950

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 988

OBSERVATIONS OF THE EFFECT OF WING APPENDAGES AND FLAPS ON THE SPREAD OF SEPARATION OF FLOW OVER THE WING

By G. Hartwig

Luftfahrtforschung
Vol. 18, Nos. 2-3, March 29, 1941
Verlag von R. Oldenbourg, München und Berlin

Washington
September 1941

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 988

OBSERVATIONS OF THE EFFECT OF WING APPENDAGES AND FLAPS ON THE SPREAD OF SEPARATION OF FLOW OVER THE WING*

By G. Hartwig

SUMMARY

The spread of the separation of flow on three tapered wings in symmetrical and unsymmetrical flow was observed with silk tufts. By equal thickness and chord distribution the wings manifested a different form of lifting line. One of the wings - with twist and dihedral - was, in addition, explored with fuselage, engine, nacelles, and flaps deflected. The principal result of the study was that the wings of themselves alone first disclosed complete breakdown of flow at the tips, even the one with twist, but that after adding fuselage and engine nacelles, the twisted wing broke down first completely in wing center. The observed boundary layer motions transverse to the main flow direction were briefly explored as to their possible influence on the spread of the separation. On top of that certain disclosures were afforded in which the transverse motions observed in the boundary layer become perceptible even above the boundary layer.

While the relationship between breakdown of flow and contour and twist has been experimentally studied by various sources, there is little data on the breakdown of flow over the wing in the presence of appendages such as fuselage, engine nacelles, or deflected flaps within the practical range of spans. In the course of development of the Focke-Wulf-FW 200 (Condor) wind tunnel tests were made on the breakdown of flow on several wings of identical chord distribution but dissimilar course of the lifting line, and extended on one wing to the case of appended fuselage, engine nacelles and flaps deflected. The results are hereinafter described.

---

*"Beobachtung des Einflusses von Flügelanbauten und Klappen auf den Abreissverlauf der Tragflügelströmung." Luftfahrtforschung, vol. 18, no. 2-3, March 29, 1941, pp. 40-46.

INTRODUCTION

The problem which was to be solved by the present test series is to be so understood that by consecutive observation of the wing flow in relation to positive angle of attack critical areas were to be detected in order to obtain first of all qualitative data on the changes in the flow. On top of that, the closest possible sequence of the observations were to furnish qualitatively appraisable results.

From the practical point of view the most convenient method of observing flows is by means of tufts; although the question is justified to what extent a tuft is, after all, in the position to indicate with sufficient accuracy a critical flow process, such as the start of separation of flow. So far as the tuft on the upper surface is not fastened too close to the nose of the wing, it is located on modern airfoils at a thickness of 0.3 to 0.5 millimeter and the model chords and air speeds customary in average wind tunnels imbedded in the boundary layer, and specifically in the presence of severe tunnel turbulence, small vibrations and roughnesses already outside the laminar approach in the turbulent boundary layer and in part in the ever present laminar sub-layer beneath. Struck by the flow the tufts become taut and adhere smoothly to the surface if the flow is sound. At the starting point of the separation the character of the velocity field in the boundary layer undergoes a radical change, since it is the very zone in which the reverse flow begins, hence in which considerable vortex formation prevails. If, then, the end of a tuft extends into this zone, it follows this vortex motion and begins to flap. If the whole tuft is in the separation zone, its motions become so violent that it frequently becomes entangled. In this manner the travel of the separation zones can be followed with serviceable accuracy. Taking into consideration the limit set by adequate visualization itself, the tufts can be very fine and fastened direct to the surface without detracting from the indication of the separation region. The finer and more flexible the tufts and the more carefully their attachment to the surface, the smaller the disturbances which the boundary layer development itself undergoes because of the tufts.

The changes in the curve of the lifting line of the explored wing models approximately comprises the limits normally set by practical design and manufacture.

TEST MODELS AND PROCEDURE

Altogether three tapered wing sections with identical chord distribution were explored (fig. 1). The sections are derived from the NACA 22 series of airfoils (reference 1); their thickness ratio is shown in figure 2. The two tapered wings with straight leading and trailing edges had zero twist and zero dihedral, whereas the third had twist and dihedral and, in addition, ailerons and split flaps (figs. 1 and 2), to which fuselage and engine nacelles were added later on (fig. 3). The models were made of well polished gypsum over steel-zinc framework.

The suspension followed the standard Göttingen practice (reference 2). The span amounted to 1.320 meters, which is equivalent to about 63 percent tunnel width. A description of the employed tunnel plant can be found in reference 3.

The tuft material was silk fiber, divided once more into two threads, thus affording a very fine and extremely flexible tuft of good visibility on the brown wing surface. The individual tufts were about 20 millimeters long and fastened together by means of Scotch tape so that they did not interfere with each other or become entangled (figs. 16 to 26). A miniature movie camera with 1/25 second exposure was used in connection with two Nitra photo lamps by 1:3.5 objective luminous intensity.

TEST PROCEDURE

The tests were made at about 32 meters per second air speed. Exclusive of the tip-forming strip the chord changed across the span from 80 millimeters outside to 212 millimeters inside and hence the Reynolds number of the measurement from 1.79×10^5 to 4.75×10^5, and the effective Reynolds number from 2.68×10^5 to 7.12×10^5. On the tapered wings with straight leading and trailing edges the geometric angle between chord and tunnel axis served as angle of attack α, on the third wing, the angle between the reference axis of the subsequently appended fuselage and the tunnel axis. Thus the angle-of-attack data in figures 4 to 15 and 16 to 26 make no allowance for the errors due to the jet boundaries. The setting of the reference axis of the appended fuselage relative to the chord at wing center amounted to 2.5° downward.

The test procedure was such that in the angle-of-attack range for normal flow the angles were changed at 6° each; but if separation phenomena occurred, each subsequent optically determinable change was recorded and the respective angle of attack defined. The experiments were made in symmetrical flow and at $\tau = 9°$ angle of yaw, by which is meant the angle between plane of symmetry of model and vertical tunnel plane of symmetry. In the flap tests the split flaps were deflected 60° and the inboard plain ailerons 40°. No propellers were used in the tests with fuselage and engine nacelles.

RESULTS

Three distinct tuft conditions were observed:

1. The entire tuft clings quietly and smoothly to the surface: indicating adhering flow.

2. The tip of the tuft moves while the rest still adheres smoothly: a sign of incipient separation at the tip of the tuft.

3. The whole tuft flaps violently: a sign that the tuft is in completely separated flow.

The photographic records were interpreted from the same points of view. The individual separation zones are shown as shaded areas in figures 4 to 15. The position of the model mounting stirrup is indicated. According to the pictures the separation on the wings without appendages or flap deflection always starts on the trailing edge in the vicinity aft of the forward mounting stirrup, which probably is the cause of breakdown. This presumption was not experimentally verified for lack of time.

The separation of the two tapered wings with straight leading and trailing edges shows no undue differences (figs. 4 and 6). Proceeding from the separation areas behind the suspension, the separation spreads over the trailing edge and beyond until ultimately one of the tips separates completely. In leading-edge direction the separation spreads most prominently on the separation areas. It seems as if the wing with straight leading edge were a little more uniform and more propitious, although it is pointed out that unavoidable minor discrepancies in model manufacture and a certain inhomogeneity of the air stream can easily obscure the differences between two wings, as will be shown later on.

In yawed flow the separation spreads similarly as in symmetrical flow, except that the separation is shifted more toward the rearward located wing tip. Here also the wing with straight trailing edge appears to be a little more propitious.

In the analysis of the wing with twist and dihedral (fig. 8) its angle of attack data, it should be remembered, are referred to the reference axis of the subsequently appended fuselage. The chord of the center section had therefore 2.5° more setting than the values in figure 8 indicate. The separation corresponds to that of the other wings, and spreads quite uniformly over the two wing halves; here also the wing tips are first completely separated, despite the twist. In this respect it should be noted that, in contrast with the tapered wing without twist, the one with twist had ailerons and flaps as added sources of disturbance. The force measurements previously made without tufts approximately agree with the tuft observations, so far as the angle of attack for maximum lift is concerned. The maximum lift of the twisted wing was slightly higher than that of the straight wing, while the straight wings among themselves manifested identical maximum lift. The respective angles of attack (α not corrected) referred to center section chord were 17.7° (twisted) and 17° (straight). To be sure, a more exact procedure would have been to measure the forces with tuft superposition also; but lack of time must serve as excuse here also.

In yawed flow (fig. 9) the twisted wing shows, apart from the behavior similar to that of straight wings, the effect of the dihedral. Now the flow separates first completely on the advancing tip.

The twisted wing with flaps deflected (split flaps 60°, plain trailing-edge flaps 40°) (fig. 10) shows the previous separation of the tips very plainly. In yawed flow (fig. 11) the effect of the dihedral is still perceptible even though to a lesser degree than on the wing without flap deflected.

The most essential result so far is that the three explored wings taken by themselves fail to meet the requirements from the point of view of lateral controllability in the vicinity of maximum lift. This quite hopeless result anticipated changes, however, completely in the presence of appendages of the explored type. Unfortunately, the straight wings could not be studied with appendages in the prescribed test program.

In figure 12 the twisted wing is fitted with fuselage and four engine nacelles. Now the separation does not start so unequivocally solely behind the suspension stirrup but also in the diffusers between wing and fuselage. Proceeding from these areas, the separation zone spreads sidewise and forward, but in such a manner that in the region of maximum lift the flow on the outboard wing still remains sufficiently sound and the inner section first separates completely. The disturbance on the right outboard wing is apparently due to an undetected error in a tuft attachment. It also occurs in the subsequent series.

In yawed flow (fig. 13) the propitious tendency, to separate first in the center, remains, likewise when the flaps are deflected (split flaps 60°, plain trailing-edge flaps 40°) (figs. 14 and 15).

As concerns the boundary-layer motions transverse to the direction of flow, the wing with straight trailing edge manifested very little unsymmetrical flow, and especially toward the center, while on the wing with straight leading edge a quite noticeable transverse flow growing with the angle of attack was observed. The tufts were deflected toward the center, probably in consequence of a pressure gradient, the cause of which, as evinced by the dissimilar behavior of the two wings, among other factors not entering the discussion, might be found in the mutual displacement of the individual profiles across the span. The effect of the transverse flow is a transport of boundary layer material from the outboard wings toward the inside. In this manner the separation is delayed outside and therefore more propitious; but the discrepancies are not appreciable and may, in part, be obscured by other effects as previously stated.

In yawed flow the wing with straight trailing edge also manifests a perceptible transverse direction of the tufts, inward on the advancing wing half, weakly outward on the rearward half. The attendant dissimilar boundary layer effect of the two wing halves must contribute toward the creation of differences in the separation process. As already noted, the separation shifts more toward the rearward located half.

The wing with straight leading edge manifests at 9° yaw a slight inward transverse flow on the rearward half, with respect to flow direction, while the advanced half possesses so much more inward transverse flow. Again the separation shifts more toward the rearward half, but the separation is more gradual than on the 9° yawed wing with straight trailing edge.

With regard to boundary layer transverse flow the wing with straight trailing edge presents in symmetrical as in unsymmetrical flow about the same picture as the wing with straight leading edge only in more attenuated form. Aside from certain local discrepancies, especially behind the engine nacelles, this picture remains in its basic tendency even after adding the appendages or deflection of the flaps (split flaps 60°, plain trailing-edge flaps 40°).

Another point of interest was the extent to which the flow even outside of the boundary layer would follow a pressure gradient occurring along the span. With this in mind the tuft directions in relation to the distance from the upper surface of the wing was observed in several vertical planes along the span; it was found that at higher angles of attack the tufts even outside of the boundary layer were perceptibly deflected in transverse direction, as far as 20 to 30 percent profile chord. At that level above the wing the velocity component in flow direction outweighed the transverse component so that a departure from flow direction was as good as nonexistent. Figures 16 to 18 illustrate this result by way of a suggestion.

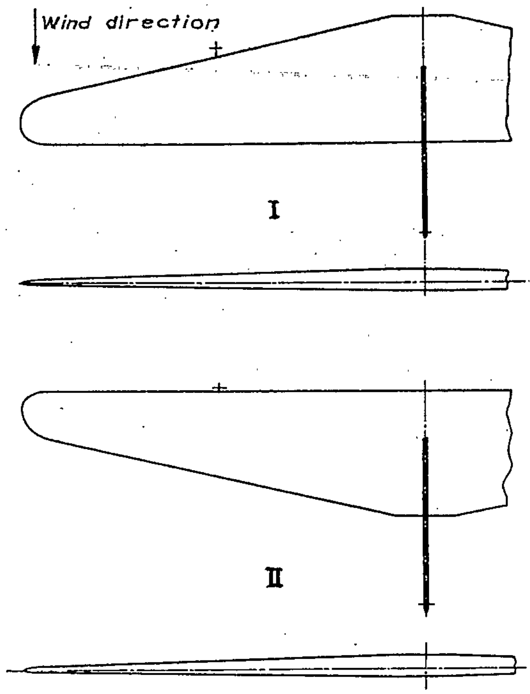
Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

REFERENCES

1. Jacobs, Eastman N., Ward, Kenneth E., and Pinkerton, Robert M.: The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel. Rep. No. 460, NACA, 1933.

2. Ergebnisse der aerodynamischen Versuchsanstalt zu Göttingen, No. I, 1921.

3. Focke, H.: Der Windkanal der Focke-Wulf Flugzeugbau, A.-G., Bremen. Z. Flugtechn. Bd. 22 (1932).



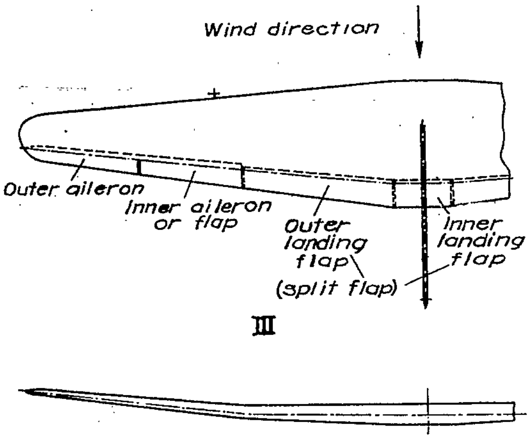


Figure 1.- Wings I,II and III.

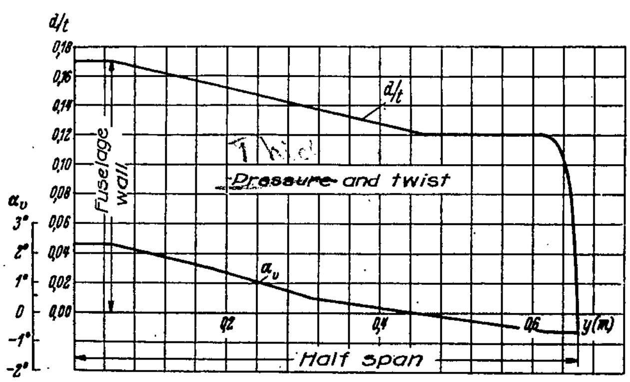


Figure 2.- Twist of tapered wing with straight 30% line and thickness curve of the three models.

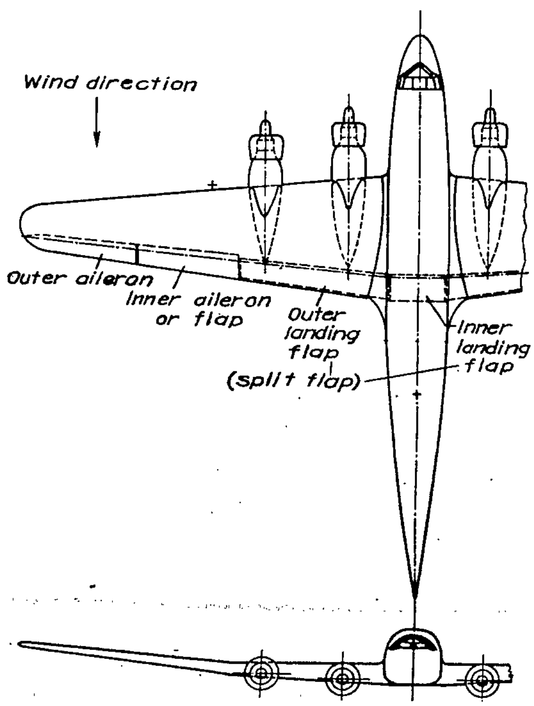


Figure 3.- Wing III with appendages.

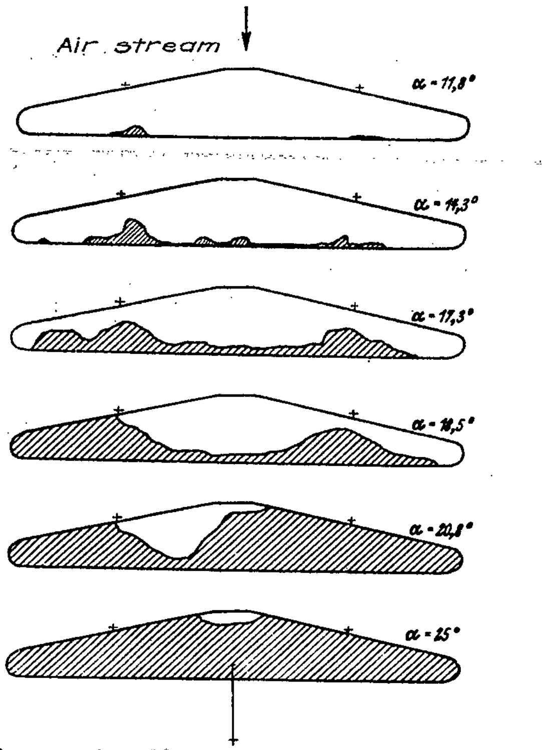


Figure 4.- Wing I, straight trailing edge, τ = 0°.

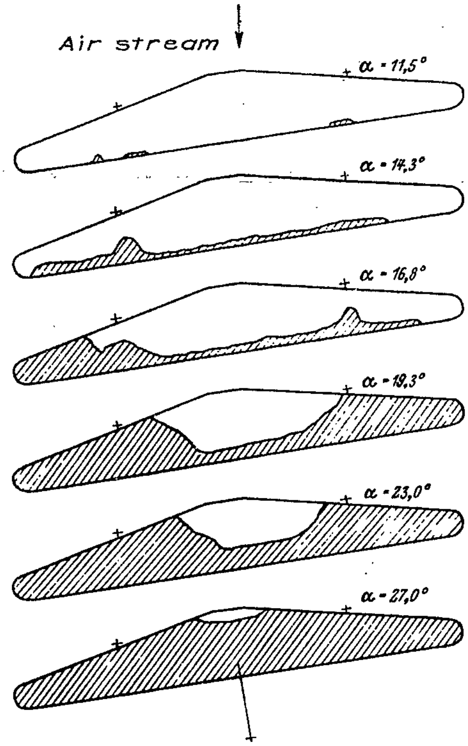


Figure 5.- Wing I, straight trailing edge, τ = 9°.

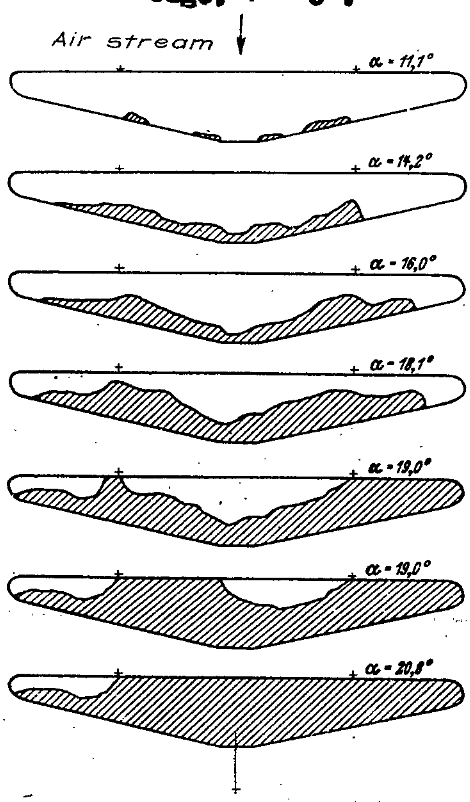


Figure 6.- Wing II, straight leading edge, τ = 0°.

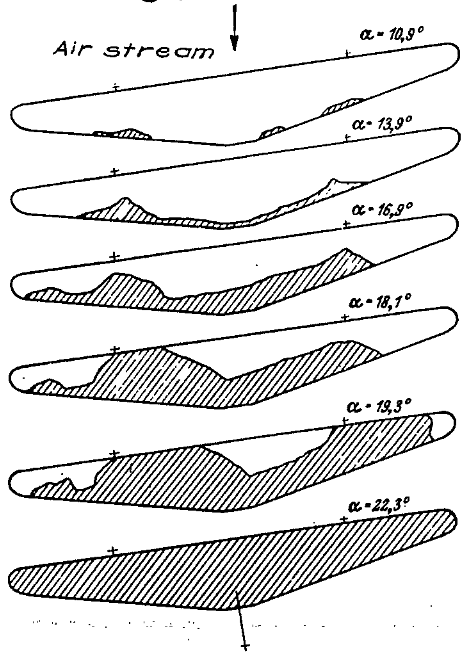


Figure 7.- Wing II, straight leading edge, τ = 9°.

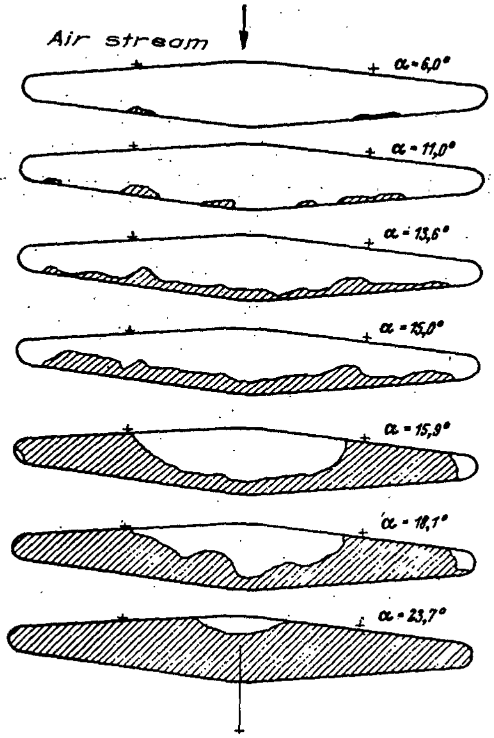


Figure 8.- Wing III, straight 30% line, twist and dihedral, τ = 0°.

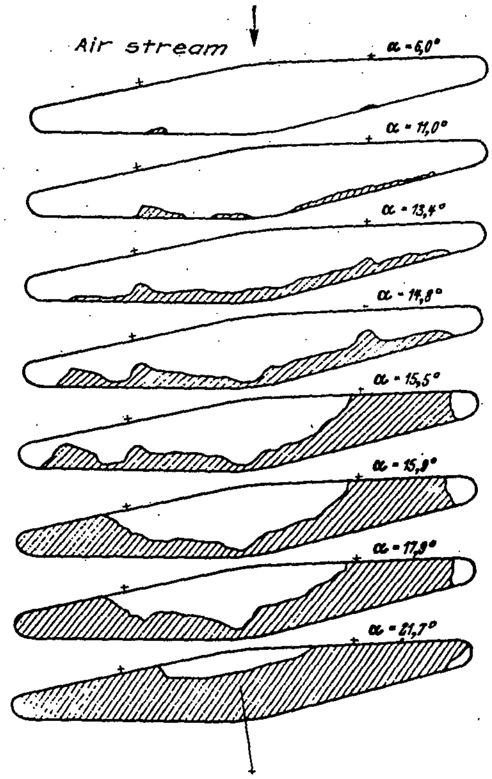


Figure 9.- Wing III, straight 30% line, twist and dihedral, τ = 9°.

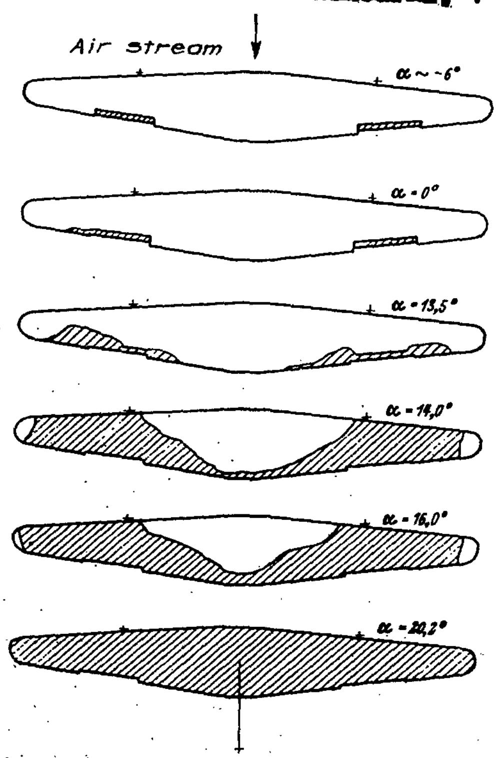


Figure 10.- Wing III, straight 30% line, twist and dihedral, flaps deflected, τ = 0°.

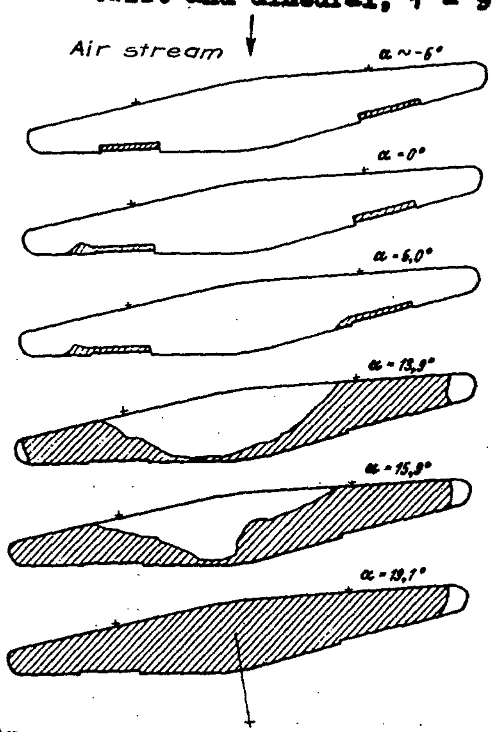


Figure 11.- Wing III, straight 30% line, twist and dihedral, flaps deflected, τ = 9°.

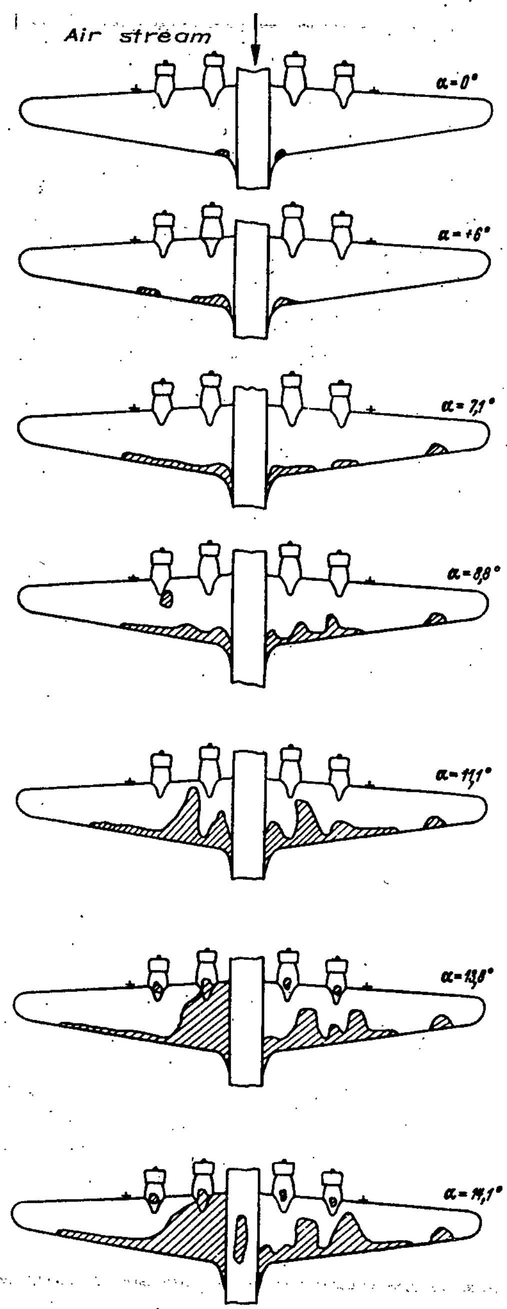


Figure 12.- Wing III with appendages, τ = 0°.

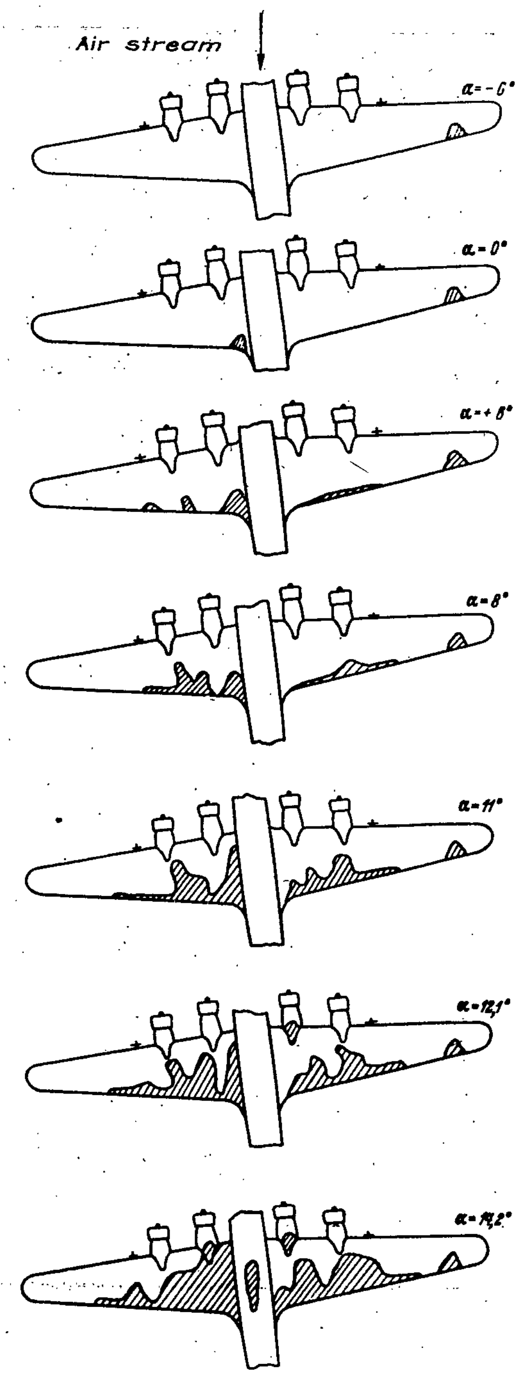


Figure 13.- Wing III with appendages, τ = 9°.

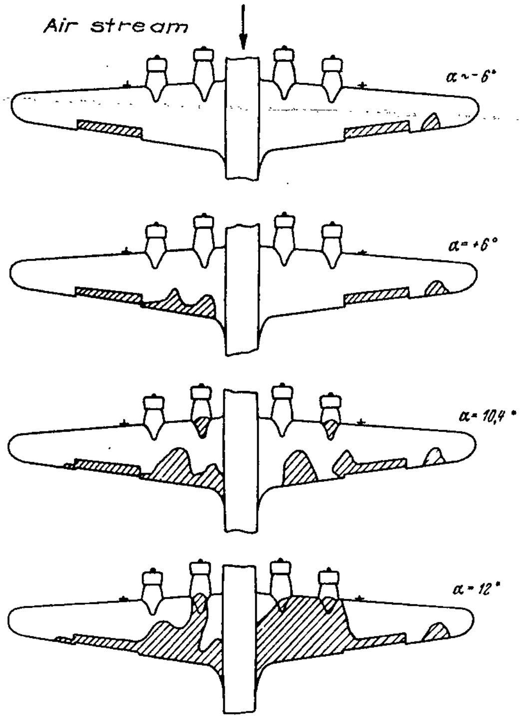


Figure 14.- Wing III with appendages, split flaps deflected, τ = 0°.

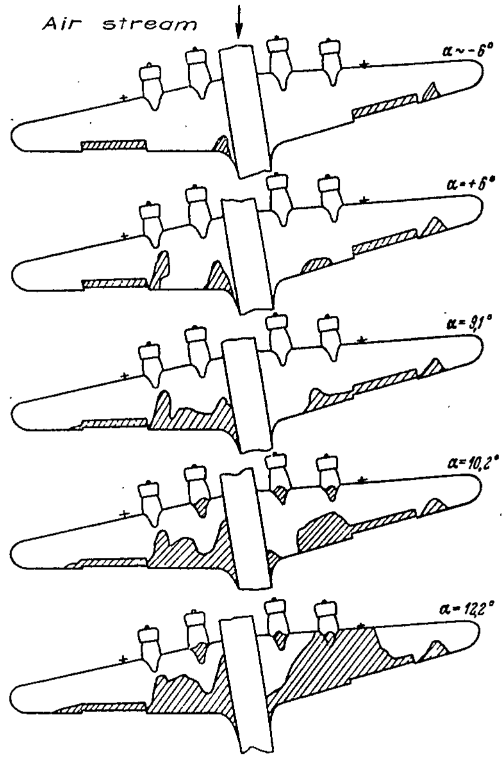


Figure 15.- Wing III with appendages, split flaps deflected, τ = 9°.

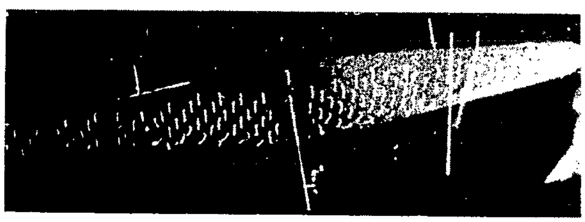


Figure 16.- Wing III, tuft survey 2 mm over upper wing surface, α = 14.5°, τ = 9°.

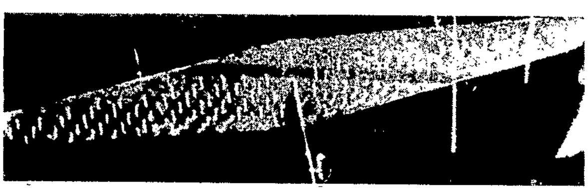


Figure 17.- Wing III, tuft survey 20 mm over upper wing surface, α = 14.5°, τ = 9°.

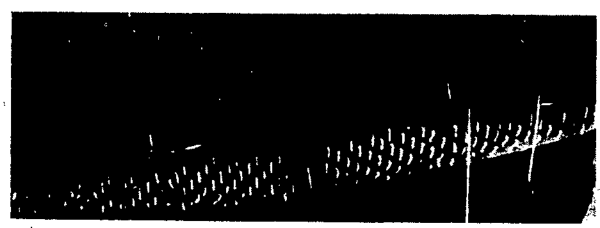


Figure 18.- Wing III, tuft survey 50 mm over upper wing surface, α = 14.5°, τ = 9°.

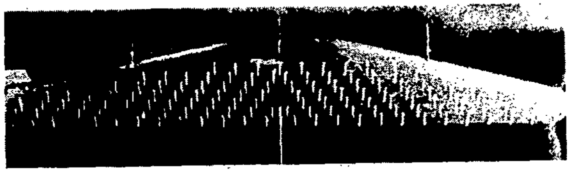


Figure 19.- Wing I, $\alpha = 11.3^\circ$, $\tau = 0^\circ$.

Figure 20.- Wing I, $\alpha = 11.5^\circ$, $\tau = 9^\circ$.

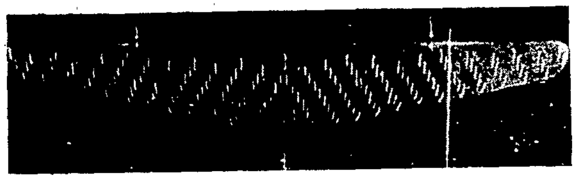


Figure 21.- Wing II, $\alpha = 11.1^\circ$, $\tau = 0^\circ$.

Figure 22.- Wing II, $\alpha = 10.9^\circ$, $\tau = 9^\circ$.

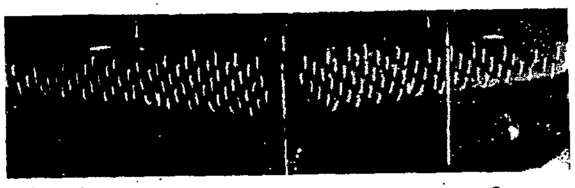


Figure 23.- Wing III, $\alpha = 11^\circ$, $\tau = 0^\circ$.

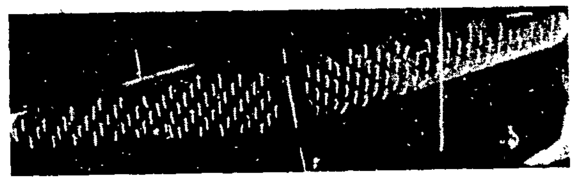


Figure 24.- Wing III, $\alpha = 11^\circ$, $\tau = 9^\circ$.

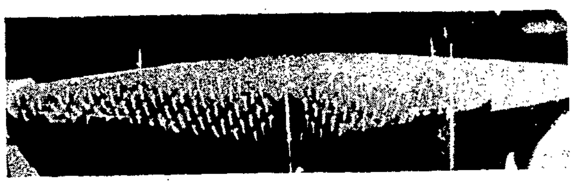


Figure 25.- Wing III, $\alpha = 13.5^\circ$, $\tau = 0^\circ$, split flaps deflected.

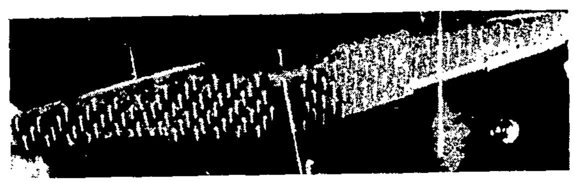


Figure 26.- Wing III, $\alpha = 6^\circ$, $\tau = 9^\circ$, split flaps deflected.