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The Application of a Surface Flow-Visualisation Technique in Flight

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The Application of a Surface Flow-Visualisation Technique in Flight

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Summary

The development of an adaptation to flight of the 'oil-flow' technique of visualising the surface flow is described as applied to a slender-wing research aircraft. The technique yielded repeatable results which, when compared with data from other sources, indicated that the visualisations achieved were valid.

* Replaces R.A.E. Technical Report 74022—A.R.C. 35 554

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1. Introduction

In the main the techniques available to the flight research worker to visualise the subsonic flow around an aircraft are similar in principle to those available in the wind tunnel, though the detailed application and interpretation of these techniques is often more demanding in the flight situation. So far as the writer is aware, however, there had been no attempt prior to the experiments which are the subject of the present report, to employ in flight a method of surface flow visualisation analogous to the 'oil-flow' techniques used in the wind tunnel. Some exploratory experiments on an adaptation of the 'oil-flow' technique to a slender-wing research aircraft are described, the results obtained are discussed and a comparison made with wind-tunnel measurements.

2. The 'Oil-Flow' Technique

2.1. In the Wind Tunnel

For readers who may not be familiar with this visualisation technique as applied in wind-tunnel tests, a brief description follows.

A suspension of particles of an opaque or fluorescent material in a liquid medium (usually a light oil) is spread thinly and uniformly (frequently by a household paint roller) over a model mounted in the tunnel at the desired attitude: the wind is then turned on and flow conditions are stabilised. The shear at the air/liquid interface causes the liquid to flow in conformity with the local airflow, and the particulate material is deposited on the model surface as the liquid dries (or is blown off the model) so forming lines substantially parallel to the local flow direction at the surface*. In the course of a few minutes running the patterns formed in this way become sufficiently 'set' to be photographed. The model can then be prepared for a further run.

2.2. In Flight—Preliminary Considerations

The flow around a slender wing generates striking, repeatable and well-defined patterns on the suction surface and the availability of a research aircraft having this planform (the Handley-Page HP 115) made it the obvious vehicle on which to attempt the development of an in-flight analogue of the wind-tunnel 'oil-flow' technique, provided this did not interfere seriously with the other flight investigations in progress. In addition a successful development would provide information on the flow situation around a full-scale wing, for comparison with wind-tunnel measurements. The aircraft has been described in detail in Ref. 1 and a general arrangement drawing of it is shown in Fig. 1.

The prospect of developing a practicable technique that involved pre-flight treatment of the aircraft's surfaces seemed most unpromising and this line of approach was dismissed from consideration.

The in-flight application of fluid to the test aircraft by external means was considered, though the severe operational and flight-safety problems this raised, coupled with the non-availability of a suitable 'tanker', soon led us to abandon the idea.

In these circumstances it was obvious that the preferred method was to carry the means of flow visualisation within the test aircraft itself and the particular solution adopted is described in the next section.

2.3. The Experimental Installation

The test aircraft was fitted with a tank (to contain the marker fluid) connected by pipes to a number of orifices in the upper surface of the wing. The tank could be pressurised before flight and a pair of solenoid-operated valves enabled the pilot to direct fluid to the array of orifices in either half-wing, or to both simultaneously. The distribution of orifices usually will be a compromise between the need to obtain an adequately detailed picture of the flow on the one hand, and complexity of the installation and the accessibility of the area under study on the other: in this exploratory investigation we aimed at the minimum installation that seemed likely to yield some useful information and fitted only five orifices in each half-wing, two at $x/C_0 = 0{\cdot}30$ and three at $x/C_0 = 0{\cdot}48$, as illustrated in Fig. 1.

The choice of suitable marker fluids is, of course, very wide and is likely, in the event, to be conditioned by considerations such as availability, convenience, etc. Our first attempt employed finely-divided carbon suspended in a kerosene-based fluid; this proved quite satisfactory, if rather slow-setting, but its use caused such a stir among the aircraft cleaners that it was abandoned. Moving to the opposite extreme, we next

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* Gravitational action usually introduces only minor deviations, even on steeply-sloping surfaces.

experimented with a suspension of kaolin (obtained from the Medical Department) in water; this yielded excellent results, producing clear, visible patterns after about one minute's stabilised flight and although these did not photograph well, the addition of a small amount of red dye (SO 43–66) to the mixture cured this defect. With this modification the mixture was used for the remainder of the tests.

First approximations to the tank pressure needed to establish flow of the marker fluid from all orifices were determined by ground tests. The pipe between the tank and the forward orifices was shorter than that to the rear orifices and in consequence the losses along it were lower; moreover, the height of the forward orifices above the tank was slightly smaller. For these reasons, a pressure just sufficient to cause fluid to well from the rear orifices produced a small jet (about 5 cm high) from the front orifices, when the aircraft was in the normal ground attitude. The height difference between the tank and the rear orifices decreased quite markedly with increasing incidence (e.g. by about 50 cm at 20 degrees) whereas the height difference at the front orifices was only about one-third as sensitive; consequently the relative flow to the two sets of orifices varied somewhat with incidence, as did the minimum pressure required to establish flow from all orifices.

Visual observation in flight showed that the minimum tank pressures established by these simple ground tests resulted in satisfactory flows in appropriate conditions. An example of the developing surface flow pattern is illustrated in Fig. 2.

To avoid accumulation of sediment in the pipes it was found necessary to flush the system through with water after each flight.

3. Test Technique

In principle the test technique was extremely simple: the pilot had first to establish some prescribed steady flight condition, then to activate one or both of the solenoid-operated valves for a time sufficient to establish the complete pattern over the wing, and finally to maintain the flight condition until the visible surface pattern had become sufficiently 'set'. The times needed for the two latter phases were established, approximately, by observation from a chase aircraft during the preliminary tests. Sample frames showing the development of the surface flow pattern, as filmed from the chase aircraft, are illustrated in Fig. 2: typically, this phase was complete in around 30 seconds and the 'setting' occupied about a further 30 seconds.

The majority of the tests were made in steady, rectilinear flight at zero sideslip and in these cases it was usual to 'expose' each half-wing separately and to change flight condition between the 'exposures', thus effectively halving the number of flights needed to cover a given set of conditions. In the main this approach was successful though a few instances of 'double-exposure' occurred. A few tests were made during steady, straight sideslips and in these cases both wings were 'exposed' simultaneously.

The majority of the tests were made with the engine thrust adjusted to give level flight or set at the maximum available, where this was less. However, a few checks were made with the engine idling to determine if the change in intake conditions had a significant effect on the flow over the wing.

All the surface flow tests were made during the last few minutes of flights having other primary objectives. They took place during summer at heights of around 1500 m (so that freezing was not a problem) and were confined to calm meteorological conditions—the last point was particularly significant at the higher incidences, where the Dutch-roll mode became divergent.[1] Relevant flight parameters (weight; airspeed; incidence, sideslip and control angles) were recorded for each run. Incidence ranged from about 5 to nearly 25 degrees, corresponding to airspeeds between 180 and 60 kn (approximately), respectively.

After the aircraft had landed the upper surface of the wing was photographed, usually from a point roughly 8 m vertically above the aircraft's cockpit. The optical axis of the camera lay approximately within the aircraft's plane of symmetry.

4. Results

Typical examples of the photographs which formed the raw data of this experiment are shown in Fig. 3: Figs. 3a and 3b relate to symmetric flight, each half-wing being 'exposed' at a different incidence, while Fig. 3c shows the results obtained in a sustained, steady sideslip with both half-wings exposed simultaneously. Failures of one or two orifices to produce a satisfactory trace occurred in about one-third of the tests and an example can be seen in Fig. 3a: usually, though not invariably, the failure(s) occurred in the rear row at the most inboard station.

Imperfections in the wing surface such as rivet heads, skin joints, etc., often resulted in a useful multiplication in the number of surface flow lines generated by a given orifice. On the other hand, the unevenness of the fabric-covered junction between the main wing structure and the wooden leading-edge resulted, occasionally, in some loss of detail or definition.

There was generally a tendency for the features of the surface-flow patterns to show less regularity than their wind-tunnel counterparts, for example features that were essentially rectilinear in the tunnel would often show some waviness in flight: it was thought that this might have arisen from the surface imperfections present in the aircraft, or from slight unsteadiness in flight conditions. By and large, however, the following major features of the surface flow were clearly discernible over a substantial area of the wing:

(a) The points of inflexion of the curved, 'herring-bone' pattern under the leading-edge vortex. (A good example of this can be seen in Fig. 3a, on the starboard wing.) The locus of these points is commonly associated with the line of peak suction.[2]

(b) The inboard limit of the band formed near the leading edge. This limit appeared to correspond to the separation of the surface flow under the leading-edge vortex as this flow moved outboard towards the leading edge (this is often referred to as the 'secondary separation' to distinguish it from the primary separation very close to the leading edge and the term is used in this sense in the present report).

(c) The outboard limit of the above band: this could be interpreted as showing the position of a tertiary separation. Tertiary separation is difficult to define (except in the trivial sense of 'that separation first encountered on moving outboard from the secondary separation') but, where it occurs, it is probably associated with flow features of the kind shown in the inset sketch in Fig. 5.

In a few instances it was possible to discern the reattachment line, defined as the junction between the essentially chordwise flow over the inner wing and the 'diagonal', sub-vortex flow immediately outboard of it. An example of this can be seen on the forward part of the starboard wing in Fig. 3a.

The spanwise positions of these features were measured at several chordwise stations for the symmetric flight cases; a process that was greatly facilitated by the presence on the wing of an accurately-known grid, formed by the lines of rivet-heads. However, the nature of the features associated with 'peak suction' and 'reattachment' made for slightly imprecise identification and the resulting measurements are probably less accurate than those of 'secondary' and 'tertiary' separations.

When expressed as fractions of the local span and plotted against the chordwise position of the measuring station the features described above conform to the classical slender-wing pattern. The main features of the surface flow are largely independent of chordwise position (i.e. the flow is almost conical). This is shown in Fig. 4. Furthermore the scatter about the mean curves, at least for the 'secondary' and 'tertiary' separations, is quite small and some of this seems to be associated with the 'waviness' referred to earlier. It was possible in a few instances to compare measurements made on separate flights under near-identical conditions and two typical examples are shown in Figs. 4a and 4b: it will be seen that the differences observed were small (usually less than 1 per cent of the local semi-span) nor were there any systematic differences between the two wings in nominally symmetric flight.

The spanwise movement of these four main surface-flow features with incidence is illustrated in Fig. 5 for chordwise stations around $x/C_0 = 0{\cdot}55$. Some of the 'reattachment' data relates to positions somewhat ahead of this station and was included here in view of the near-conical nature of the flow, as shown by other features; even with these inclusions the 'reattachment' data remain rather sparse.

5. Discussion

5.1. Comparison with other Flight Data

In-flight measurements of the upper-surface pressure distribution were available for a single spanwise line situated at $0{\cdot}58\ C_0$ (the most forward position at which access to the inside of the wing was relatively easy).

The spacing of the pressure holes was too open to define the pressure distribution uniquely over the outer part of the wing (though it was comparable with that employed in most wind-tunnel tests), and the possible consequences of this are illustrated in Fig. 6, which shows three interpretations (one 'preferred' and two fairly extreme) of a single sample of data. However, there is evidence from other sources (e.g. Refs. 2, 3 and 4) to indicate that the spanwise variation of pressure immediately around the suction peak on slender deltas is smooth, regular and approximately symmetrical about the y-ordinate through the peak; if similar characteristics can be assumed in the present case, as in the 'preferred' interpretation of Fig. 6, for example, then the probable uncertainty in determining the position of the suction peak from the in-flight measurements of pressure distribution should not exceed about 3 per cent of the local semi-span. Outboard of the secondary separation the flow may contain one or more relatively minor features, giving rise to correspondingly small excursions in pressure: such fine details of the pressure distribution could not be captured by the relatively coarse array of pressure holes used in the present tests and hence we have been quite unable to fix the positions of the minor flow features from these measurements, while similar, though less severe, uncertainties have attached to the position of the secondary separation in many cases (for example *see* Fig. 6).

For the reasons outlined above, the suction peak appeared to be the only feature of the pressure distribution that was sufficiently well-defined to form the basis of a quantitative comparison with the measurements of surface-flow. The variation, with incidence, in the position of the suction peak as determined from the pressure distributions is shown in Fig. 7, where it can be seen that the maximum scatter (about $\pm 1\frac{1}{2}$ per cent semi-span) is consistent with the earlier estimate of the uncertainty of measurement. Fig. 7 also includes the locus of the points of inflexion derived from flow-visualisation measurements and it is clear that this corresponded closely with the locus of the suction peaks. Since the near-coincidence of the suction peak with an inflexion of the surface flow lines has been demonstrated frequently on slender wings this agreement suggests that the flight technique produces a valid visualisation.

5.2. Comparison with Wind-Tunnel Data

Some surface-flow studies had been made, using standard techniques, during detailed wind-tunnel tests[5] of a $\frac{1}{8}$ scale model of the aircraft. These studies covered the incidence range from 0 to 20 degrees in 5 degree steps and were all made with the elevon angle set at zero. In some instances comparison photographs were available with the elevon hinge-gaps both in the basic un-sealed condition and sealed with tape and it was evident from these that there was considerable flow through the gaps, particularly around the hinge brackets, even with the elevons undeflected (e.g. *see* Fig. 8b): however, the main visible influence of this on the surface flow was confined to the elevon itself and that part of the wing immediately ahead of it.

Qualitatively the surface flow seen in the tunnel was, as expected, similar to that seen in flight though, of course, a much more detailed picture was obtainable in the tunnel and the 'waviness' observed in some features in flight was absent. A quantitative check was based on measurements of the secondary separation line since this feature seemed the most clearly defined in both tunnel and flight. Measurements were made at several chordwise stations and the results for two of these, $0{\cdot}58\ C_0$ and $0{\cdot}35\ C_0$, are plotted against incidence in Figs. 9a and 9b respectively. At $0{\cdot}58\ C_0$ there was good agreement between tunnel and flight data at incidences above about 9 degrees; at lower incidences the two sources diverged and at the lowest incidence reached in flight (about 5 degrees) the discrepancy amounted to 3 to 4 per cent of the local semi-span, the secondary separation being further outboard in flight. A broadly similar trend was shown by the measurements made at $0{\cdot}76\ C_0$. The data available at $0{\cdot}35\ C_0$ (Fig. 9b) did not extend below about 7·5 degrees incidence and, therefore, were not sufficient to establish the existence of a similar divergence at this station, though the data suggest the possibility. Over the incidence range covered, the agreement between tunnel and flight for this station was generally good.

It is unfortunate that the elevon settings used in the wind tunnel were not those appropriate to trimmed flight since this led to results that were not strictly comparable. The fact that the positions of the secondary separations appear similar, at least at the higher incidences, shows that the influence of the elevons on this feature was not significant even at stations as far downstream as $0{\cdot}8\ C_0$: however, this does not necessarily imply that the pressure distribution in this region was similarly insensitive.

The disparities seen at lower incidences, which extended at least as far forward as $x/C_0 = 0{\cdot}55$, could perhaps be explained in terms of a relative strengthening of the flow induced by the elevon, at these lower incidences.

The wind-tunnel tests of Ref. 5 included measurements of C_L and C_m covering a range of Reynolds number, the elevons being undeflected: the results showed no perceptible scale effects between $3{\cdot}1 \times 10^6$ and $7{\cdot}9 \times 10^6$ (based on centre-line chord), though some differences were apparent in the results obtained at $1{\cdot}6 \times 10^6$—perhaps due to laminar flow over part of the fuselage.[5] The flow visualisation tests in the wind tunnel were made at a Reynolds number of $7{\cdot}9 \times 10^6$, as were most of the static-force and moment measurements, while the flight test Reynolds numbers ranged from about 65×10^6 at the lowest incidence (5 degrees approximately) to about 22×10^6 at the highest (25 degrees approximately). In these circumstances it seems unlikely that the disparities noted at low incidence between the secondary separations in tunnel and in flight could be attributed to scale effects on the development of the main flow: however, the flow through the elevon hinge-gaps would have been sensitive to scale effects, though the extent to which this might have modified the flow upstream is not clear.

6. Conclusions

The development of an adaptation to flight of the 'oil-flow' technique of visualising the surface flow has been described as applied to a slender-wing research aircraft. The results obtained were found to be highly repeatable and the close agreement between certain features of the visible flows and associated features of the spanwise pressure distribution indicate that the visualisation was a valid one. The technique is regarded as successful and, hopefully, will form a useful addition to the methods available to the flight research worker.

Although the oil-flow technique had been applied to a wind-tunnel model of the test aircraft the control settings were not appropriate to flight. Despite this the positions of the secondary separation (which was the most readily-compared feature) were similar in the tunnel and in flight, for chordwise stations well ahead of the elevon hinge-line and for incidences exceeding about 10 degrees, though there were significant disparities at lower incidences.

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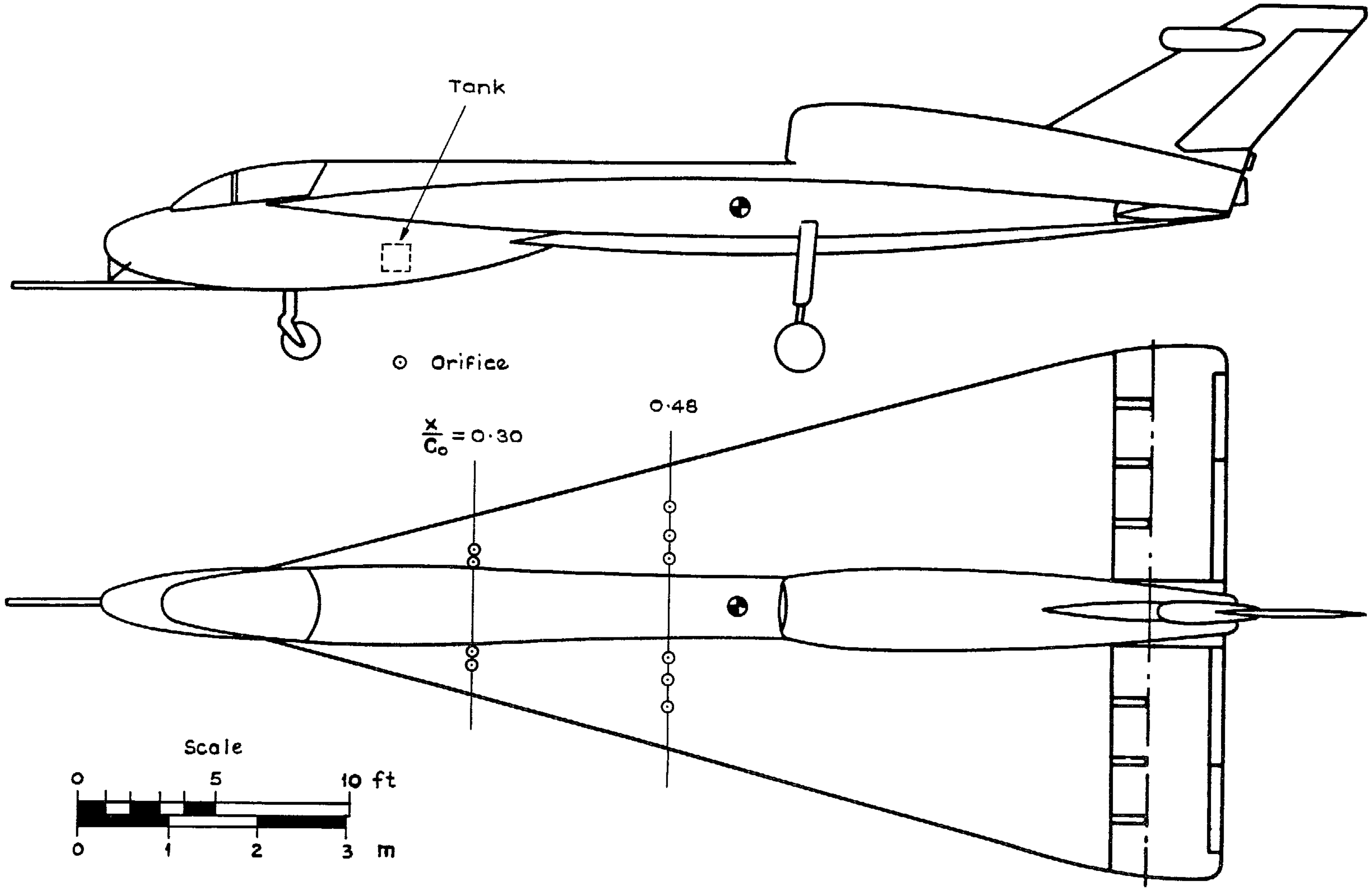


FIG. 1. General arrangement of Handley-Page HP 115.

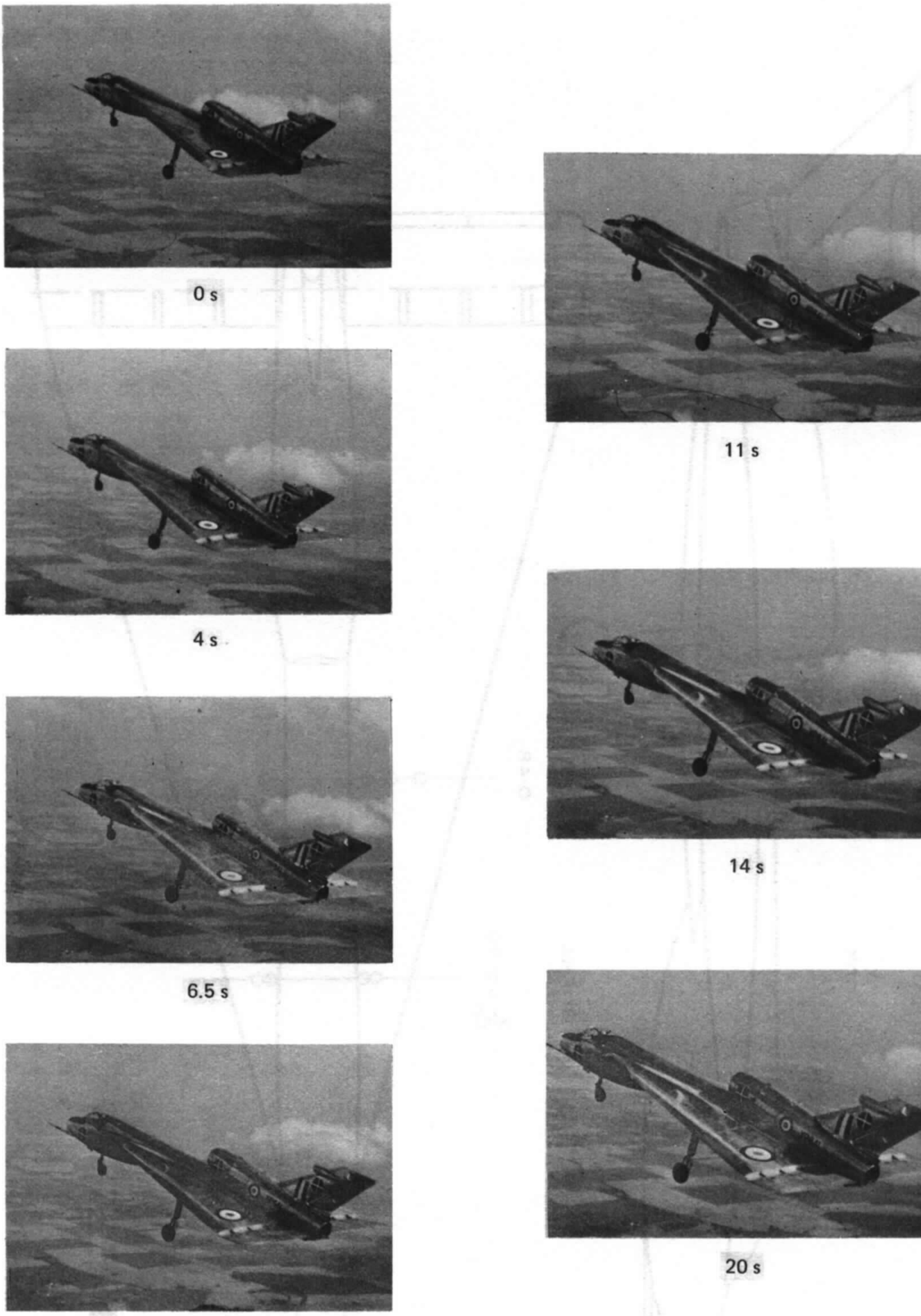
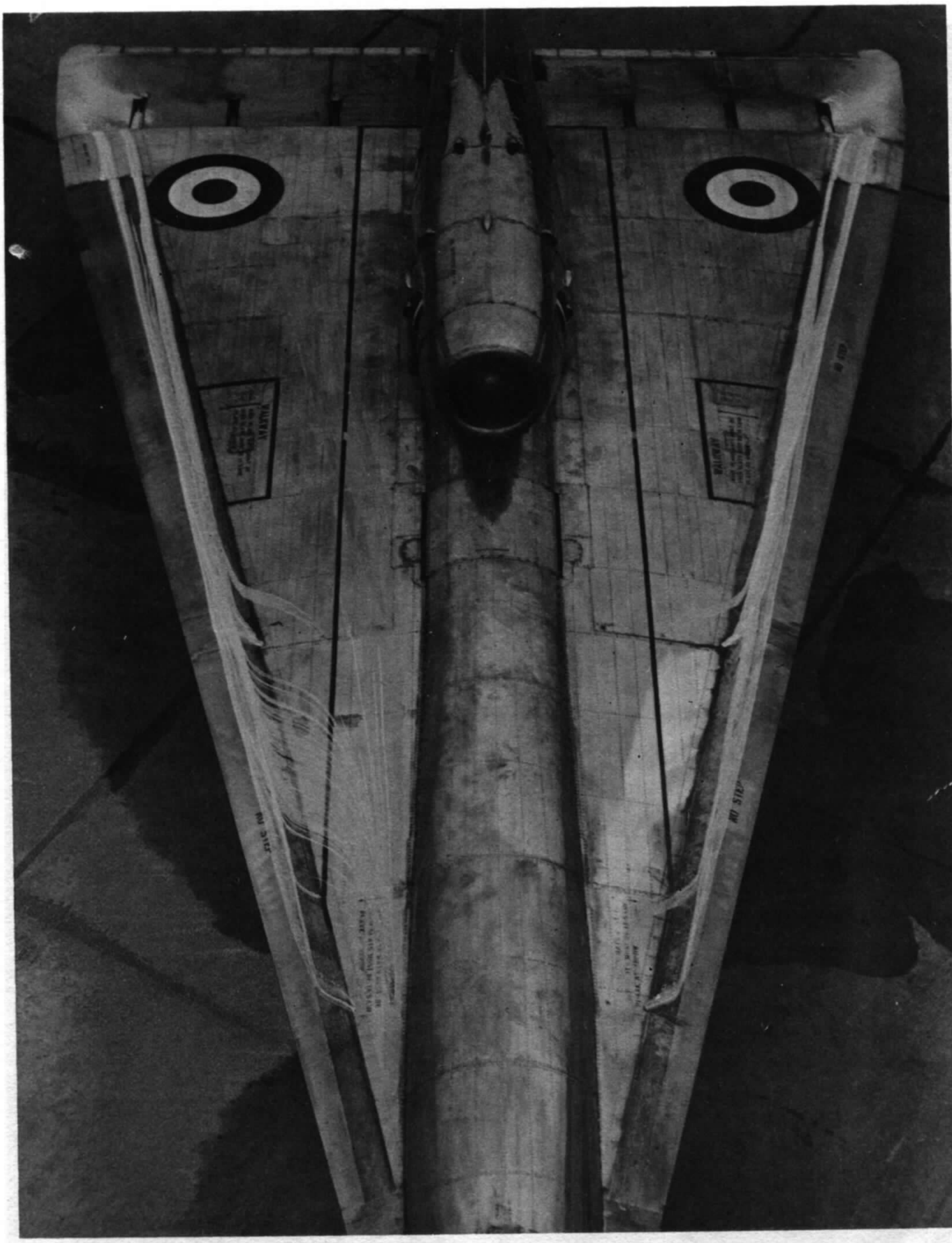
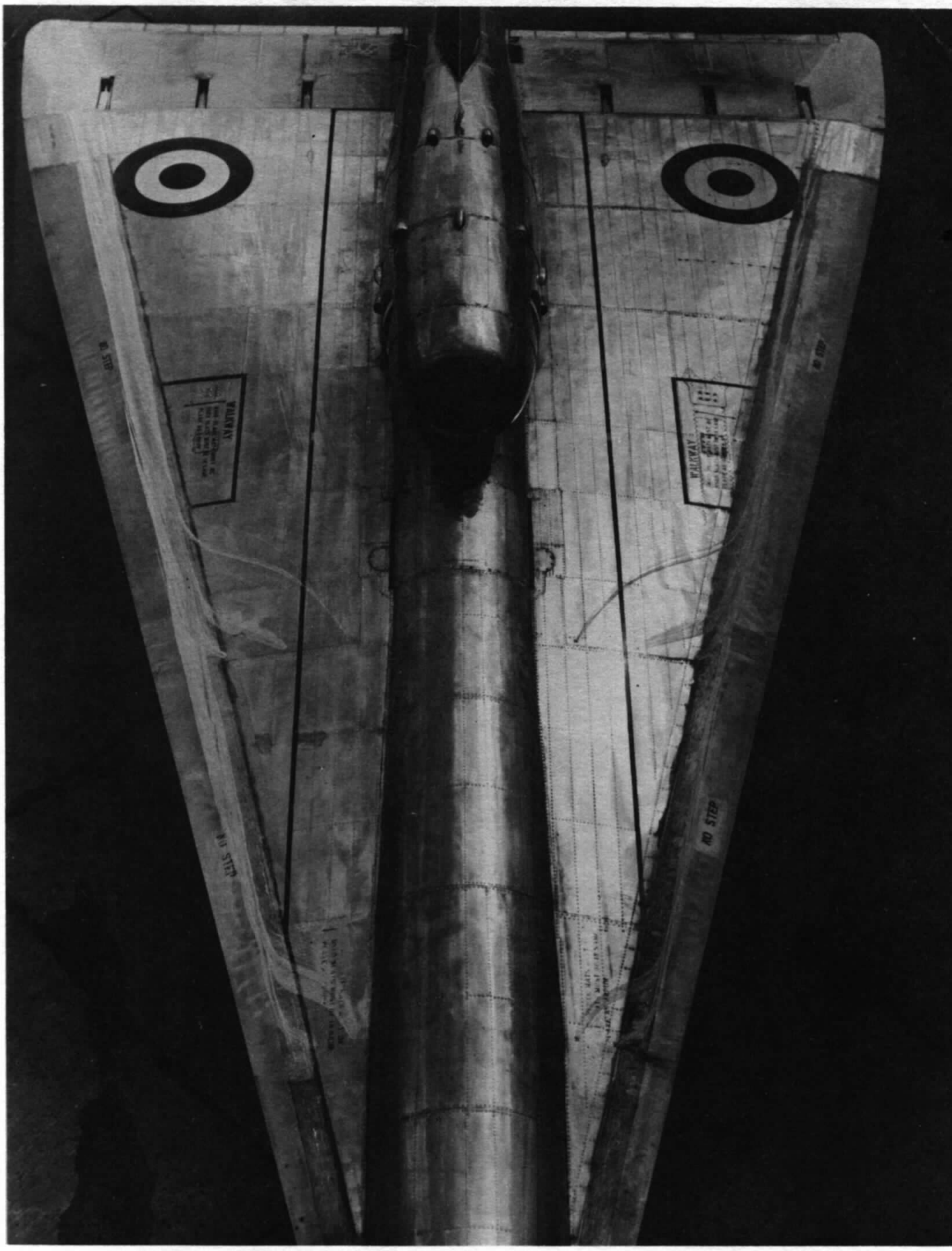


FIG. 2. Development of flow pattern in flight.



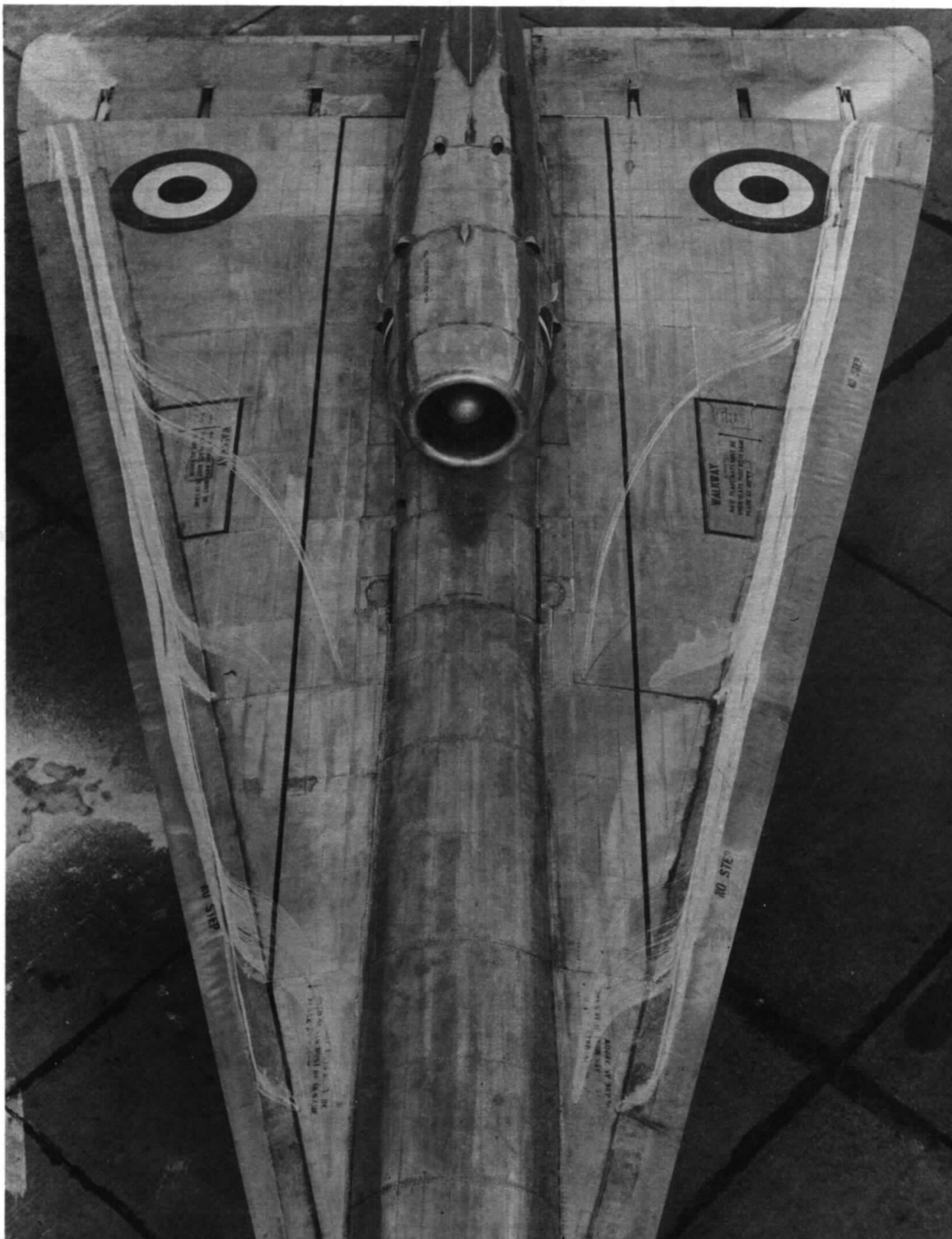
Incidence 15.9° (Starboard) 18.4° (Port)

FIG. 3a. Typical surface flow patterns.



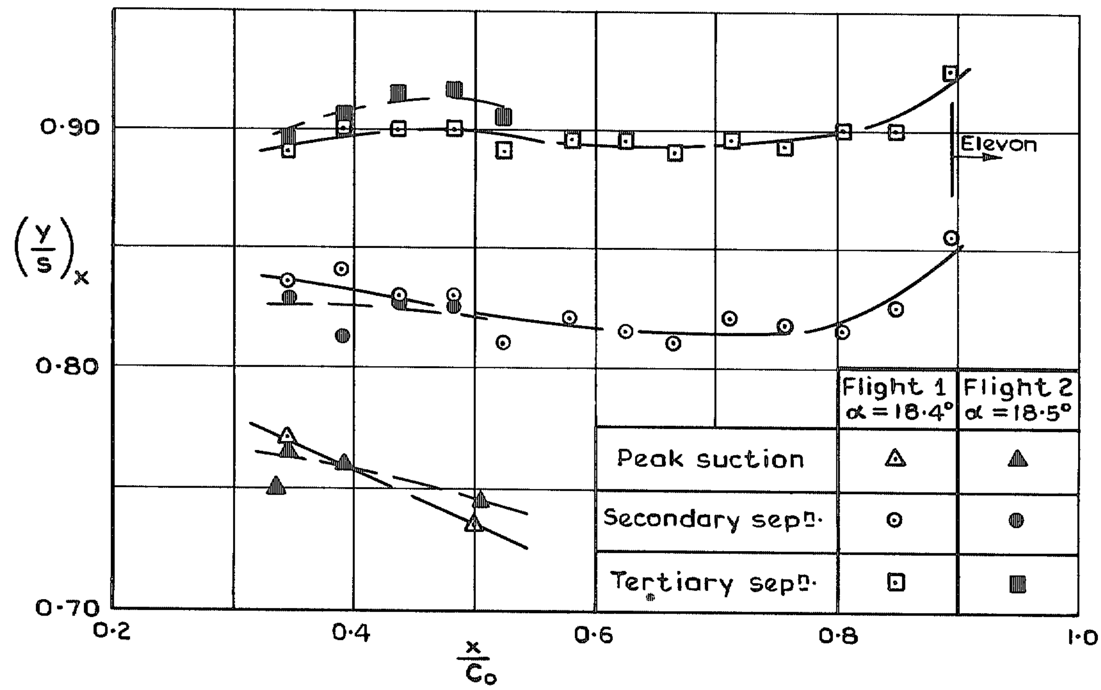
Incidence 22.1° (Starboard) 23.5° (Port)

FIG. 3b. Typical surface flow patterns.

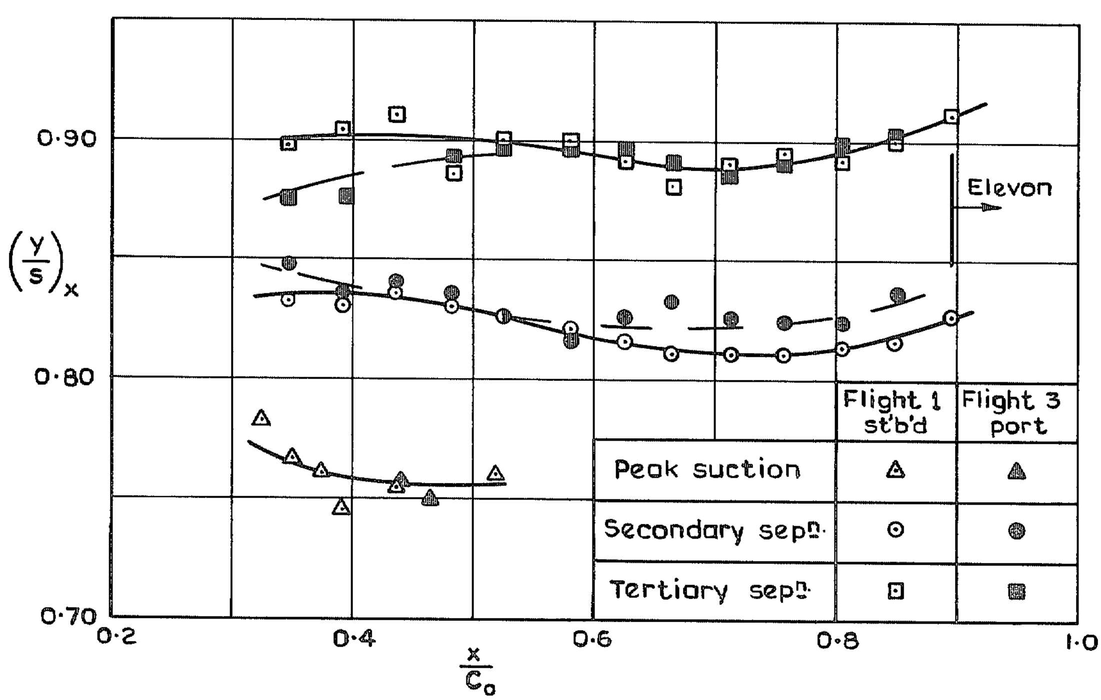


Incidence $\sim 17.5^{\circ}$ Sideslip $\sim -4^{\circ}$

FIG. 3c. Typical surface flow patterns.



a Port wing



b α = 15·9°

FIG. 4a and b. Plan position of typical surface flow features.

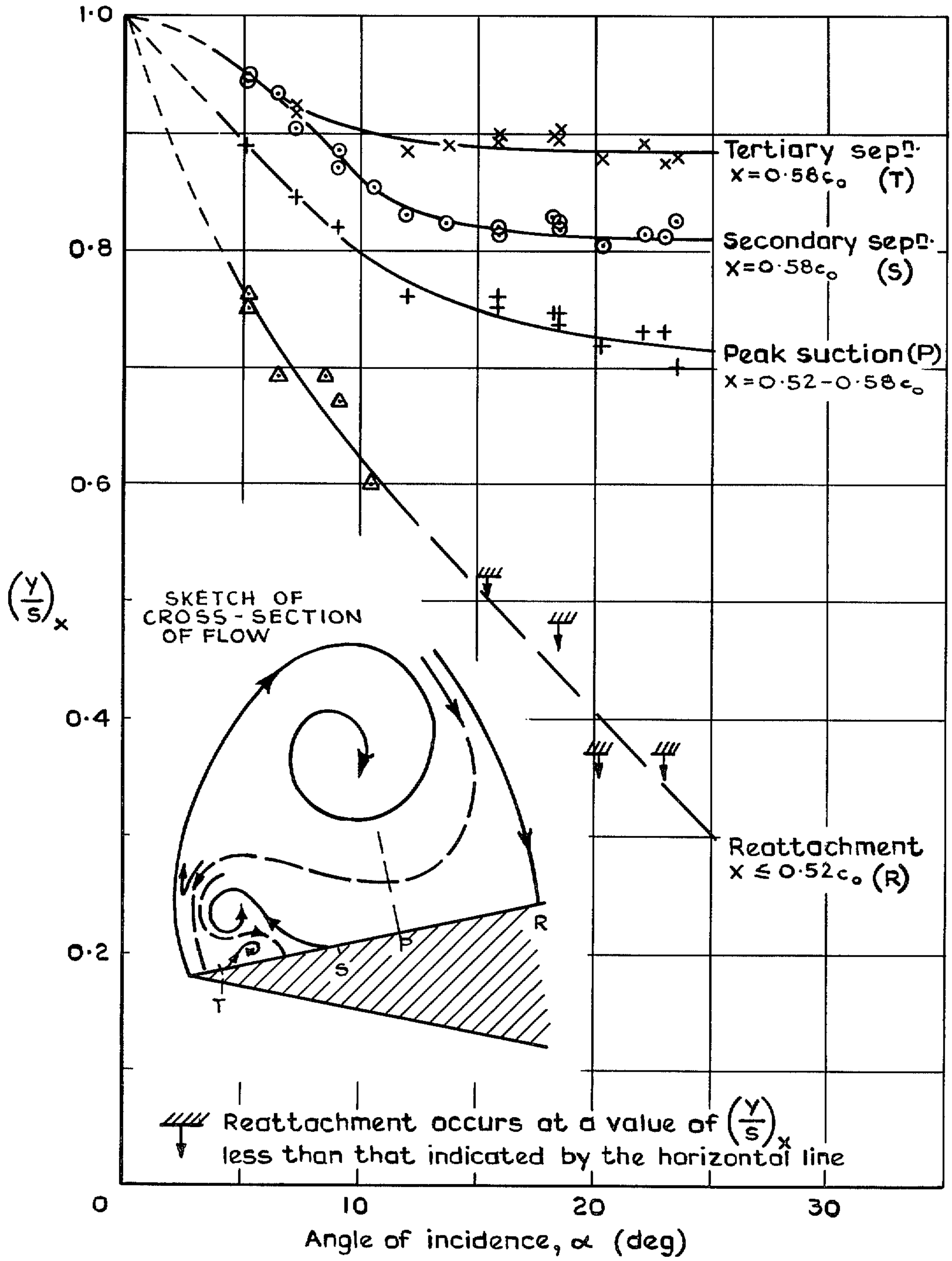


FIG. 5. Variation with incidence of spanwise position of major flow features.

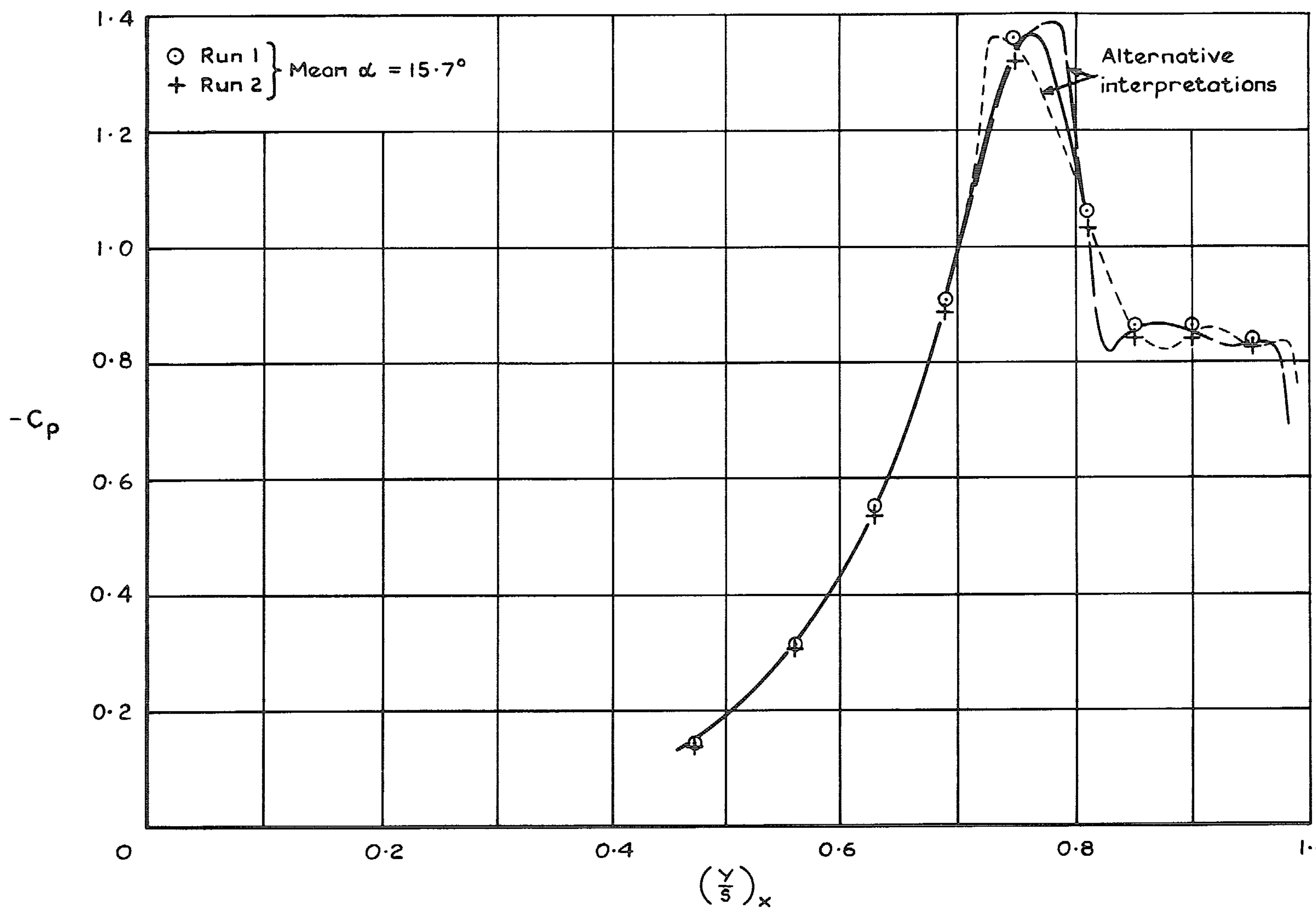


FIG. 6. Typical spanwise variation of pressure coefficient at $x/C_0 = 0{\cdot}58$.

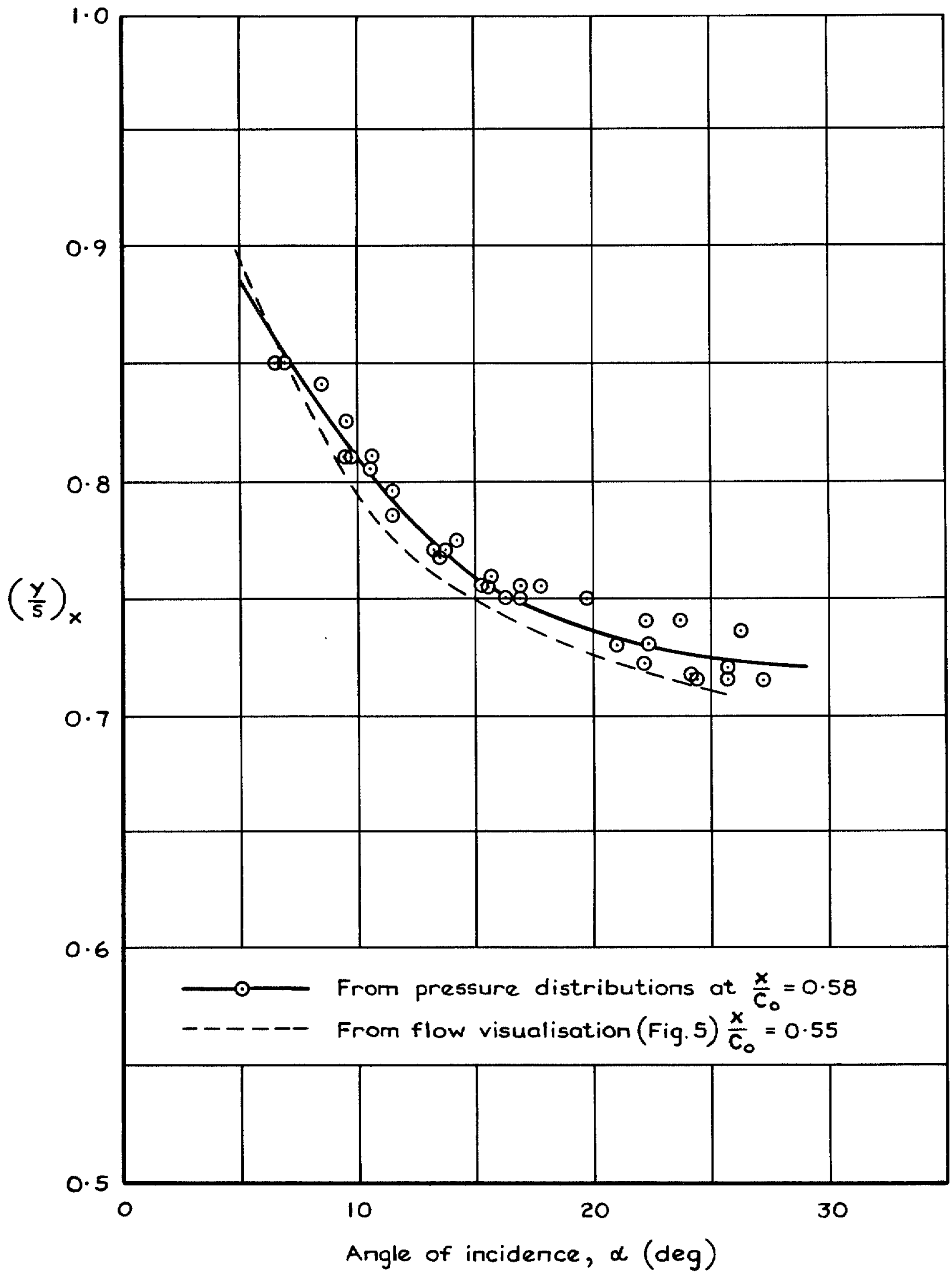
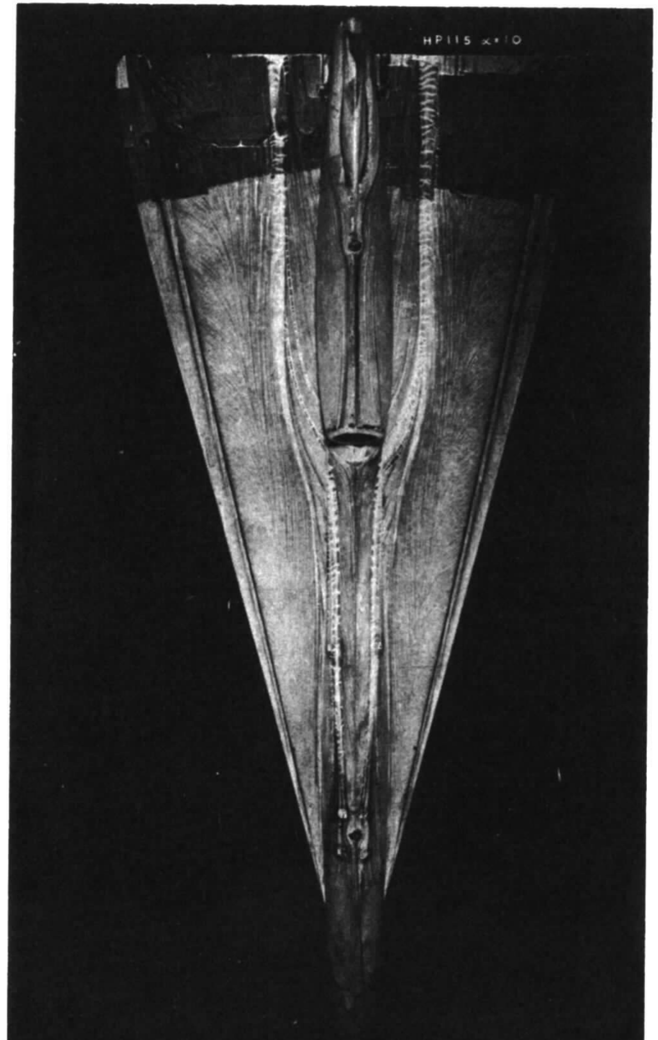
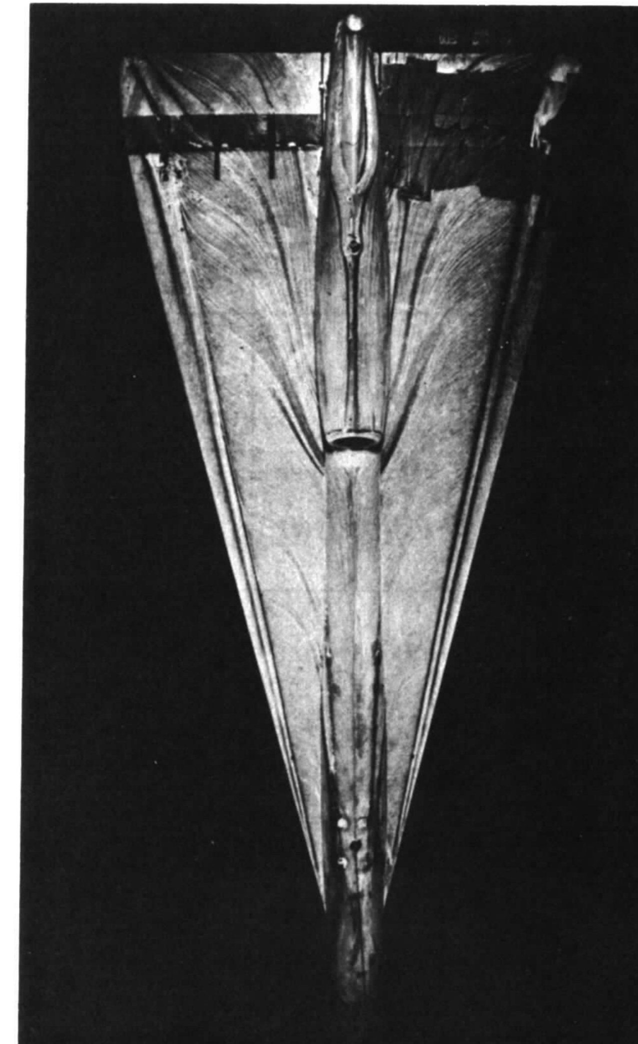


FIG. 7. Comparison of peak suction positions derived from pressure distributions with those deduced from flow visualisation.



(a)



(b)

FIG. 8. Surface flow on $\frac{1}{8}$ scale model with elevons undeflected (a) $\alpha = 10°$; (b) $\alpha = 20°$, starboard hinge-gap unsealed.

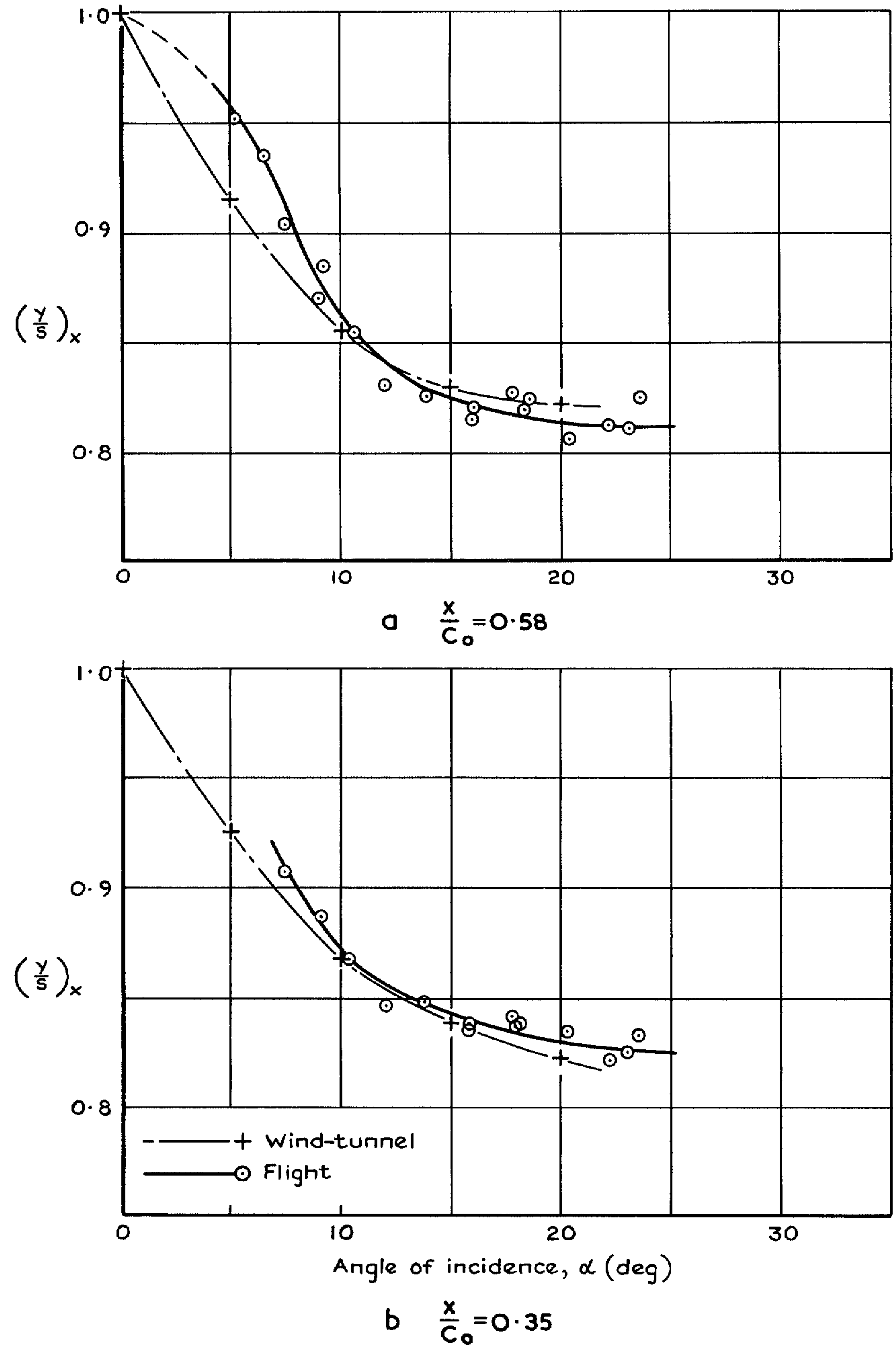


FIG. 9a and b. Comparison of secondary separation positions observed in flight and in wind-tunnel.

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