J. Fluid Mech. (1971), *vol.* 45, *part* 2, *pp.* 209–224
Printed in Great Britain

Bluff bodies and vortex shedding – a report on Euromech 17

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(Received 24 August 1970)

European Mechanics Colloquium number 17 was held at Cambridge from 1 to 3 July 1970, when the subject of bluff bodies and vortex shedding was discussed. The following report summarizes some of the papers presented. No formal proceedings of the meeting will be published.

Vortex shedding

In the past ten years there have been three major review papers on the subject of vortex shedding, by Wille (1960, 1966) and Morkovin (1964), and papers are still being produced on various aspects of this basic problem in fluid mechanics. As pointed out by Gerrard*, in the opening review paper of the meeting, there is still a preponderance of experimental over theoretical papers in this subject and there is a need for more theoretical work to be attempted. Whilst it was recognized that great advances have been made in obtaining numerical solutions of the Navier–Stokes equations it was thought that further progress would more profitably be made with a phenomenologically based theory, possibly along the lines suggested by Gerrard (1967). All theories at the present, however, are necessarily for two-dimensional flows whilst most experimental investigations have revealed some three-dimensionality. Indeed much of the present interest in bluff body flows is centred around the three-dimensionality of the vortex shedding which arises from a body such as a circular cylinder which in spanning a wind tunnel is nominally two-dimensional. In his review paper Gerrard discussed in particular the low Reynolds number range (< 2000) where frequencies other than the main shedding (Strouhal) frequency may be found in the separated shear layers. In this range transition waves are observed and at Reynolds numbers of about 1500 it is possible for these transition waves and the shedding to have similar frequencies, leading to the possibility of intermittent symmetric shedding and hence a large low-frequency signal. It was suggested that at these low Reynolds numbers the controlling parameter is the movement of the transition in the separated shear layer, since turbulent mixing in the near wake probably governs the whole mechanism of vortex shedding.

In the Reynolds number range $50 < R < 160$, Tritton (1959) found two

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* Asterisks are used to indicate papers presented at the meeting, of which a full list is given at the end of this paper.

modes of vortex shedding (low speed and high speed) separated by a discontinuity at a Reynolds number of about 100. Recently Gaster (1969) was unable to find this discontinuity and he fitted his data to Roshko's (1954) original continuous curve for the Strouhal number given by $S = 0{\cdot}212 - 4{\cdot}5/R$. This discrepancy in the two sets of results was discussed at the meeting by Tritton* and by Gaster. Tritton reported a repeat of his earlier measurements which again reproduced the discontinuity at $R \approx 100$, with regular shedding on either side of this discontinuity and with a modulated shedding occurring at $R \approx 100$. Gaster tested a slightly tapering circular cylinder and found that shedding occurred in spanwise cells, in each of which the shedding was constant and regular and the mean Strouhal number followed Roshko's curve. Between the cells, however, there were regions where the shedding was not continuous. Similarly, a nominally uniform cylinder in a not quite uniform flow showed repeatable regions where irregular shedding occurred. He therefore argued that Tritton's observations of two modes of shedding might well have been due to three-dimensionality in the flow. Berger also found the Tritton phenomena, with intermittent changes in shedding at $R \approx 90$, but found that very small transverse oscillations of the cylinder could make the shedding regular and the vortices parallel to the cylinder. One of the most disquieting results presented by Berger in this discussion was that shedding was influenced over the entire span of the cylinder by the presence of a hot wire in one of the shear layers and that this effect was also dependent on the overheat ratio of the wire. Whilst no definite conclusion came from these investigations it was obvious that at these low Reynolds numbers three-dimensional effects are very important.

It has been well known for a long time that the total amount of circulation (Γ_0) shed from one side of a bluff body during one cycle of the vortex formation is more than the amount of circulation found in one fully formed vortex (Γ), various investigators finding that the ratio Γ/Γ_0 is between 0·5 and 0·6. Gerrard (1966) proposed a model of the transfer of circulation in the base region in which part of the circulation from one shear layer is transferred across to the other shear layer and some circulation is transferred into the recirculation region immediately behind the base. Wood* reported at the meeting an experimental investigation of this transfer of circulation. His apparatus consisted of a bluff-based body which could be towed through water and the flow visualized with polystyrene beads. In this way not only could the flow be photographed but quantitative measurements of the circulation could also be obtained. In his first experiment beads were scattered all over the flow field and he found that the ratio Γ/Γ_0 was about 0·66. In the second experiment beads were injected at a controlled rate into one of the shear layers and by counting the particles it was found that about 15 % of the circulation in the shear layer was transferred across into the other shear layer and about 4 % was transferred into the recirculation region. Hence in any one cycle the amount of circulation available to form a vortex is the amount passing into the shear layer coming off the body minus 4 % which moves into the recirculation region, 15 % which passes across into the other shear layer and another 15 % which is destroyed by circulation coming from the other shear layer. This leaves therefore 66 % of the original circulation as found by the first experiment. It is interesting to note that the theoretical model proposed by Abernathy & Kronauer (1962) predicts that Γ/Γ_0 is 0·61.

Bearman (1967) has shown that the injection of fluid into the base region of a blunt-based body will alter the drag of the body and affect the vortex shedding and the characteristics of the wake. Two papers at the meeting by Castro* and by Valensi & Zeytoun* presented results of a logical continuation of this work, a study of the wake and vortex shedding from a perforated body. For a perforated two-dimensional flat plate normal to the stream it was found that for a porosity β less than 0·2 there was well-defined vortex shedding, where β is the ratio of the area of the holes to the total surface area. For $0{\cdot}2 < \beta < 0{\cdot}5$ there was a periodicity in the wake which, according to Castro, seemed to be caused by an instability in the wake far downstream and there was little interaction between shear layers from opposite sides of the plate. It was also found that as β increased the vortices formed further downstream and the turbulence intensity in the wake decreased. Valensi & Zeytoun also reported some experiments with perforated circular cylinders. Here, as with the flat plates, a dominant frequency was discernible in the wake for $\beta < 0{\cdot}5$ but, whereas with the flat plates the Strouhal number progressively increased with increasing porosity, with the circular cylinder the Strouhal number first decreased and then increased with increasing porosity. The changes in flow pattern with changing porosity of the circular cylinder are obviously rather complex; for a slight porosity there will be an inflow at the front and an outflow in the region of the minimum pressure, causing premature separation. A higher porosity will cause a change in the whole pressure distribution and eventually a decrease in drag. One feature of Castro's work was the use of a pulsed hot wire developed initially by Bradbury (1969), which offers great advantages over the ordinary hot wire for the investigation of separated flows.

Bruun & Davies* presented some measurements of the unsteady pressures on a circular cylinder at subcritical and critical Reynolds numbers. At subcritical Reynolds numbers the frequency spectrum of the pressure fluctuations exhibited the expected peak at the vortex-shedding frequency but as the critical Reynolds number was approached the low-frequency component of the spectrum increased significantly, with a very rapid drop in the power at the shedding frequency. One of the most marked effects of the change of Reynolds number about the critical was on the spanwise correlation of the pressure fluctuations. For instance, at a Reynolds number of $2{\cdot}4 \times 10^5$ the correlation coefficient of the pressures along the generator at 40° from the front of the cylinder was 0·7 for a separation distance of two diameters but at a Reynolds number of $4{\cdot}8 \times 10^5$ the correlation coefficient had dropped to 0·14. A fall in correlation with increase in Reynolds number was present for all angles round the cylinder but this fall was not uniform. As an example, at a Reynolds number of $2{\cdot}4 \times 10^5$ the spanwise correlation along the 20° generator was higher than those along the 40° and 60° generators but at a Reynolds number of $4{\cdot}8 \times 10^5$ the situation was reversed, with a better correlation along the 60° generator than along the 40° generator which was itself better than that along the 20° generator. From this it is obvious that the flow around a circular cylinder is very complicated, particularly in the critical Reynolds number range and much more work is required, especially on the three-dimensionality of the flow.

One practical problem which is even more complicated is the effect of free-stream turbulence on the flow round a circular cylinder. This was dealt with in two papers by Petty* and by Surry*. In the first paper Petty showed that for low-intensity turbulence of small scale the effect of the turbulence was additive to the vortex-shedding effects, but for scales of turbulence of the same order of or greater than the cylinder diameter the shear layers and the vortex shedding were affected even to the extent of suppressing vortex shedding. Smaller turbulence scales, however, acted through the boundary layers, changing the separation points. Surry investigated various scales and intensities of turbulence and found that for mean flow Reynolds numbers between 3·4 and $4{\cdot}4 \times 10^4$ the mean drag coefficient was influenced in an ordered manner by the Taylor parameter $(\bar{u}/\bar{U})(D/L)^{0{\cdot}2}$, where $\bar{U}$ is the mean velocity, $\bar{u}$ the root-mean-square fluctuating velocity, D the diameter and L the lateral integral scale of the turbulence. In the discussion it was pointed out that the Taylor parameter was originally derived with some drastic approximations and that it is not necessarily applicable to bluff bodies. It is apparent that more investigations are required to clarify the use of this parameter. Surry also found that with the highest turbulence generated (15 %) the fluctuating drag force was increased six times but the lift force was hardly changed. In the light of these two papers it is therefore clear that the action of turbulence in the free stream cannot be considered simply as an effective increase in the Reynolds number of the flow.

For cylinders of square cross-section, whose front face is normal to the flow, the effect of turbulence will be felt on the separated shear layers springing from the front corners of the square, as pointed out by McLaren*. He showed that for turbulence whose length scale was less than the length of a side of the square, increasing turbulence brought the shear layers closer together, whereas with length scales greater than the length of the side the effect was to produce a flapping of the shear layers.

Cylinders placed in a shear flow such that the axis of the cylinder is normal to the vorticity vector of the flow would be expected to exhibit unusual types of vortex shedding. It was reported by Shaw* and in the discussion by Turner and Williams that the vortex shedding from a circular cylinder in a shear flow occurred at the same frequency at all points along the cylinder. This does not agree with the findings of Chen & Mangione (1969) for a circular cylinder, or of Maull (1969) for a flat plate across a shear flow, and the reason for this difference is not known, although in this type of flow the influence of end effects may well be very important. A similar problem is that of the flow past a slender circular cone normal to a uniform stream. This flow has been investigated by Gaster (1969) who at the meeting presented a ciné film of the shedding of vortices in this situation, which confirmed his earlier finding that the vortex shedding occurred in patches, with the predominant frequency of the patch varying continuously along the cone.

It has been known for some time that at some Reynolds numbers a stationary cylinder will shed vortices obliquely but that a vibrating cylinder will shed vortices parallel to its axis. At a Reynolds number of 96, Berger *et al.** have investigated the effects of vibration and found that the vortex frequency will lock on to the vibration frequency when the vibration frequency is below the natural vortex frequency and unlock when the vibration frequency is above the natural vortex frequency. The range of shift in the shedding frequencies was found to be a function of the amplitude of the oscillation relative to the cylinder diameter. It was also found that when the cylinder was not oscillating the velocity fluctuations downstream in the wake were not very highly damped but when the cylinder was oscillating at a frequency not near the shedding frequency the fluctuations were very quickly damped downstream. It is not known, however, if this phenomena occurs at higher values of Reynolds number.

Oscillations induced by vortex shedding

It is well known that the fluctuating force associated with the periodic shedding of vortices from a two-dimensional bluff body may cause the body to oscillate, particularly if the vortex shedding is well correlated along the span of the body. The fluctuating force has components both along and across the stream, but, as the latter component is considerably greater than the former, attention has been concentrated mainly on transverse oscillations.

Dye* has used small air bubbles to visualize the flow of water past a flexibly mounted cylindrical tube of relatively low mass. Because the tube had a low mass the hydrodynamic forcing was relatively large and the tube oscillated over a range of flow velocities, with frequency proportional to the flow velocity. Dye showed that as each vortex is shed there is a force acting on the cylinder directed away from the vortex. This fluctuating force (superposed on the steady drag force) has a transverse component whose frequency is equal to the vortex-shedding frequency and a smaller longitudinal component of twice this frequency. The resulting motion of the cylinder is like a figure of eight.

Feng & Parkinson* used spring-mounted cylinders of circular and D-section in an air stream to study the more usual case in which the mass of the cylinder is relatively large, so that oscillations of large amplitude occur only when the vortex-shedding frequency is not too far removed from the natural frequency f_n of the cylinder on its spring support. The cylinders were free to oscillate only in the transverse direction and measurements were made of displacement and fluctuating pressure distribution. As the wind speed V was gradually increased, with corresponding increase of the vortex-shedding frequency f_{v_s} for the stationary cylinder, oscillations of the circular cylinder began when f_{v_s} was only slightly below the natural frequency f_n of the cylinder. At a wind speed V^* the frequency f_{v_s} became equal to f_n but the amplitude of oscillation continued to increase with wind speed up to about $1{\cdot}3V^*$, decreasing again to a small value at about $1{\cdot}7V^*$. As the wind speed was decreased again through this range a hysteresis effect was observed, the maximum amplitude being considerably less when the wind speed was gradually decreasing than when it was increasing.

Feng & Parkinson also studied the 'locking-in' of vortex-shedding and cylinder oscillation frequencies which has been observed in a number of earlier experiments. The frequency f_{v_s} is of course proportional to V, but as V was increased above V^* the actual vortex-shedding frequency f_{v_o} for the oscillating circular cylinder remained almost equal to f_n (and was thus less than f_{v_s}) until V reached about $1{\cdot}5V^*$. At this wind speed the frequencies f_{v_o} and f_{v_s} suddenly became equal and remained equal for higher wind speeds.

In their experiments on cylinders of D-section (with the flat face upstream) Feng & Parkinson found that the 'locking-in' occurred mainly at wind speeds below V^*, whereas the circular cylinder locked in at speeds above V^*. The reason for this difference of behaviour is not understood; it is suggested that it might be useful to make some further experiments in which the cylinders are mechanically disturbed at various wind speeds.

The range of wind speeds for which 'lock-in' occurs includes the range giving oscillations of large amplitude and with increasing amplitude there is a substantial increase in the spanwise correlation of the shed vortices and the fluctuating pressures. This increased correlation strengthens the overall aerodynamic forcing and helps to maintain a large amplitude of oscillation. The amplitudes of oscillation were generally larger with the D-section than with the circular cylinder, probably because the fixed separation position on the D-section increased the spanwise correlation still further.

Taking a different point of view in relation to the same type of flow, Armitt* considered the form of the aerodynamic damping term. At wind speeds outside the 'lock-in' range it may be permissible to consider the problem quasistatically and assume that there is an instantaneous drag force acting along the line of relative motion between the cylinder and the undisturbed air. The transverse component of this force gives a positive damping, so that any oscillations are of small amplitude. In the 'lock-in' range, however, the important effects are the increased spanwise correlation of the vortex shedding and the locking of the shedding frequency to the oscillation frequency. The result is a greatly increased aerodynamic forcing which Armitt interprets as a negative damping.

Some other aspects of 'locking-in' have been studied by Graham*, using a flat plate with a blunt trailing edge, 1 m long and 38 mm thick, mounted in the centre of a wind tunnel parallel to the stream. Earlier work by Cumpsty & Whitehead (1970) had shown that at the appropriate wind speed the vortex shedding from the blunt trailing edge could excite an acoustic standing wave across the wind tunnel. This standing wave was of the kind considered by Parker (1967) in connexion with cascades of plates.

In Graham's experiments, as the wind speed was gradually increased, a sudden change occurred at a speed of about $0{\cdot}97V^*$, where V^* is the wind speed at which the vortex-shedding frequency would become equal to the acoustic resonant frequency f_a if there were no locking in. At this speed of $0{\cdot}97V^*$ the shedding frequency increased suddenly to f_a and at the same time the signals from hot wires placed just outside the wake showed that the shed vortices had become almost exactly two-dimensional. The power spectra obtained from the hot-wire signals showed that the peak at the shedding frequency was considerably sharper in the lock-in range than outside that range. The upper end of the lock-in speed range was about $1{\cdot}03V^*$, but at this speed there was no sudden change of shedding frequency.

Using the same flat plate, Graham studied another form of lock-in by hinging a small portion of the plate near the trailing edge to form a flap and driving this in an oscillating motion with small amplitude. The flap frequency was well removed from the acoustic resonant frequency so that in the flap experiments there were no significant acoustic effects.

Keeping the flap frequency fixed, the wind speed was increased gradually. At a speed such that the vortex-shedding frequency f_v was considerably smaller than the flap frequency f_f, the spectrum obtained from a hot wire just outside the wake showed two peaks, a sharp one at f_f and a rather broader one at f_v. With increasing wind speed the frequency f_v moved closer to f_f but two peaks could always be detected except when f_v became exactly equal to f_f. Thus there was no wind speed at which f_v jumped suddenly to become equal to f_f, but the relative magnitude of the two peaks did change, the one corresponding to f_v becoming relatively smaller as f_v approached f_f. The probable explanation of these results is that vortices were being shed in short bursts, alternately at the frequencies f_v and f_f, so that the time-averaged spectrum showed both peaks. As f_v moved close to f_f the duration of shedding at frequency f_f became larger than the duration at f_v, making the observed peak at f_f larger than that at f_v.

As in the acoustic resonance experiments, the hot-wire signals with the driven flap showed a greatly increased spanwise correlation in the wake when f_v was close to f_f. In contrast to the case considered by Feng & Parkinson the observed behaviour was exactly the same whether the wind speed was increasing or decreasing, i.e. there was no hysteresis.

Some unusual experiments related to the problem of oscillating cylinders were described by Hancock*. He used a specially designed wind tunnel in which the direction of the stream could be varied periodically at a prescribed frequency f_t. In some experiments with a circular cylinder, in which f_t was about half the vortex-shedding frequency f_v, he found that the maximum amplitude of fluctuating pressure at the frequency f_t occurred at about 30° from the mean front stagnation point, a position close to that giving maximum $dC_p/d\theta$ in steady flow. He measured the spectral distribution of fluctuating pressure at this 30° position and found that for $f_t < f_v$ the power at the frequency f_t was large, while for $f_t > f_v$ the power at this frequency was relatively small. This may perhaps mean that the flow can be thought of in quasi-steady terms for $f_t < f_v$ but not for $f_t > f_v$. In some further experiments with cylinders of square section, Hancock found that at zero incidence (with the front face normal to the mean stream direction) there was the expected large increase of fluctuating pressure amplitude when f_t became equal to f_v, but at 12° incidence no such large increase was found. This result is not understood, but it may perhaps be significant that 12° is close to the minimum incidence for re-attachment of flow on one face in a steady stream.

Armitt* has considered qualitatively the effect of turbulence in the stream on the oscillations of a circular cylinder. He concludes that if the turbulence scale is small compared with the diameter of the cylinder there will be little interaction between the vortex shedding and the turbulence, so that the fluctuating load due to turbulence can be simply added to that caused by vortex shedding. If the scale of turbulence is large, so that there is significant turbulent energy at frequencies much less than the vortex-shedding frequency, the main effect of this low-frequency turbulence is to modulate the effective wind speed and hence the vortex-shedding frequency. The aerodynamic forcing due to vortex shedding is then spread over an increased band-width and the forcing at the mean vortex-shedding frequency is decreased, although there is an increase of forcing at frequencies near to this.

Some further experiments by Armitt* have shown that a flow of gas out of the top of a chimney of circular section leads to a large increase in the oscillatory response at frequencies near to the vortex-shedding frequency, probably because the gas efflux improves the spanwise correlation of the shed vortices.

The prediction of the oscillatory response of bluff bodies of various kinds in a wind is obviously of importance to engineers and much of the work already discussed has been done with this object in view. The quasi-two-dimensional case of a circular cylinder in a uniform non-turbulent stream is now fairly well understood for practical engineering purposes, but the engineer is often concerned with more complex shapes. Försching* has shown that a simple strip theory, based on the known properties of two-dimensional circular cylinders, can be used to predict with reasonable accuracy the oscillatory response of cones and stepped cylinders in a wind.

Devices to suppress wind-excited oscillations of chimneys and other cylindrical structures have been studied in a number of laboratories and the helical strakes proposed by Scruton (1963) are now well known. These and other devices have been described by Walshe & Wootton (1970). Alexandre* has made experiments with simple longitudinal fins and has shown that some arrangements of these are very effective in preventing oscillations. For a cylinder with the wind direction always in the plane *AB*, as shown in figure 1, the four fins that are shown suppress the oscillations very effectively. The fins are fixed in the 45° position and extend over the whole length of the cylinder. It seems probable that separation occurs at the fins on the upstream side and that there is no reattachment. With this type of flow the separated shear layers may be expected to oscillate at the vortex-shedding frequency but the associated pressure fluctuations are probably small.

For a vertical cylinder like a chimney, where the wind may blow in any direction, a different approach is needed. No satisfactory arrangement was found with each fin extending over the whole length of the cylinder, but the arrangement of short staggered fins shown in figure 2 was found to eliminate vibration at the vortex-shedding frequency when the fin height was 9 % of the cylinder diameter. In this case the main effect of the fins is probably to destroy the spanwise correlation of the shed vortices, as with the helical strakes proposed by Scruton.

In connexion with a study of the unsteady aerodynamic load on oscillating

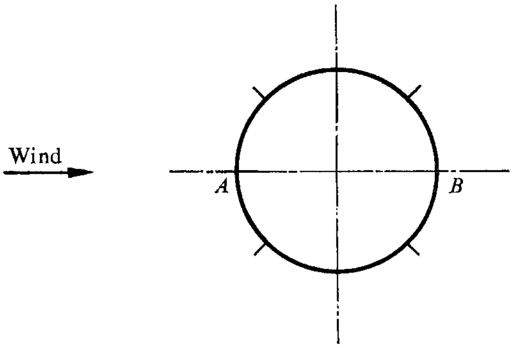

FIGURE 1. Longitudinal strakes for suppressing vibration of a horizontal cylinder in the natural wind.

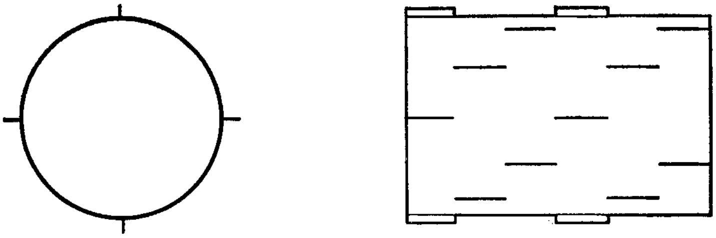

FIGURE 2. Strakes at 90° spacing for suppressing vibration of a vertical cylinder in the natural wind.

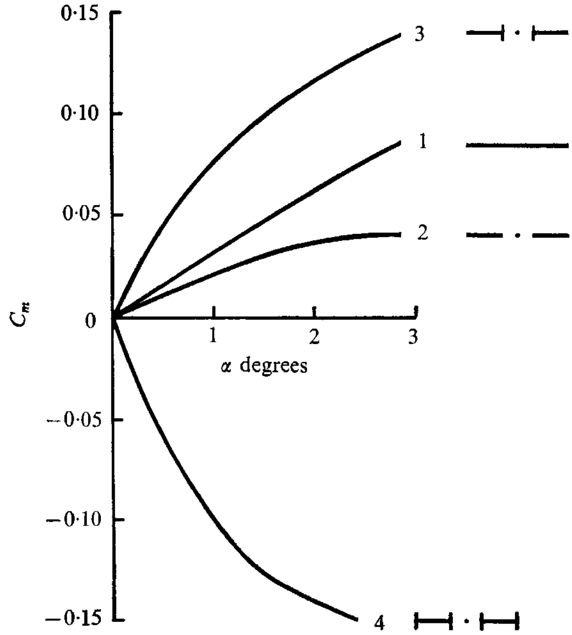

FIGURE 3. Pitching moments of slotted plates. C_m = coefficient of pitching moment about mid-chord axis; α = angle of incidence.

two-dimensional plates in a wind Herlach* has measured pitching moments in steady flow on plates with slits and with cross-plates normal to the chord (figure 3). In all cases the thickness of the plate is 0·04c, where c is the chord, the length of the slit in models 2, 3 and 4 is 0·3c and the height of the cross-plates in 3 and 4 is 0·16c. Of particular interest are the large changes caused by addition of the cross-plates in models 3 and 4; these are probably associated with separation and re-attachment at the edges of the cross-plates.

Groups of bodies

There is as yet little understanding of the complex general problem of a group of bluff bodies in an air stream, although some progress has been made in the special case where a single body is placed downstream of another one (Mair & Maull 1971).

Some work by Armitt* illustrates how the behaviour of a bluff body in an air stream may sometimes be strongly influenced by the presence of another body, either upstream or downstream of the first one. He placed a model chimney of constant diameter d and height 10d in an air stream and measured the amplitude of the transverse oscillations over a range of wind speed. When a rectangular block of height 2·6d, representing a model building, was placed with its centre about 3·5d upstream of the chimney the peak amplitude of oscillation of the chimney was halved, probably because the non-uniformity of the stream approaching the chimney reduced the spanwise correlation of the vortices shed from it. The presence of the building upstream of the chimney also increased by about 10 % the wind speed at which the peak amplitude occurred; this is an expected effect of the reduced mean velocity of flow in the wake of the building.

Armitt found that when the same model building was placed at a distance of 3·5d downstream of the chimney it completely eliminated the usual peak in the curve relating amplitude of oscillation to wind speed. In this case, although the height of the building was only about a quarter of the height of the chimney, the building must have changed completely the character of the wake from the chimney, perhaps eliminating altogether the periodic shedding of vortices.

Calvert & Rowbottom* discussed the force on one cylinder in the wake of another and referred to the work of Counihan (1963) which showed that a circular cylinder in the wake of another one, but not at the centre of the wake, experiences a mean transverse force component towards the centre of the wake. In contrast to this, the theory for a circular cylinder in an inviscid shear flow gives a lift force acting towards the high-velocity region if there is no circulation, but since any arbitrary circulation can be added this is not a unique solution for a cylinder in an inviscid shear flow. A further point of interest is that the theory for a cylinder in shear flow at very low Reynolds numbers also gives a lift acting towards the high-velocity region.

The experimental results reported by Calvert & Rowbottom show that at a given longitudinal station the static pressure decreases slightly towards the centre of the wake. The direct effect of this would give a small force acting towards the centre but this force would be much smaller than the one observed.

A more important effect of the transverse variation of static pressure may be the consequent variation of pressure gradient on the surface of the cylinder; this might affect the position of separation but it is not clear whether it would cause earlier or later separation on the side nearer the centre of the wake.

Calvert & Rowbottom suggested that the transverse force observed by Counihan was caused by the gradient of turbulence intensity across the wake. In the appropriate range of Reynolds number the higher intensity of turbulence nearer the centre of the wake might promote earlier transition in the boundary layer on that side and delay separation. This would explain the transverse force acting towards the centre of the wake. There is some doubt, however, about the validity of this explanation because the difference of turbulence intensity between two streamlines close to and on either side of the stagnation streamline would be small.

In the discussion of this subject Kinns described some unpublished measurements made in the wake of a two-dimensional body of D-section (with the flat face on the downstream side). He found that there was a mean inflow from outside the wake towards the centre, probably associated with entrainment of fluid into the turbulent wake. This would give a mean drag force inclined towards the centre and hence a transverse force component. Kinns also suggested that at Reynolds numbers near the critical range the inwardly directed mean transverse force component might be enhanced by effects of the large fluctuations in the local direction of flow. His measurements show that when the flow is directed towards the centre of the wake it is less turbulent than when it is directed away from the centre. Near the critical Reynolds number this would make the drag greater when the flow is inclined towards the centre than when it is inclined outward.

The discussion of Counihan's result revealed how little is known about bodies in wakes. It is possible that the result is strongly dependent on Reynolds number and further experiments are needed to explore this. Since there are large fluctuations in flow direction in the wake of any bluff body it is likely that any attempt to explain the result in terms of quasi-steady flow will be unsatisfactory and perhaps misleading. For a full understanding of the interaction between two cylinders it will be necessary to measure fluctuating force, and perhaps pressure, on the downstream cylinder, as well as instantaneous velocity (magnitude and direction) at points in the wake. The intermittency of turbulence near the edge of the wake may be important and it is likely that the wake of the upstream cylinder modifies substantially the vortex shedding from the downstream cylinder.

Bauly* described some experiments on vibration of banks of cylinders as used in heat exchangers. He showed that vibrations could be excited by the vortex shedding from the first row of cylinders. The vortex shedding was shown to be associated with a travelling wave in the wake from each cylinder in the first row, the wavelength being of the same order as the longitudinal pitch of the cylinders.

Aerofoils with blunt bases

Naumann, Morsbach & Kramer (1966) showed that broken or corrugated separation wires could be used on a circular cylinder to vary the position of separation along the span; the resulting three-dimensional disturbances then prevented the formation of the usual vortex street.

This suggested to Tanner* that if suitable three-dimensional disturbances were introduced on an aerofoil with a blunt base the vortex street might be suppressed and there might be a consequent rise of base pressure and reduction of drag. He made experiments in which the trailing edge of a blunt-based aerofoil was serrated in plan view and found that suitable serrations did indeed give a large reduction of drag, rather better than the reduction obtained either with a splitter plate or with a ventilated cavity as described by Nash (1967). It has been suggested that the main effect of the serrations is to introduce streamwise vortices and that these prevent the formation of the normal vortex street.

Three-dimensional bodies

Much of the work that has been done on bluff bodies has been related to quasi-two-dimensional flow and except for the special case of the sphere there has been little attention given to three-dimensional shapes.

Some experiments have been made by Lozowski, List, Rentsch & Byram* on spheroidal models representing hailstones. The minor axis varied from $0{\cdot}5D$ to D, where D is the major axis, and measurements were made of lift, drag and pitching moment at angles of incidence from 0 to 90°. The main feature of interest in the results is the critical change that occurs in most cases at a Reynolds number (based on D) in the range 2×10^5 to 4×10^5. As the Reynolds number increases through the critical value the drag coefficient falls (as for a sphere) and the coefficients of lift and pitching moment rise, although the details of the changes depend to some extent on the incidence and fineness ratio. When the spheroids were mounted with freedom to rotate about a transverse axis it was found that auto-rotation occurred in this critical range of Reynolds number.

During the discussion of this work Viets described some experiments on freely falling spheres in which the centre of gravity was displaced very slightly from the geometric centre. The motion of these spheres involved a zig-zag wandering superposed on the vertical descent, accompanied by an oscillatory rotation at the same frequency as the wandering. The suggested explanation is that the bias of the centre of gravity leads to the oscillatory rotation and this rotation then causes an oscillatory side force.

Maskell described some experiments on spheres at Reynolds numbers near to the critical range in which a side force had nearly always been found, even though the spheres had not been allowed to rotate. This is yet another illustration of the extreme sensitivity of bluff-body flows to small disturbances, when the Reynolds number is near to the critical range.

Achenbach* described experiments on the flow in a tube with a sphere mounted centrally. He defined a blockage ratio B as the ratio of sphere diameter to tube diameter and covered a range of values of B up to 0·9. He based his drag coefficient C_D and Reynolds number R on the theoretical velocity in the annular gap between the sphere and the tube wall, as calculated for one-dimensional flow. He found the usual fall of C_D as R increased through a critical range but the critical value of R increased with B. At subcritical values of R the usual value of C_D was increased by the presence of the tube, approximately in the ratio $(1+1{\cdot}5B^4)$.

Conclusions

When planning this meeting we hoped that papers would be offered on vortex shedding from axisymmetric and three-dimensional bluff bodies. It seems, however, that very little work is in progress, at least in Europe, on this type of three-dimensional vortex shedding and most investigators are still concentrating on nominally two-dimensional situations. A recurring theme of the meeting was that in most nominally two-dimensional situations, with the model stationary, the vortex shedding was not really two-dimensional but varied along the span of the model, with changes in phase and possibly amplitude of the shed vortices.

There is certainly a need for more work on these three-dimensional effects on nominally two-dimensional bodies to explain the low spanwise correlation lengths, for instance, on circular cylinders. The actual mechanism of the destruction of ordered vortex shedding by modifications to the base of bluff bodies is also little understood. The phenomena of 'lock-in' which was widely mentioned at the meeting is obviously of great practical importance. Some controlled experiments appear to be required on this topic to try and separate the effects of amplitude and frequency of oscillation, to decide how important Reynolds number is and to investigate 'lock-in' for different bodies with free and fixed separation points.

One question raised at the meeting was whether results at low Reynolds number could be used as a guide to high Reynolds number flows. Some workers maintain that the essential mechanisms of vortex shedding are the same over a wide range of Reynolds number and that progress can best be made by experiments at low Reynolds numbers, because the important mechanisms are then less obscured by turbulence in the near wake. Others maintain that results at low Reynolds numbers may be seriously misleading if they are used as a guide to the behaviour of the flow at high Reynolds numbers.

There was little discussion of numerical techniques at the meeting. It was felt that since many of the flows considered showed marked three-dimensional characteristics a two-dimensional computation, whilst being of interest, would not be very useful. It is possible, however, that with an increase in the size of computers a useful three-dimensional calculation could become a reality.

The authors acknowledge with gratitude the assistance given by Dr J. M. R. Graham and Mr R. Kinns in the preparation of this paper.

Papers presented at the meeting

E. Achenbach. Investigations on the flow around a sphere in an air stream involving blockage ratios up to 0·90.

M. Alexandre. Experimental study of the action of vortex shedding on cylinders with longitudinally welded fins.

N. A. Anderson & G. T. S. Done. Tests on slender model buildings at various aspect ratios.

J. Armitt. Cross-wind vibration of chimneys.

J. A. Bauly. Tube and acoustic vibrations in heat exchangers due to vortex shedding.

L. Belík. Cylinders in shear flow.

E. Berger, R. Landl & M. Sedrak. Wake and drag of a vibrating cylinder at low Reynolds numbers.

A. R. J. Borges. Blockage effects on bluff bodies of prismatic shape in a closed wind tunnel.

H. H. Bruun & P. O. A. L. Davies. Fluctuating pressures on a circular cylinder.

J. J. Bukovský. The influence of turbulence level on the aerodynamic characteristics of circular cylinders.

J. R. Calvert & M. D. Rowbottom. The forces on one cylinder in the wake of another cylinder.

I. P. Castro. Wake characteristics of two-dimensional perforated plates normal to an air stream.

R. C. F. Dye. Visualization of flow in vortex-induced vibration of a circular cylinder.

F. Etzold. Diffusion of matter in the near wake of cylindrical bodies protruding into a cross-flow.

C. C. Feng & G. V. Parkinson. Vortex-induced effects in flow past stationary and oscillating circular and D-section cylinders.

H. Försching. The theoretical prediction of the aeroelastic stability of slender three-dimensional structures with circular cross-section.

M. Gaster. Film of vortex shedding from a cone.

J. H. Gerrard. Introductory survey: Bluff bodies and vortex shedding.

J. M. R. Graham. The effect of an oscillating trailing edge on vortex shedding.

G. J. Hancock. Unsteady flows about circular and square cylinders.

U. Herlach. Unsteady aerodynamic loads on oscillating blunt cylinders.

R. S. Hill. Measurement of aerodynamic forces experienced by a cylinder spanning a wind tunnel.

T. V. Lawson. Effect of scale of turbulence on vortex shedding from a tower block.

E. P. Lozowski, R. List, U. H. Rentsch & A. C. Byram. The aerodynamics of oblate spheroidal hailstone models.

F. G. McLaren. The effect of free-stream turbulence on the vortex shedding from bluff sharp-edged cylinders.

E. Parker. Higher modes of vibration of a cylinder due to vortex shedding.

D. G. Petty. Vortex shedding from circular cylinders in turbulent flow.

T. L. Shaw. A circular cylinder in shear flow.

D. Surry. Some effects of free-stream turbulence on vortex shedding from a circular cylinder at subcritical Reynolds numbers.

M. Tanner. A method for reducing the base drag of wings with a blunt trailing edge.

D. J. Tritton. Vortex streets behind circular cylinders at low Reynolds numbers.

J. Valensi & D. Zeytoun. Vortex shedding from porous-walled bodies.

C. J. Wood. An examination of vortex street formation by particle tracers.

M. M. Zdravkovich. Smoke visualization of some three-dimensional flow patterns in nominally two-dimensional wakes.

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