of width equal to twice the cylinder diameter. At intermediate gap widths the flow was less well behaved and frequencies associated with a single and a double body could both be detected. Vortex shedding frequency measurements by Hori (1959) over a Reynolds number range from 500 to 10 000 are in fairly close agreement with those of Spivak.

Von Kármán (see Milne-Thomson 1938, p. 341) represented the vortex-street wake which forms behind a bluff body by an idealized potential-flow model consisting of a double row of staggered point vortices. Landweber (1942) extended the use of the von Kármán model to the wake behind a pair of adjacent parallel cylinders normal to a stream. Using arguments based on the stability of rows of vortices he predicted that three types of wake could result and the fluctuating lift forces generated on the two cylinders could be either in phase or 180° out of phase. One possibility is that a single vortex-street wake results from the cylinder pair. Alternatively, two vortex streets are formed and in one case if vortices from the outer edge of one cylinder and the inner edge of the other cylinder are shed in phase then the resulting forces on the cylinders are in phase. If two vortex streets are formed in which vortices from the outer edges of the cylinders are shed in phase then the cylinders will experience forces 180° out of phase. In this paper the results of correlation measurements taken across the wake are presented and from these it is possible to identify the type of wake pattern formed.

There is the further possibility that the interference between two cylinders may effect a change in the spanwise correlation length of shed vortices. It is known, for instance, that lateral movement of a bluff body can cause an increase in the correlation of vortex shedding and a subsequent increase in the magnitude of the unsteady forces. Perhaps, therefore, when the cylinders come under the mutual influence of their oscillating velocity fields their correlation lengths may increase. Measurements of the correlation length at various cylinder separations are presented.

2. Experimental arrangement

The experiments were conducted in a $1 \times 0{\cdot}58$ m wind tunnel. The tunnel is of the closed-return type and has a free-stream turbulence level of less than 0·2 % and a top speed of 38 m/s. The cylinders used in the investigation spanned the horizontal 0·58 m dimension of the tunnel. The cylinders, which were made from steel rod, were 1·9 cm in diameter. To obtain some measure of the uniformity of the flow across the span, one cylinder had pressure tappings inserted every 5 cm in two rows diametrically opposite each other. The other cylinder had pressure tappings, again on opposite sides of the cylinder, but only at the mid-span position. Both cylinders could be rotated, allowing pressure measurements to be made at all angular positions. Great care was taken to ensure that the gap between the cylinders remained constant along their span and that their plane of separation was normal to the free stream.

Velocity fluctuations in the neighbourhood of the cylinder pair were detected with Disa constant-temperature hot-wire anemometers and correlation measurements were made with a Disa type 55A06 analog correlator. The frequency of vortex shedding was measured on a Muirhead K-134-A wave analyser. Further details of the experimental arrangement and the experimental techniques used are given by Wadcock (1970).

3. Experimental procedure and results

The major part of the investigation was carried out at a Reynolds number of $2{\cdot}5 \times 10^4$ and this is within the range where a circular cylinder is relatively insensitive to Reynolds number changes. A single cylinder occupied 1·94 % of the area of the tunnel working section and according to the blockage correction method of Maskell (1965) the corrected value of the drag coefficient would be about 1·5 % lower than that measured. With two cylinders in the tunnel, at certain separations, marked flow asymmetry was found and it was not thought possible to correct accurately for the effects of blockage. Therefore results are presented uncorrected.

Pressure measurements

The distribution of the base pressure coefficient C_{pb} (defined as the pressure coefficient at $\theta = 180°$, where θ is measured from the front stagnation point) along the span of one of the cylinders in isolation is shown in figure 1. The influence of the end-wall boundary layers is felt across the complete span. To increase the degree of two-dimensionality of the flow end plates were fitted and the resulting base pressure distribution, also plotted in figure 1, shows a marked improvement in uniformity. The end plates were made from thin steel plate and extended four diameters both ahead of and behind the cylinders. All further measurements were carried out with end plates in position.

With both cylinders in the tunnel pressure measurements were made at 6° intervals around one of the cylinders. The resulting pressure distributions were suitably integrated to determine C_D and C_L for several values of δ, where δ is the ratio of the gap between the cylinders to the cylinder diameter. The measurements of C_D and C_L are shown in table 1 and the isolated-cylinder result is shown for comparison. Isolated-cylinder results were adjusted by Maskell's blockage correction method to give the measurements that would have been recorded in a tunnel of half the height thereby exposing the single and double cylinders to the same degree of wind-tunnel blockage.

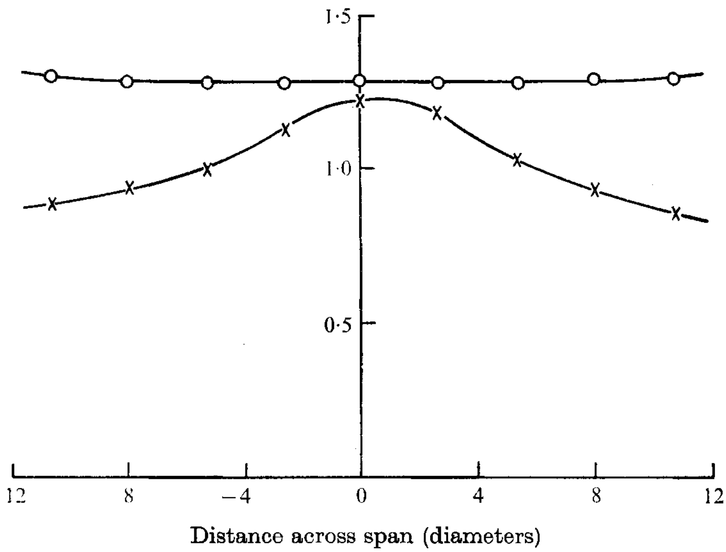


FIGURE 1. Spanwise base pressure distributions on an isolated cylinder at $Re = 2{\cdot}5 \times 10^4$. $\times$, without end plates; $\bigcirc$, with end plates.

δ	C_D	C_L†
0	1·62	1·13
0·5	1·29	0·34
1	1·40	0·22
∞	1·28	0

† Positive values of C_L represent a repulsive force between the cylinders.

TABLE 1

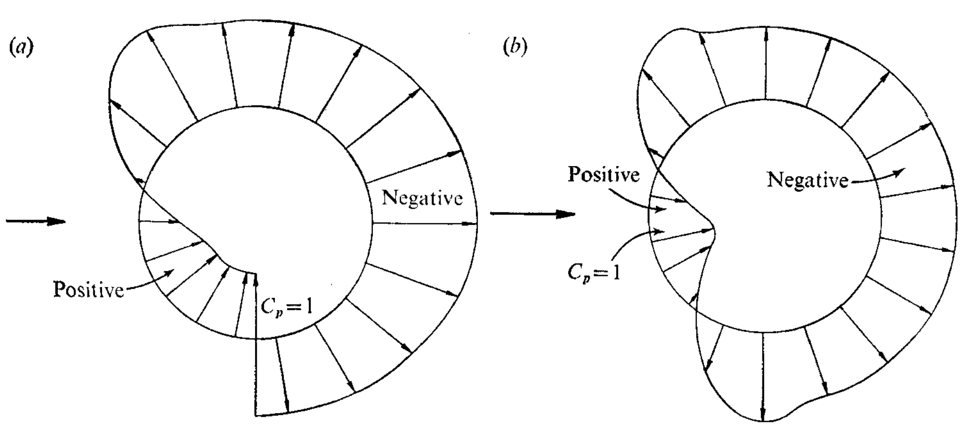


FIGURE 2. Polar plots of C_p around upper cylinder for (a) zero-gap and (b) $\delta = 0{\cdot}5$.

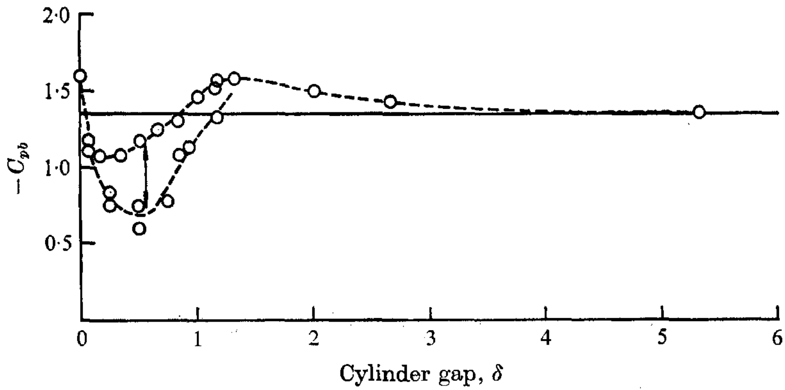


FIGURE 3. Base pressure coefficient versus cylinder separation.
——, isolated-cylinder result.

To obtain the zero-gap result a very thin strip of plasticine was placed between the cylinders to ensure no leakage of air into the wake. The pressure distributions, plotted in a polar form, for zero separation and $\delta = 0{\cdot}5$ are shown in figures 2 (*a*) and (*b*) respectively.

While making these pressure measurements it became clear that there was a gross unsteadiness in the flow for values of δ in the range 1·0 to 0·1. Measurements of base pressure were made simultaneously on both cylinders and it was discovered that, in this range of δ, the two cylinders experience different base pressures. The measurements of base pressure are shown in figure 3. The base pressure changed from one steady value to another, or simply fluctuated between the two extremes. Various checks suggested that this asymmetry was a genuine property of the flow and not a feature of our apparatus. Stopping and starting the tunnel again could cause the pressures to change over. The pressure distribution plotted in figure 2 (*b*) and the values of C_L and C_D quoted throughout the paper, for gaps where the flow was asymmetric, are for the cylinder with the lower base pressure.

Strouhal number measurements

Initially the frequency of vortex shedding was detected by a hot wire positioned just outside the wake of the cylinder pair and approximately 5 or 6 diameters downstream. The probe was supported on a 0·64 cm diameter rod spanning the tunnel and located well outside the wake. In order to minimize any asymmetry, a dummy support was located on the opposite side of the wake. The measurements of shedding frequency are presented non-dimensionally in the form of a Strouhal number S, where $S = nD/U$ and n is the frequency, U the free-stream velocity and D the cylinder diameter. S is shown plotted in figure 4 for a range of cylinder separations. The hot wire was brought closer to the cylinder pair and Strouhal number measurements were made on the gap centre-line and outside the wake of the cylinder pair at a point lying in the same plane as the axes of the two cylinders. This latter position is referred to as the outer 90° point. These results are included in figure 4 and it can be seen that between $\delta = 0{\cdot}5$ and 1 the

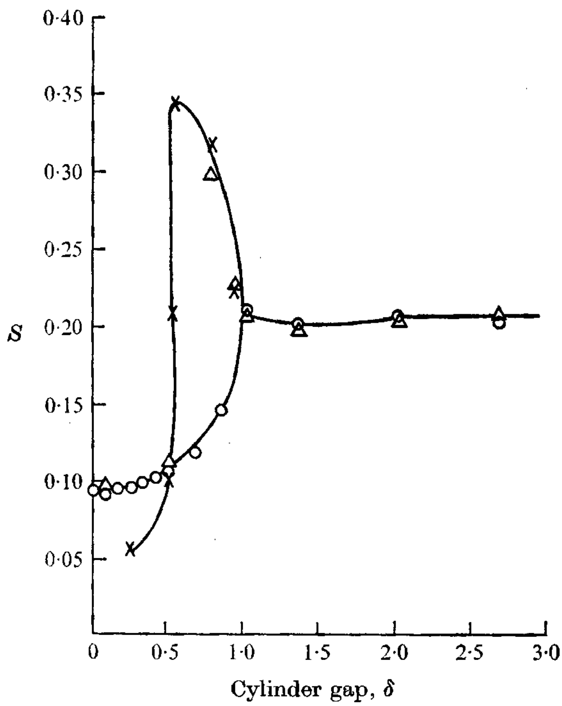


FIGURE 4. Strouhal number versus cylinder separation. ○, hot wire 6 diameters downstream of cylinder pair, outside the wake; △, hot wire at outer 90° point; ×, hot wire on gap centre-line.

measurements of S near the cylinders show substantially higher values than those measured downstream. Although there was a predominant frequency near the cylinders in this range of δ the shedding appeared to be weak and intermittent.

Correlation measurements

When estimating the magnitude of the fluctuating lift acting on a length of cylinder it is important to know how the correlation between values of the local lift measured at two stations varies with separation between the stations. The main reason for a drop in this correlation is the lack of two-dimensionality of the shed vortices. A measurement of the spanwise uniformity of the vortices can be obtained by correlating the output of two hot wires, displaced along a line parallel to the cylinder axis.

Spanwise correlation measurements were performed outside the wake of one of the cylinders with hot wires displaced along a line passing through what has been called earlier the outer 90° point. The correlation on an isolated cylinder at the same Reynolds number was measured for comparison. The hot wires had to be positioned far enough away from the cylinder surface to avoid turbulence within the shear layer being convected over the probe but near enough to ensure a strong shedding signal. Correlation measurements were made using the unfiltered hot-wire anemometer outputs and results are presented in the form of

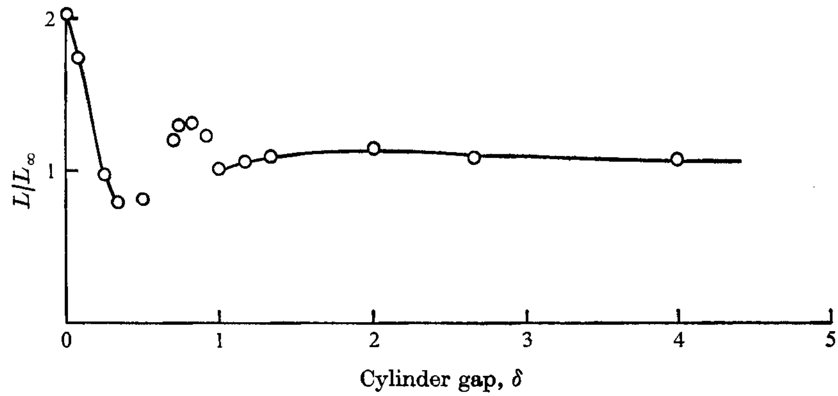


FIGURE 5. Variation of the spanwise correlation length measured outside the cylinder pair with cylinder separation.

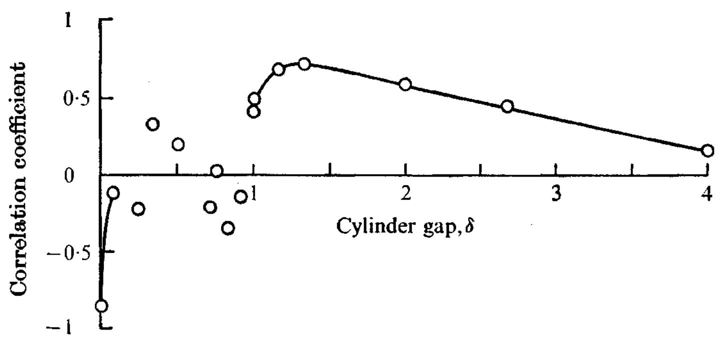


FIGURE 6. Correlation across the cylinder pair versus cylinder separation.

correlation coefficients. The correlation length L_∞ of the isolated cylinder, i.e. the area beneath the correlation curve, was found to be 3·7 diameters. This is close to the value measured by Prendergast (1958), who used a surface pressure correlation technique. Gaster (1973, private communication) employed a hot-wire method and found L_∞ to be 3·6 diameters at a Reynolds number of $2{\cdot}5 \times 10^4$. The variation of the correlation length L with cylinder separation is presented in figure 5, where this correlation length has been divided by the correlation length L_∞. The results for δ between about 0·2 and 1 are thought to be unreliable owing to the asymmetric nature of the flow.

In addition correlation measurements were made across the cylinder pair with hot wires at the two outer 90° points. If the cylinders were far apart no interaction would be expected and the correlation coefficient C should approach zero. A positive correlation indicates that, on average, the cylinders are shedding vortices in phase from their outer surfaces whereas a negative correlation indicates out-of-phase shedding. The results of these correlation measurements are shown in figure 6. Again no line has been drawn through the results in the asymmetric flow regime. The variation of this correlation coefficient with downstream distance for $\delta = 1{\cdot}33$ is shown in figure 7, where it can be seen that the

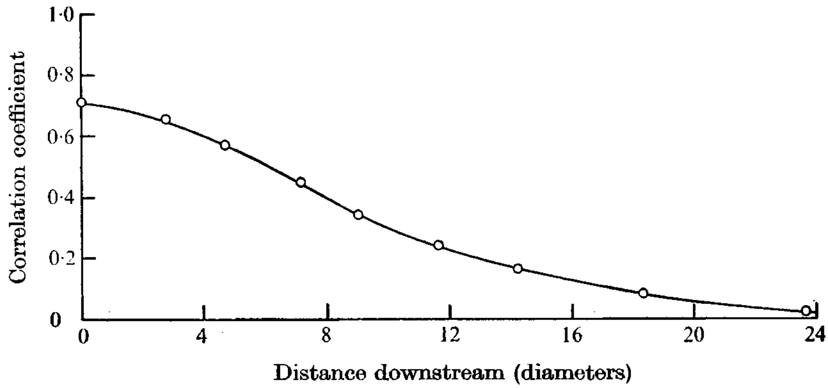


FIGURE 7. Variation of the correlation across the cylinder pair with downstream distance for $\delta = 1{\cdot}33$.

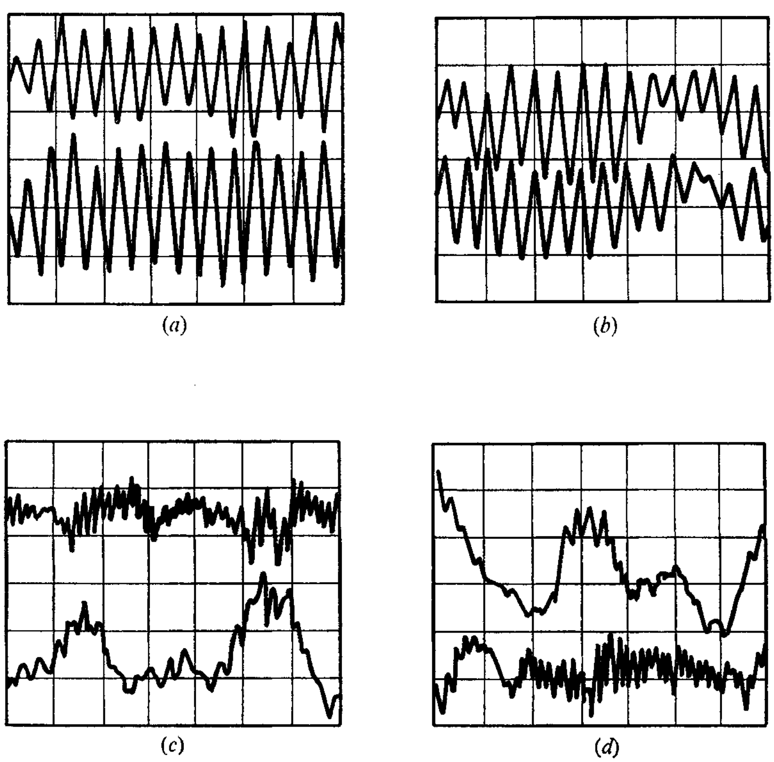


FIGURE 8. Hot-wire signals recorded at the outer 90° points. (a) Isolated cylinder. (b) $\delta = 1{\cdot}17$. (c), (d) $\delta = 0{\cdot}75$.

positive correlation is sustained for some distance downstream. A selection of oscilloscope records of the hot-wire signals at the two outer 90° points are presented in figure 8 and it should be noted that traces (*a*) and (*b*) have a different time base to traces (*c*) and (*d*). Figure 8 (*a*) shows the expected out-of-phase shedding from an isolated cylinder whereas in 8 (*b*), for a separation of $\delta = 1{\cdot}167$,

δ	C_L	C_D	ϕ_s°	θ°
0·5	0·34	1·29	9·4	8·9
1·0	0·22	1·40	14·3	14·8

TABLE 2

in-phase shedding across the pair is indicated. Figures 8 (*c*) and (*d*) show two sets of traces for $\delta = 0{\cdot}75$ and again the asymmetry of the flow in this range of δ is clearly illustrated. The low frequency fluctuations were recorded outside the cylinder experiencing the lower drag while the other cylinder appears to be shedding vortices.

4. Discussion of results

The flow about a pair of circular cylinders is complex nevertheless it is possible to draw some conclusions from the experimental results. Measurements show that the mean pressure on the cylinders in the separated region is sensibly constant between the two separation points. For non-zero gaps the pressure distributions look surprisingly symmetric about the front stagnation point. Taking as an example the distribution in figure 2 (*b*), the movement of the stagnation point due to the proximity of the other cylinder appears to rotate the resultant force vector thus giving a component in the lift direction. To test this hypothesis the angle θ, where $\theta = \tan^{-1} C_L/C_D$, was calculated and compared with the angular position ϕ_s of the stagnation point measured from the pressure distributions. θ and ϕ_s are compared in table 2 for $\delta = 0{\cdot}5$ and $1{\cdot}0$.

The measurements of base pressure shown in figure 3 illustrate the asymmetric nature of the flow for a range of gaps. The plot shows two branches and when one cylinder has a low base pressure the other experiences a high base pressure. It is difficult to draw general conclusions about the lift forces and the interference drag for this range of gap sizes. The measurements of Bierman & Herrnstein (1933) were made on one cylinder, assuming symmetric flow, and this may be the reason for the large amount of scatter in their data. Hori (1959) carried out an interesting experiment whereby he took a cylinder pair, at a fixed separation, and rotated the combination about an axis normal to the flow direction and parallel to the cylinder axes. As the cylinders passed through a plane normal to the free stream the base pressure, which was measured on only one of the cylinders, showed a discontinuity for gaps of $\delta = 0{\cdot}2$ and $1{\cdot}0$. When $\delta = 2{\cdot}0$ no such change occurred. The scale of the discontinuities he measured is comparable with the changes in base pressure measured in this investigation.

It is interesting to note that the base pressure measured with very small gaps is substantially higher than that measured on the cylinders when they were touching. This is in qualitative agreement with what might be expected from a knowledge of the effect of base bleed. Bearman (1967) has shown that if low momentum fluid is bled into the separated region behind a bluff body then the position of vortex formation is moved downstream. The injection of fluid

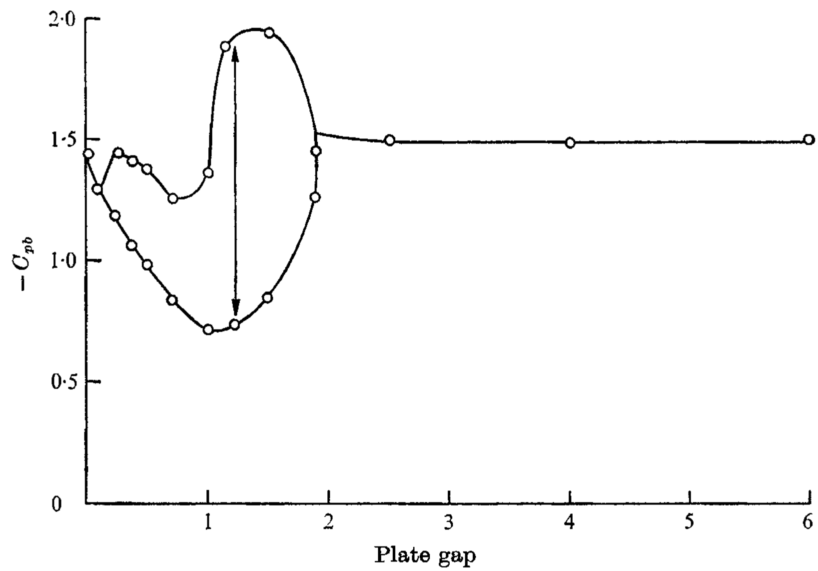


FIGURE 9. Base pressure measured on two flat plates versus plate separation at $Re = 4{\cdot}3 \times 10^4$.

provides some of the entrainment required by the free shear layers and the vortices. Thus the entrainment from within the separated near-wake region is reduced and the base pressure increases. Base bleed is only effective if low momentum fluid is fed into the wake and as the gap width is further increased a flow bearing appreciable momentum is injected which will itself entrain fluid from the wakes of the cylinders. This leads to shedding from the inner shear layers.

At first it was supposed that the asymmetry was primarily a boundary-layer effect and was due to the flow through the gap attaching itself more to one cylinder than the other. Therefore a further set of measurements of base pressure was carried out on a pair of two-dimensional flat plates set normal to the flow, and the results are described by Andreopoulos (1972). Figure 9, reproduced from the work of Andreopoulos, shows the flow to have the same asymmetric character. The flat plates experience asymmetric flow over a larger range of gap sizes and the differences in base pressure are even more marked than on the circular cylinders. These results pose the question as to whether buildings in close proximity experience large fluctuations in loading triggered perhaps by the approach of large-scale eddies.

The asymmetry mentioned above has features similar to those found behind wind-tunnel screens and banks of circular cylinders. Bradshaw (1965) describes how non-uniformities are found in the flow behind screens with open-area ratios less than 0·57. This corresponds to an equivalent gap between elements of the screen larger than the critical gaps found for a pair of bluff bodies. However, Bradshaw also shows a visualization of the flow behind a monoplanar grid of circular cylinders with a spacing of about 0·5 diameters and asymmetries in the flow about the cylinders are clearly visible.

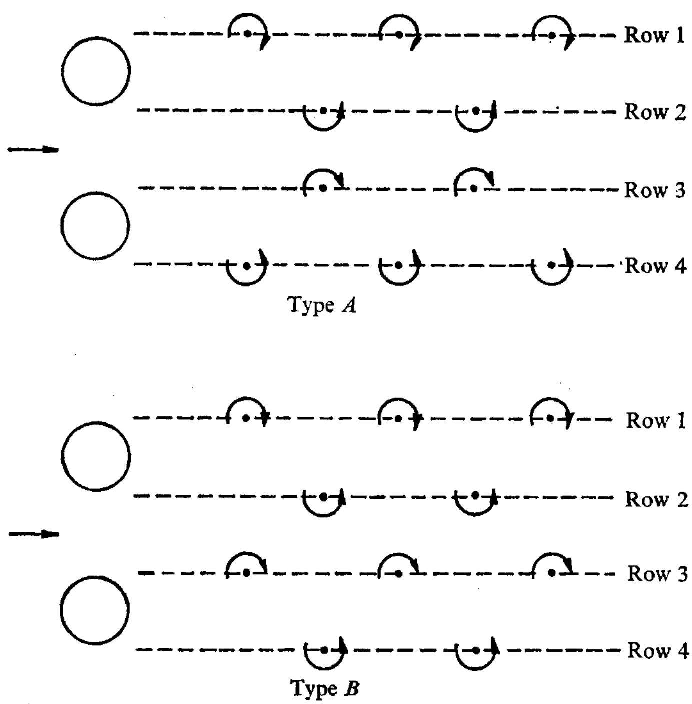


FIGURE 10. Possible double vortex-street arrangements. Type *A* vortices in phase in rows 1 and 4; type *B* vortices in phase in rows 1 and 3.

Hot-wire measurements have shown that vortices are shed from the cylinder pair. When the gap is such that both cylinders are shedding then four rows of vortices will be formed and these will induce velocities on each other. If the vortices are to form themselves into a fixed pattern which convects down the wake then two stability requirements must be satisfied. The transverse component of the velocity induced on each vortex must be zero and the convection speed of the vortices in all four rows must be the same. Applying the first condition in an infinite double vortex-street wake limits the number of possible configurations to two: type *A*, where the vortices are in phase between the outer rows (rows 1 and 4, see figure 10), and type *B*, where the vortices are out of phase between the outer rows. Landweber (1942) has investigated the effects of applying the second condition to the two types of double vortex-street arrangement. He assumed that the lateral spacing between vortices in one vortex street was equal to the cylinder diameter. The main conclusion he reached was that for stable configurations the strengths Γ_1 and Γ_2 of the vortices in the inner rows and the outer rows cannot be the same. Summarizing his results we can say that for type *A* to form Γ_2 must be greater than Γ_1 and for type *B* to occur Γ_2 must be less than Γ_1 and, in addition, δ must be greater than about 0·5. If δ is less than 0·5 the circulation of the vortices formed from the outer edges must change sign.

The concept of vortices of different strengths being shed from either side of a cylinder is difficult to reconcile with physical observation. Pressure measurements on one cylinder of the cylinder pair show that, in the mean, there are no pressure gradients within the separated region. Therefore in the mean the velocity outside the boundary layers, just prior to separation, will be the same at both separation points and the mean rate of shedding of vorticity will be the same on both sides of the cylinder. Gerrard (1966) describes how, on a single body, vorticity is cancelled within the near-wake region as fluid bearing vorticity of opposite sign is drawn across the wake into the growing vortex. The resulting vortices have a net strength equal to about half the vorticity shed. The cancellation process will be similar behind each of the two cylinders and since it affects both feeding shear layers equally the resulting vortices will be of the same strength on both sides of a cylinder wake. The conclusion would appear to be that vortex wakes from a pair of bluff bodies are less stable that those formed behind a single body. More work is required, particularly the measurement of the convection speed of individual vortex rows, to substantiate this claim.

It is only when the cylinders are very close together that vorticity of opposing signs, within the two shear layers between the cylinders, can mix before rolling up into vortices.

More information on the shedding arrangement was provided by flow visualization studies. The flow about a pair of circular cylinders was examined in a smoke tunnel. The smoke tunnel has a working section 1·22 m wide by 0·61 m high and the cylinders used were 1·27 cm in diameter and spanned the shorter dimension. Photographs taken at $\delta = 2{\cdot}0$ and 0·85 are shown in figure 11 (plate 1) but these should be interpreted cautiously since the Reynolds number of the flow was about 5×10^2 compared with $2{\cdot}4 \times 10^4$ in the wind-tunnel experiments. Nevertheless the photograph for $\delta = 2{\cdot}0$ clearly shows a symmetric in-phase shedding pattern with no mixing between the two inner shear layers before roll-up, whereas at $\delta = 0{\cdot}85$ the flow is confused with no apparent dominant vortex structure. A filament passing between the cylinders is seen to be biased towards one of the cylinders. The flow would remain biased in this direction for some time before swapping to the other side.

The shedding of vortices cannot remain symmetric up to the point of contact of the cylinders because we know that then there must be out-of-phase shedding. Rather than make a distinct change at a precise separation the flow passes through a complex transition during which shedding breaks down first on one of the cylinders. The hot-wire traces in figures 8 (*c*) and (*d*) show shedding on one cylinder only and this shedding is at a higher Strouhal number than that for an isolated cylinder. Figure 4 shows that this frequency is only detectable near the cylinder and further downstream a lower frequency is measured. When the cylinders are very close the vorticity shed within the gap is diffused between the two shear layers and this flow acts like a simple bleed and shedding develops across the cylinder pair.

For gaps between 1 and 4 diameters the spanwise correlation length is found to be slightly higher than that measured on an isolated cylinder. At zero separation it is exactly twice the isolated-cylinder value. When the cylinders are touching the base width is effectively doubled, hence one would expect all lengths to be roughly doubled. Measurements taken between $\delta = 0{\cdot}1$ and 1 have little meaning because of the non-stationary nature of the flow around the pair.

5. Conclusions

Surface pressure measurements show that there is a mean repulsive force acting between two circular cylinders in close proximity. The repulsive force originates from a rotation of the resultant force vector due to the presence of the other cylinder. At gaps between 0·1 and 1·0 diameters there is a marked asymmetry in the flow with the two cylinders experiencing different drags and base pressures. The base pressure was found to change from one steady value to another or simply fluctuate between the two extremes. A similar effect was found on a pair of bodies with sharp-edged separation and it is deduced that this asymmetry is due to a near-wake phenomenon rather than being related to the position of boundary-layer separation. At very small gaps the drag of the cylinders in combination is less than the sum of the drags of the cylinders in isolation. This is attributed to the gap flow, which acts like a form of base bleed.

The cylinders shed vortices in the form of two vortex streets when the gap is greater than one diameter with shedding in phase across the cylinder pair. When the cylinders are nearly touching alternate vortex shedding is detected with only one street forming. The spanwise correlation length measured on a pair of cylinders in contact is double that measured on one of the cylinders when the gap is greater than about one diameter. Very little can be deduced about the form of the wake flow for the range of gap sizes where the flow is asymmetric except that the cylinder with the higher drag sheds weak vortices whereas no shedding could be detected from the other cylinder. Considerations of the strengths of shed vortices suggest that, when two vortex streets are formed, cylinder proximity may have a destabilizing effect on the vortex-street structure.

One of the authors (A. J. W.) was in receipt of a maintenance grant from the Science Research Council. The authors would like to thank T. Lye for constructing the apparatus. Thanks are also due to Mr J. P. O'Leary and Mr P. Pongprudhanon for their generous help and unrelenting perserverance in establishing and photographing the filament patterns shown in figure 11.

REFERENCES

Andreopoulos, A. 1972 M.Sc. project report, Imperial College, London.

Bearman, P. W. 1967 *Aero. Quart.* **18**, 207–224.

Bierman, D. & Herrnstein, W. H. 1933 *Nat. Adv. Comm. Aero. Wash. Tech. Rep.* no. 468.

Bradshaw, P. 1965 *J. Fluid Mech.* **22**, 679–687.

Gerrard, J. H. 1966 *J. Fluid Mech.* **25**, 401–413.

Hori, E. 1959 *Proc. 9th Japan Nat. Cong. Appl. Mech.* pp. 231–234.

Landweber, L. 1942 *David Taylor Model Basin Rep.* no. 485.

Maskell, E. C. 1965 *Aero. Res. Counc. R. & M.* no. 3400.

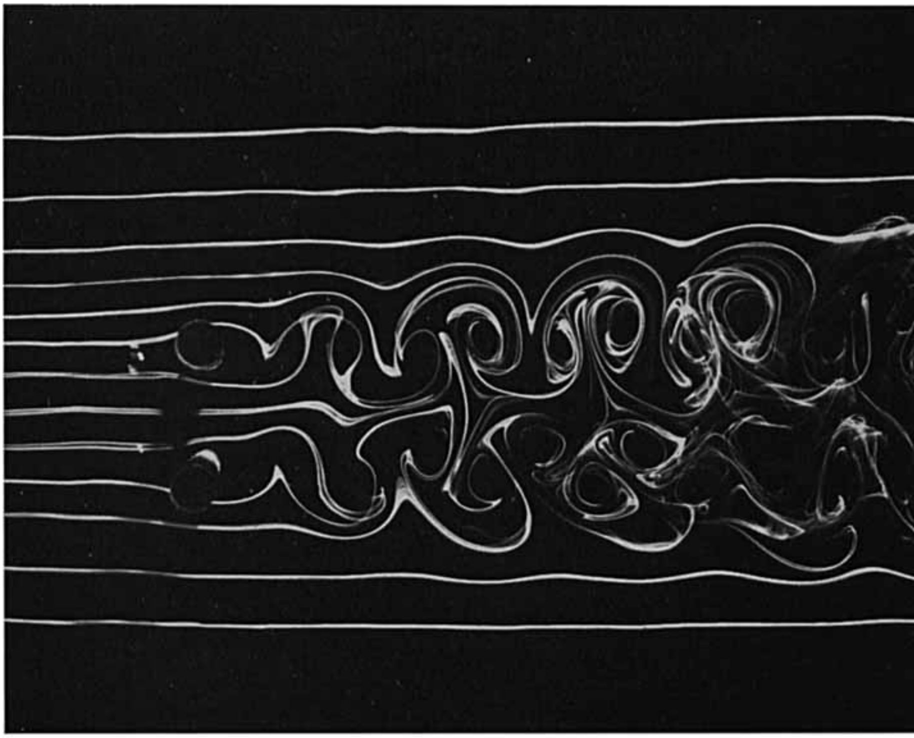
Milne-Thomson, L. M. 1938 *Theoretical Hydromechanics*. Macmillan.

Morkovin, M. V. 1964 Flow around circular cylinders: a kaleidoscope of challenging fluid phenomena. *Symp. on Fully Separated Flow*. A.S.M.E.

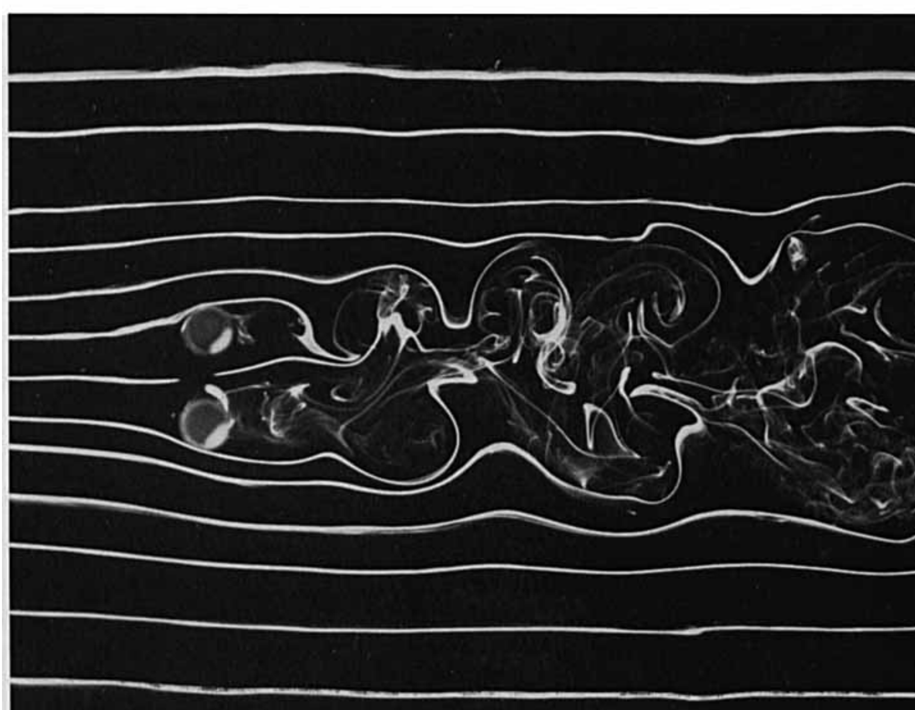
Prendergast, V. 1958 *University of Toronto U.T.I.A. Tech. Note*, no. 23.

Spivak, H. M. 1946 *J. Aero. Sci.* **13**, 289–301.

Wadcock, A. J. 1970 M.Sc. project report, Imperial College, London.



(*a*)



(*b*)

FIGURE 11. Photograph of smoke flow past two cylinders.
(*a*) $\delta = 2{\cdot}0$. (*b*) $\delta = 0{\cdot}85$.