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Some Visual Observations of the Flow Over a Swept-back Wing in a Water Tunnel, with Particular Reference to High Incidences

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31st May, 1954

SUMMARY

An exploratory and solely qualitative investigation has been made consisting of visual observations of the flow over a small swept-back wing. The tests were of necessity restricted to low Reynolds numbers (about 10^5 based on mean chord). Visualization was effected by two techniques, namely, (i) the addition of small aluminium particles to the water, and (2) the introduction of air into the stream close to the model. In addition, the surface patterns produced by the flow after the wing had been coated with oil were obtained.

Attention has been mainly concentrated on the type of flow that exists at high incidence. This flow is characterized by a flat horn-shaped region of separated flow expanding in extent over the suction surface from a position inboard near the leading edge. A "part-span" trailing vortex has been revealed and appears to be a continuation of a discrete vortex situated in the separated region.

Further work is planned to investigate the effects of sweepback angle on the character of the flow.

1. Purpose of the Investigation

The investigation was initiated by a request from the Performance Sub-Committee for exploratory tests in a water tunnel to obtain visual information on the flow over a swept wing particularly at the higher angles of incidence. One purpose was to see whether the flow phenomena described by Küchemann[1], particularly the part-span vortex system, could be observed, and another to attempt to correlate the observed flow outside the boundary layer with surface flow patterns such as those obtained by Black[2] using the paraffin-lampblack technique.

2. Range of Investigation

The investigation was solely qualitative and consisted of observations of the flow over a small half-span model wing with a leading edge sweepback of 44°. The observations were made at a water speed of about 5 ft/sec corresponding to a Reynolds number of about 10^5 based on the mean chord. The incidence was varied up to 25°. Visualization of the flow was obtained by two techniques, namely, (i) the addition to the water of small aluminium particles and (ii) the injection of air into the stream close to the model. In addition the surface patterns produced by the flow after the wing had been smeared with oil were obtained. The flow patterns were recorded by photographs.

3./

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3. The Model Wing and the Tunnel

A stainless steel half-span model of the D.H.108 wing which had previously been used in high speed tunnel tests was supported on a wall of the water tunnel, and means were provided for incidence variation. Fig. 1 shows the plan-form of the wing and gives the principal features and dimensions. The tunnel has a working section 13" × 10".

4. Description of the Techniques

Aluminium Particles.- The particles are obtained in the form of a powder which, after degreasing with a wetting agent, forms a suspension in water. The particles themselves are very small highly polished lamellae, less than 100 mesh, and each acts as a tiny mirror. When a quantity of the powder is suspended in water and illuminated by a lamp of high brightness particles orientated appropriately with respect to the lamp and the observer appear as bright points of light. The arrangement for observing flow in the water tunnel is shown in Fig. 2. The light from a mercury discharge tube is concentrated by a cylindrical lens and enters the glass-walled working section of the tunnel as a fairly thin sheet. Only the particles situated within the sheet of illumination will be observed, the usual direction of observation being approximately normal to the sheet. In undisturbed flow in a direction in the plane of the sheet of illumination particles appear to the observer and are recorded in a photograph as long bright streaks, which correspond to the particle paths of the fluid. In disturbed or turbulent regions of flow, for instance wakes, a particle will rotate so that the appropriate orientation for reflecting light to the observer will no longer be maintained. Turbulent regions appear to an observer as a scintillation, and on a photograph as regions of very short tracks or dots. Even with non-turbulent flow in a direction which is not in the plane of illumination, the lengths of the tracks will be curtailed by the particles moving out of the illuminated region. The above points have been stressed to prevent any attempt being made to use the lengths of the tracks in the photographs as measures of the fluid velocities.

In uniform flow the particles are randomly orientated, and thus only a small proportion of those within the sheet of illumination will be observed. In some cases of curved flow it is evident that on account of the lamellar form of the particles they tend to lie in a definite orientation. This preference for a particular orientation appears as an apparent increase or decrease of the particle density according to the relative disposition of the light source and the observer. Bourot[3] has pointed out, and our own experience has confirmed his experimental evidence, that in vortex motion the particles tend to set in the manner shown in Fig. 3. We do not yet fully understand this phenomenon.

Air Injection.- Several methods of visualization involving the introduction of air into the tunnel were attempted during the tests. The most successful for the purposes of this investigation consisted of ejecting a jet of air from a nozzle just ahead of the leading edge of the wing.

Due to the difference between the densities of air and water, a bubble of air in a stream of water is more responsive to the pressure changes encountered along its path. Along a path with a decreasing pressure gradient a small bubble will be accelerated more than the surrounding water; against a positive pressure gradient the bubble will experience more retardation. In curved flow an air bubble will tend to leave the water particle paths and move to the centre of curvature. These properties can be described in broad terms by the statement that the air has a tendency to seek, and to remain in, regions of low pressure. Thus injected air will move to the centre of a vortex, and it has been observed that an almost permanent air bubble will sometimes occupy a region of separated flow.

Clearly/

Clearly the flow régime must be altered to some extent by the presence of air bubbles which will deviate from the water particle paths for the reasons stated above, and also on account of buoyancy, but the technique has proved extremely useful for the manifestation of regions of separation and discrete vortices.

Surface Oil Patterns.- The technique in which observation is made of the movement of, and the patterns produced by, a thin film of liquid on a wing surface in a wind tunnel has been used by several investigators[2,4,5]. In the present experiments the wing, after being carefully dried, was coated with a mixture of light machine oil and a vivid red dye (monolite fast red); the wing was then replaced in the tunnel, set at the required incidence and the stream started immediately. Usually the oil flowed over the surface in rivulets and collected in some regions to be swept away by the stream. The details of the pattern were continually changing with time, but certain features would persist until eventually all the oil had been removed from the wing.

5. Description and Discussion of the Observed Flow

A general description of the flow can best be given by considering two ranges of incidence:-

(i) low incidences up to 9°, and

(ii) higher incidences (i.e., above 9°).

The Lower Incidences.- Figs. 4 and 6 ((a) to (f)) show the flow, as indicated by aluminium particles, for 6° incidence which is typical of the lower incidence range. The curvature of the particle paths over the suction surface are seen in Fig. 4 for which the sheet of illumination was arranged to include the wing surface. Particles in the boundary layer or in the wake (those producing short tracks) are deflected towards the tip. Fig. 6 shows that the thickness of the wake is much the same at all positions along the span. Although not clearly seen in the photographs, the observed deflections of the particle paths over the leading edge at positions outboard of about half-span suggest that separation and then reattachment of the flow occurs close behind the leading edge. This suggested behaviour is confirmed by the surface oil pattern shown in Fig. 5 in which a band of oil remains in the separated bubble near the leading edge.

In Fig. 6(f), which refers to the tip, the rope-like appearance of the particle paths and the apparent increase in particle density are indicative of the trailing vortex from the tip. In this photograph the majority of tracks in the wake are just outboard of the tip and thus they show pronounced upwash.

The Higher Incidences.- Between 9° and 10° incidence a radical change occurs in the flow characteristics. There is a thickening of the wake at stations towards the tip, and between 0.8 span and the tip the flow has completely separated from the suction surface as shown in Fig. 7 ((a) to (c)). At $10\frac{1}{2}$° incidence a new flow régime has been established which persists with gradual modification up to at least 25° - the highest incidence reached in the tests. The features of this régime are outlined in the sketch shown in Fig. 8 which has been drawn on the basis of observations at 15° to 18° incidence, but which is typical of the higher incidences generally. In the diagram, OABC represent a free boundary which, together with the wing surface, encloses a flat horn shaped region of separated flow extending over the suction surface of the wing. The horn expands spanwise and rearwards and turns downstream over the outboard half of the wing to form a wake. The forward boundary of the separated region lies close behind the leading edge. A trailing vortex leaves the wing near half-span just inboard of the wake.

Fig. 9/

Fig. 9 ((a) to (f)) shows the flow across the chords at various spanwise stations at 15° incidence. Fig. 9(a), which corresponds to a section such as X_1 in Fig. 8, shows the separation near the leading edge and the subsequent reattachment of the flow. The apparent increase in particle density behind the wing indicates rotation of the aluminium particles into a definite orientation due to proximity to a trailing vortex. Fig. 9(b) corresponds to a cross-section such as X_2 in Fig. 8. Here the flow after separating near the leading edge "reattaches" close to the trailing edge. The appearance of a bright rope-like region behind the wing indicates very close proximity to the trailing vortex. The strong downwash behind the wing is also evident in this photograph. Fig. 9(c) corresponds to a section X_3 for which the flow is completely separated from the suction surface. At about two chords behind the trailing edge the turbulent wake is no longer cut by the sheet of illumination. Figs. 9 (d) (e) and (f) show sections such as X_4 through the highly turbulent wake that leaves the wing at the more outboard positions.

Fig. 10 shows the flow over the suction surface, again at 15° incidence. For this photograph the sheet of illumination was inclined so that it was just grazing the wing surface as shown in the sketch.

The introduction of a jet of air close to the leading edge near the root leads at the higher incidences to the formation of a horn-shaped air bubble, as shown in Fig. 11, which occupies approximately what would in the absence of the air be the region of separated water flow. Comparison with the observations made using aluminium particles suggests that the character of the flow outside the separated region is unaffected by the introduction of the air.

Fig. 11 shows that the air bubbles from the jet are "caught" by the low pressure of the separated region, and that a single bubble becomes established at the apex of the horn. The forward boundary of the air bubble is clearly defined over the inboard portion of the wing and is situated at some small distance behind the leading edge. The fairly clear outline of the bubble is broken at about half span where mixing with water takes place, and then nearer the tip a host of small bubbles is lost downstream in the wake. Some of the air is drawn into the low pressure core of the trailing vortex leaving the wing at about half-span; this core is shown in the photograph as a discrete trail of air which is similar to that obtained from a wing tip at low incidence.

The course of the air from the jet has been observed, although it is not clearly visible in the photograph. After being drawn into and folding round the rearward edge of the horn, which motion suggests the presence of a vortex, some of the air moves across the wing surface in a spanwise direction before arriving at the mixing region. When the supply of air is stopped the apex of the bubble persists for some time, thus showing that with air at least, this is a "dead air" region except for possible internal vortex motion. The shape of the bubble was found to be only slightly dependent on the position of the nozzle provided it was outboard of the apex of the separated region. If the jet of air is introduced very close to the root the horn is not revealed except at very high incidences.

A photograph of the surface oil pattern for 15° incidence is given in Fig. 12. A feature of significance is the "parting" which is situated approximately at the rearward edge of the separated horn. The parting is a region of intense scouring and represents the dividing line between the fluid which is drawn into the horn and the downstream flow. The parting resembles the "herring bone' pattern found on a 45° swept-back wing by Emslie, Hosking and Marshall[5] using a paraffin and lampblack technique in a wind tunnel. On the outboard side of the parting the oil flows forward and outboard. Further outboard the oil flow turns more towards the leading edge, and then turns again to travel inboard close behind the leading edge to accumulate at A. This accumulation has the appearance of a whirlpool and is clearly similar to the phenomenon observed by Black[2] who identified it with a standing vortex in the main flow. In the present experiments the significance of the position of this accumulation of oil is not clear.

Fig. 13/

Fig. 13 has been prepared from tracings of photographs of the air bubble and the oil flow pattern. It will be noticed (i) that the parting in the oil flow lies inside the rearward boundary of the air bubble - this suggests that the presence of the air increases the extent of the separated region, and (ii) that the position where the rearward boundary of the air bubble crosses the trailing edge coincides with the point where the ridges in the oil pattern are tangential to the trailing edge.

Observation indicates that a particle* entering the separated region over the more inboard portion of the wing follows some kind of spiral path until it is discharged downstream in the wake between B and C (Fig. 8). Apart from strong vortex motion in the vicinity of the rearward edge of the separated region some spiral paths occur inside the wake near the tip. In character the flow over the tip is similar to that which occurs when a two-dimensional aerofoil is completely stalled.

Details of the motion inside the separated region, particularly near the apex of the horn, could not be clearly observed with aluminium particles, but the observed motion outside the separated region and the evidence of the oil patterns, particularly the high scouring along the parting, are consistent with a discrete vortex filament situated a little above the wing surface and forming the rearward boundary of the separated region as shown in Fig. 14. The strength of the vortex appears to increase with distance from the apex. On reaching the trailing edge the filament turns downstream and becomes a trailing vortex. A similar phenomenon has been detected by Örnberg[6] in experiments on delta wings.

The probable structure of the separated region is sketched in Fig. 15 (a) which represents the flow components in plane AA Fig. 15 (b). The free boundary springing from the separation point just behind the leading edge rolls up to form a discrete vortex. The division of the flow to each side of the stagnation point S leads to the parting in the oil pattern (Fig. 15 (b)).

It will be noted that Fig. 15 (a) also represents the separation from the leading edge of a two-dimensional wing at high incidence very soon after the motion has started. For a two-dimensional system, the fluid in the rolled up vortex sheet and its vorticity can only be convected downstream in the plane of the diagram, and the sketch represents only a transient condition. In the three-dimensional motion associated with a swept-back leading edge it is possible for an additional velocity component normal to the plane of the diagram to remove the vorticity continuously in the outboard direction. Sketch Fig. 15 (a) thus represents a possible steady condition in three-dimensional motion. The vorticity thus removed in the outboard direction augments the vorticity springing from the leading edge separation at positions further outboard. Thus the strength of the vortex grows in the outboard direction.

6. Variation of Incidence in the Higher Incidence Range

After the horn-shaped region of separated flow has been established at 9° to $10\frac{1}{2}^\circ$ incidence it grows in extent with increasing incidence. The changes that occur are conveniently indicated by Figs. 16, 17, 18 and 19 which show the air bubble obtained at 9°, $10\frac{1}{2}^\circ$, 18° and 21° incidence respectively. At 12° incidence the part-span trailing vortex leaves the wing at about half-span, from whence it moves gradually inboard with increasing incidence reaching quarter span at some 20°.

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*Occasionally the complete path of small particles in the water (evidently not aluminium lamellae) could be observed, although their brightness was not sufficient for photography.

7. Scale Effects

In view of the low Reynolds number of the experiments (about 10^5), the question naturally arises as to the extent to which the observations are applicable to the flow conditions at higher Reynolds numbers. There is some justification for the view that, although the flow at a particular incidence and the critical incidences at which changes of flow pattern occur will be dependent on Reynolds number, the flow at high incidence when leading edge separation occurs will be similar in general character over a wide range of Reynolds number.

In conjunction with the work of Messrs. Garner and Bryer of the N.P.L. different types of surface pattern have been obtained with two similar wings at Reynolds numbers of $1 - 2 \times 10^6$ in air and 10^5 in water respectively. Unlike the water tunnel patterns no "parting" or "herring bone" was apparent in the wind tunnel patterns. However this difference is not necessarily indicative of a scale effect. The techniques used in obtaining the patterns were not comparable with regard to the physical characteristics of the oil, or to the thickness of the film in relation to the boundary layer (the film used in the water tunnel experiments was relatively much thicker than that used in the wind tunnel tests), and it is possible that the character of the pattern depends to a large extent on these factors. In this connection it is relevant to note that the "herring bone" pattern of Emslie, Hosking and Marshall[5] was obtained on a 45° swept-back tip-to-tip wing of constant chord at a Reynolds number 0.5×10^6 (based on wing chord).

8. Conclusions

The investigation has shown that some features of the flow over swept-back wings can readily be made manifest by visualization techniques in a water tunnel. A type of flow at high incidence has been revealed which is characterized by a region of separation expanding in extent over the suction surface from an inboard position near the leading edge. This region would appear to be related to the "long bubble" of two-dimensional flow as described by Küchemann, except that the observations indicate considerable vortex motion inside the separated region near its rearward boundary. A part-span trailing vortex has been detected which may be compared with the rolled-up part-span vortex sheet also described by Küchemann. The trailing vortex appears to be a continuation of a discrete vortex situated in the separated region.

So far the investigation has been mainly confined to a single plan-form, but it is intended to make observations of the flow for:-

(i) a family of tapered wings covering a range of sweep back angles

(ii) a family of delta wings with variation of the apex angle.

In each case it is hoped to make pressure measurements, particularly within the separated region, for comparison with the visual observations.

Acknowledgement.- The authors wish to acknowledge helpful suggestions from Dr. Küchemann of the R.A.E. regarding the use of air for visualization.

References/

References

No.	Author(s)	Title, etc.
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2	J. Black	Pressure distribution and boundary layer investigations on a 44° sweptback tapered wing. C.P.137. December, 1952.
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5	K. Emslie, L. Hosking and W. S. D. Marshall	Some experiments on the flow in the boundary layer of a 45° sweptback untapered wing of aspect ratio 4.- The College of Aeronautics Report No. 69. February, 1953.
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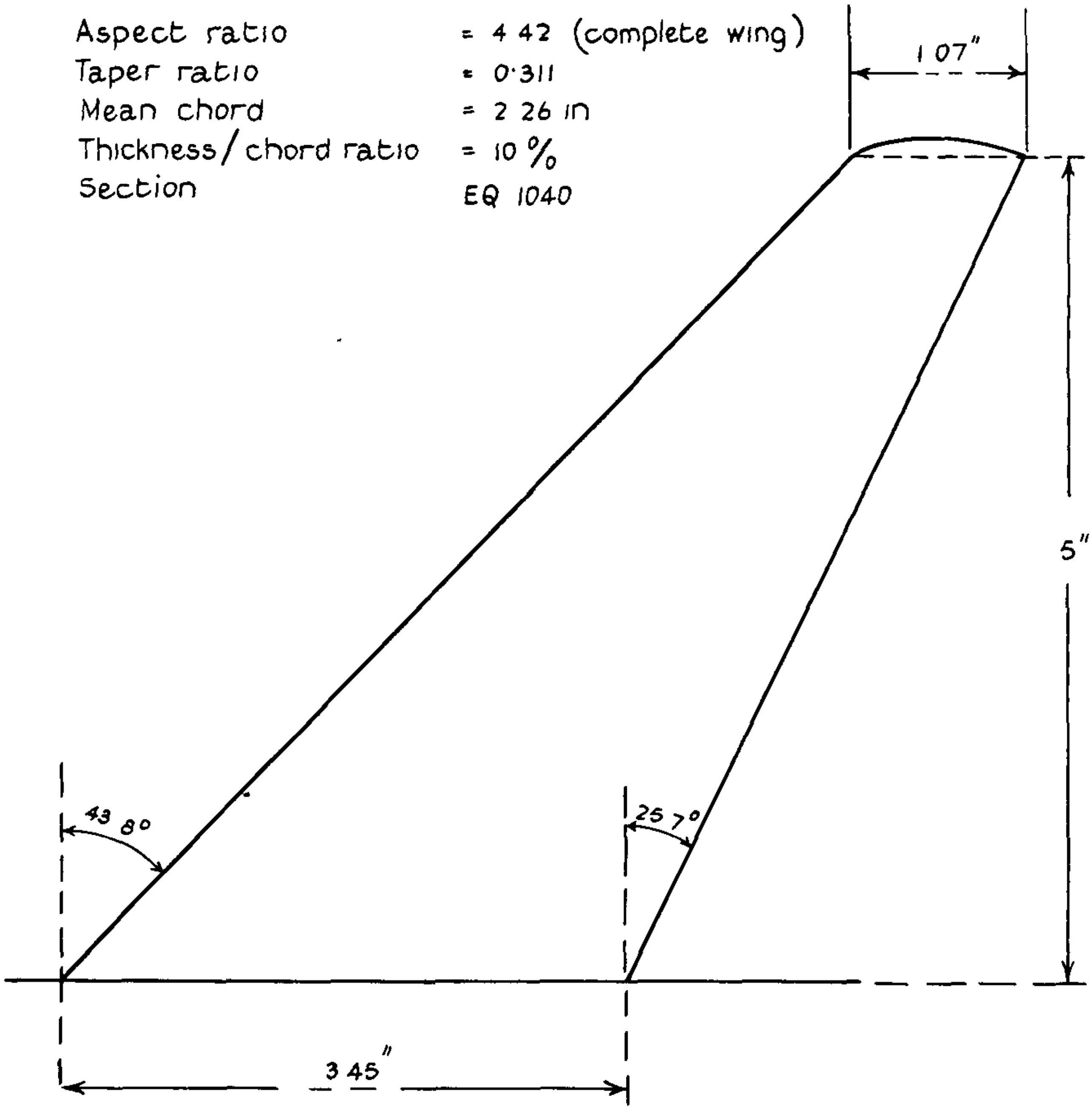
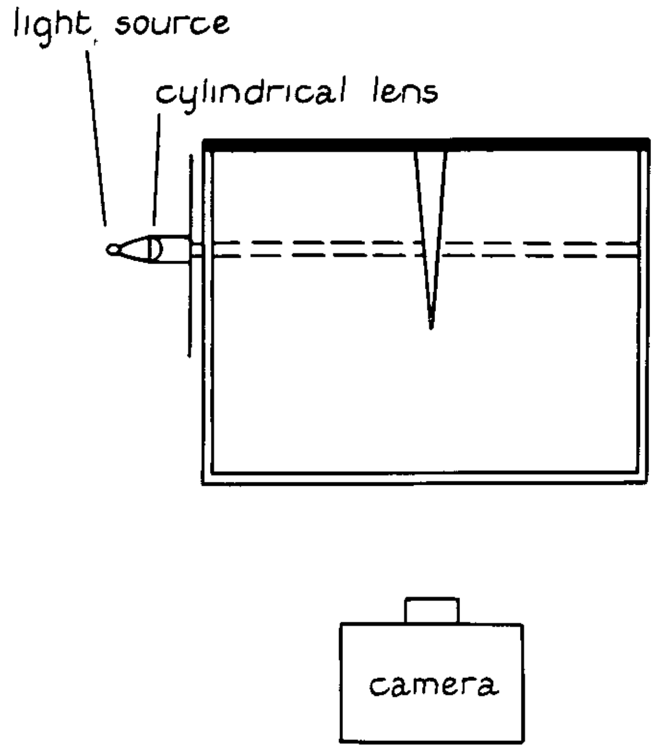
FIG 1



The model wing (full size).

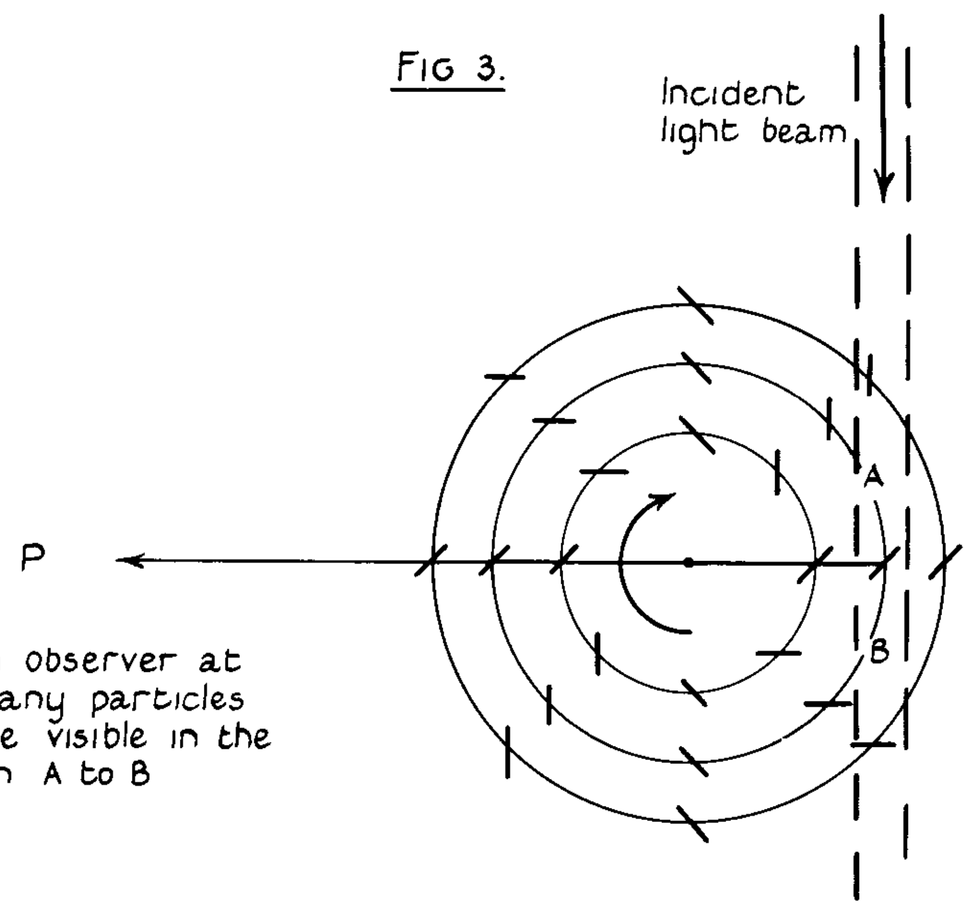
FIGS 2 & 3

FIG 2



Arrangement for visualisation using aluminium particles

FIG 3.



To an observer at P many particles will be visible in the region A to B

Orientation of particles in vortex motion.

FIGS. 4 & 5

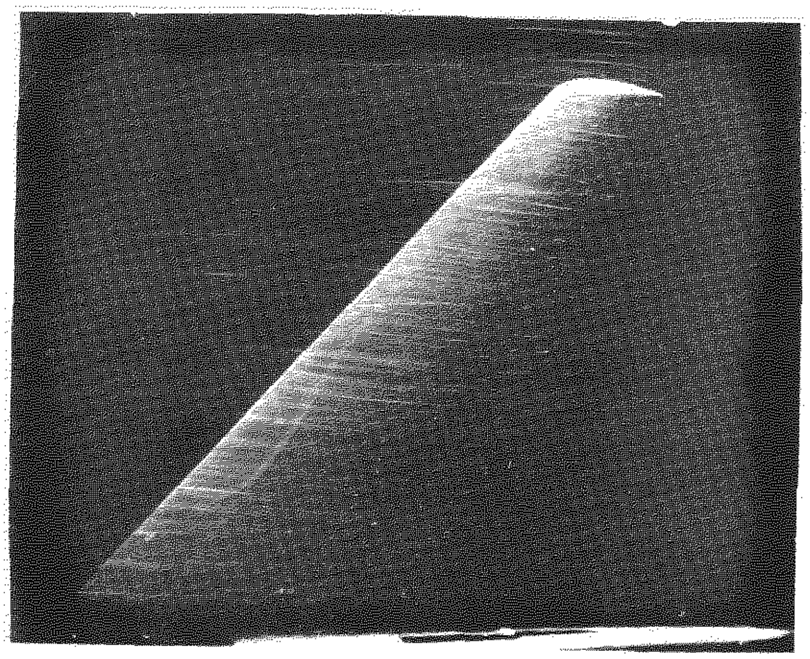


FIG. 4.

Flow over suction surface at 6° incidence

Band of oil remains

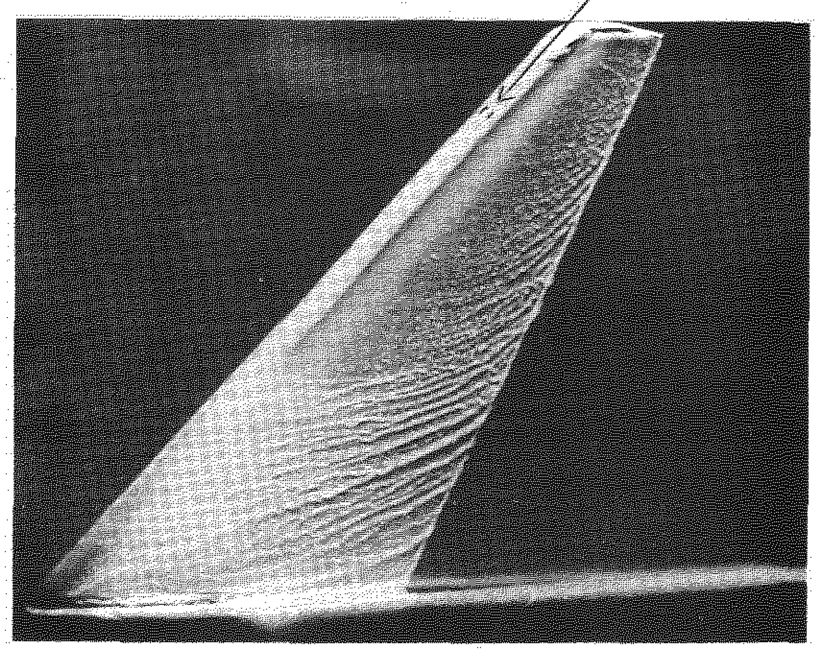
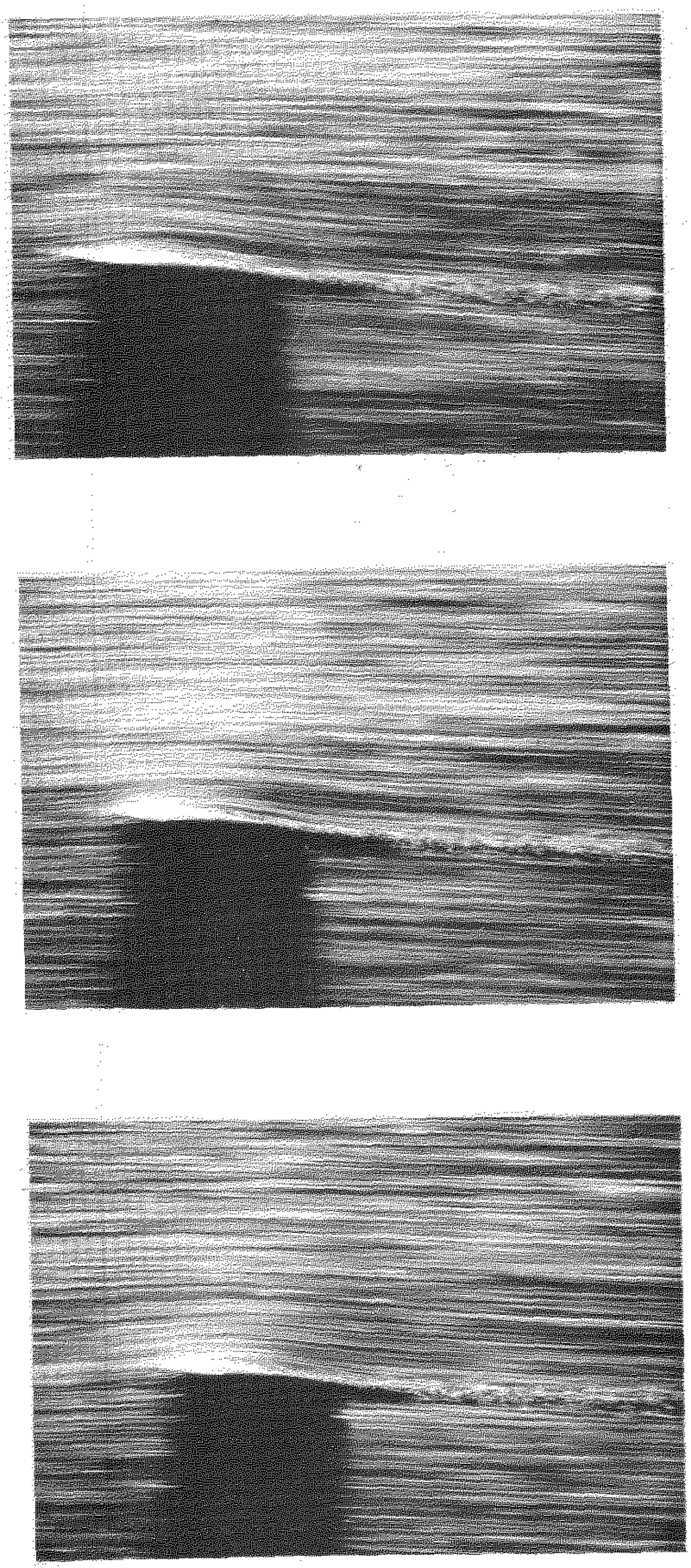


FIG. 5

Oil pattern on suction surface at 6° incidence

FIG. 6 a-c



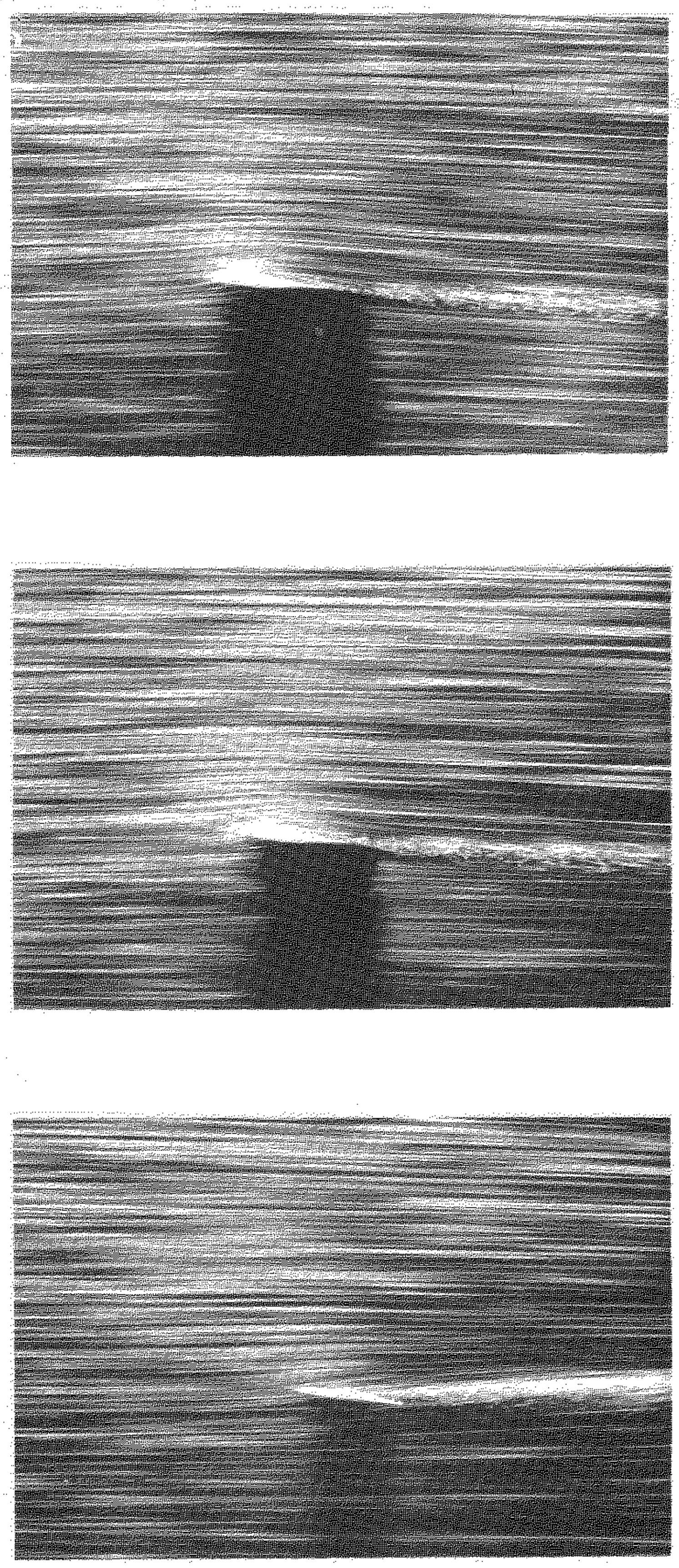
(a) 0·25 span

(b) 0·40 span

(c) 0·55 span

Flow at 6° incidence

FIG. 6. d-f



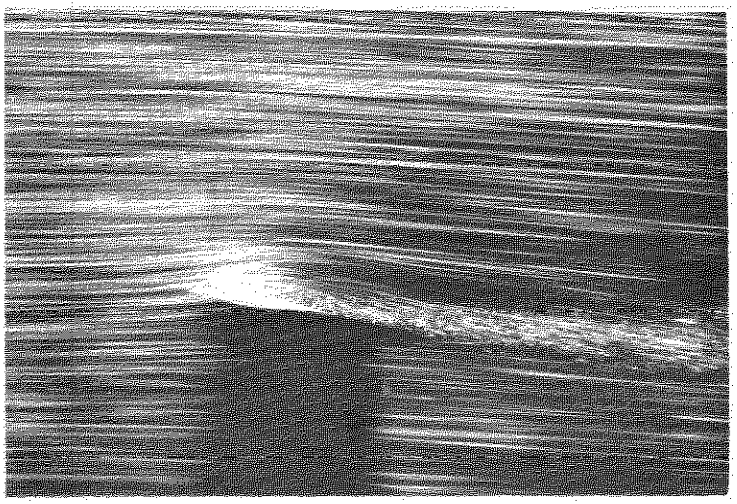
(d) 0·70 span

(e) 0·85 span

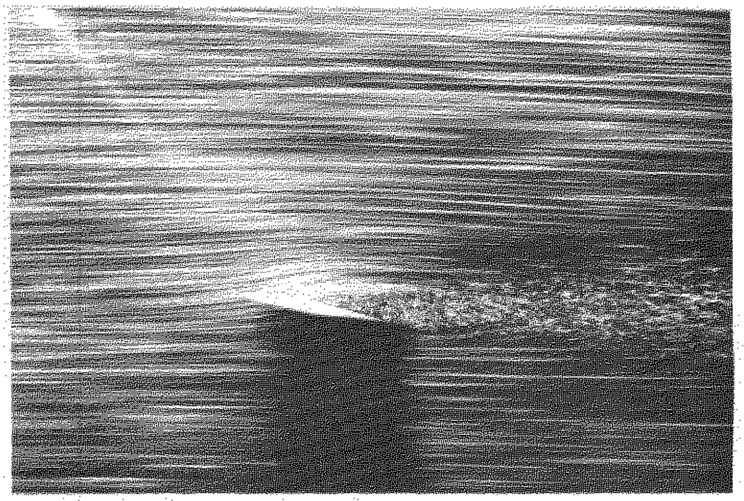
(f) Tip

Flow at 6° incidence

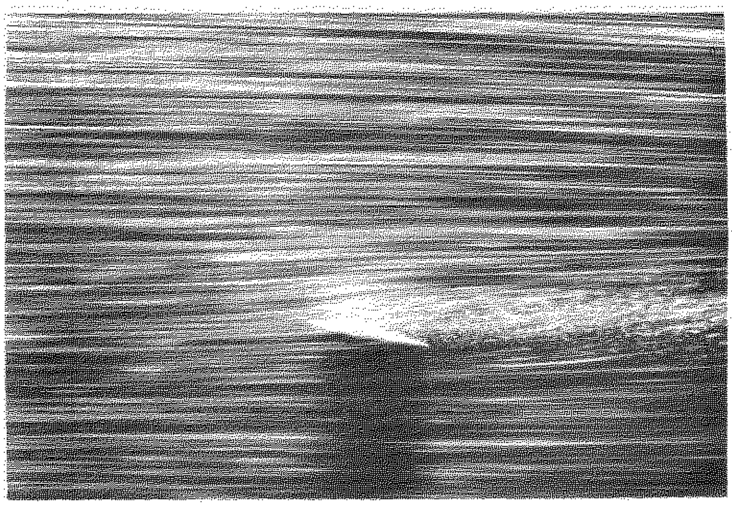
FIG.7. a-c



(a) 0·7 span.

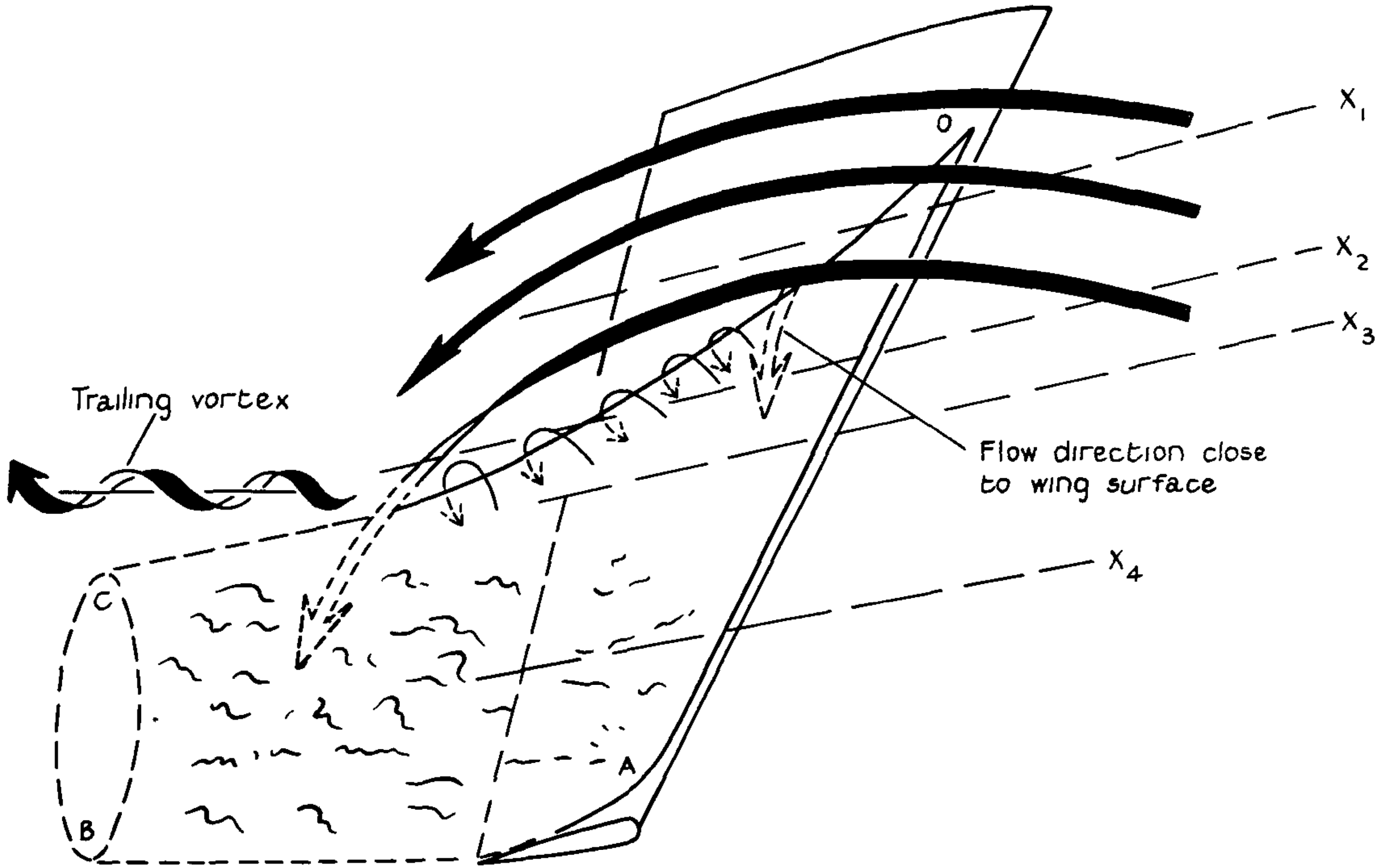


(b) 0·85 span



(c) Tip

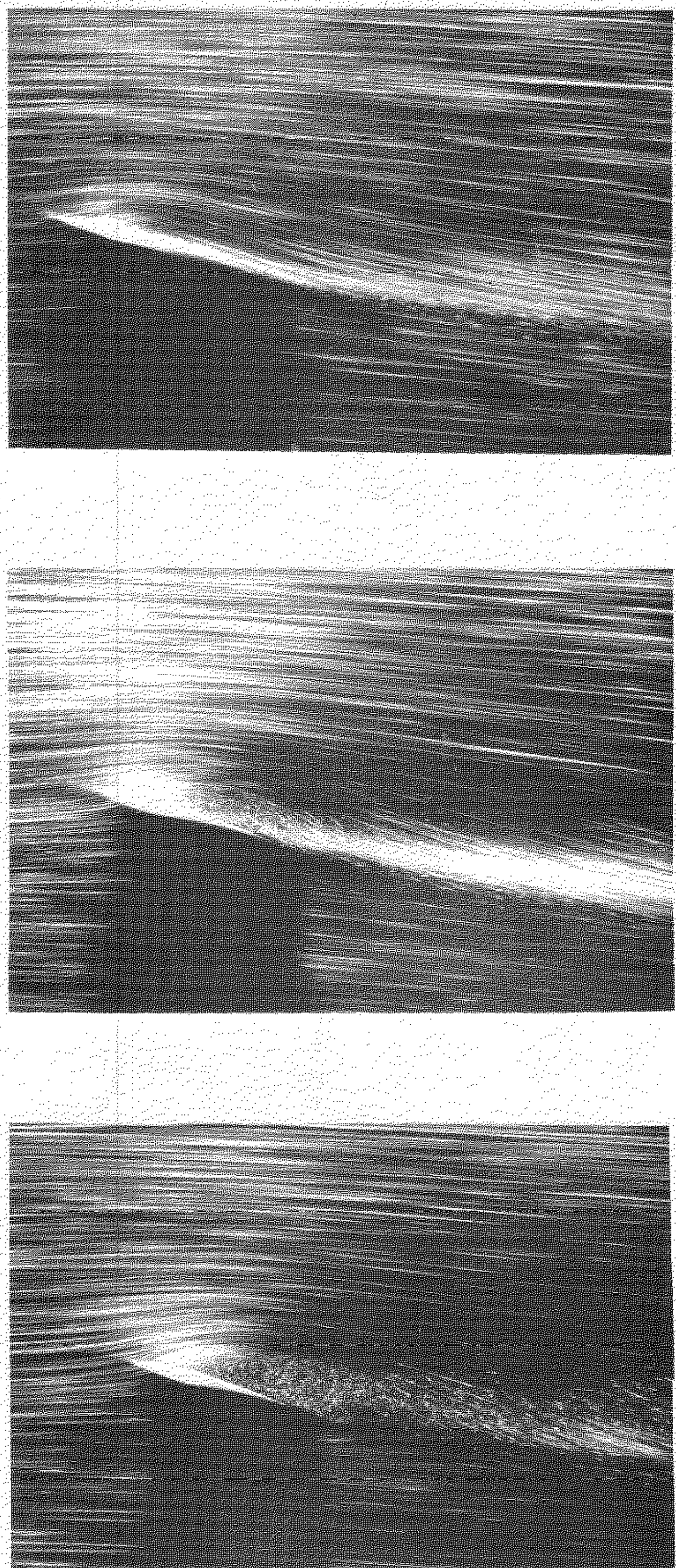
Flow at 9° incidence



Flow over suction surface at high incidence.

FIG 8.

FIG. 9 a-c



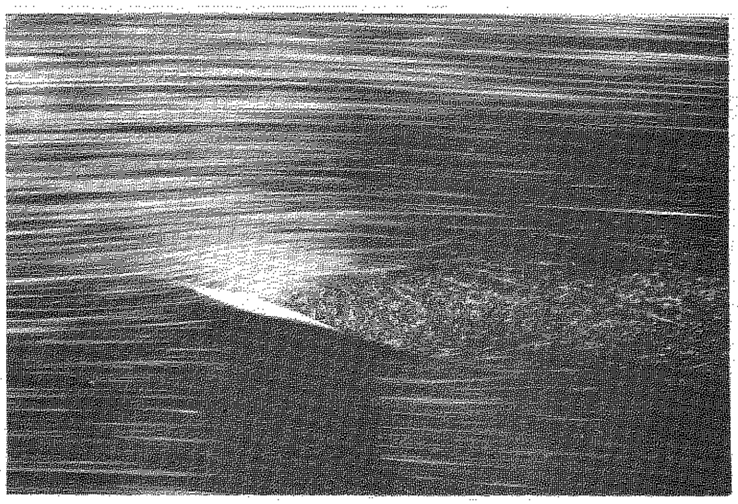
(a) 0·25 span

(b) 0·40 span

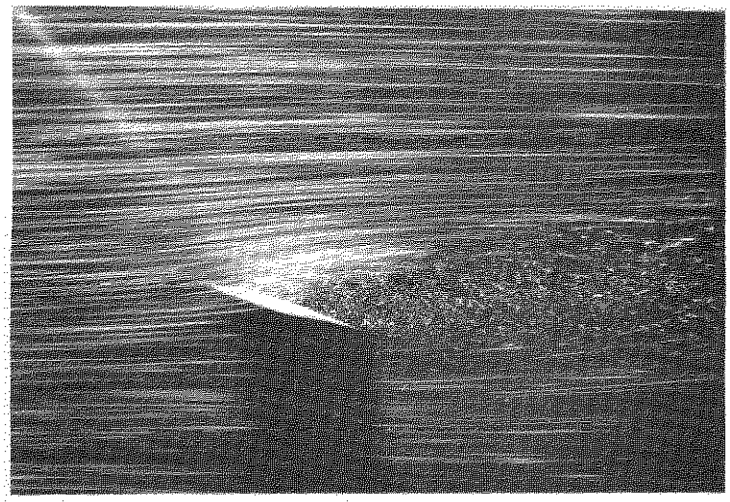
(c) 0·55 span

Flow at 15° incidence

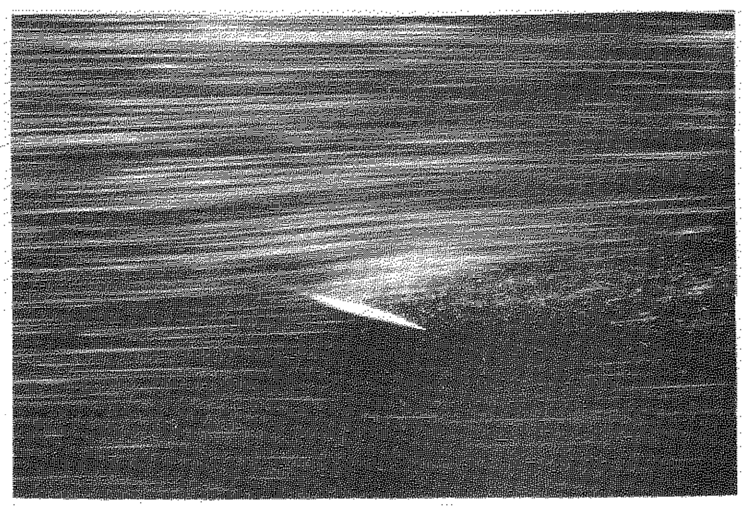
FIG. 9 d-f



(d) 0·70 span



(e) 0·85 span

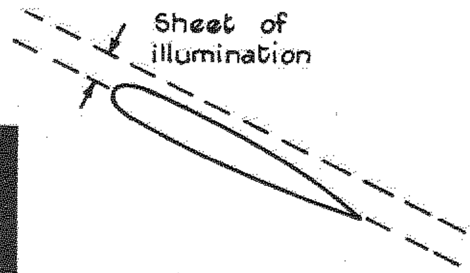


(f) Tip

Flow at 16° incidence

FIGS. 10 & 11

Direction of incident light



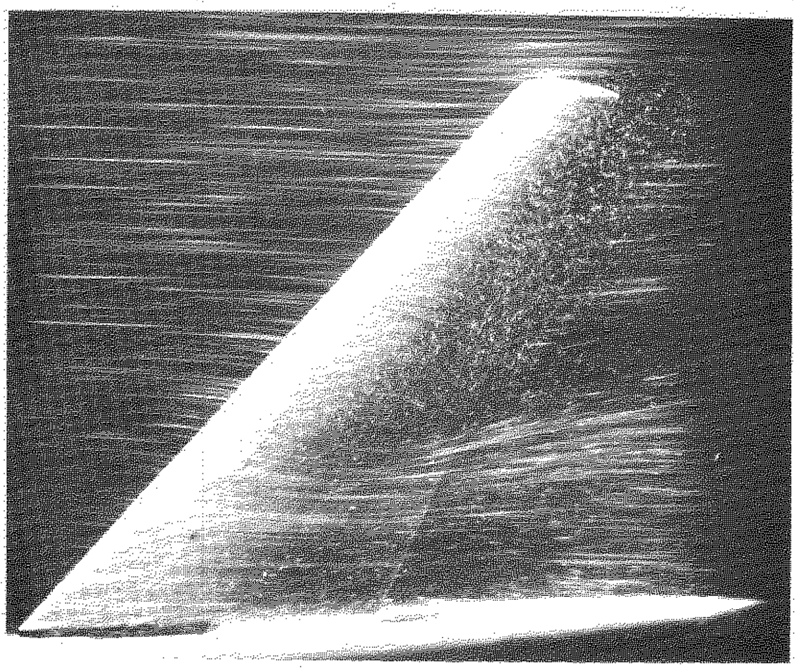


FIG. 10.

Flow over suction surface at 16° incidence

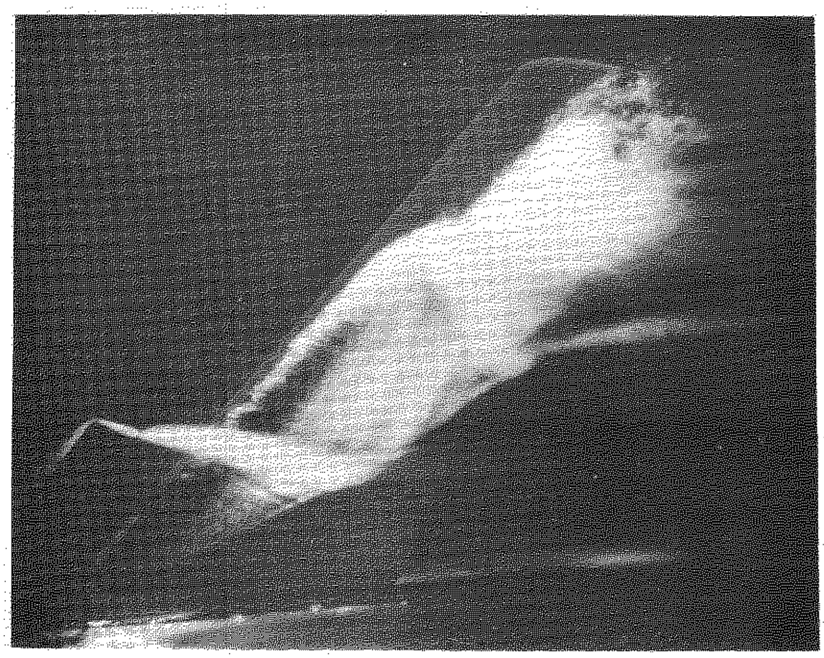
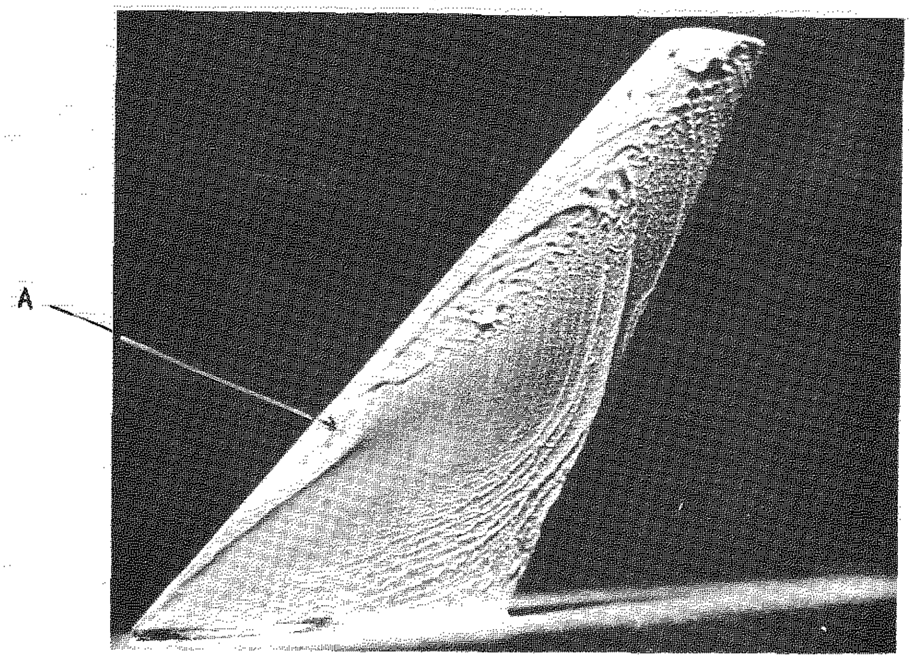


FIG. 11.

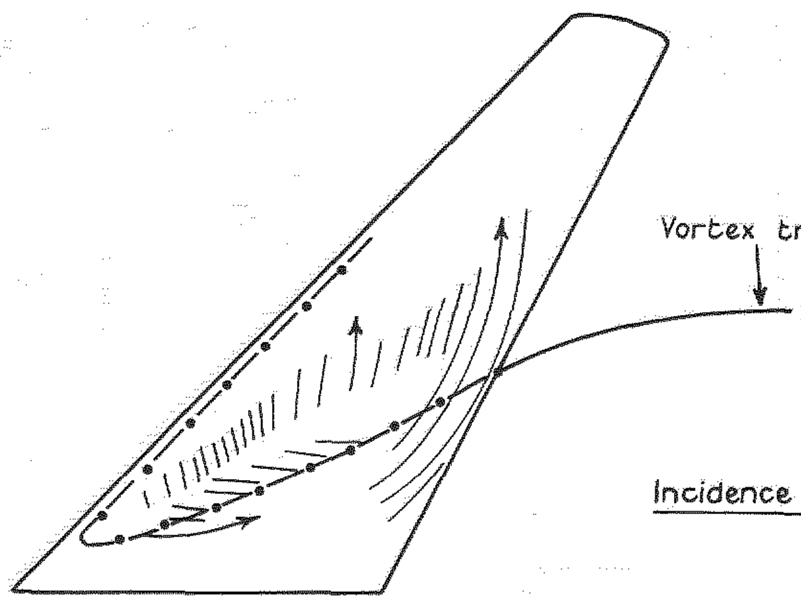
Air bubble on suction surface at 15° incidence

FIG. 12.



Oil pattern on suction surface at 15° incidence.

FIG. 13.

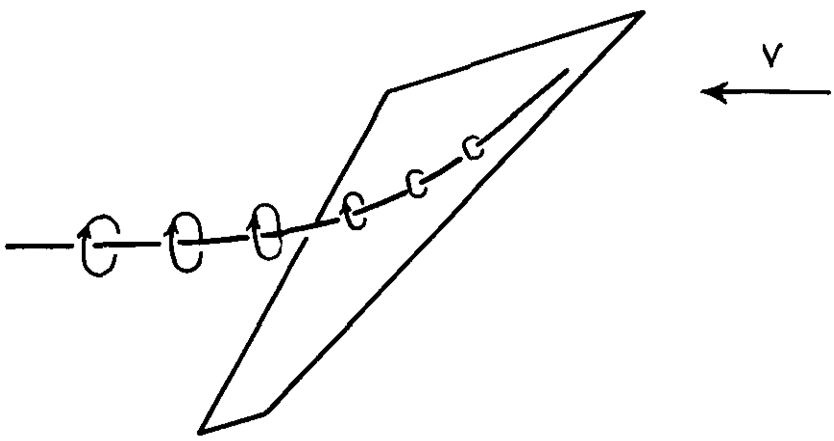


Outline of air bubble.
Other lines on wing indicate directions of oil flow.

Comparison of air bubble with oil pattern.

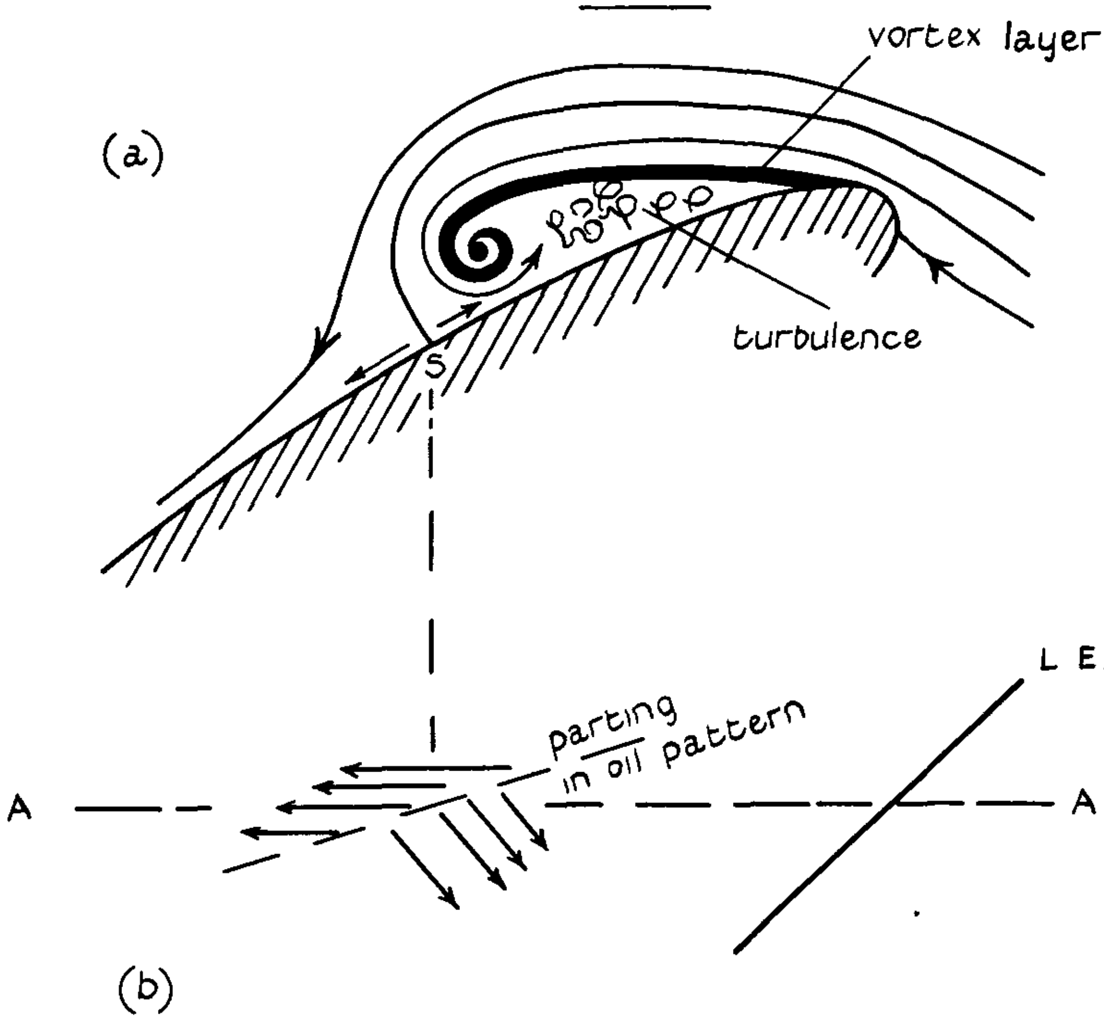
FIGS 14 & 15

FIG 14.



Position of discrete vortex

FIG 15



Suggested structure of separated region

FIG. 16. 9° incidence

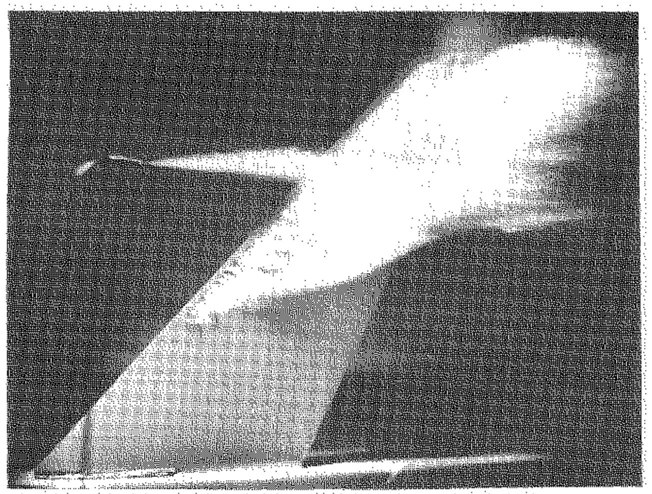


FIG. 17. 10½° incidence

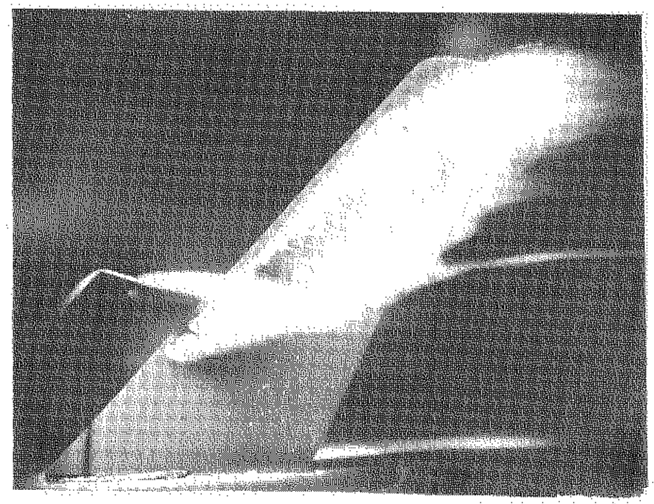


FIG. 18. 18° incidence

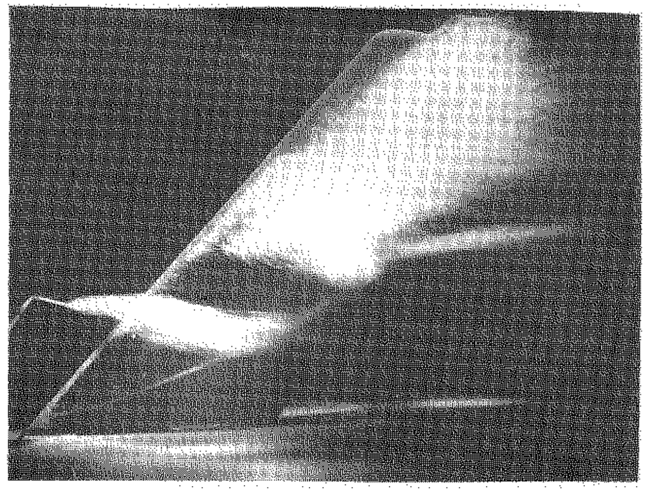
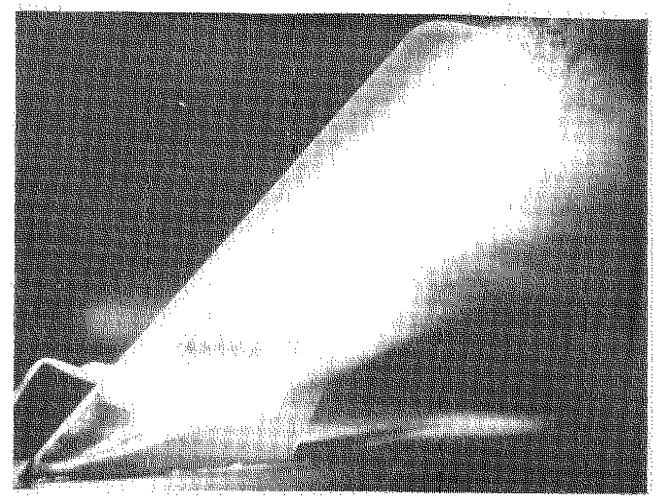


FIG. 19. 21° incidence



Figs. 16, 17, 18 and 19. Air bubbles on suction surface at various incidences.

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