ter of scale. The swirling action of the smallest eddies is probably similar to that of the largest, although their origin is not the same.

This cycle of wave formation, vortex growth and entrainment, vortex decay and turbulent diffusion continues until the velocity defect and mean strain field are removed. At this point viscous forces have become important and the turbulence energy is dissipated as heat.

References

[1] Townsend, A. A., "The Mechanism of Entrainment in Free Turbulent Flows," *Journal of Fluid Mechanics*, Vol. 26, Pt. 4, Dec. 1966, pp. 689–715.

[2] Mobbs, F. R., "Spreading and Contraction at the Boundaries of Free Turbulent Flows," *Journal of Fluid Mechanics*, Vol. 33, Pt. 2, Aug. 1968, pp. 227–239.

[3] Keffer, J. F., "The Uniform Distortion of a Turbulent Wake," *Journal of Fluid Mechanics*, Vol. 22, Pt. 1, May 1965, pp. 135–160.

[4] Oswald, L. J. and Kibens, V., "Measurements in the Wake of a Disk," Ph.D. thesis, University of Michigan, to be published.

[5] Miles, M. W., "On the Generation of Surface Waves by Shear Flows, Part 5," *Journal of Fluid Mechanics*, Vol. 30, Pt. 1, Oct. 1967, pp. 163–175.

Flowfield Produced by Trailing Vortices in the Vicinity of the Ground

J. K. Harvey* and F. J. Perry†
Imperial College, London, England

WITH the current interest in the behavior of aircraft trailing vortices it is unnecessary to emphasize the importance of studying how these are influenced by the ground during the takeoff and landing phases. The motion of the cores has been experimentally shown, for example by Dee and Nicholas,[1] to agree moderately well with the paths predicted by the simple two-dimensional theory for a pair of concentrated vortices above an infinite plane. They follow curves in the cross flow plane, of the form

$$1/y^2 + 1/z^2 = \text{const}$$

and, as Fig. 1 shows, the transition from the vertical descent to a horizontal motion is fairly abrupt. The observed flight data of Dee and Nicholas[1] show tolerable agreement with this predicted path except for a feature which was not strongly emphasized in their report. Examination of the tabulated data shows that in many tests the vortices departed from the

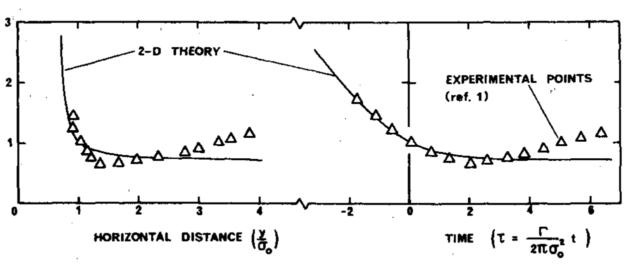

Fig. 1 Theoretical and experimental vortex paths.

Received March 16, 1971; revision received May 3, 1971.
Index Categories: Airplane and Component Aerodynamics; Aircraft and Component Wind Tunnel Testing; Jets, Wakes and Viscid-Inviscid Flow Interactions.

* Lecturer. Member AIAA.

† Advanced Course Student, Athlone Fellow.

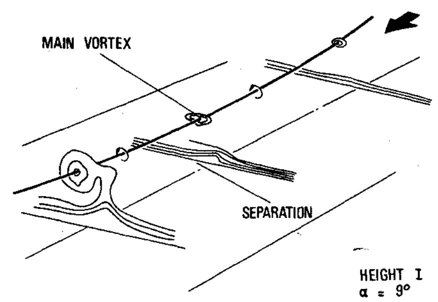

Fig. 2 Total head contours in planes across the flow downstream of the wing.

theoretical path by rising again after having descended close to the ground (Fig. 1).

To attempt to explain this phenomenon, an experiment was conducted at Imperial College to qualitatively determine the cause. A half span rectangular wing of 8 in. chord and 20 in. semispan was mounted on the wall of a 5 × 4 ft low-speed wind tunnel so that the single trailing vortex passed over a moving floor to correctly simulate the ground boundary condition. The test speed was 87 fps.

Since the primary objective was to establish the features of the flowfield that cause the vortex to rise, the investigation was centered around a series of total-head surveys in planes across the flow performed with a $\frac{1}{16}$ in. o.d. Kiel tube[2] (i.e., a yaw-insensitive total-head probe). A few additional surveys were made with a 5-tube yaw-meter to measure the strength of the trailing vortex.

Two typical total head surveys are presented as contour maps in Figs. 2 and 3. They depict what would have been the nearer of a pair of trailing vortices, and they reveal important details of the flowfield which account for the departure of vortices from the theoretical prediction. The surveys can be interpreted by recalling that the total head remains constant throughout a steady flowfield except where viscosity is active. In regions of shear (e.g., boundary layers, vortex sheets and cores) the total head falls below the freestream value. Thus at the most upstream station in Fig. 2, we can readily identify the vortex core and a small remnant of the tunnel boundary left above the moving floor because of insufficient bleed. The vortex induces a cross flow on the floor with an attendant suction peak beneath the core. Consequently, the boundary layer resulting from this cross flow has to negotiate an adverse pressure gradient once it has passed under the vortex. When the vortex is sufficiently near the ground, the pressure gradient is strong enough for separation to occur, and a bubble forms containing vorticity of opposite sense to main vortex (Fig. 4a). Progressing downstream, we find this bubble growing rapidly to the point where it detaches from the floor as a secondary vortex fed by a vortex sheet from the separation point (Fig. 4b). The development of this flow can be traced from the measured total-head surveys shown in Figs. 2 and 3.

The subsequent motion of two vortices is a complicated problem in vortex dynamics, but while the secondary core remains outboard of the main core, it will induce an upward

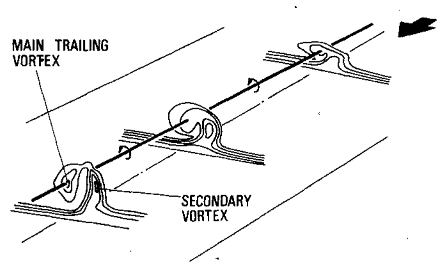

Fig. 3 Surveys of total head taken with the wing at a lower height.

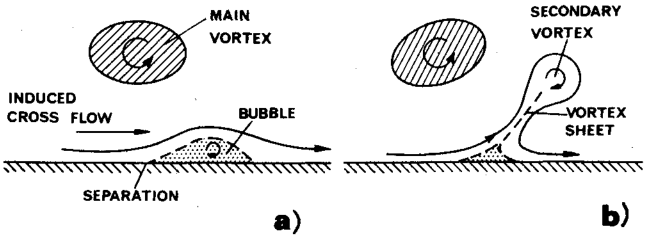

Fig. 4 Suggested interpretation of the total-head surveys: a) a section downstream of the initial separation, b) the subsequent development of the secondary vortex.

velocity, thus causing it to rise as seen in the flight tests. The paths of the main core are shown in Fig. 5 for the two examples depicted in Figs. 2 and 3 together with two different incidence cases. Values measured for circulation Reynolds number (Γ/ν) and the points where the floor separation was first detected are indicated. It is clear that the displacement effect of the bubble, and the influence of the reversed-sense vorticity within it, immediately effect the main core by checking its downward motion. The subsequent development of the secondary vortex causes the main core to rise. It also tends to arrest the trailing vortex's horizontal motion and in some configurations actually reverses its direction. The flight tests of Dee and Nicholas[1] show evidence to confirm this retardation but the dominating influence of cross winds coupled with experimental scatter preclude any positive confirmation. The reversal of the motion could be possibly attributed to tunnel wall interference but this is unlikely.

It is interesting to note the similarity between these observations and the flow over slender delta wings with leading edge separation[3,4] where the vortex sheet shed by each leading edge rolls up to form a concentrated core above the upper surface, inducing a secondary separation as in this experiment. There are, however, two significant differences between the two flows.

First, the secondary vortex formed above the ground is not confined by a vortex sheet feeding the main core. So it is free to rise and, under the influence of the stronger main vortex, would eventually spiral around it. In these experiments there was no indication of spiralling, and this may indicate that the secondary vortex quickly grows to a strength comparable with the main core. The rapid rate at which the main core rises (Fig. 5) would tend to confirm this, but the vortex sheet from the ground feeding the secondary vortex may be a contributory factor in preventing the spiralling.

Second, the surface boundary conditions are quite different in the two cases; one moving, the other fixed. Yet both flows exhibit the same qualitative features of secondary separation. This poses the question of whether the moving floor is essential for correct wind-tunnel simulation of trailing-vortex-ground interactions. Total-head surveys with the floor stationary clearly showed that, although the over all character of the flow remained unaltered, there were significant quantitative discrepancies. This presents a serious problem, as extending the limited scope of these tests, especially to higher Reynolds number, would demand an extremely large moving floor. A series of careful full-scale flight tests made under still conditions and aimed at specifically investigating this phenomenon would be invaluable in verifying the relevance of these observations to actual aircraft wakes.

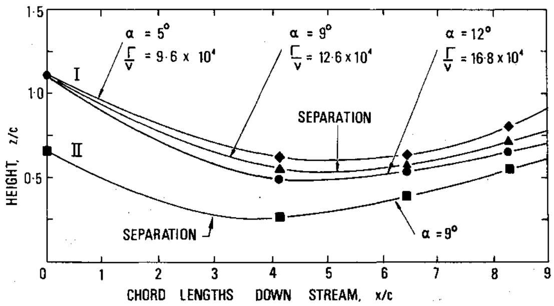

Fig. 5 Paths followed by the main vortex cores.

References

[1] Dee, F. S. and Nicholas, O. P., "Flight Measurement of Wing Tip Vortex Motion near the Ground," CP 1065, Jan. 1968, British Aeronautical Research Council, London, England.

[2] Kiel, G., "A Total Head Meter with a Small Sensitivity to Yaw," TM 775, 1935, NACA.

[3] Ornberg, T., "A Note on the Flow around Delta Wings," KTH-Aero TN 38, Feb. 1964, Royal Inst. of Technology, Stockholm, Sweden.

[4] Harvey, J. K., "Some Measurements on a Yawed Slender Delta Wing with Leading-Edge Separation," R&M 3160, Oct. 1958, British Aeronautical Research Council, London, England.

Characteristics of a Magnetic Annular Arc Operating Continuously at Atmospheric Pressure

John E. Harry*
BOC-Murex Welding Research and Development Laboratories, London, England

In a recent paper[1] Garrison and Smith reported results from an arc operating continuously at atmospheric pressure, in which an apparently diffuse discharge filling the annular region between the electrodes was obtained.

Cathodes of copper and thoriated tungsten were used with a hemispherical tip 25 mm diam with a copper anode 34 mm i.d. An axial magnetic field of up to 2.5 Tesla and d.c. arc currents of from 700 amp to 2000 amp were used in nitrogen at atmospheric pressure.

The arc was photographed with a framing camera at 10,000 frames/sec with a shutter speed of 2 μsec. Examples of a spoke (constricted) discharge were shown at a magnetic flux density of 0.27 Tesla and an arc current of 760 amp, a transi-

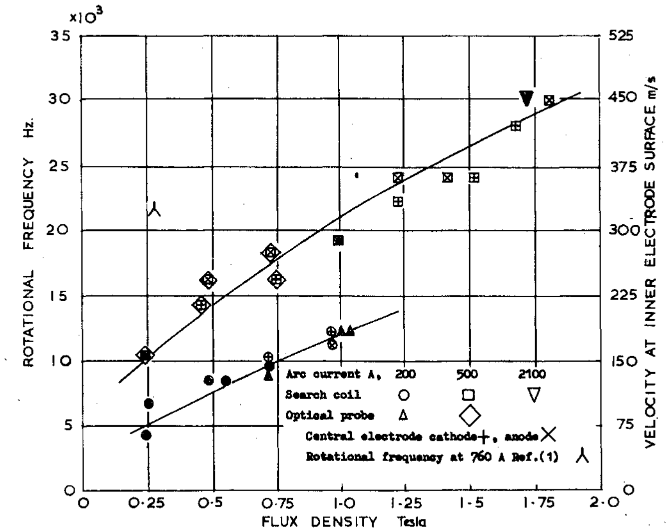

Fig. 1 Variation of arc velocity and rotational frequency with the magnetic flux density at various values of arc current.

Received February 8, 1971; revision received April 26, 1971.

* Senior Development Engineer.