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EXPERIMENTAL INVESTIGATION OF THE FLOW ON THE SUCTION SIDE OF A THIN DELTA WING

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16. Abstract

Surface oil flow patterns have been photographed and pressure-distribution measurements have been carried out on a sharp-edged delta wing of aspect ratio Λ=1.0 in order to determine the influence of Reynolds number and of vortex breakdown on the flow on the suction side of the wing. The formation of the secondary vortex occurs due to separation of a laminar boundary layer in the front part of the wing and due to separation of a turbulent boundary layer in the rear part of the wing. In the case of turbulent separation the secondary separation line is closer to the wing leading edge than in the laminar case. The position of the transition depends on the Reynolds number and on the angle of incidence. The breakdown of a vortex above the wing leads to a kink in the secondary separation line.

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1. INTRODUCTION

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Flow already separates at low angles of attack at the leading edges of sharp edged slender wings. Vortex surfaces emanate from the separation edges which roll up over the wing into two concentric vortices. This vortex formation was already discussed in many papers. For example, D. J. Marsden, R. W. Simpson, W. J. Rainbird [1], N. C. Lambourne and D. W. Bryer [2], D. H. Peckham [3]. It is shown schematically in Figure 1a.

There is a direct relationship between the free vortices above the wing and the variation of the flow along the suction side of the wing. The two vortices induce additional velocities along the top side of the wing which have a maximum below the two vortex axes. Therefore, the pressure distribution has a minimum there. The characteristic pressure distribution in a section perpendicular to the symmetry plane of the wing is shown schematically in Figure 1b. The additional velocities caused by the vortices are directed to the side and outward along both wing halves. The wall streamlines, therefore, go to the outside along both halves of the wing. Below the vortex axis they have an inflection point because there the additional velocities are the largest.

There is a very large pressure gradient between the suction peak of the pressure distribution and the leading edge which leads to separation of the boundary layer already at very small angles of attack. Therefore, a wall streamline figure has a separation line which goes from the wing tip to the trailing edge in the vicinity of the leading edge, along which the boundary layer separates and there a secondary vortex forms. This secondary vortex is shown also in Figure 1a. Its direction of rotation is opposite to that of the additional main vortex. The secondary vortex also induces additional velocities along the top side of

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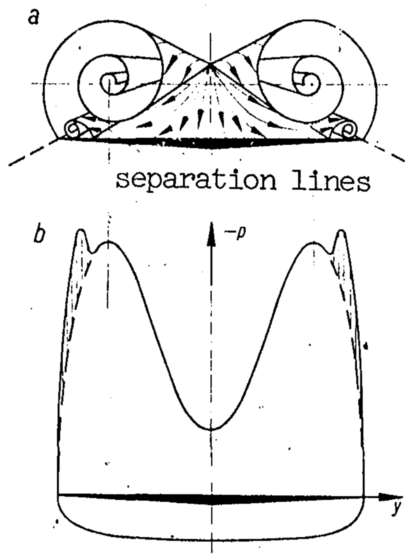


Figure 1. Flow over a sharp edge, slender Delta wing
a) vortex formation and course of the wall streamlines
b) pressure distribution over a section perpendicular to the incident flow

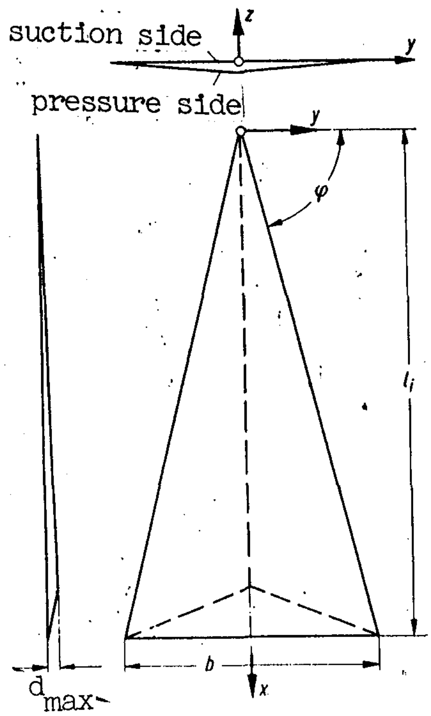
the wing. The related change in the pressure distribution is shown in Figure 1b by shading.

The course of the separation line (Figure 1a) is influenced greatly by two factors: The Reynolds number and the bursting of the vortex.

The formation of the secondary vortex can occur by separation of a laminar or a turbulent boundary layer. Since the state of the boundary layer depends on the Reynolds number, for different Reynolds numbers one would expect different forms of the secondary vortex. The first part of the present investigations /248 is concerned with this influence of Reynolds number on the course of the wall streamlines.

For large angles of attack and large sideslip angles, a structural change occurs in both free vortices, which is called bursting of the vortex (breakdown, vortex bursting). This phenomenon was already discussed in several experimental papers [4 to 10]. It was found that downstream of the so-called bursting point, the speed in the vortex center decreases substantially and there is even partial reverse flow. In [10] the effect of the bursting of the vortex on the aerodynamic properties of a slender wing was discussed. It was found that the lift, drag and pitch moment as well as the side force, roll moment and yaw moment decreased when

Figure 2. Delta wing with the aspect ratio Λ=1.0; summary
$l_i = 750$ mm, $b = 375$ mm, $d_{max} = 16$ mm (at $x/l_i = 0{,}9$)



the vortices burst over the wing. These changes of the forces and moments occur because the suction peaks of the pressure distribution are reduced in the part of the wing which is downstream of the bursting point. Since the pressure distribution along the suction side of the wing changes because of the bursting of a vortex above the wing, one would also expect a dependence of the course of the separation line on the position of the bursting point in the vortices. This relationship will be discussed in the second part of the present paper.

2. TEST CONFIGURATION AND TEST TECHNIQUE

The investigations were made in the 1.3 meter wind tunnel of the Fluid Mechanics Institute of the Braunschweig Technical University using a sharp edge Delta wing with an aspect ratio of Λ=1.0. Figure 2 gives a summary of the dimensions of the wing model. A cross-section perpendicular to the wing center line is a flat triangle. In order to measure the pressure distribution, small tubes are recesssed into the wing top side which have a large number of pressure measurement taps. A flat side of the wing was used as a suction side which in part of the experiments had a covering of a thin black foil, in order to obtain a suitable background for the paint photographs. In [10] we reported about the six component measurements on this wing.

The position of the bursting point in the vortices is determined by scanning the flow field using a stethoscope as described in [10]. We made use of the fact that downstream of the bursting point there is a sudden increase in the degree of turbulence in the vortex center. The state of the boundary layer (laminar or turbulent) over the wing was also determined using the stethoscope method. The course of the wall streamlines along the suction of the wing was made visible using a paint method. In this procedure, the wing was painted with a mixture of aluminum oxide powder in petroleum and gasoline (mixture ratio 1 g aluminum oxide with 3 cm^3 petroleum and 1 cm^3 gasoline) and it was briefly exposed to the flow.

3. RESULTS

3.1. Influence of Reynolds number on the course of the wall streamlines

Figure 3 shows paint images from the suction side of the wing. In all cases, the angle of attack was α=26.4° and the side slip angle was β=0°. The Reynolds number $Re = U_\infty l_i/\nu$ was changed by changing the incident speed U_∞. The two vortices over the wing had not burst for this angle of attack.

The paint images show the course of the wall streamlines discussed above which are directed outwards from the center of the wing along both halves of the wing because of the influence of the vortex above the wing. The separation line for all Reynolds numbers along the front part of the wing is a straight line to the tip of the wing. At a certain distance from the wing tip, which increases with decreasing Reynolds number, there is a displacement of the separation line. Behind a short transition part, separation takes place closer to the leading edge. In this rear region, the separation line is again approximately a straight line to the wing tip. Scanning of the wall boundary layer using a stethoscope shows that in the front part, a laminar boundary layer separates and a secondary vortex is formed. On the other hand, in the rear part, that is downstream of the short transition part, a turbulent boundary layer separates. A turbulent boundary layer is capable of following the pressure increase longer so that the separation line in the rear part is closer to the leading edge.

From the paint images we produced here for the angle of attack $\alpha=26.4°$, we find that the Reynolds number $Re_u = U_\infty x_u/\nu$ formed with the distance of the transition region from the wing tip x_u is constant for arbitrary incident speeds U_∞. Investigations for other angles of attack also showed this effect. Figure 4 shows a dependence of this Reynolds number Re_u on the angle of attack α for the present wing. The measured Reynolds numbers /249
Re_u are on the order of the critical Reynolds number Re_{krit} of the flat plate without a pressure gradient for all angles of attack. This value for the flat plate is the following according to [11]:

$$Re_{krit} = 3.5 \cdot 10^5 \text{ to } 10^6 .$$

The result is understandable if we consider the fact that on the suction side of the Delta wing along the separation line the static pressure is approximately constant because the separation line represents a special wall streamline.

3.2. Influence of the bursting of the vortices on the course of the wall streamlines

The pressure distribution along the suction side of a Delta wing is determined essentially by two parameters for large angles of attack. With increasing angle of attack, the bursting point

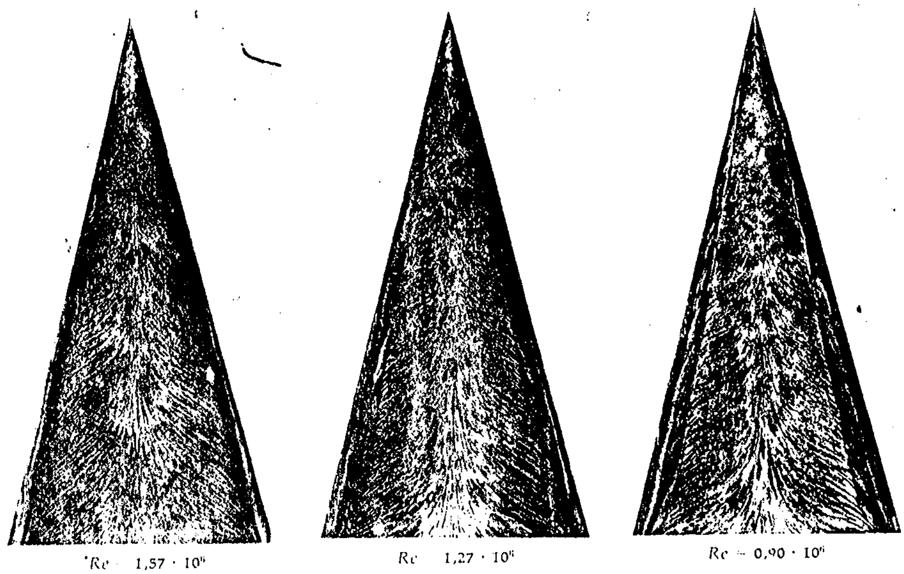


Figure 3. Variation of wall streamlines along the suction side of a Delta wing with the side ratio $\Lambda=1.0$ for various Reynolds numbers. Angle of attack $\alpha=26.4°$, side slip angle $\beta=0°$, no bursting of the vortices over the wing

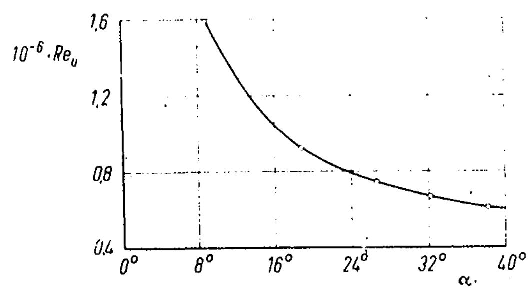


Figure 4. Dependence of the Reynolds number $Re_u = U_\infty x_u/\nu$ on the incidence angle α for the Delta wing with the aspect ratio of $\Lambda=1.0$

migrates in both vortices upstream so that over increasing parts of the wing the maximum underpressures are reduced. In addition, with increasing angle of attack, the vortex axes bend in the direction of the incident flow in the vicinity of the trailing edge which also leads to a reduction of the suction peaks of the pressure distribution along the back part of the wing. Since in this case two parameters influence the pressure distribution along the wing, it is not appropriate to use an angle of attack series to study the influence of the bursting of the vortices on the course of the separation line. Investigations,

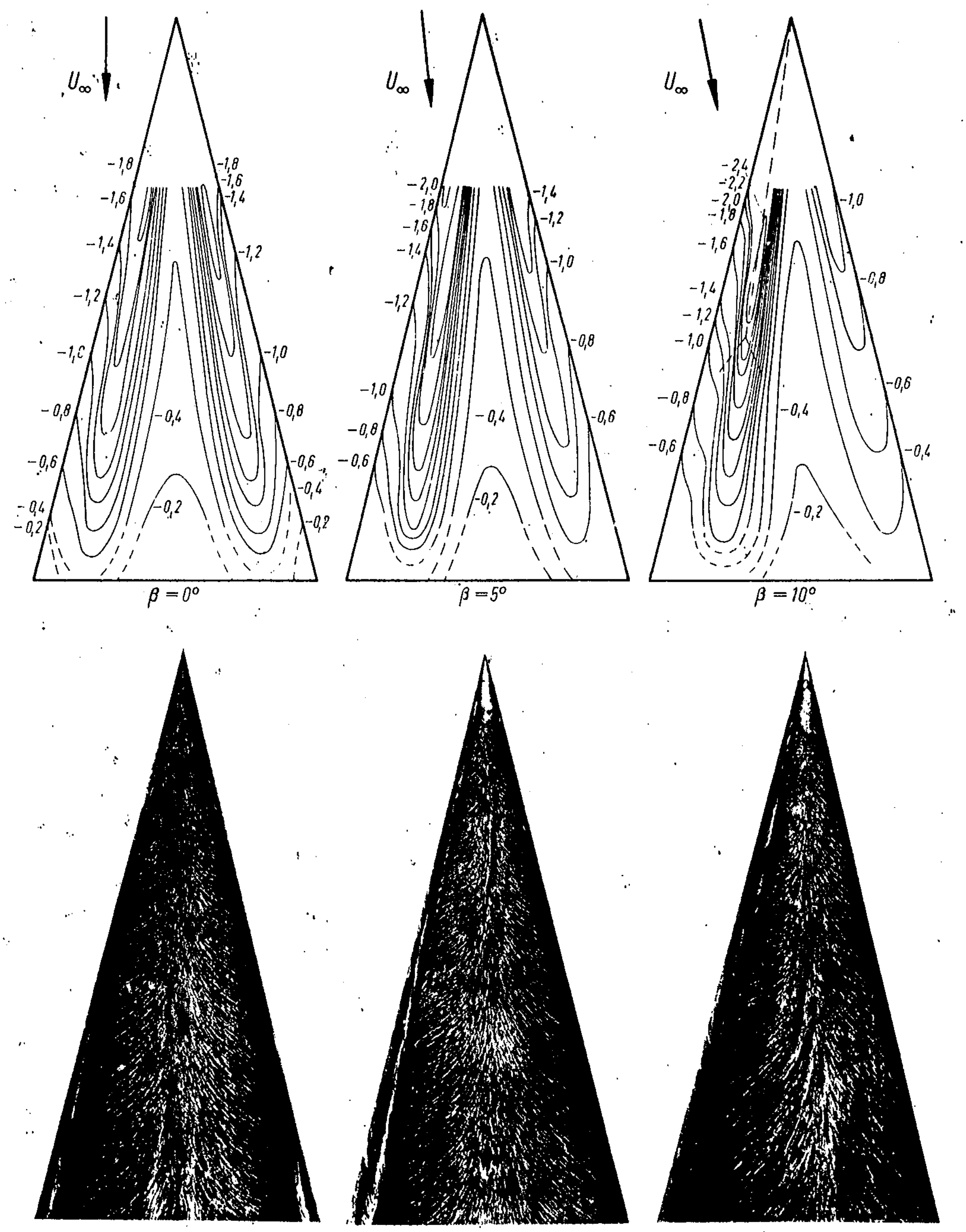
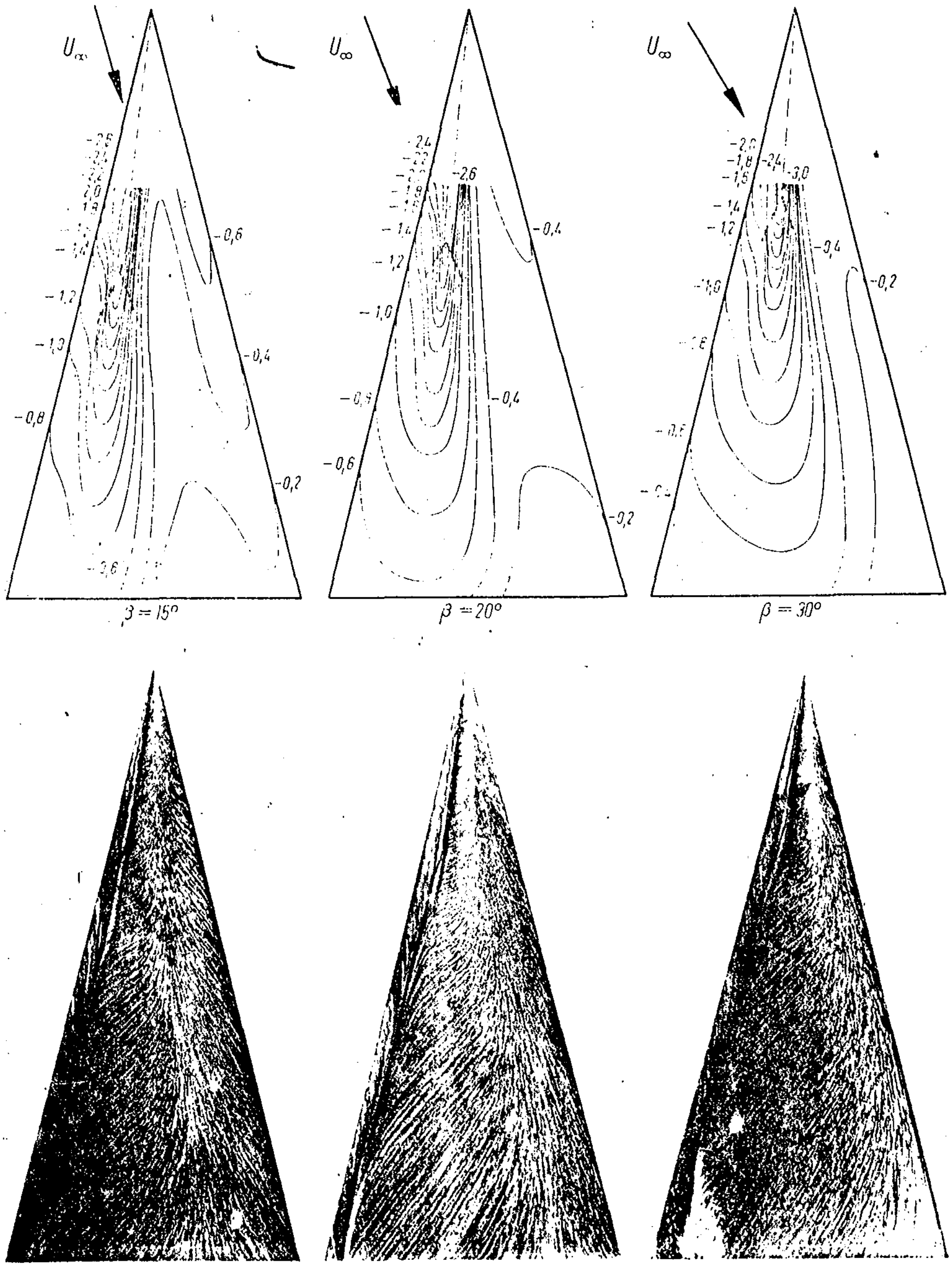


Figure 5. Course of the wall streamlines and pressure distribution along the suction side of the Delta wing with the aspect ratio $\Lambda=1.0$ at $\alpha=26.4°$ and $Re=2 \cdot 10^6$ for different side slip angles.
The bursting point in the vortex along the advancing half of the wing is marked.



Continuation of Figure 5

therefore, were carried out on a wing with sideslip, where the bursting point in the vortex migrates along the advancing wing side with increasing sideslip angle. In this case, the distance of this vortex from the wing top side changes only slightly with sideslip angle so that a decrease in the suction peaks of the pressure distribution only comes about by the bursting of the vortex.

The investigations were carried out for the angle of attack $\alpha=26.4°$ and for a Reynolds number of $Re=2.0 \cdot 10^6$. Figure 5 shows paint photographs and the corresponding pressure distributions in the form of lines of equal static pressure $c_p = (p - p_\infty)/q_\infty =$ const along the suction side of the wing for different sideslip angles. The course of the vortex axis along the advancing wing half and the position of the bursting point in this vortex are also shown.

At a certain distance from the wing tip $x_u/l_i = 0{,}35$, which changes only slightly with increasing sideslip angles, the transition from laminar separation to turbulent separation of the boundary layer takes place. With increasing sideslip angle, the distance between the leading edge and the separation line along the advancing half of the wing increases, whereas it becomes smaller along the trailing side of the wing. The suction peaks of the pressure distribution along the wing determine this displacement. Their distance from the leading edge along the advancing wing half does increase, but the magnitude of the suction peaks increases very drastically with increasing sideslip angles. The pressure gradient between the suction peak and the leading edge, therefore, becomes larger with increasing sideslip angle, and the separation occurs farther away from the leading edge. Similar statements can be made in the opposite sense for the lagging half of the wing. For sideslip angles of $\beta \geq 15$, no secondary vortex formation can be found any more.

For β=0° and β=5°, the vortex does not burst along the advancing wing side. The under pressures along the wing extend to

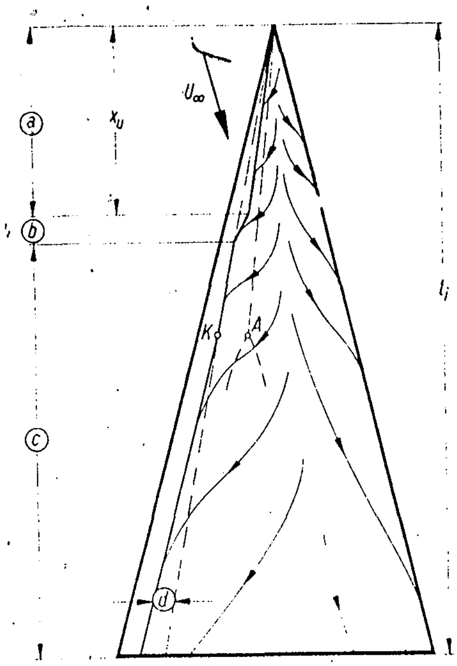


Figure 6. Streamlines along the suction side of the wing at $\alpha=26.4°$, $\beta=15°$ (schematic).
(a) Secondary vortex formation by separation of a laminar boundary layer,
(b) transition region,
(c) secondary vortex formation by separation of a turbulent boundary layer,
(d) displacement of the separation line of the turbulent boundary layer due to bursting of the advancing vortex
A = bursting point in the vortex
K = bending point of the turbulent separation line

close to the trailing edge. The separation line is a straight line through the wing tip ahead and behind the transition region. For $\beta=10°$, the bursting point in the vortex along the advancing wing half is located at $x/l_i=0.57$. Downstream of this point, /250 the pressure distribution shows a decrease in the under pressures. The pressure gradient between the suction peak and the leading edge becomes smaller. Therefore, the boundary layer separates closer to the leading edge. The turbulent separation line has a bend close to the bursting point and downstream of it it was parallel to the leading edge. With increasing sideslip angle, the bursting point in the vortex migrates and, therefore, the bending point in the separation line also migrates upstream. For $\beta=15°$, it is located at x/l_i=0.45 and for β=20°, it is located at x/l_i=0.40. In this case, the bending point is located close behind the transition region from laminar separation to turbulent separation at the beginning of the turbulent separation line. The pressure distributions show the strong decrease in the under pressure along the wing downstream from the bursting point. For sideslip angles of β=30°, the bursting point lies at x/l_i=0.32. The transition region from laminar separation to turbulent separation vanishes. Under the influence of the bursting of the vortex, the turbulent separation already starts at the bending point at x/l_i=0.32.

The important features of these paint photographs are shown in Figure 6 in a schematic representation of the course of the wall streamlines for the case α=26.4°, β=15°. For the transition from the laminar separation to the turbulent separation, the separation line is displaced toward the leading edge and the separation line ahead and behind the transition region is a straight line through the wing tip. Because of the bursting of the vortex along the advancing wing side, the pressure gradients on the wing are reduced. The separation is closer to the leading edge and the turbulent separation line has a bend close to the bursting point.

These results agree very well with earlier observations of N. C. Lambourne and D. W. Bryer [6] with a swept wing as well as with newer investigations of J. A. Lawford [12] with a Delta wing for symmetric incident flow which became known to the author only after these present investigations had been concluded.

4. SUMMARY

Using a sharp edged Delta wing with an aspect ratio of Λ=1.0 and for incompressible flow, we investigated how the Reynolds number and the bursting of the vortices influence the course of the wall streamlines along the suction side of the wing using paint images and pressure distribution measurements.

Secondary vortices are found along the front part of the wing by separation of a laminar boundary layer. On the other hand, separation of a turbulent boundary layer occurs along the rear part of the wing. The turbulent separation line is closer to the leading edge than is the laminar one. Both are straight lines through the wing tip. The distance x_u of the transition region between laminar separation and turbulent separation from the wing tip depends on the Reynolds number $Re = U_\infty l/\nu$ and the angle of attack α. However, the Reynolds number $Re_u = U_\infty x_u/\nu$ formed with x_u is constant for fixed angle of attack α.

When a vortex bursts over the wing, the suction peaks of the pressure distribution are greatly decreased downstream of the bursting point. The separation line has a bend approximately at the bursting point and is parallel to the leading edge downstream.

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