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Lift exerted on stationary spheres in turbulent flow

By BRIAN B. WILLETTS AND COLIN G. MURRAY
Department of Engineering, University of Aberdeen

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The purpose of the study was to examine the influence of a nearby wall on the lift experienced by spheres fixed in a fluid stream, and the decay of this influence with increasing separation from the wall. For gaps less than one quarter of the sphere diameter, wall effects were found to dominate all dependencies other than that on Reynolds number. At larger gap ratios the lift vector rotates around the flow axis, sometimes this way and sometimes that but only occasionally changes direction abruptly. The rotation seems to be associated with free-stream turbulence and is inhibited by shear or by uneven surface roughness. These effects are not influenced by sphere mounting, and sphere rotation does not seem important.

Three series of experiments are described, each using different apparatus. In a Reynolds number range 3000–50 000, calculated from sphere diameter and relative local velocity, repeatable lift values were observed in zones close to a flow boundary (the wind-tunnel wall), and remote from a boundary for smooth spheres. For rough spheres, results were erratic remote from the boundary.

Large persistent lift forces away from the boundary were found when the gap was less than 0·02 diameters and when it lay between 0·1 and 0·2 diameters (all these fractions being approximate). For larger gaps the lift force was strongly time-dependent and time-averaged values were smaller than those for gap ratios less than 0·2.

Lift forces are related to localized downstream displacements of the separation line round the sphere whose origin seems to lie in the response of the sphere's boundary layer to turbulent structures in the free stream. Weak regularities of the lift record are related not only to the incidence of such features but also to a natural time-scale of response of the boundary layer. Separation line disturbances do not propagate in a predictable fashion but do develop sharp boundaries as a result of recirculation in the wake.

In one series of experiments considerable pains were taken to allow the sphere to rotate freely about an axis parallel to the local tunnel wall and normal to the flow direction. No significant rotation occurred and the effects reported are not associated with sphere rotation. In shear flow remote from a boundary mean lift acted down the gradient of relative velocity.

1. Introduction

This paper reports measurements of lift on spheres fixed in turbulent flows near, and remote from, a boundary; in the latter case with and without a velocity gradient. It discusses these lift forces in association with visual observations of the flow near the sphere.

Lift is taken throughout to mean a force generated normal to the time-averaged relative flow direction. In some passages it refers to the force component in an assumed direction in the normal plane, elsewhere to the resultant force in that plane; the distinction will be made clear at appropriate points in the text.

Whereas laminar flows and irrotational flows round solid spheres in some circumstances have been analysed (Saffman 1965; Milne-Thomson 1968), and in turbulent potential flow there is good empirical knowledge of lift on a spinning sphere (Swanson 1961), much less attention has been paid to the lift force in turbulent flow when the sphere is not constrained by external means to spin. In particular, little has been published about lift on a sphere fixed relative to a flow which has a transverse velocity gradient, and most of those studies which have been reported concern one member of a bed composed of an array of spheres.

However, Bagnold (1974) measured the lift on a cylinder and a sphere held at various distances from the smooth bed of a water channel, the sphere being fixed in position but free to rotate about an axis normal to the flow and parallel to the bed. He asserts that its immersion in a velocity gradient is bound to induce the sphere to spin, in the sense of local vorticity, and that this rotation gives rise to a lift force away from the boundary (and up the velocity gradient). Such spin was only observed haltingly in his experiments and, since it was seen to be persistent when the sphere drifted with the flow, was thought to be prevented by pivot friction. Substantial lift forces were observed at small values of gap between the sphere and the bed, decaying to zero when the gap increased to approximately one diameter. These experiments were done at Reynolds numbers between 800 and 3000; the force balance measured time-average forces.

Thomschke (1971) used a sting-mounted sphere in air flow to measure lift forces when the sphere was mounted near to a plane boundary. He found that the force was always repulsive and was greatest when the gap equalled one tenth the sphere diameter. It decreased rapidly when the sphere was traversed towards the wall from this position, and less rapidly when the gap ratio was increased above one tenth. Having explored the range of Reynolds numbers $1{\cdot}5 \times 10^5$ to 5×10^5, he found that lift coefficients were greatest at 4×10^5. Coleman (1967) found a reversal of lift at Reynolds numbers less than 100, when the sphere was enveloped in the laminar sub-layer. Achenbach (1974) too has observed lift forces acting towards a near-by wall.

Variations with time of lift forces have been inferred by several investigators and measured by Willmarth & Enlow (1969). They have been linked with perturbations of the separation line and with wake structure, in recent studies by Taneda (1978).

Lee (1979) studied lift experienced by one of a pair of spheres fixed side-by-side at a range of centre-to-centre spacings, and it has been suggested that this is closely analogous to the sphere near a wall (the plane with respect to which the sphere positions are symmetrical being a virtual boundary). The analogy is incomplete because the boundary layer on the wall is absent and because the virtual boundary concept fails when the flow has unsteady features. Nevertheless Lee's lift coefficient results make an interesting comparison with ours and Tomschke's, rising *monotonically* from a low value at equivalent gap ratio 0·9 to a peak value at contact. (The paper does not give enough data to assign values to the lift coefficient.)

There is considerably more published information about flow effects on cylinders than there is about spheres. Cautious comparisons are permissible between them

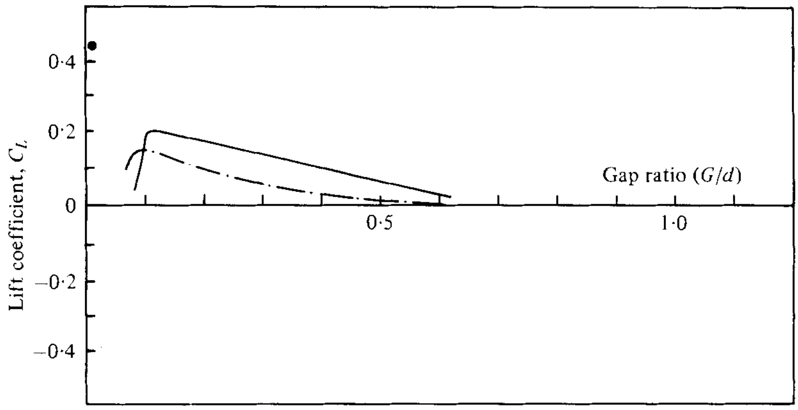

FIGURE 1. Lift observations of earlier investigators. ●, Bagnold, d = 16 mm, Re = 2900, ——, Thomschke, d = 240 mm, Re = 360000; — · —, Thomschke, d = 240 mm, Re = 440000. (d is sphere diameter; G, the gap between the sphere and the wall.)

provided that the differences are kept in mind between the flow-field geometry, particularly when the gap ratio is small, and in the statistical averaging of stimuli from impinging turbulent structures which occurs only in the case of the cylinder if it spans a considerable band of the flow field. Because one possibility under scrutiny was that lift force behaviour is conditioned by disturbances moving along the separation line, it has seemed important in this study to be particularly wary of direct comparisons, since the cylinder can be considered to have two separation lines but the sphere only one. The migration of such a disturbance along the sphere's separation line might, if it were linked with lift, rotate the lift vector through a position of sign reversal whereas no such reversal would follow similar behaviour on a cylinder.

However, we note that Kiya, Arie & Tamura (1979) report mean lift directed down the velocity gradient for a cylinder held in the shear layer at the edge of free jet at Reynolds number between 2×10^4 and 4×10^4. They note earlier findings, however, that small cylinders in an extensive linear velocity profile experience lift directed up the velocity gradient. These forces were inferred from measurements of time-averaged pressure at points round the circumference of the cylinder. As is clear from the direct force measurements of the present study, small mean lift forces are often associated with much larger transient peak values (such is almost certainly the case at the edge of a free jet). The inexactitude of time averaging each set of pressure readings taken at a sequence of angular positions may well produce an error in the *sign* of the mean lift.

The present paper reports lift measurements made in a variety of circumstances, extending those of an experiment reported earlier by the authors (Murray & Willetts 1978), and confirming most of the features of lift variation reported then. Explanations are suggested on the basis of wake and separation line observations made by Taneda and ourselves. The experiments were all done in turbulent flow in ducts of cross-section much greater than the aspect area of the sphere: the Reynolds number range was 3000–50000. Spheres were studied in the three following situations.

(*a*) Close to one wall of the duct and equidistant from the two adjoining walls.

(*b*) In shear flow remote enough to be beyond the influence of a wall.

(*c*) In quasi-potential flow (at the centre of the duct).

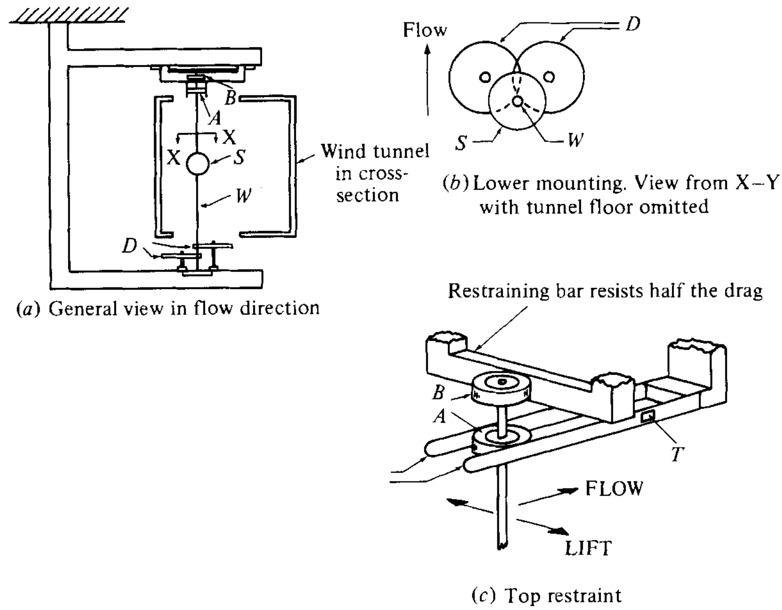

FIGURE 2. Sphere mounting, series A experiments: air flow, cross-section 0·457 m square; sphere Re 6000 to 50 000; diameters 32, 44, 53 mm. (a) General view in flow direction; (b) lower mounting, view from X – X with tunnel floor omitted; (c) top restraint. A, B, ball races; D, freely rotating disks; L, leaf-springs restraining lateral movement; S, sphere; T, strain gauges monitoring lateral force; W, sphere-mounting rod.

Case (b) is difficult to set up satisfactorily and most of the sound data concerns cases (a) and (c). However, observations of the latter two cases help in the interpretation of the results of shear flow experiments and therefore all three cases are discussed despite reservations about the shear flow data.

Figure 1 shows discrepancies between the lift observations near a wall of different observers. Our attempt to resolve them involves three series of experiments, each using quite different force transducers and together embracing two methods of sphere mounting and two working fluids (air and water). Each series contains two subseries, in one of which the sphere is mounted close to a flow boundary and in the other is remote from the direct influence of any boundary. Measurements in the first situation afford direct comparisons with the data of figure 1, while those of the second kind illuminate the changes observed as the sphere is traversed slowly into the range of influence of the wall.

2. Experiments

It is necessary first to describe the sphere mountings and force-measuring systems used in each series of experiments. Their geometries are shown in figures 2–4 together with the range of conditions in which each was used. Certain features were common to all three. In all of them the 'sphere' was a billiard ball, and force was measured by means of wire resistance strain-gauges mounted on an appropriate elastic part of the mounting structure. In each apparatus the sphere could be traversed normal to one

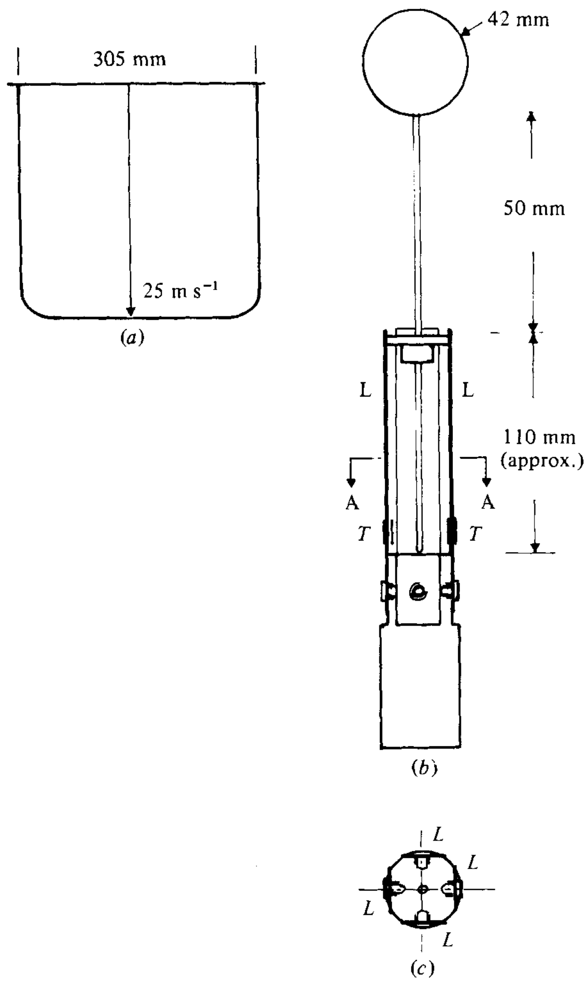

FIGURE 3. Sphere mounting, series B experiments: air flow, cross-section 0·304 m square; sphere Re 5000 to 50000; diameter 42 mm. (a) Velocity profile; (b) front elevation (front spring removed); (c) plan on A – A. L, leaf-springs restraining lateral movement, one pair for each of two orthogonal axes; T, wire resistance strain gauges, one pair for each spring.

flat flow boundary and any gap between the sphere and the boundary determined to within 0·1 mm. In each case the force balance was calibrated directly by observing outputs of the strain-gauge bridge in response to known lateral forces.

The series A mounting was carefully executed to permit rotation of the sphere about an axis normal to the flow and parallel to the adjacent flow boundary (or normal to the direction of velocity variation in the cross-section). This mounting has the major disadvantage that the transfixing rod emerges at two points on the transverse meridian very close to the separation line which it undoubtedly distorts. Since very feeble and sporadic inclination to rotation was observed, and rotation was not apparently linked to lift, the later two mountings for series B and C were more conventional sting mountings and in those series, therefore, rotation was prevented.

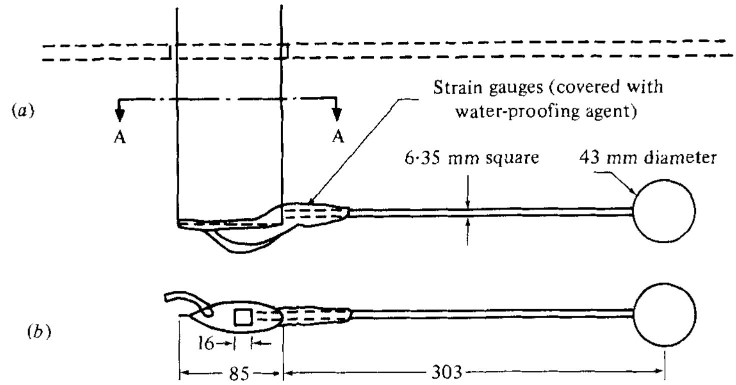

FIGURE 4. Sphere mounting, series C experiments: water flow, cross-section 0·457 m square; sphere Re 3000 to 20000; diameter 42 mm. (a) Side elevation; (b) plan in section through A – A.

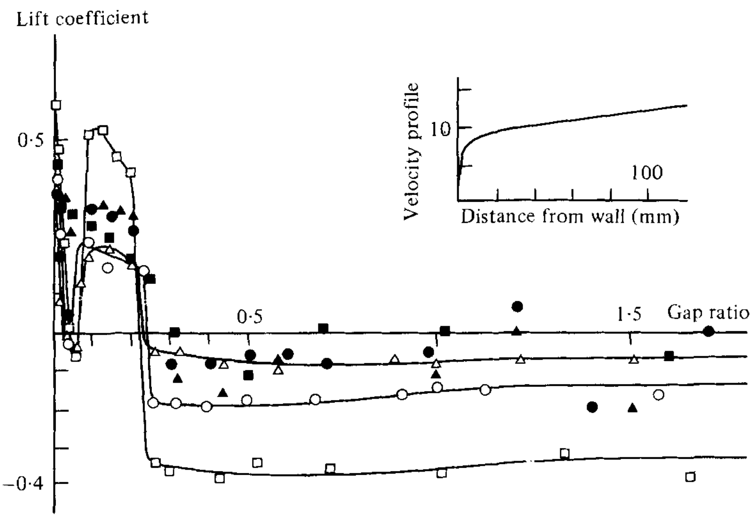

FIGURE 5. Variation of lift coefficient with gap ratio, series A: open symbols represent smooth spheres and solid symbols, rough spheres. The lift on roughened spheres fluctuates more violently than that on smooth spheres. △, ▲, d = 32 mm, $Re \sim$ 23000; ○, ●, d = 44 mm, $Re \sim$ 32000; □, ■, d = 53 mm, $Re \sim$ 3800.

2.1. *Force measurements*

Series A, Re 6000–50000. The sphere mounting is shown in figure 2. Six spheres of three diameters were used in a wind tunnel of cross-section 0·457 m square, the spheres being two billiard balls of each of the diameters 32, 44 and 53 mm; one of each diameter was roughened by scribing grooves approximately $\frac{1}{2}$ mm deep in its surface. Before each experiment the balance of the sphere and mounting rod was checked carefully, as was the freedom of the sphere to spin.

Variations of lift with distance from the wall of the wind tunnel are summarized in figure 5. During the experiments flow in the tunnel was induced to have a velocity gradient, as shown inset in the diagram, so that beyond the influence of the wall the lift decays not to a mean value of zero, but to a value associated with the shear flow condition. It was clear immediately that rather violent fluctuations of lift with time

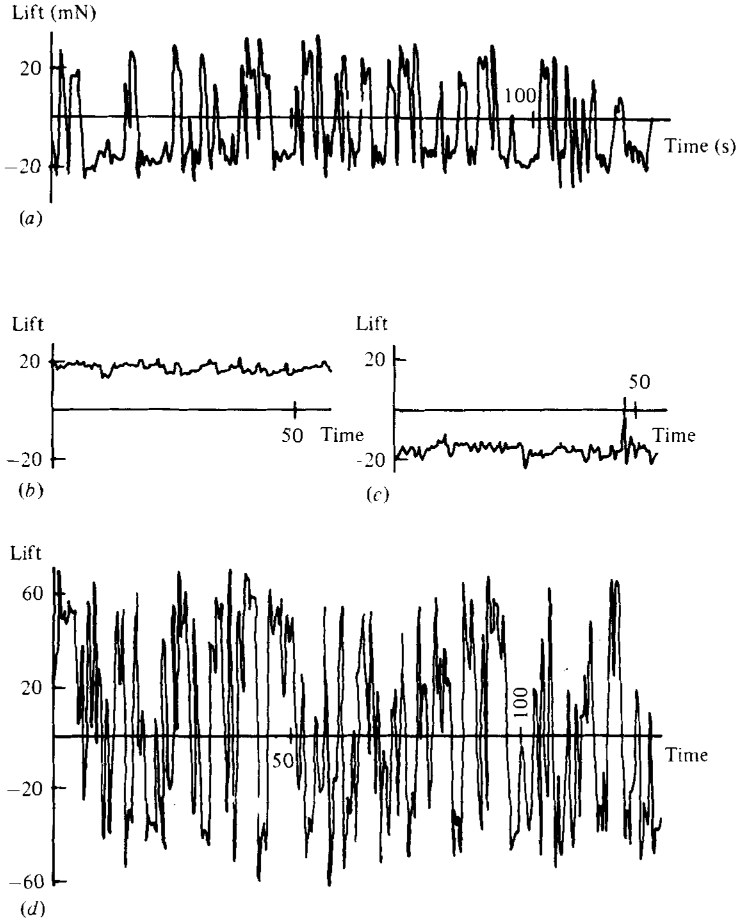

FIGURE 6. Variation with time of lift component normal to the wall, series *A* (lift away from the wall positive). (*a*) Smooth sphere, gap ratio 0·25, d = 44 mm, Re = 33000. (*b*) Roughened sphere, gap ratio 0·1, d = 32 mm, Re = 23000. (*c*) Smooth sphere in shear flow, gap ratio 5·0, d = 44 mm, Re = 39000. (*d*) Smooth sphere, gap ratio ≈ 8, d = 53 mm, Re = 47000.

occur except very close to the wall, and some observations were made of their pattern at various gap ratios and in flow with no time-averaged velocity gradient (figure 6). Throughout this series lift was taken to be a force normal to the wall (and up to the velocity gradient).

Since figure 5 is a dimensionless plot one might hope that graphs for different sphere sizes would be more similar than they are, at least in the region close to the wall where gap ratio G/d is the dominant independent variable. (For values G/d greater than 0·3, this dominance is absent and an independent variable representative of the velocity gradient would be more appropriate if that zone were of primary interest). For gap ratios of less than 0·3 differences between the graphs for smooth spheres might be associated with the Reynolds number difference associated with the difference in size, or with the fact that for different diameters a nominated gap ratio implies a different range of incident velocities, not only because the sphere samples a wider or narrower band of the velocitd profile but also because the position of its

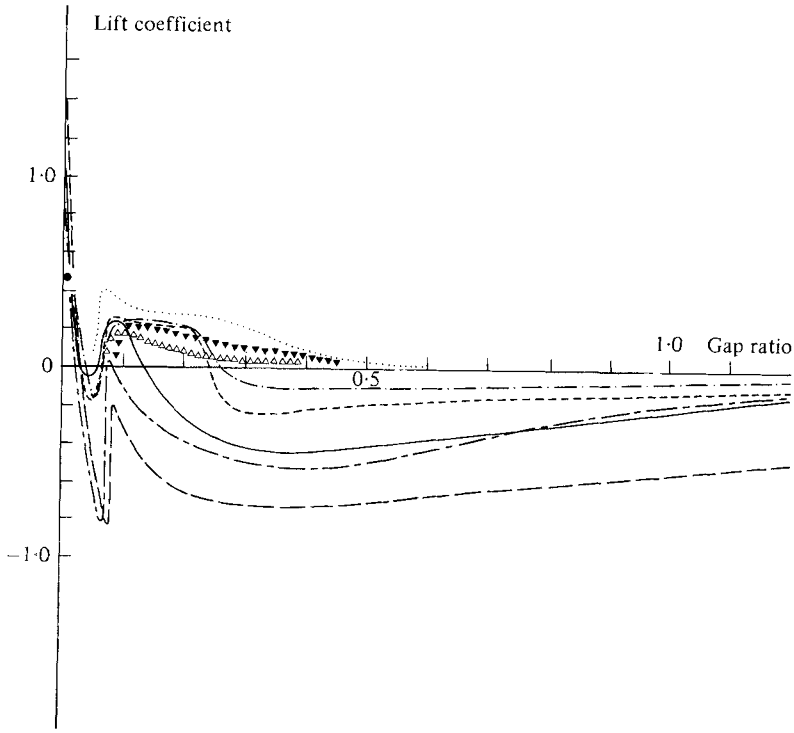

FIGURE 7. Variation of lift coefficient with gap ratio: present and earlier studies. ●, Bagnold, $Re = 2900$; ▼, Thomschke, $Re = 360000$; △, Thomschke, $Re = 440000$; — · —, series *A*, $Re = 23000$; - - - -, series *A*, $Re = 32000$; · · · · ·, series *B*, $Re = 40000$; ——, series *C*, $Re = 23000$; —— - ——, series *C*, $Re = 19000$; —— ——, series *C*, $Re = 18000$.

centre is different. In particular, large and small spheres at the same (small) gap ratio will be differently positioned relative to the elbow of the velocity profile. Such comparisons as can be made with results of Tomschke and our series *C* experiments (figure 7) suggest that the latter effect is more important than the Reynolds number difference in accounting for the disparities between the graphs for different sphere sizes.

More detail of these experiments is given elsewhere (Murray & Willetts 1978) but an insidious doubt remained that the results were distorted by the diametral shaft mounting and by flexure of the shaft under the loading created by drag on the sphere. (On the other hand there was good evidence that sphere rotation could be ignored and that lift on the shaft was negligible in the measurements.) Further experiments were therefore planned with sufficiently different apparatus that the equipment dependency of this first series could be tested.

Series B, *Re* 5000–50000. These experiments were done in a wind tunnel of cross-section 0·305 m square, using a billiard ball of diameter 42 mm which at no stage was roughened. The velocity distribution in the tunnel was more uniform than that used for series *A* experiments; figure 3 shows the velocity profile. As will be evident, no shear flow measurements were made and rotation of the sphere was prevented by the sting type of mounting. Two orthogonal components of lift were measured in this series so that a resultant could be computed in the plane normal to the flow direction.

The changes of lift coefficient with gap ratio which had been observed in the series *A* experiments were seen again. In particular, the double sign reversal was evident in the *gradient* of the lift coefficient graph in the range of gap ratio 0–0·2. More attention was paid to the variation of lift force with time in quasi-potential flow. It was thought that in this circumstance the lift force might be linked to a disturbance propagating on the separation line, and therefore exhibit modest changes in magnitude and much larger and rather regular changes of direction. Neither supposition proved well founded, as will be discussed below, but large changes with time of magnitude and direction were observed.

Series C, *Re* 3000–20000. This third series was conducted in a water tunnel of cross-section 0·457 m square, again using an unroughened billiard ball and a Reynolds number range for the duct flow of 35700 to 238000. Resultant lift forces were again measured for the two sphere circumstances, (*a*) close to a wall and (*b*) remote from the wall in the absence of a velocity gradient. The same general features were found in both circumstances as had been seen in the earlier series. Figure 7 summarizes the observed variation of lift coefficient with gap ratio in the three series of experiments, superimposed on the earlier data of figure 1.

2.2. *Visualizations*

In the first series, oil film on the spheres and smoke injected in the wake had revealed separation line rotation and wake deflection (from the flow direction) which appeared to be linked to lift force. This final series, using water as working fluid, made available much better visualizations of these flow features and clarified some of the links. Figure 8 illustrates changes seen with increasing gap ratio at sphere Reynolds number 20000. Potassium permanganate dye was injected in the wake region close to the root of the sting. In order to select features of interest the flow was first video-taped and photographs were then taken of selected stills from the video sequence.

3. Discussion

3.1. *Lift in the absence of a local boundary and of a velocity gradient*

Mean lift would be expected to be zero in this circumstance. Yet observations of the motion of spherical weather balloons by Scroggins (1967) could only be interpreted consistently with the aid of unexpected lift forces, and Taneda's (1978) observations of wake deflection imply the presence of lift. All three series of experiments reported above, measured lift forces which varied greatly with time (figure 6). Visualizations of wake flow revealed distortions of the wake at the higher end of our Reynolds-number range associated with localized delay of separation so that the separation line was worn askew for the duration of the perturbation. The duration of a typical event of this kind varied between approximately 2 seconds and 7 seconds at Reynolds number 20000; the photographs in figure 9 illustrate the sequence. In the series *A* experiments video recordings of the smoke-filled wake synchronized with lift measurements suggested strongly that lift and wake deflection were associated with one another. Taneda described wake movement in the Reynolds-number range 10^4–10^6 as an oscillation in a plane which was itself rotating intermittently about the axis of flow with respect to the sphere, a description of a reasonably regular event which was

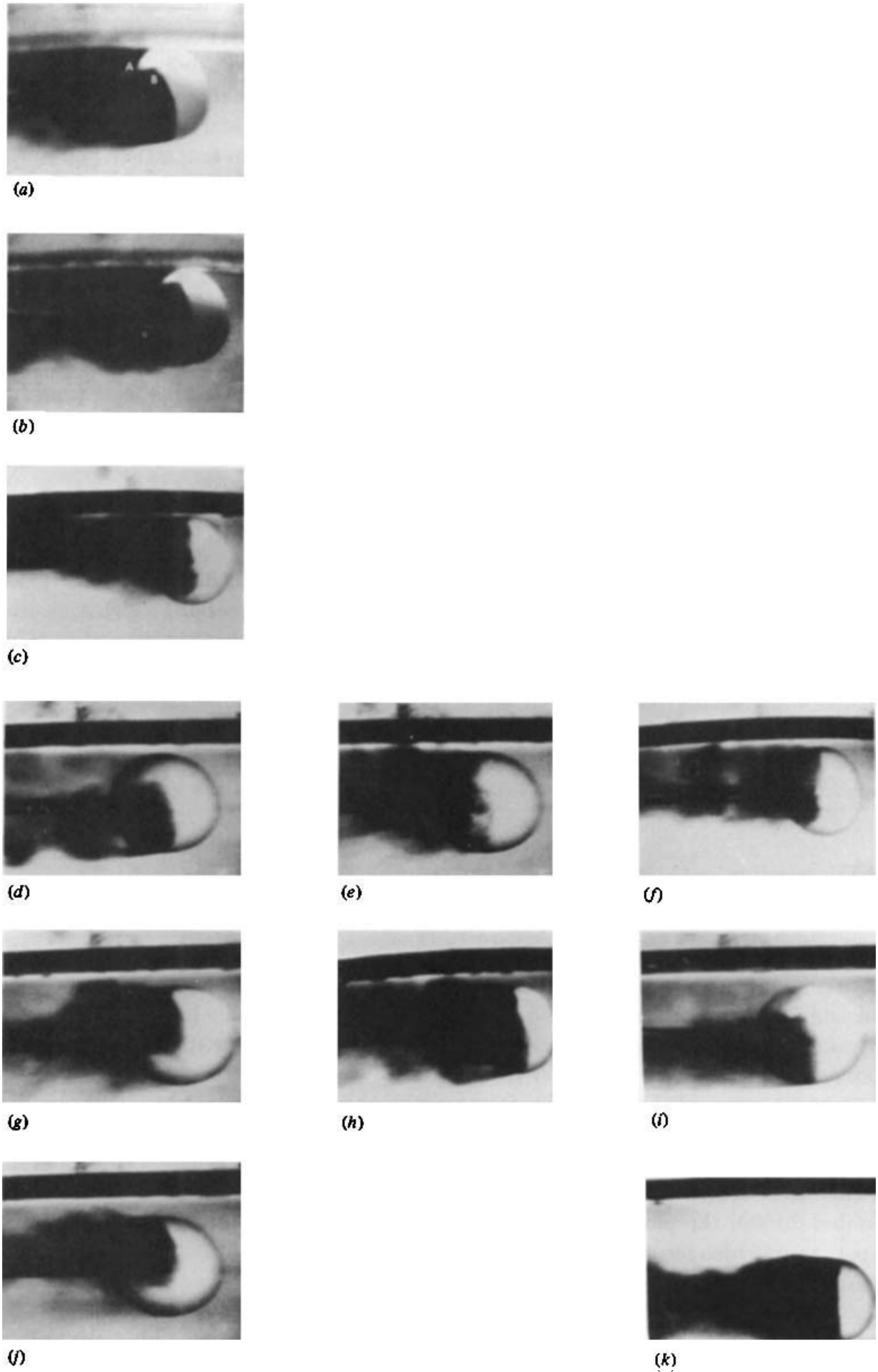

FIGURE 8. Wake and separation line visualizations at different gap ratios, series C, Re = 20000. The gap ratios are: (*a*) 0·0; (*b*) 0·05; (*c*) 0·07; (*d, e, f*) 0·12; (*g, h, i*) 0·19; (*j*) 0·24; (*k*) 0·9.

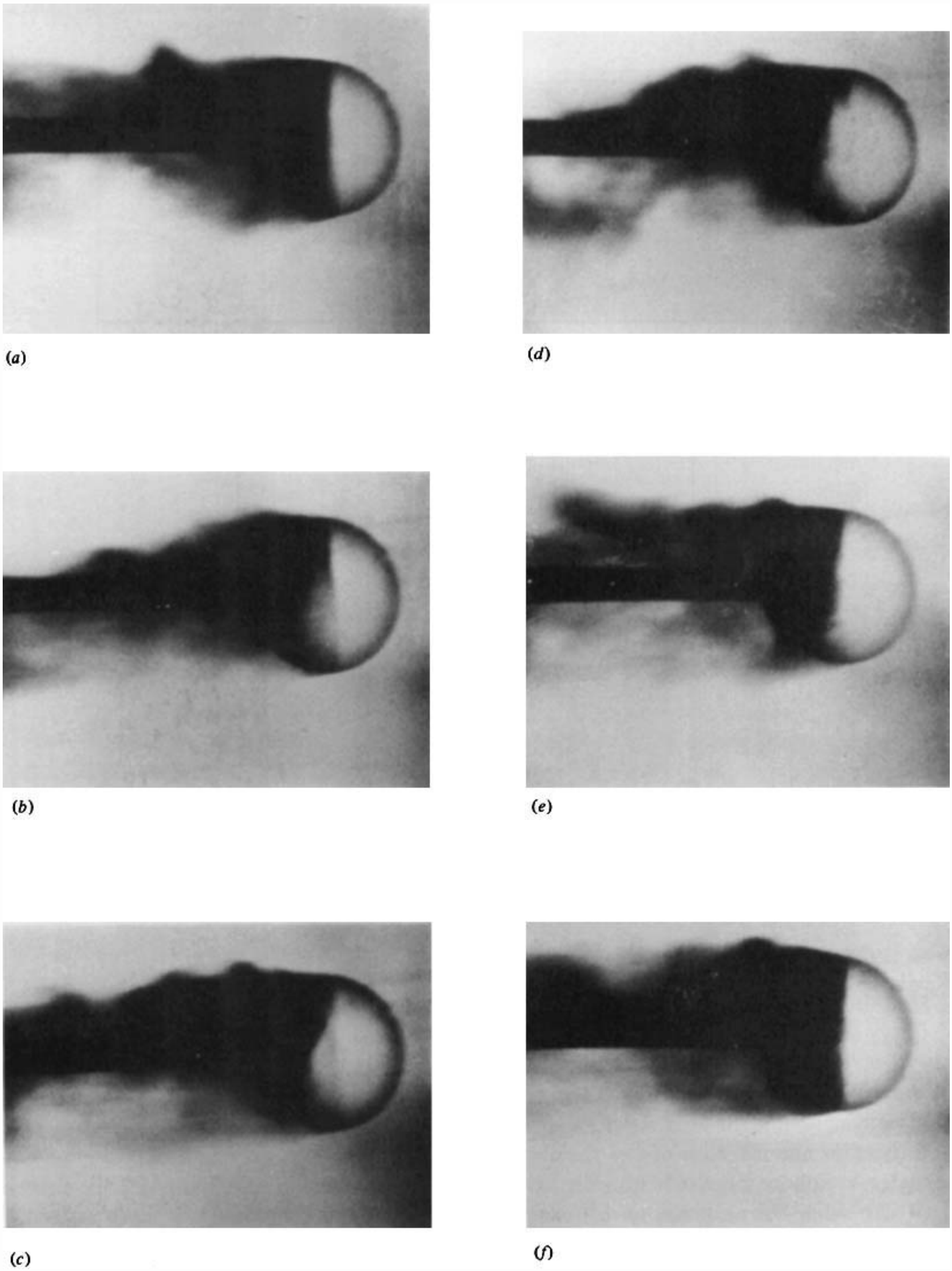

FIGURE 9. History of a localized delay in separation: sphere remote from the boundary, series C, $Re = 20000$. (a) $t = 0{\cdot}0$ s; (b) $t = 0{\cdot}3$ s; (c) $t = 0{\cdot}5$ s; (d) $t = 0{\cdot}9$ s; (e) $t = 1{\cdot}4$ s; (f) $t = 1{\cdot}9$ s.

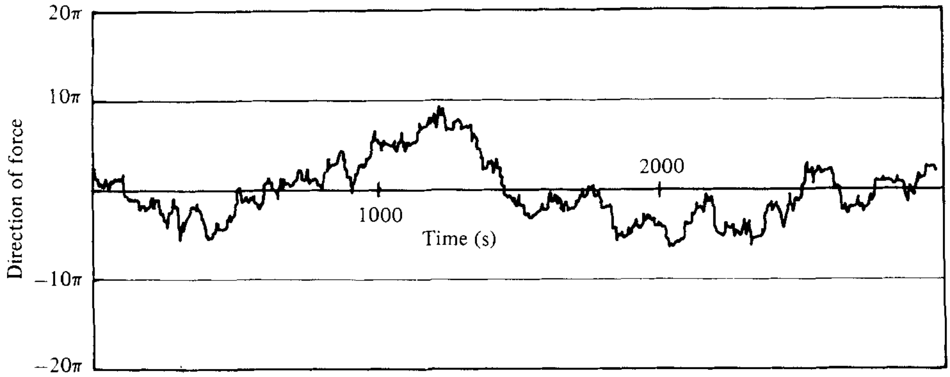

FIGURE 10. Variation with time of the angle between the lift vector and a datum direction normal to the flow.

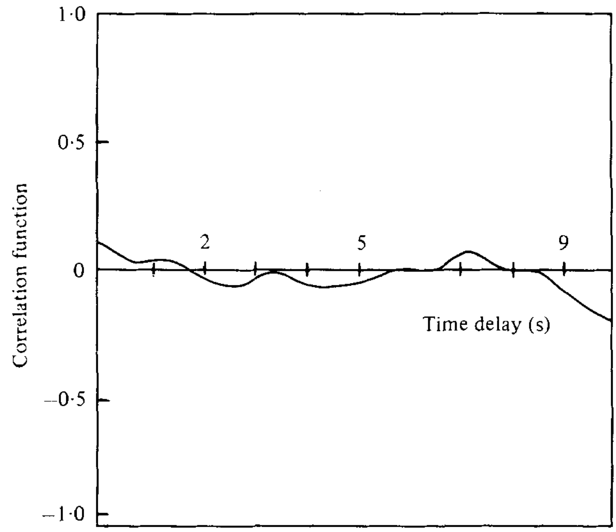

FIGURE 11. Correlation between X and Y components of lift with varying time delay, series C, Re = 20000.

supposed to depend on a disturbance propagating on the separation line. This would imply some regular features in the variation of lift with time.

Two components of lift were separately measured in the series B and C experiments, were digitized at intervals of 0·1 seconds and resolved to produce the magnitude and direction of a resultant force, also at one tenth of a second intervals. Figure 10 illustrates the rotation of the resultant vector with time in a typical experiment in water at sphere Reynolds number 20000. While the rotation remains predominantly in one sense for as much as 500 seconds at a time, the progression is very ragged, containing fleeting reversals and stagnations. The impression conveyed by a trace such as figure 10 is that the angle varies randomly: it is not hard to visualize a similar progression in a gambler's bank account. Figure 11 shows the correlation between the two orthogonal components with varying time delay between them in one particular experiment. The low peak values of correlation coefficient ($\sim$0·1–0·2) are typical of all the other analysed traces. Rather more regular fluctuations with delay are seen

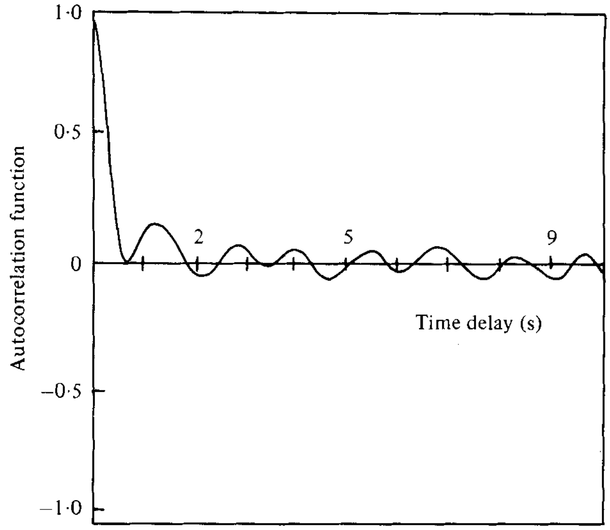

FIGURE 12. Auto-correlation of force magnitude with varying time delay, series C, $Re = 20000$.

(figure 12) in the autocorrelation of force magnitude. The natural frequency of vibration of the sphere on its support structure is 4 Hz and each force component signal was low-pass filtered at 1 Hz.

There are good reasons, both deductive and observational, for believing that lift forces are produced by disturbances of the separation line such as can be seen in figure 9. Regular propagation of the disturbances has not been detected. It seems likely that they originate in mainstream turbulence features which cause spasmodic delays of separation fairly randomly distributed round the sphere. The slightly regular features of the lift record would then be associated with the time scales of development and collapse of zones of the boundary layer which are particularly reluctant to separate, and of the convection of mainstream eddies onto the sphere. The persistence of lift components indicates that they result not from crude buffeting by the lateral velocities of large eddies, but rather from patterns induced in the boundary layer of the sphere by the impinging eddies which may be quite small.

3.2. *Lift when the sphere is close to a boundary*

As is evident in figure 7, the general features of the variations of lift coefficient with gap ratio for smooth spheres are consistent in all experiments (lift here meaning the force away from the boundary). There are some differences between the values of gap ratio at which stationary values of lift coefficient occur in different circumstances and also in those stationary values, but there are three of them in all cases. Two of them occur when the gap is less than one fifth of a diameter and the third, which is more difficult to locate, when it is considerably greater. It is possible to discuss zones of the graph with reference to observed flow structures and for this discussion the geographical reference system of figure 13 is proposed. The poles point directly upstream and downstream so that the equator is in a plane normal to the boundary and to the flow direction. The line of zero longitude is that which approaches closest to the boundary. The north pole points upstream. In all experiments the *mean* separation line position lay between 5 °N and 15 °S.

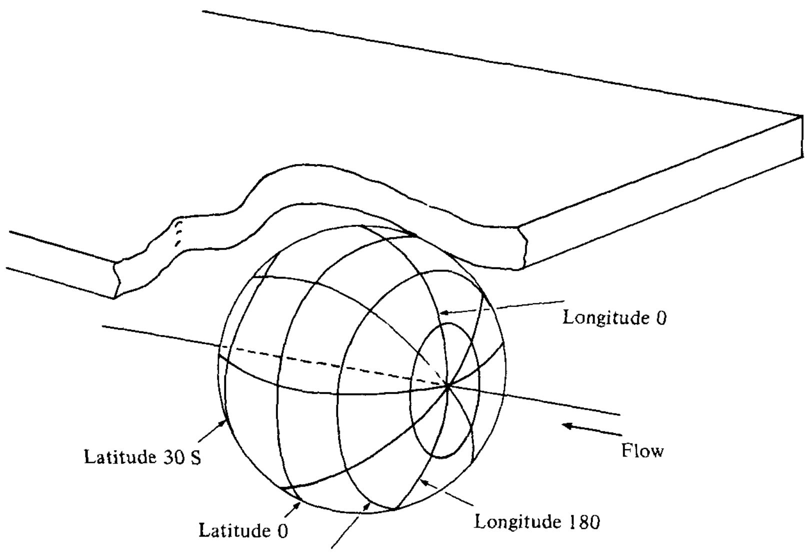

FIGURE 13. Geographical reference framework. (Closest approach to the wall is at latitude 0, longitude 0.)

3.2.1. *Gap ratio less than* 0·05. Over the whole Reynolds-number range indentations were seen in the separation line around longitude 10° and 350°, at which it was swept in a southerly direction locally on either side of a stagnant zone at longitude 0 (figure 8*a* shows one such indentation). Recirculations (from *A* to *B* in the illustration) sharpen the demarkation between the indentation and the remainder of the separation line. As the gap increases in this range, the lift diminishes sharply as the stagnation between the sphere and the wall decays. Fluctuations of lift and separation line with time are small.

3.2.2. *Gap ratio between* 0·05 *and* 0·1 (*approximately*). Fluid now passes freely between the sphere and the wall, accelerates in doing so and produces low pressure on the surface of the sphere at longitude 0. This is associated with a force component directed towards the wall. The remote side of the sphere is exposed to the faster and more turbulent mainstream. At $Re \sim 20000$ separation is spasmodically delayed around longitude 180. Again, displacement of the separation line is not smoothly progressive between longitude 0 and 180 but, due to re-circulation in the wake, has almost a step discontinuity. Figure 8*b* illustrates the effect. The wake downstream of the sphere approaches the wall obliquely. At $Re \sim 2500$, the separation line position is more stable and, as can be seen in figure 14, is delayed on the wall side of the sphere, the (southerly) latitude of separation decreasing gradually between longitudes 0 and 180°. The wake is now inclined slightly away from the wall and coherent wake structures can be seen developing.

3.2.3. *Gap ratio between* 0·1 *and* 2·0. In the gap-ratio range 0·1–0·15 for $Re \sim 20000$ a transition takes place to a pattern in which the delay of separation at longitude 0 becomes spasmodic. Thus, between 0·15 and 2·0 there are two apparently random series of 'events' (i.e. zones of late detachment), those in one series producing positive lift and in the other negative lift. The observed lift record results from the

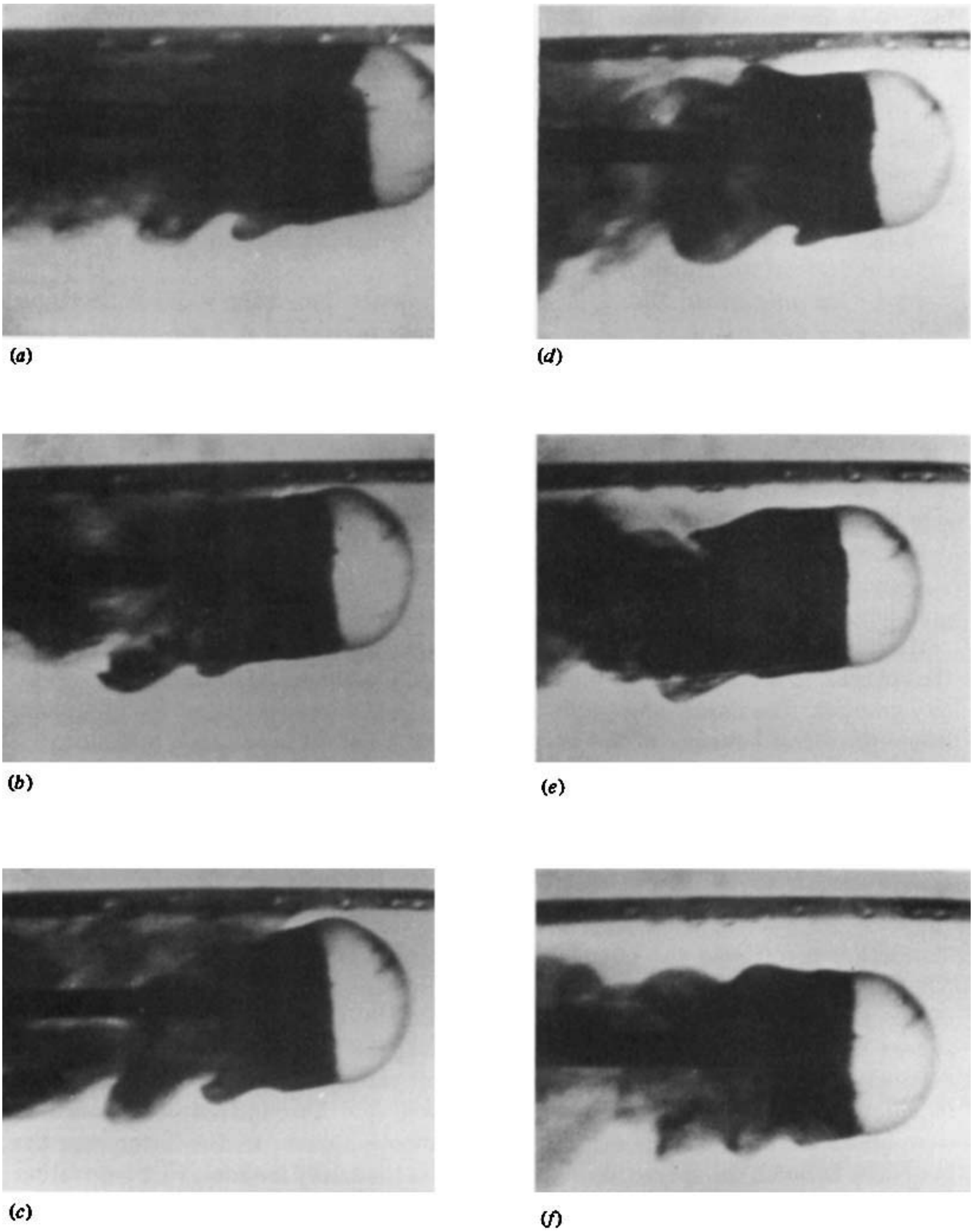

FIGURE 14. Separation line tilt at *Re* 2000, series *C*, for the following gap ratios: (*a*) 0·0; (*b*) 0·06; (*c*) 0·08; (*d*) 0·13; (*e*) 0·18; (*f*) 0·37.

combined sequence of events. However, whereas the separation delays at zero longitude are more vigorous, those in the region of longitude 150–210 are more frequent, and the time-averaged lift in this gap ratio range is negative.

At $Re \sim 2000$ in this range of gap ratios the behaviour at longitude zero dominates the lift behaviour, delayed separation near longitude 180 being much less common. There appears to be much less vigorous re-circulation in the wake than at higher Reynolds number, and the separation line is tilted and gently curved rather than indented with local bald patches. The contrast is evident in comparison of figure 8 with figure 14. The shear layer surrounding the wake can be seen breaking up into coherent vortical structures.

3.2.4. *Gap ratio greater than* 2. At gap ratios greater than 2 the wall has negligible influence on flow round the sphere and behaviour reverts to that discussed in §3.1 above.

3.3. *Lift in shear flow remote from a boundary*

It is difficult to experiment in detached shear layers because such layers quickly disintegrate into discrete vortices. However, a weak velocity gradient was produced in one experimental programme by using a screen of porosity which varied from one side of the wind tunnel to the other. Because of the weakness of the gradient, wake deflection was not confined to any one particular plane of longitude. The superficial impression therefore was of behaviour identical with that in flow without a velocity gradient.

However, wake displacement was more frequently towards the low-velocity side of the sphere and accordingly the lift record showed a preference for lift down the velocity gradient. The mean value of lift in figure 5 therefore is negative when the sphere leaves the direct influence of the wall. This direction of lift is contrary to that which would be expected from an argument based on circulation such as has been proposed by Bagnold (1974) among others. The tendency for lift to be directed down the velocity gradient is bound to be more pronounced as the gradient becomes steeper within the Reynolds number range of these experiments.

3.4. *The effect of surface roughness*

To further investigate the boundary layer at separation, a trip in the form of a 500 μm wire was glued to the (42 mm) sphere surface at latitude 35 °N. The design of the trip was based on that used by Maxworthy (1969) to induce a turbulent sphere boundary layer. As can be seen from figure 15, separation was generally delayed to a position approximately 10° south of the equator, but similar persistent indentations of the separation line near the wall and intermittent ones elsewhere were observed, as had been evident on the smooth sphere. In the latter case the boundary layer on the sphere was apparently less than fully laminar, with separation occurring at latitudes slightly south of the equator. Although one cannot be sure that the trip wire produced a fully turbulent boundary layer, the delayed separation induced, together with the presence in *both* circumstances of similar separation line behaviour, and consequent lift pattern strongly suggest that the origin of these events lies outside the boundary layer.

Those of the series *A* experiments which were done with roughened balls gave results very similar to those involving smooth balls when the gap ratio was less than 0·2. Beyond that distance from the wall, however, lift measurements were more

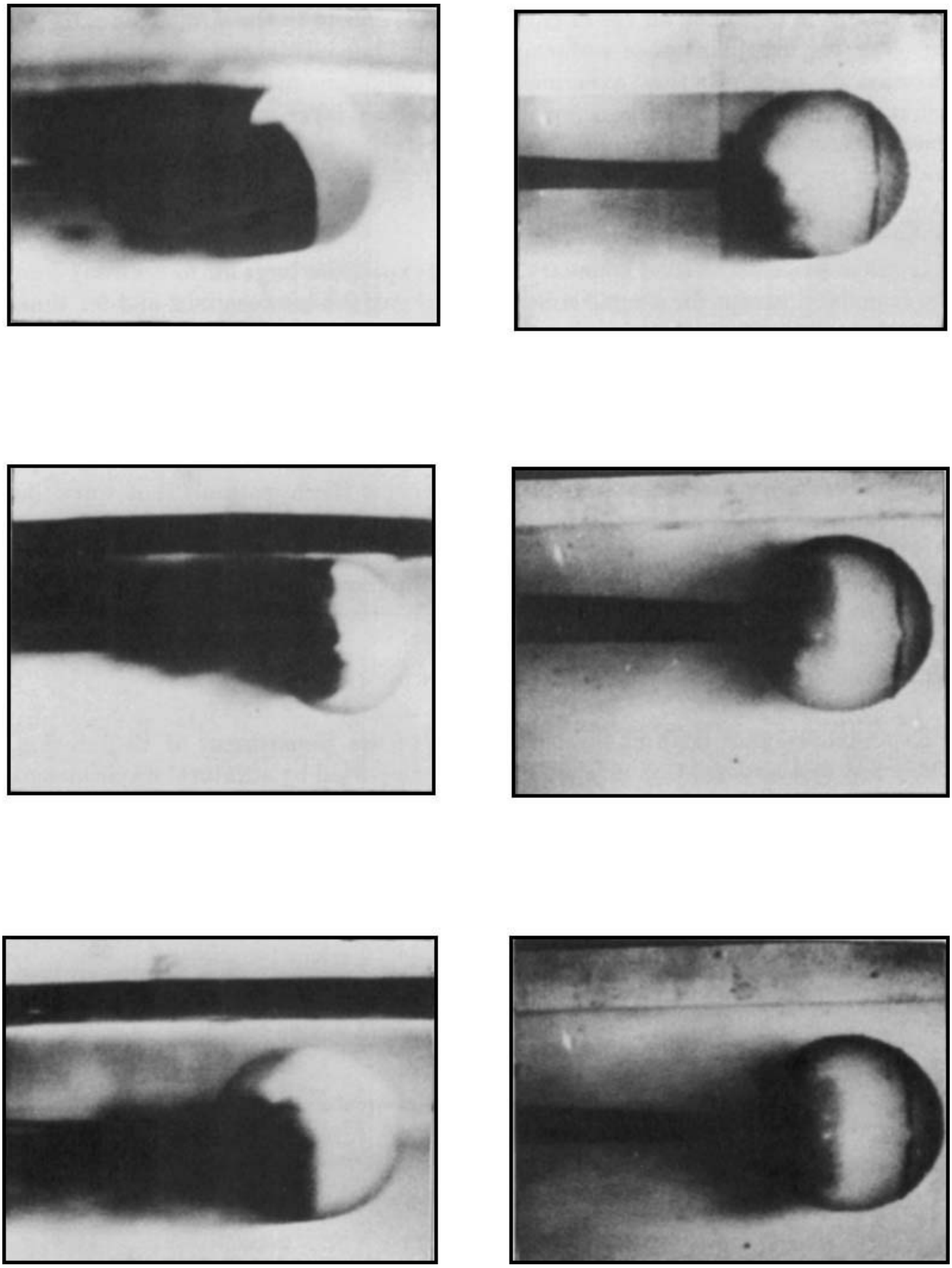

FIGURE 15. Separation delay in presence of a trip wire: series C, Re = 20000. Gap ratios: top, 0; centre, 0·07; bottom, 0·19.

erratic for rough than for smooth spheres. The reading obtained at a given gap and flow condition depended on the orientation of the sphere to the flow, quite insignificant-seeming irregularities of surface texture making substantial differences to the recorded lift. In none of these experiments were conditions such that sphere roughness might be expected to produce a turbulent boundary layer (e.g. by criteria such as those of Szechenyi (1974) concerning cylinders).

4. Conclusions

(1) Close to a smooth solid boundary, spheres experience large lift forces away from the boundary, except for a small zone when the gap lies between 0·02 and 0·1 times the sphere diameter.

(2) For larger gaps the lift record is strongly time-dependent, the fluctuations being associated with the effect of free-stream turbulence on the boundary layer of the sphere.

(3) Regular features of the time-dependent lift record were feeble but not completely absent; no support was found, however, for the hypothesis that wave-like disturbances propagate along the separation line.

(4) A sphere in a velocity gradient remote from a boundary experiences lift which instantaneously may have a resultant in any direction but when time-averaged is down the gradient of relative velocity. This is contrary to a prediction based on a circulation argument.

(5) These effects are not associated with sphere rotation.

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