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Aerodynamic Behaviour of Bodies in the Wakes of other Bodies

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Aerodynamic behaviour of bodies in the wakes of other bodies

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Wakes of two-dimensional bluff bodies are described, with emphasis on the properties of the wake which influence the loads on other bodies placed in the wake. The unsteady irrotational flow outside the true wake is included in the discussion. Some limited information on the wakes of three-dimensional bluff bodies is also considered.

The interaction between two bodies is subdivided into two categories: (i) when the bodies are close together and the upstream body is influenced by the downstream one and (ii) when the bodies are so far apart that only the downstream body is affected.

Experiments are described in which the load on an aerofoil in the wake of a two-dimensional bluff body was measured. The results are presented in the form of an aerodynamic admittance and these experiments are used to illustrate the type of problem associated with the determination of the loads on a bluff body in a wake.

Experiments are also described which show the large variation of time-averaged load which can be developed on a body which is part of a closely packed complex of bodies, as the orientation of the complex to the wind is varied.

Finally, some ideas for future research are outlined.

1. Introduction

Before starting to consider the behaviour of bodies in the wakes of other bodies it is necessary to consider some of the properties of these wakes. The wakes to be considered will be those formed behind *bluff* bodies, i.e. bodies that are not of streamline shape so that separation occurs either at a blunt base or ahead of the downstream edge of the body. The results to be described are relevant to tall and relatively slender buildings rather than low squat ones.

The real case of a building in the natural wind will be simplified by ignoring the shear flow and turbulence in the atmosphere. Thus the body whose wake is to be considered is assumed to be in a non-turbulent stream of uniform velocity. For this case the true wake of the body, as usually understood, is the region downstream of the body in which there is vorticity and reduced total pressure. For the bluff bodies considered here the flow in the wake is usually unsteady, often with marked periodicity, and the unsteadiness persists outside the true wake in the region of irrotational flow. Because of the important effect of unsteady flow on the loads on bodies the unsteady region outside the true wake will be included in the discussion.

When two bodies in an air stream are far apart it is possible to consider separately the wake produced by the upstream body and the effect of this wake on the downstream body. When the two bodies are close together the problem cannot be split up in this way because the flow round the upstream body may be influenced by the downstream body. A well-known example of the latter case is the influence of a splitter plate on the flow past a circular cylinder, as studied by Roshko (1954) and others. Some further examples of upstream influence by a downstream body will be considered later.

2. Wakes of bluff bodies

(a) *Nominally two-dimensional wakes*

At Reynolds numbers above about 50 the wake of a bluff body in a flow that is nominally two-dimensional takes the form of the well-known Karman street and consists of a double row of vortices. Much of the available information on wakes of this kind at various Reynolds numbers is derived from experiments on circular cylinders, but the limited results that are available for other shapes, such as rods of rectangular section, indicate that the general form of the wake is not much influenced by the shape of the body.

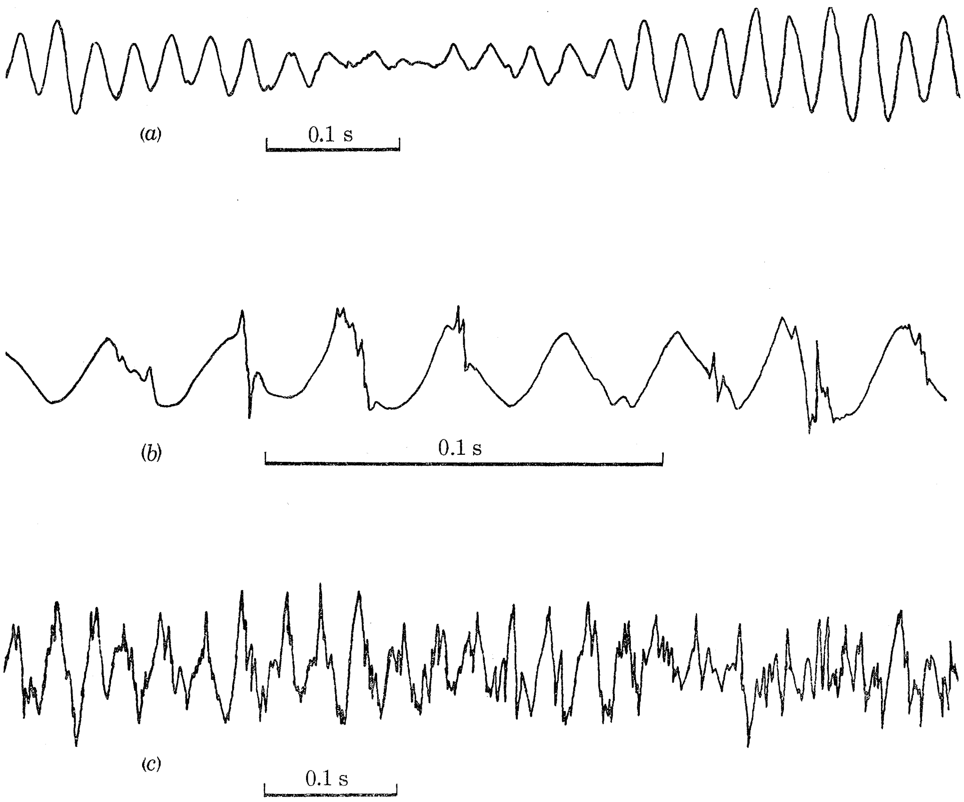

Figure 1. Velocity fluctuations behind a flat plate with blunt trailing edge.

With increasing Reynolds number the transition to turbulent flow in the shear layers downstream of the body moves upstream and turbulence is then superposed on the pattern of vortices. It appeared from some early experiments (Goldstein 1938) that the vortex wake with periodic shedding might not be present at high Reynolds numbers, but experiments by Roshko (1961) have shown that there is a clearly defined periodicity in the wake of a circular cylinder even at a Reynolds number as high as 8×10^6. In Roshko's experiments care was taken to avoid compressibility effects by keeping the Mach number below about 0.25; this has not always been possible in other experiments such as those by Cincotta, Jones & Walker (1966), using a freon wind tunnel, in which a Reynolds number of 18×10^6 was reached at a Mach number of 0.4. At this high Reynolds number Cincotta *et al.* found that there was a definite periodicity in the unsteady lift force on a circular cylinder, indicating that periodic shedding of vortices was occurring. It seems probable that periodic shedding would still have occurred at this Reynolds number, even at a Mach number low enough to avoid compressibility effects.

Figure 1 shows velocity fluctuations as recorded by a hot-wire anemometer downstream of a thick plate set parallel to an air stream. The plate was 1.05 m long and 32 mm thick, with a blunt trailing edge. The wind speed was 6.4 m/s and the hot wire was placed at various distances from the centre line at a station 0.2 m downstream of the trailing edge of the plate.

This plate was a rather extreme form of bluff body; the ratio of length to thickness was more than 30 and the thickness of the turbulent boundary layer on each side of the trailing edge was about 20 mm, i.e. of the same order as the thickness of the plate. Yet the records shown in figure 1 resemble closely those obtained behind other shapes of bluff body, e.g. those given by Toebes (1969) for a circular cylinder.

Figure 1*a* refers to a position in the potential flow just outside the turbulent wake. The periodicity is caused by regular shedding of vortices but the large variation of amplitude is more difficult to explain. Toebes (1969) also observed this with a circular cylinder and showed that it was caused, not by swinging of the wake from side to side but by 'pulsing', i.e. by low-frequency variations of vortex strength and mean wake width. It seems likely that these low-frequency variations are associated with changes in the three-dimensional pattern of vortex formation.

Figure 1*b* shows the record obtained with the hot wire close to the mean position of the edge of the turbulent wake. The burst of turbulence that occurs once in each cycle, while the velocity is decreasing, indicates that for this part of the cycle the hot wire is in a protruding lobe of the turbulent wake, while for the remainder of the cycle the wire is in non-turbulent potential flow. Again, a similar effect was observed by Toebes (1969) behind a circular cylinder.

Figure 1*c* was obtained with the hot wire moved further into the wake so that the flow was always turbulent. There is still a marked periodicity and this seems to be a characteristic feature of most of the measurements that have been made in wakes of two-dimensional bodies. The variation of amplitude of the periodic fluctuations is less noticeable than in figure 1*a*, partly because it is obscured by the superposed turbulence but also probably because the pulsing of the wake affects figure 1*c* mainly through the variation of vortex strength, whereas figure 1*a* is affected additionally by the variation of mean wake width.

Close to the centre of a vortex wake the predominant frequency is doubled because the fluctuating velocity is affected by both the rows of vortices instead of only one as in figure 1*c*.

In some recent unpublished work, R. Kinns has studied the statistical properties of the wake behind a two-dimensional body of D-section at a Reynolds number of 8×10^4. The records of either the longitudinal velocity component u or the transverse component w were of the same general form as those shown in figure 1. For statistical analysis the measured velocity components were recorded first in analogue form on magnetic tape, then converted to digital form and stored in a computer. The spectra showed the expected sharp peak at the vortex shedding frequency.

For the body of base height d, measurements were made at a distance $4d$ behind the base at several transverse positions. Measuring z upward from the centre of the wake, and the transverse velocity component w in the same direction, the local instantaneous angle of incidence is $\alpha = \tan^{-1}(w/u)$ and is positive when the velocity vector is inclined upward. Figure 2 shows the probability density $P(\alpha)$ for three positions below the centre of the wake defined by the stated negative values of z/d. A notable feature is the asymmetry of all these curves; the most probable incidence is always positive, corresponding to a flow inclined towards the centre of the wake.

In contrast to this, the greatest extreme values of α are in the negative sense. The first of these effects, the general bias towards positive incidence, is more pronounced at greater values of $|z|$ and is probably associated with a mean flow towards the centre due to entrainment of fluid into the wake. The second effect is most noticeable at the smaller values of $|z|$ and is probably connected with variations of turbulence intensity between different parts of the vortex street.

The extensive range of incidence shown in figure 2*a* is obviously important in relation to the loads generated on bodies in the wake. With such a large range, nonlinear variations of load are to be expected for all shapes of body.

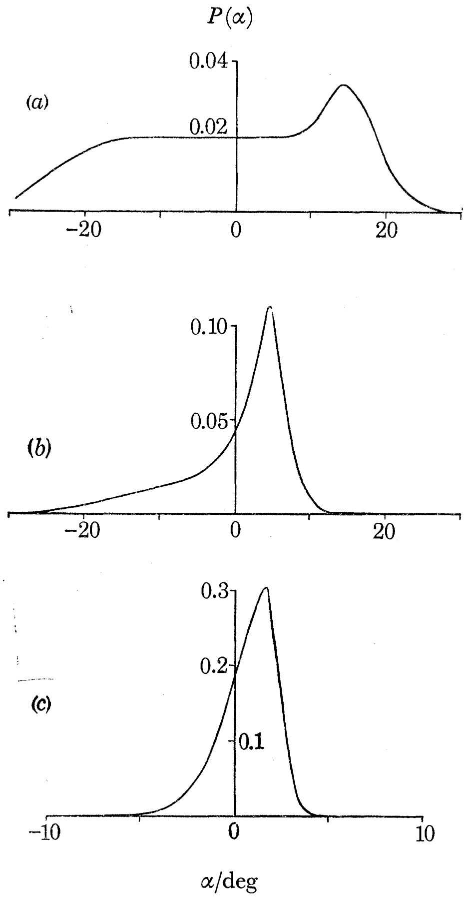

FIGURE 2. Probability density of incidence α behind a body of D-section. (*a*) $z/d = -0.67$; (*b*) $z/d = -1.33$; (*c*) $z/d = -2.0$.

(*b*) *Three-dimensional wakes*

It has been known for some time that even when the conditions of an experiment are nominally two-dimensional the wake of a bluff body is almost always three-dimensional, i.e. there are significant spanwise variations of instantaneous velocity. These spanwise variations have been investigated by Gerrard (1966), using ten hot wires simultaneously in the wake of a circular cylinder. At low Reynolds numbers (e.g. 200) the vortex lines were inclined to the axis of the cylinder. Other, more complex, three-dimensional effects were also present and these changed with increasing Reynolds number. At his highest Reynolds number of 2×10^4 Gerrard found that the vortices were shed with their axes substantially parallel to the axis of the cylinder, but there was still some random variation of amplitude in a spanwise direction.

Graham (1969) measured spanwise correlations of the longitudinal component of fluctuating velocity behind a two-dimensional body of D-section, at a Reynolds number of 2.7×10^4. With the hot-wire output filtered to pass only a narrow band near the shedding frequency, the correlation coefficient became small for spanwise distances greater than about three or four base heights, indicating that the periodically shed vortices were not two-dimensional for greater spanwise distances.

It has often been observed that regular periodic shedding of vortices from a circular cylinder appears to cease when the Reynolds number increases through the critical value of about 4×10^5. This seems surprising in view of other evidence that regular shedding occurs from a two-dimensional body whether the boundary layer is laminar or turbulent at separation. The matter has recently been explained satisfactorily by Bearman (1969*a*) who has shown that the observed cessation of regular vortex shedding is due to gross three-dimensionality of the flow, caused by

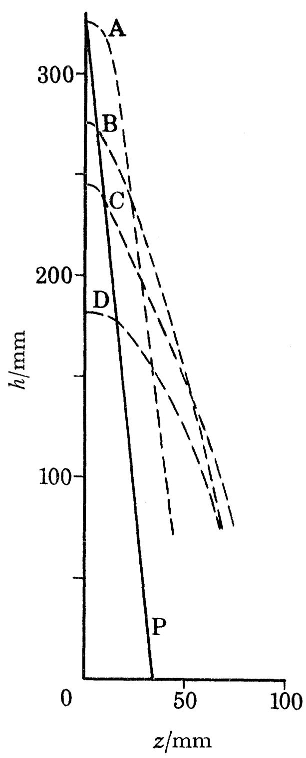

FIGURE 3. Wake boundaries behind tapered flat plate normal to a stream. h = height above floor of wind tunnel; z = lateral distance from plane through centre line of plate. P, outline of plate; A, wake edge 25 mm behind plate; B, wake edge 125 mm behind plate; C, wake edge 175 mm behind plate; D, wake edge 250 mm behind plate.

turbulent wedges from the front of the cylinder. At considerably higher Reynolds numbers, when the boundary layer is uniformly turbulent ahead of separation, Roshko (1961) has shown that regular vortex shedding occurs as for other shapes of body.

Buildings and other structures which cause wakes in the natural wind are necessarily of finite height and therefore three-dimensional. Although the wakes may bear some resemblance to the nominally two-dimensional wakes that have been studied in wind tunnels, it is to be expected that the free end at the top of the structure will have an important effect.

It has been known for some time that there is a downward flow on the lee side near the top of a tall bluff body such as a chimney. (For example, Wootton (1969) refers to the downflow of smoke on the downwind side of a stack as a well-known phenomenon.) Recent unpublished measurements in a wind tunnel by R. A. Young have shown that on the lee side of a bluff body the pressure increases as the top of the body is approached and this must cause a downward acceleration of air in this region.

Unfortunately no detailed studies of the wakes of cylindrical bodies of finite height are known to the authors, but some unpublished measurements by A. B. Jackson & P. R. Samworth give the mean velocity distribution in the wake behind a triangular flat plate of 11.8° apex angle. The plate was 330 mm high and was mounted normal to the air stream with its base on the floor of a wind tunnel. The 'wake edge' was defined arbitrarily in terms of the position, where the measured stagnation pressure was equal to the arithmetic mean of the stagnation pressures in the free stream and close behind the plate far from the tip. Using this definition figure 3 shows

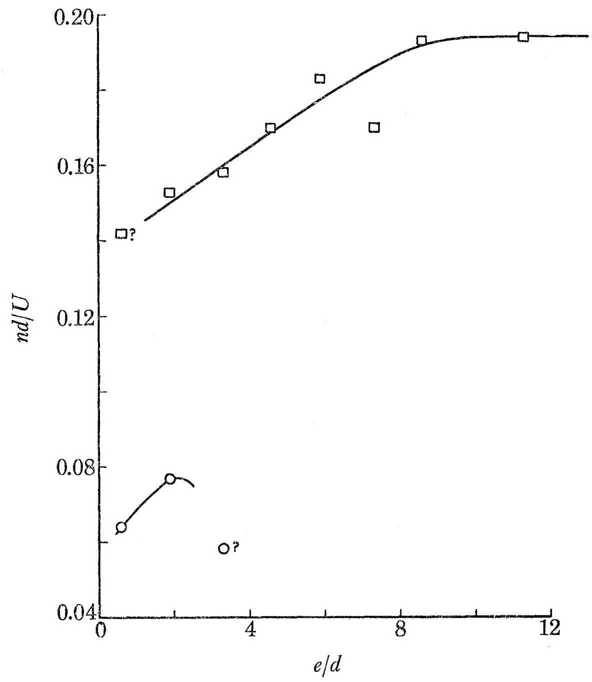

FIGURE 4. Strouhal numbers observed by Wootton for circular cylinder of finite height.

boundaries of the wake edge for four distances behind the plate. This shows that the wake becomes lower and wider with increasing distance downstream. At a given distance downstream there is a substantial decrease of wake width with increasing height above the floor, but it is not clear how much of this effect is caused by the taper of the plate.

Gaster (1969) has shown that for a tapered circular cylinder at low Reynolds numbers (up to 200) the shedding frequency varies along the length of the cylinder so that the Strouhal number based on local frequency and diameter is constant. It is likely that the flattening and widening of the wake shown in figure 3 occurred also in Gaster's experiments, but Gaster's smoke photographs show that any downward inclination of the mean streamlines was quite small.

Wootton (1969) has measured the fluctuating velocity just outside the boundary layer of a circular cylinder of finite height. The Reynolds number was subcritical and for these measurements the cylinder was mounted rigidly. He found that near the tip of the cylinder the spectrum showed two frequency peaks, the corresponding Strouhal numbers being about 0.07 and 0.15. As the distance from the tip increased the peak at the lower frequency died away while that at the higher frequency became more intense. Figure 4 shows the Strouhal number nd/U plotted

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against the ratio of the distance e from the tip to the diameter d. (The points marked ? represent doubtful peaks of low amplitude.)

It has been shown by Roshko (1954) and others that a wake Strouhal number S^*, defined in terms of the wake width and the velocity at the edge of the wake, has a value that is roughly constant for all two-dimensional wakes. This led Wootton to suggest that the increase of nd/U with e/d, shown in the upper curve of figure 4, might be associated with increased wake width near the top of the cylinder, caused by downflow of air on the lee side near the top. It seems quite likely that the wake width close behind the cylinder does vary in this way, although figure 3 shows that further downstream the wake width is smaller near the top, by an amount that seems too large to be explained by the taper of the plate used in those experiments. (Curve A of figure 3 shows a relatively gradual decrease of wake width as the tip is approached and this may well be caused mainly by the taper of the plate.)

A further cause of varying frequency of vortex shedding from a structure in the natural wind is the shear flow in the atmosphere. Maull (1969) has shown that in a shear flow the frequency of vortex shedding from a body of constant width varies in such a way that the local Strouhal number remains approximately constant.

All these results indicate that the most important practical problems involve wakes that are considerably more complicated than the wake of a nominally two-dimensional body. Nevertheless it seems that the best way to obtain some understanding of the fundamentals of the practical problem is to consider first a relatively simple case and many of the results to be given later in this paper refer to flows that are at least nominally two-dimensional.

3. Loads on bodies

The load on a body that is in or near to a wake of the kind already discussed may be expected to be unsteady. It is convenient to consider this load in terms of unsteady and time-averaged components and deal with these separately.

(a) *Unsteady loads*

Since the wake of a body is unsteady and quite often random, the first problem is to relate the fluctuating velocity in the wake with the fluctuating load induced on a body in the wake.

Considering a linear oscillating system excited by a sinusoidal force $F(t)$, it may be shown that

$$\overline{G^2} = \overline{F^2}/|z(\omega)|^2,$$

where $\overline{G^2}$ is the mean square of the response of the system and $|z(\omega)|^2$ is the absolute square of the impedance of the system at frequency ω, the angular frequency of the forcing.

If F is not sinusoidal but random, power spectra $f(\omega)$ and $g(\omega)$ must be defined, such that

$$\overline{F^2} = \int_0^\infty f(\omega)\,\mathrm{d}\omega \quad \text{and} \quad \overline{G^2} = \int_0^\infty g(\omega)\,\mathrm{d}\omega,$$

and hence

$$g(\omega) = f(\omega)/|z(\omega)|^2$$

and

$$\overline{G^2} = \int_0^\infty \frac{f(\omega)}{|z(\omega)|^2}\,\mathrm{d}\omega.$$

Hence to describe the response of a linear system to a random forcing function it is necessary to know two quantities: the spectrum of the forcing and the impedance of the system.

To illustrate this idea consider an aerofoil in an unsteady velocity field. If the velocity field is made up of a steady horizontal velocity U and a fluctuating vertical velocity $w(t)$, there is an unsteady angle of incidence $\alpha = \tan^{-1} w/U$. This will produce an unsteady lift coefficient $C_L(t)$ on the aerofoil which can be related to the angle of incidence by means of an admittance (the reciprocal of the impedance) for the aerofoil.

Sears (1941) considered the response of an aerofoil to a two-dimensional moving gust field of the type

$$w(x, t)/U = \alpha_0 e^{i\omega(t - x/U)},$$

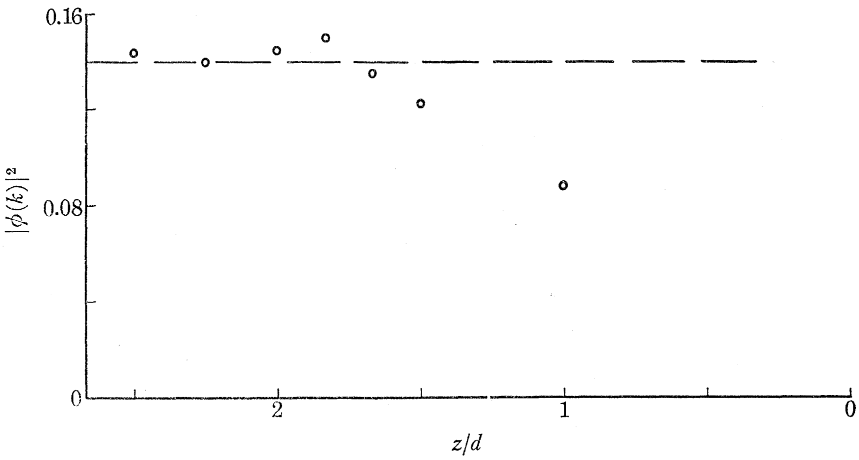


FIGURE 5. Admittance of an aerofoil at various distances from the centre line of the wake of a bluff body. ———, $|\phi|^2$ from Sears's analysis.

consisting of waves of angular frequency ω and wavelength $2\pi U/\omega$. He showed that

$$C_L(t) = 2\pi\alpha_0 e^{i\omega t}\phi(k),$$

where $k = \omega c/2U$, c is the aerofoil chord and $\phi(k)$ is the admittance. Hence if $f(k)$ is the power spectrum of $\alpha(t)$ and $g(k)$ is the power spectrum of $C_L(t)$,

$$g(k) = f(k)\,|\phi(k)|^2.$$

The theoretical value of $\phi(k)$ is

$$\frac{J_0(k)\,K_1(ik) + iJ_1(k)\,K_0(ik)}{K_1(ik) + K_0(ik)}$$

and a good approximation is $$|\phi(k)|^2 = 1/(1 + 2\pi k).$$

Thus the spectrum of the unsteady lift may be related to the spectrum of the unsteady velocity fluctuations. The complete formulation for an aerofoil as given here is due to Liepmann (1952) and the application to the wind loading of structures has been considered by Davenport (1961).

In an attempt to verify Sears's admittance function experimentally, some measurements of $f(k)$ and $g(k)$ have been made. The centre section of a rectangular aerofoil, which spanned the wind tunnel, was mounted on a dynamic balance so that the unsteady lift force and hence $g(k)$ could be measured. The aerofoil was placed outside the wake of a two-dimensional bluff body. The ratio $g(k)/f(k)$, where $f(k)$ is the spectrum of the vertical velocity fluctuation at the aerofoil position, gave values of the admittance $|\phi(k)|^2$ as shown in figure 5. Here k is the wavenumber for the natural shedding frequency in the wake. The admittance, in this figure, is plotted against the distance of the aerofoil from the wake centre line and it is seen that while the theory of Sears is satisfactory outside the wake, as soon as the aerofoil enters the main rotational part of the wake the admittance drops. The discrepancy between theory and experiment in the wake region is due to the fact that the theory is linear, assuming small perturbations, whereas in the wake the velocity fluctuations are large and a linear theory is not adequate. Thus any theory which is to be useful inside the wake must be a nonlinear one, in which ϕ will be a function of k and the root-mean square of the velocity fluctuations.

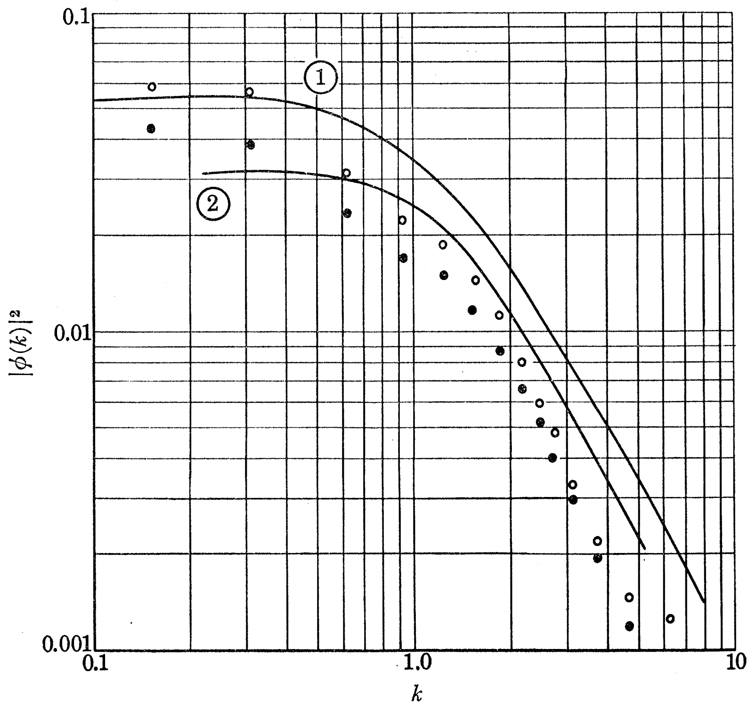


FIGURE 6. Admittance of a wing in grid turbulence as a function of wavenumber. ○, infinite wing; ●, finite wing, aspect ratio 2.84; ①, computed from strip theory (Jackson); ②, computed from Graham's method.

This result gives some idea of the difficulty of estimating the fluctuating load on a bluff body which is near to the wake of another body. The theory of Sears not only requires that the fluctuations are small but also that the lift-angle relationship for the aerofoil is linear. For shapes that are representative of buildings, say square cylinders, the lift is by no means a linear function of incidence, as found by Parkinson & Brooks (1961). Thus a linear theory cannot be expected to handle the unsteady flow around this type of body. In this case the admittance will be a function of frequency, amplitude of velocity fluctuation and also the mean angle of incidence of the body.

In the aerofoil measurements mentioned above the integral scale along the span of the vortex wake was about twice the span of the element of the wing being measured and thus the flow over the element was approximately two-dimensional. Most wakes, however, are three-dimensional in nature and for an isolated body in the atmospheric boundary layer the aerodynamic input to the body (the velocity fluctuation) is also three-dimensional. Thus the ideas of admittance presented above must now be applied to the three-dimensional problem. The two-dimensional aerofoil used in the experiment already described was mounted in a wind tunnel in a turbulent stream generated by a square mesh grid. The results for the two-dimensional wing are presented in figure 6, together with some results for a wing of finite aspect ratio. In this figure the admittance is plotted against the wave number for the particular case in which the ratio of the span (s) of the measuring element of the wing (or the wing span in the case of the finite aspect ratio wing) to the integral scale of the turbulence (L_x) was 6.4. Also shown in this figure are two theoretical calculations for the infinite wing based on theories by Graham (1970) and Jackson.

It is essential that similar types of experiment and theoretical approaches are developed for building shapes. Very little has been carried out with this class of body, the nearest being the

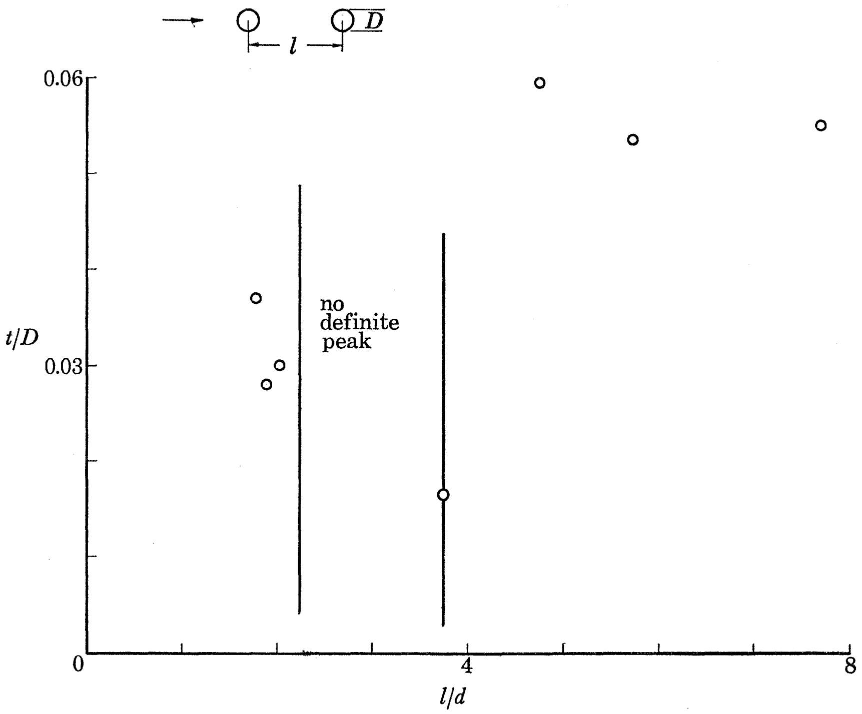


FIGURE 7. The maximum amplitude of oscillation of one body behind another.

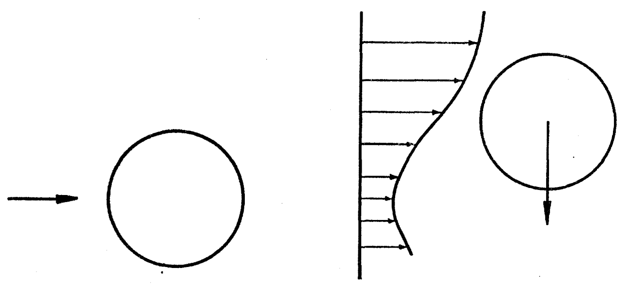


FIGURE 8. The direction of the force on a body in the wake of another body.

experiments of Wardlaw & Davenport (1964), Vickery (1965) and Bearman (1969*b*), all of which were on flat plates normal to a turbulent flow.

The problem of one building in the wake of another and close to it is more complicated than the idealized situations mentioned above. This can be illustrated by some experiments of Whitbread & Wootton (1967) on oscillations of two aeroelastic models of octagonal section, placed in line with the wind. The spacing between the two models was varied and the resulting maximum amplitude of oscillation of the tip of the downstream model was recorded. The results are shown on figure 7. For spacing ratios less than about $2\frac{1}{4}D$, where D is the maximum cross-sectional dimension, the maximum amplitude t of the tip oscillation occurred at values of U/nD

ranging from about 7 to 9, indicating that the rear model was being forced by the combined wake of the two models rather than the wake of the first model alone. For spacing ratios between $2\frac{1}{4}$ and 4 there was no definite peak amplitude, the amplitude rising steadily with increasing U/nd. This indicates that the rear model was being forced by an almost random input from the wake of the upstream model. Above a spacing ratio of 4, however, the rear model is in that part of the wake of the upstream model which exhibits a definite peak in its velocity spectrum, so that the rear model is excited to very high amplitudes and these occur at the same value of U/nD for all spacing ratios greater than 4.

(b) *Time-averaged loads*

The mean velocity profile in the wake of a bluff body is sketched on figure 8 (this only shows the horizontal component of the velocity). If another body is placed in this velocity profile, potential

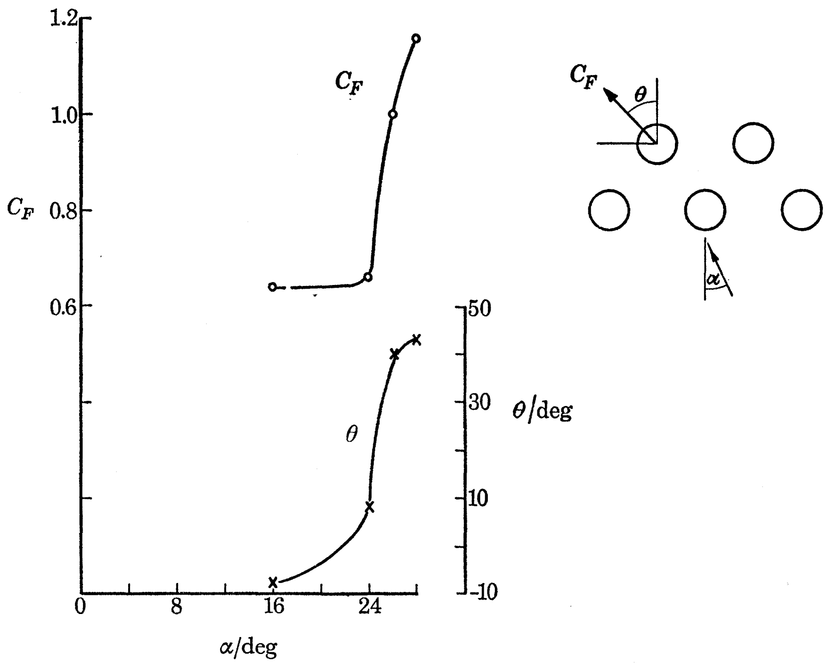


FIGURE 9. The force on one cylinder in a group.

flow theory predicts that the force acting on the downstream body is directed away from the centre line of the wake. Experiments, however, by Counihan (1963) show that the force is directed towards the centre line. It has been suggested that the difference between theory and experiment may be due to earlier boundary-layer transition on the side of the cylinder nearer the wake centre line, caused by greater turbulence in that region. This seems unlikely, since the turbulence varies only gradually across the wake and it is probable that transition will occur at approximately the same place on both sides of the cylinder. A more likely explanation is that the entrainment into the wake produces a local mean velocity vector directed towards the wake centre line and hence a force having a component towards the centre line. This explanation is supported by the results shown in figure 2.

To illustrate the complex types of flow which can occur in non-aeronautical fluid mechanics some experimental results will be considered for closely packed groups of simple structures.

In the first case five cylinders were arranged as in figure 9. The cylinders were 5 cm diameter, 10 cm apart and 91 cm high and the Reynolds number based on the diameter was 1.5×10^5

(Maull 1966). The pressure distribution on one of the cylinders in the rear row was measured and the force coefficient C_F and its angle θ measured for different orientations of the group α to the free stream. An interesting feature of these results is that over a small range of angle α the force C_F can change by almost 100 %. Hence, on a quasi-steady argument, for this configuration, if the mean wind is at an angle of 26° to the group and fluctuates $\pm 2°$ about this mean this can produce an oscillating force coefficient on the rear cylinders varying from 0.67 to 1.17.

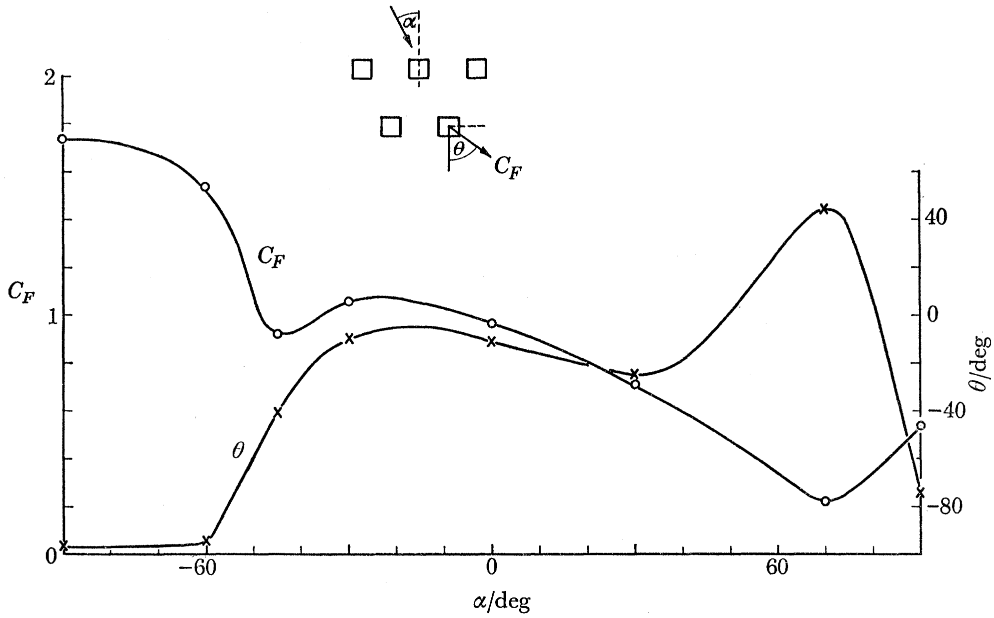


FIGURE 10. The variation of the force on a rectangular cylinder as a function of the angle of the group (α) to the wind.

Similar tests were carried out in this laboratory by Mitchell (unpublished) for a configuration of square-section towers as shown in figure 10. Again there is a large variation of C_F with α and this can be explained by examining the smoke photographs of the flow in figure 11. In figure 11*a* the angle α is $-60°$ and the separating shear layer from the upstream tower in the front row is reattaching approximately on to one corner of the block behind in the rear row. In figure 11*b* the group has been moved a further 10° ($\alpha = -50°$) and now the shear layer is reattaching on to the outside face of the rear block. As can be seen from figure 10 this small change in angle can cause a very large change in C_F and θ.

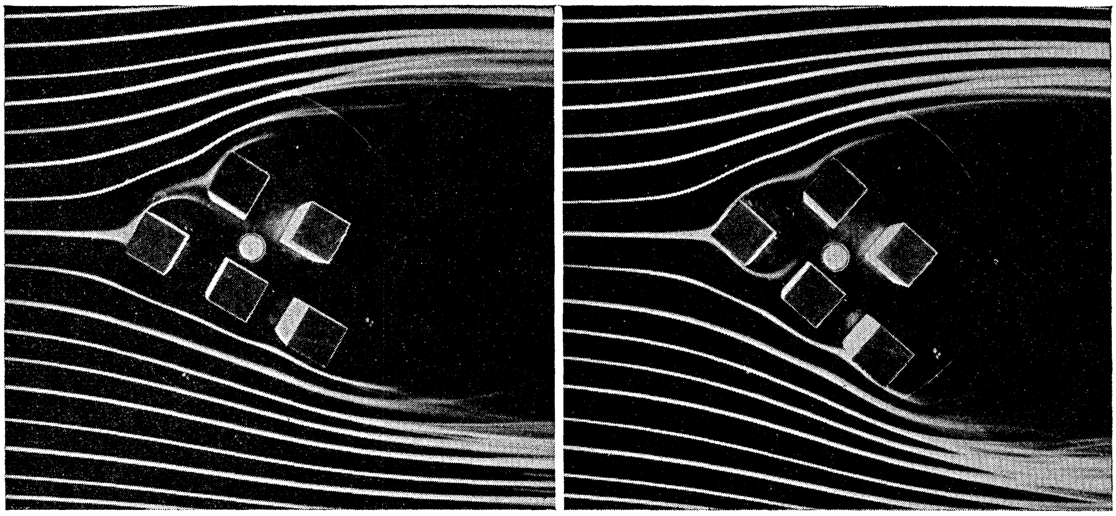
4. Suggested further research

The aerodynamics of structures is undoubtedly complicated, involving unsteady flows around bluff bodies which may be grouped close to each other. It is suggested that future work could profitably be carried out as indicated below:

(i) There is a need for further research on the basic aerodynamics of three-dimensional bodies and their wakes.

(ii) The natural wind is unsteady in time with a non-uniform velocity profile. Both these properties must be simulated in the wind tunnel. It is important, however, to try and differentiate between the two effects and experiments must be done both with turbulence alone and shear alone.

(iii) Theoretical work to predict the flow around groups of structures seems at the moment to present large difficulties. Theory, however, might give some guidance in planning and interpreting wind tunnel experiments. There is a danger of *ad hoc* testing leading to a proliferation of undigested and uncorrelated data.



(*a*) (*b*)

FIGURE 11. The flow around a group of rectangular cylinders; (*a*) $\alpha = -60°$; (*b*) $\alpha = -50°$.

(iv) Very little is known about the aerodynamics of bluff bodies in unsteady flow. What are required are investigations of the effects of turbulence and discrete gusts on the loads on bluff bodies.

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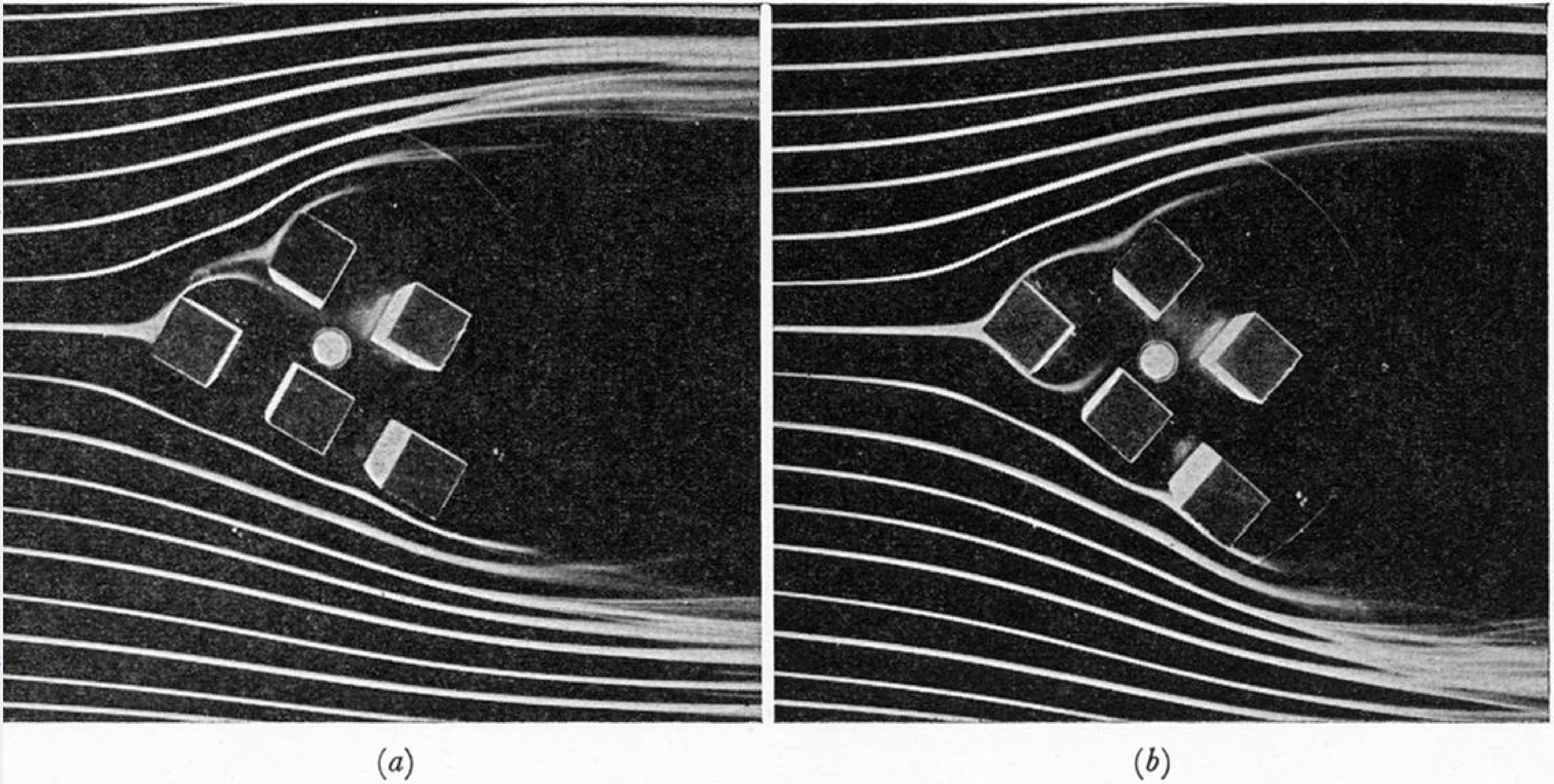

FIGURE 11. The flow around a group of rectangular cylinders; (a) $\alpha = -60°$; (b) $\alpha = -50°$.