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Wind-Tunnel Observations of Boundary-Layer Transition on a Wing at Various Angles of Sweepback

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Summary.—Visual observations have been made of boundary-layer transition on a wind-tunnel model of constant chord at zero lift over a range of sweepback angles from zero to 50 deg. At each angle above 25 deg, a critical speed could be found within the speed range of the tunnel (400 ft/sec) at which striations appeared within the laminar boundary layer, while the transition line itself lay at 50 per cent to 60 per cent chord. As the speed was further increased, transition started to move forward, finally occurring close to the leading edge. The wind speed at which the striations appeared and the forward movement of transition started, decreased with increasing angle of sweepback.

1. *Introduction.*—Visual observations made in flight indicated that sweepback may have a powerful destabilising effect on laminar boundary-layer flow ; it was found that above a certain forward speed, depending on the section shape and sweepback angle, laminar boundary layers could not be maintained aft of the wing leading edge. The tests described in this report were made on a wing of constant chord, in order to study systematically the effect on boundary layer transition of variations in sweepback angle and wind speed.

2. *Model Details.*—The wing was 8-ft span and 4-ft chord, rectangular in plan-form at zero sweep. The section was symmetrical, 15 per cent thick normal to the leading edge, with maximum thickness at 40 per cent chord ; the nose radius was 0·8 in. There was a line of pressure holes in the wing; the pressure distribution† as measured in the course of the present tests is shown in Fig. 1.

The wing was mounted at zero incidence, projecting through the floor of the No. 2, $11\frac{1}{2}$-ft Wind Tunnel of the Royal Aircraft Establishment, and the angle of sweepback could be varied from 0 deg to 50 deg by rotating the wing about a centre just below floor level. The gap between the wing and the floorboards was roughly sealed ; complete sealing of the gap in specific cases did not appear to alter the observed flow. The rig is shown in Fig. 1.

The tests were made during April and May, 1952. The wind speed varied between 100 and 400 ft/sec. The corresponding variation in Reynolds number, referred to the chord normal to the leading edge, was from $2·5 \times 10^6$ to 10×10^6.

* R.A.E. Tech. Note Aero. 2170, received 16th July, 1952.

† The velocity distribution normal to the leading edge (U/U_0, where U is the velocity on the wing just outside the boundary layer and U_0 is the velocity component normal to the leading edge, in the undisturbed stream) was hardly affected by sweepback.

One side of the wing had been given a smooth black finish, and was sprayed with china clay. Both paraffin and oil of wintergreen were used as indicators on the china clay.

3. *Test Results.*—3.1. *Variation of Transition Position with Wind Speed and Angle of Sweepback.*—With the wing set at a given angle of sweepback, paraffin was rubbed on to the china clay surface and the tunnel was run at a constant speed until the position of the boundary-layer transition showed by full evaporation (light) in the turbulent region, and partial evaporation (dark) in the laminar region. Full evaporation always occurred near the leading edge, even when the boundary layer was laminar, because of the high skin friction in that region.

Because the intermediate speeds, which were passed through while the tunnel was running up, sometimes left their own boundary-layer patterns, thus confusing the picture, air was normally blown out into the air stream through one of the surface pressure holes after the steady test speed had been reached. The wedge of turbulent flow so formed showed the true extent of the surrounding laminar region.

Photographs of some of the flow patterns obtained are shown in Fig. 2. The camera was mounted outside the tunnel and ahead of the model, so that, in the pictures, the perspective gives the wing the false appearance of being tapered when highly swept. In most cases, the paraffin was spread as far aft as the flap hinge-line (which was at 75 per cent chord), but sometimes only the front part was covered. This accounts for the sharp discontinuity showing in the photographs for 40-deg sweep, $V = 300$ and above ; the true transition region can be seen further forward. By the time the wing was set at 50-deg sweep, the china clay had worn thin, and dark spanwise streaks were visible on the surface after the paraffin was applied (*see* Fig. 2, $V = 225$, $\Gamma = 50$ deg).

The observations recorded are those for the mid-span part of the wing. For the top two or three feet, tip effects caused a small forward movement of transition when the wing was swept back. Near the tunnel floor, transition was a little further aft than over most of the span, presumably owing to the fact that the flow near the floor resembles that near the centre of a swept-back wing where the spanwise velocity component vanishes.

The results are given in Table 1 and are plotted in Fig. 3 as the variation of transition position with wind speed, for each angle of sweepback. It can be seen that at low speeds, the transition line was clearly defined in the region of 65 per cent chord from the leading edge, for all angles of sweepback.

For the unswept wing, the transition line moved steadily forward from 65 per cent chord at low speed to 45 per cent chord at the highest tunnel speed available—about 400 ft/sec.

With 25-deg sweepback, the picture was identical with that for the unswept wing, within the range of wind speeds covered in the experiment.

With 30-deg sweepback, the behaviour was the same up to 350 ft/sec, which was the highest speed used in this case.

For 35-deg, 40-deg, 45-deg and 50-deg sweepback, the transition line moved forward as wind speed increased, the effect occurring earlier and becoming more sudden as the angle of sweepback became larger.

Owing the high relative rate of evaporation of the paraffin close to the model leading edge, it was impossible to trace the movement of transition right up to the leading edge, but it can be seen that transition was definitely occurring within a few per cent of the nose by 400 ft/sec for the 40-deg wing, by 320 ft/sec for the 45-deg wing, and by 250 ft/sec for the 50-deg wing.

As the transition line moved forward, the laminar boundary layer became more and more sensitive to the surface condition, as shown by the increasing number of wedges of turbulent flow starting inside the laminar region. Sometimes these occurred as thin lines of uniform width extending for 5 to 10 per cent chord in the stream direction before opening out into the normal wedge shape. Some of these disturbances could be traced to surface irregularities or minute particles of dirt or one of the surface static holes fitted in the model*. The transition line in these cases has been defined by the furthest aft limit of laminar flow that could be recognised in between the turbulent wedges. In some cases where transition was well forward it became difficult to establish its exact position even with repeat runs.

When the wing was swept back at 35 deg, 40 deg or 45 deg and the wind speed had increased to a value that made the transition line move forward to the region of 20 per cent chord, the wedges caused by random disturbances on the wing surface were largely replaced in the picture by a regular saw-tooth pattern of small wedges, with apices at about 7 per cent chord, uniformly spaced at about 1-in. pitch spanwise, and with apex angles rather less than was usual with normal turbulence wedges. Some such cases can be discerned in the photographs in Fig. 2.

3.2. *Striations Observed in the Laminar Boundary Layer.*—Having established that the position of boundary-layer transition moved forward in the manner described above, it was obviously important to make any further tests which might help to discover why. A theoretical study of this problem had suggested that the instability was of the dynamic type and was not due to amplified Tollmein-Schlichting waves. If it were the former, a regular pattern of vortices coincident with the streamlines near the outer edge of the laminar boundary layer ought to have appeared above a certain Reynolds number at a given angle of sweep. The paraffins used in the tests of section 3.1 had failed to show these up. However, in a concurrent test proceeding at the National Physical Laboratory on a yawed wing, the vortex traces had been made visible as striations by the evaporation of oil of wintergreen on china clay. This technique was therefore employed on the R.A.E. model in the following tests.

At each angle of wing sweepback, the tunnel was run at a series of wind speeds as before, and the normal picture of boundary-layer transition occurred in agreement with the paraffin tests of section 3.1. As each test run continued, this picture naturally faded considerably, and at low wind speeds the result was that the wing had a diffused granular appearance, which consisted of very short lines or grains lying along the direction of the air stream. This pattern had no connection with the striations sought, because it also appeared at zero sweepback when no vortex traces could exist. As the wind speed of successive tests was raised, a critical value was attained at which vortex traces were first discernible to the naked eye, superimposed on the background ' grain '; this background made it very difficult to obtain the value of the critical speed accurately†.

As the test speed was increased further, the striations rapidly became much clearer, but did not appear to alter their geometry in any way. They started as far forward as could be seen (about 5 per cent chord) and reached back through the laminar layer to the region of the transition line, where they became diffused.

Fig. 4 shows a photograph of the striations in a test on the 50-deg wing at a wind speed of 160 ft/sec. The striations had first become visible in this case at 140 ft/sec. The unevenness in the rate of evaporation of the wintergreen from different parts of the surface was due to lack of uniformity in the original spraying of the wing with china clay, and in the subsequent spraying with wintergreen. However, enough lines were visible to give a clear answer.

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* Some of the wedges are those caused deliberately by blowing air out of the static holes, as already explained.

† The critical speed could be confirmed from subsequent tests at a higher speed by seeing if the striations became any more definite, but it was found impracticable to approach the critical speed from above in the first place because there was a tendency for the ' past history ' of previous tests to appear in subsequent runs, even though a thorough drying out of the surface was attempted in between tests.

The fact that the normal transition picture had to evaporate and the wing be nearly dried off before the striations would appear, does not mean that the formation of the striations was a delayed action, but that the rate of evaporation associated with them was nearly equal to that in the surrounding laminary layer.

The striations consisted of parallel lines about $\frac{1}{10}$ in. or $\frac{1}{8}$ in. apart. The pattern was remarkably regular apart from an occasional line slightly thicker and darker than the average. In the area where they were visible they were very nearly straight, and inclined slightly inwards away from the wing tip. At 50-deg sweepback a rough measurement gave a 5-deg inclination of the lines from the free-stream direction, that is, the same order of angle as that of the streamline inclination outside the boundary layer.

The critical velocities at which the striations were first considered to appear are summarised for the various angles of sweepback in Table 2, and are plotted in Fig. 5. It will be seen that the striations appear at roughly half the wind speed necessary to bring transition right forward to the leading edge. Comparing with Fig. 3, we see that these critical speeds do in fact roughly mark the points at which transition starts to move forward from the ' datum ' position defined by zero sweepback. This illustrates the argument that the vortices, of which the striations are a sign, are the prime cause of the premature forward transition. The vortices disintegrate to give a turbulent flow and presumably the disintegration occurs progressively nearer the leading edge as the wind speed increases.

4. *Summary of Conclusions.*—Wind-tunnel tests at zero incidence have confirmed the observation originally made in flight that wing sweepback may have an adverse effect on the position of boundary-layer transition ; in some cases sweepback caused the position of transition on the model to move forward close to the leading edge.

At low wind speeds, transition occurred in the region of 65 per cent chord at all angles of sweepback tested (up to 50 deg). Above 30-deg sweep, a critical wind speed could be found at which striations appeared inside the laminar boundary layer. There was no immediate corresponding effect on transition position but, as wind speed was increased, the striations grew stronger and transition moved forward. The greater the angle of sweepback, the lower the critical speed, and the more sudden the forward movement of transition. At a wind speed roughly double that at which the striations were first apparent, transition had moved forward to the leading edge.

The results support the suggestion that the laminar boundary-layer instability is of the dynamic type leading to the formation of vortices which ultimately break up to give turbulence.

TABLE 1

Observed Position of Boundary-layer Transition

given as a percentage of the chord from wing leading edge.

Γ = sweepback angle, degrees. V = tunnel wind speed, ft/sec

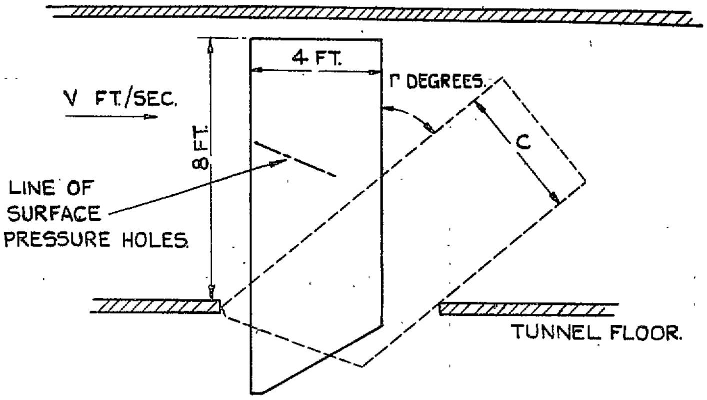
Γ (deg)	$V = 80$	100	122	150	200	220	243	250	290	320	350	390
0	—	—	—	—	61	—	—	—	—	—	48	45
25	—	65	—	—	60	—	—	58	55	—	47	45
30	—	—	—	—	60	—	—	—	55	—	47	—
35	—	—	—	—	61	—	—	52	32	—	30	14
40	—	65	—	61	55	—	—	43	22	—	15	8
45	—	65	62	60	50	—	—	28	14	*		
50	65	65	—	56	42 30	25	15	*				

TABLE 2

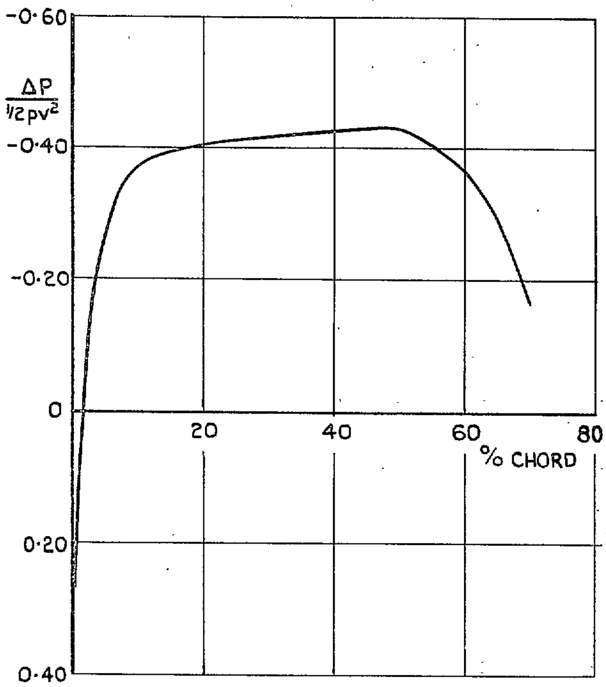
Critical Velocities at which Striations First Appeared

Sweep angle (deg)	Wind speed (ft/sec)	
	Striations first visible	Transition near wing L.E.
30	280—300	—
35	190—210	—
40	150—170	400
45	140—160	320
50	140	250

* Means that transition was ahead of 5 per cent—actual position unknown because of high rate of evaporation of paraffin near wing leading edge.



ARRANGEMENT OF MODEL IN TUNNEL.



POSITION x/c	POSITION S	$\Delta P / \frac{1}{2}\rho v^2$
0	0	0·978
0·83	0·87	0·206
1·67	1·35	-0·005
2·50	1·81	-0·118
3·33	2·27	-0·195
4·17	2·73	-0·247
5	3·18	-0·268
10	5·62	-0·374
20	10·43	-0·408
30	15·24	-0·417
40	20·03	-0·426
50	24·78	-0·433
60	29·64	-0·367
70	-	-0·161

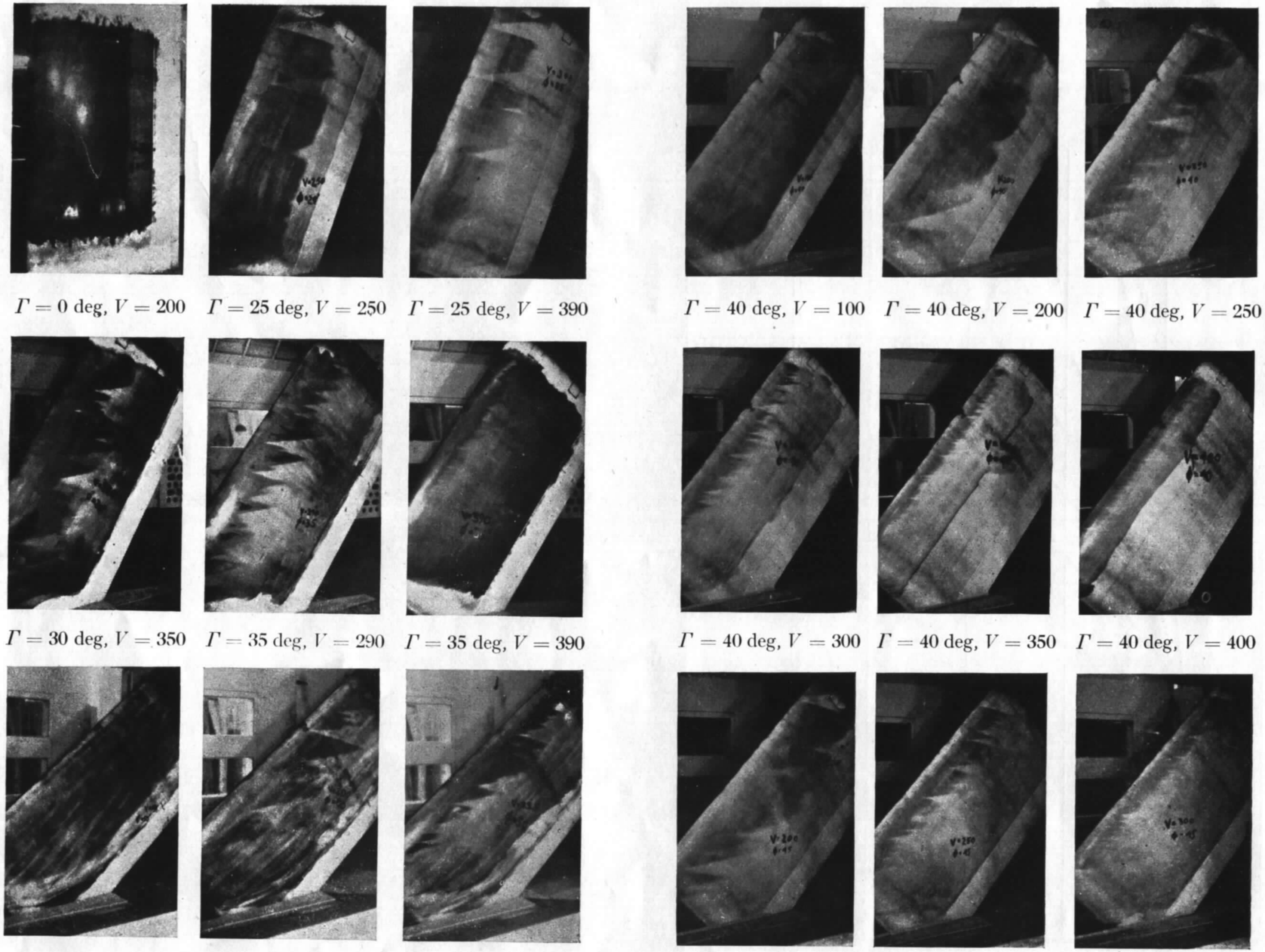
SURFACE PRESSURE DISTRIBUTION AT ZERO SWEEPBACK.

x/c = PERCENT CHORD DISTANCE FROM L.E.

S = DISTANCE IN INCHES MEASURED ROUND SURFACE.

C = CHORD NORMAL TO L.E. = 4 FT.

FIG. 1. Model rig and wing surface pressure distribution.



$\Gamma = 0$ deg, $V = 200$ | $\Gamma = 25$ deg, $V = 250$ | $\Gamma = 25$ deg, $V = 390$ | $\Gamma = 40$ deg, $V = 100$ | $\Gamma = 40$ deg, $V = 200$ | $\Gamma = 40$ deg, $V = 250$

$\Gamma = 30$ deg, $V = 350$ | $\Gamma = 35$ deg, $V = 290$ | $\Gamma = 35$ deg, $V = 390$ | $\Gamma = 40$ deg, $V = 300$ | $\Gamma = 40$ deg, $V = 350$ | $\Gamma = 40$ deg, $V = 400$

$\Gamma = 50$ deg, $V = 100$ | $\Gamma = 50$ deg, $V = 200$ | $\Gamma = 50$ deg, $V = 225$ | $\Gamma = 45$ deg, $V = 200$ | $\Gamma = 45$ deg, $V = 250$ | $\Gamma = 45$ deg, $V = 300$

FIG. 2. Transition patterns. Γ = angle of sweepback. V = wind speed, ft/sec

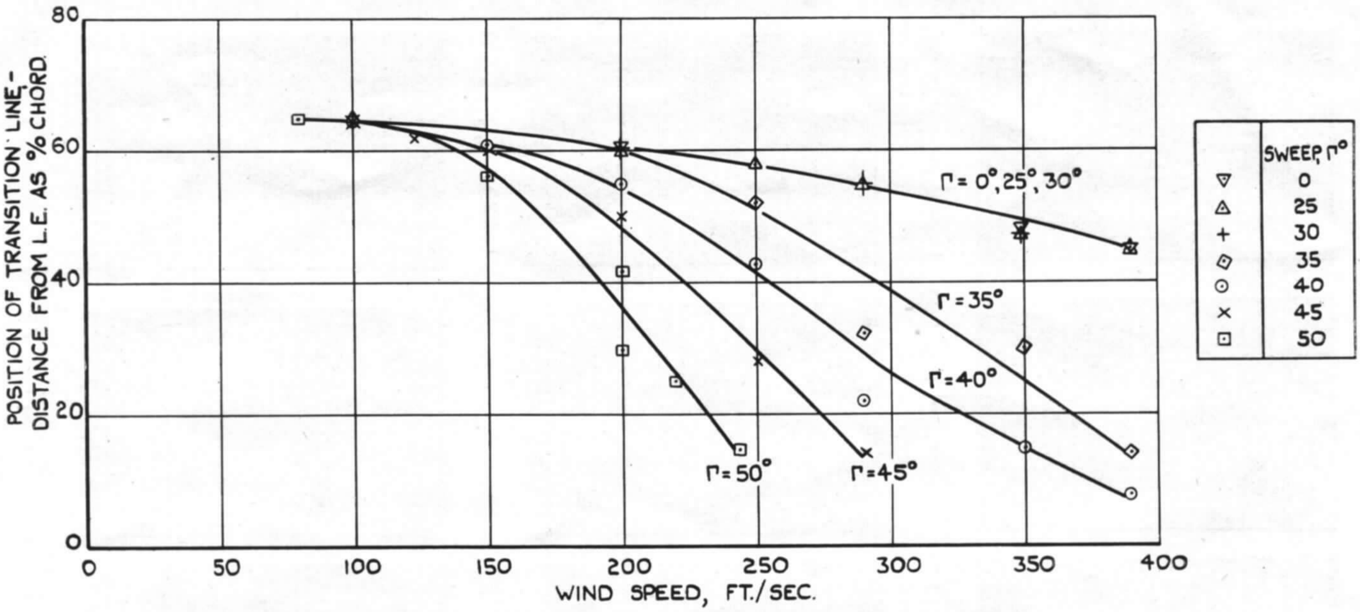
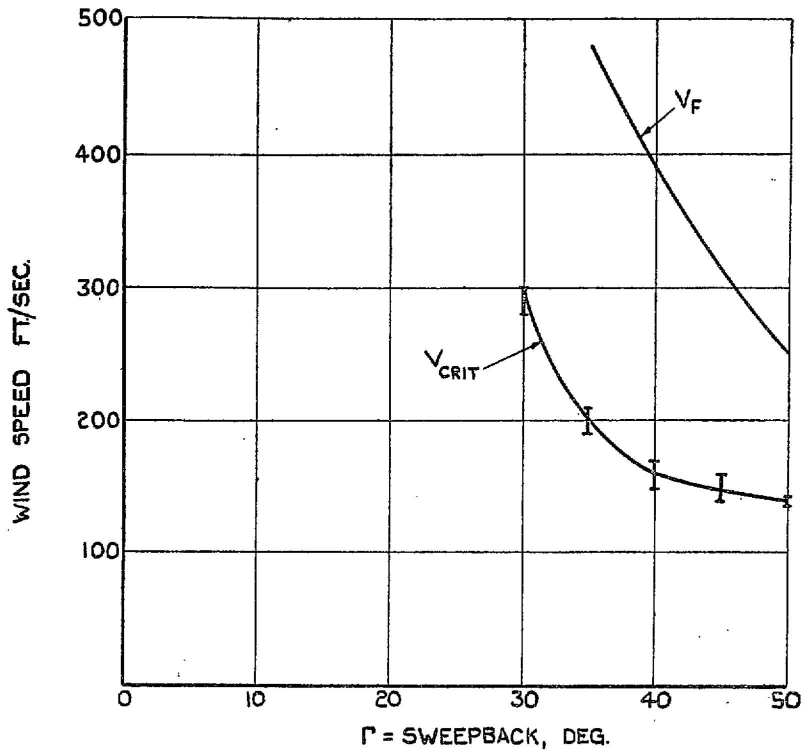


FIG. 3. Effects of wind speed and wing sweepback on transition.

FIG. 4. Striations in laminar boundary layer. $\Gamma = 50$ deg, $V = 160$ ft/sec, transition at 55 per cent chord.



V_{CRIT} = OBSERVED SPEED AT WHICH STRIATIONS FIRST APPEARED (SEE TABLE II)

V_F = SPEED AT WHICH TRANSITION WOULD BE FORWARD TO ABOUT 5% CHORD FROM L.E., EXTRAPOLATED FROM FIG. 3.

FIG. 5. Effect of sweepback on critical velocity at which striations first appear.

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