

# Lift force of delta wings

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On a delta wing, the separation vortices can be stationary due to the balance of the vorticity surface flux and the axial convection along the swept leading edge. These stationary vortices keep the wing from losing lift. A highly swept delta wing reaches the maximum lift at an angle of attack of about  $40^\circ$ , which is more than twice as high as that of a two-dimensional airfoil. In this paper, the experimental results of lift forces for delta wings are reviewed from the perspective of fundamental vorticity balance. The effects of different operational and geometrical parameters on the performance of delta wings are surveyed.

## 1. INTRODUCTION

An aircraft undergoing maneuvering requires a well-defined lift force in a wide range of angle of attack. For example, a  $70^\circ$  swept delta wing can continue to increase its lift until the angle of attack reaches approximately  $40^\circ$ . In contrast, a two-dimensional steady NACA 0012 airfoil will reach its maximum lift at only about  $15^\circ$  angle of attack. At higher angles, the flow on the suction side of the airfoil does not follow the surface. Vorticity starts to accumulate and forms vortices. On a two-dimensional wing, there is no way of convecting vorticity downstream other than shedding downstream with the free stream velocity. The shedding of vortices is intermittent and, most importantly, is not in phase with the spanwise direction. Therefore, it results in a fluctuating and low lifting force; thus the 2D airfoil stalls. On the other hand, a delta wing separates at a fairly small angle of attack, say about  $5^\circ$  or less. The vorticity generated at the leading edge can be carried downstream by the velocity component along the inclined leading edges. When the vorticity diffused from the surface balances with the convected vorticity, the separation vortices become stationary. The stationary vortices make the potential flow near the leading edge create a convex curvature that produces a suction. The suction contributes to increased  $C_L$  even after the flow has separated at the leading edge. As the angle of attack increases, the vortex breaks down with the vortex burst propagating from the trailing edge to the apex. With further increasing angle of attack, the velocity above the suction side decreases. The ability of convecting vorticity is reduced and changes the balance of vorticity. Eventually the leading edge vortices cannot be held in place and thus start to shed. The three-dimensional equivalent to the two-dimensional stall occurs and the flow over the suction side separates globally.

It is clear that the main aerodynamic difference between the delta wing and the two-dimensional wing depends on the behavior of the separation vortices. The principal source of vorticity is at the leading edge. The vorticity diffuses from the surface into the flow and lumps into vortices. The vorticity balance between diffusion and convection at different operating conditions will then determine the state of the vortices, eg., stationary, vortex burst as well as shedding. Therefore,

we can understand the aerodynamics of a wing if the fundamental vorticity balance is clarified. This is the approach chosen for the review of the existing experimental works on the delta wing.

In the present paper, a brief summary of the fundamental concepts is first presented. Next, the different parameters affecting steady and unsteady flow over delta wings will be discussed. Finally, the results of the different schemes employed to control the lift will be examined.

## 2. VORTICES AND LIFT FORCE

### 2.1 General Features of Leading Edge Vortices

The two spiralling vortices on a delta wing are formed from the separated shear layers which originate from the leading edge (Fig. 1). On a wing with rounded leading edge, Earnshaw and Lawford (1964) found that these vortices did not appear until the angle of attack was more than  $5^\circ$ . For a sharp leading wing, the separation vortices start at a smaller angle of attack (Ericsson and Reding 1977). The transverse size of the LE vortices is in the order of the half span. A large portion of the lift on the wing is contributed by these spiraling vortices, which produce suction footprints on top of the wing. The pressure measurements by Fink and Taylor (1967) in Fig. 2 show that the locations of maximum suction are beneath the cores of the vortices.

Secondary structures of the leading edge vortices have been observed. Small vortices which develop from the Kelvin-Helmholtz instability waves of the thin separating shear layer are superimposed on the large vortices (Gad-el-Hak and Blackwelder 1987). These small vortices (Fig. 3; Payne et al. 1988) are scaled with the thickness of the shear layer which is usually more than one order of magnitude smaller than the span. Under the LE vortices and slightly outboard from the cores, there is a pair of secondary vortices [Figs. 1(a) and 2(a)] induced by the primary vortices.

At large angles of attack, the LE vortices will suddenly expand in size. This is coupled with a sharp increase in the dynamic pressure and a decrease in axial velocity. This phenomenon is called vortex burst or breakdown. Flow visualizations obtained by Lambourne and Bryer (1961; Fig. 4) show that the transformation can take a very abrupt form. The measurements made by Hummel (1965) in Fig. 5 reveal that the vortex is spread out over a larger region after the breakdown as

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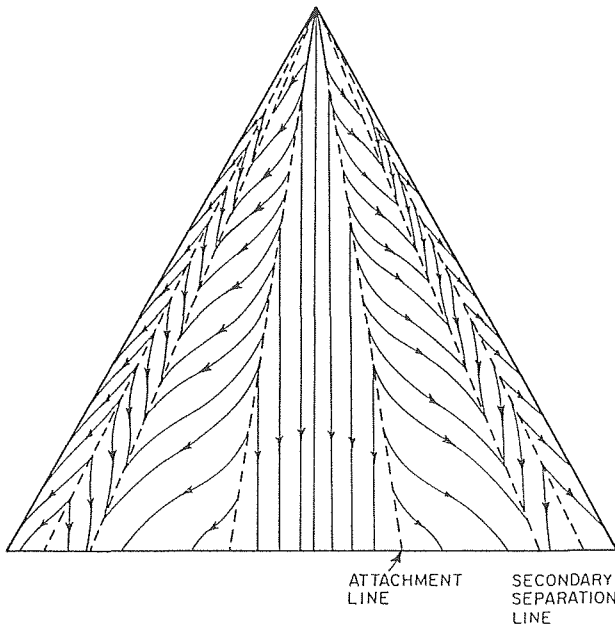
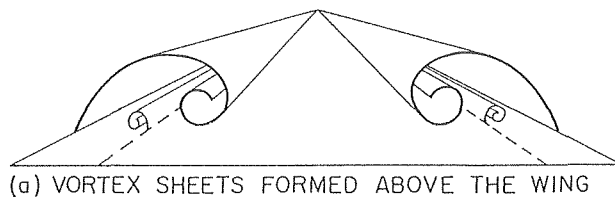


FIG. 1. (a) Leading edge vortices and (b) surface flow pattern (Eamshaw and Lawford, 1964).

indicated in the flow visualization. The vortex breakdown is associated with changes in the lift characteristics of some but not in all types of delta wings (section 3.1).

## 2.2. Balance of Vorticity

The solid surface is the only source of vorticity which enters the flow by being diffused into the boundary layer. In an attached flow, the vorticity is removed continuously by free stream convection. The vortical boundary layer stays thin and follows the surface. At the onset of separation, a local shear layer forms near the wall (Didden and Ho 1985). The shear layer is unstable and extracts energy from the high speed free stream onto the wall region. The high level vorticity in the shear layer lumps into large vortical structures. The boundary layer is substantially thickened and the vortices are convected downstream with the velocity of the free stream. A fully separated flow takes place. Therefore, the balance between surface vorticity flux and vorticity transport in the free stream dictates the vorticity accumulation or depletion above solid surfaces. The importance of the vorticity balance concept was emphasized by Reynolds and Carr (1985) in their review of separation driven flows. The underlying assumption is that two- and three-dimensional separated flows are dominated by large concentrated vortices.

Reynolds and Carr (1985) have shown further that the surface vorticity flux is governed by the local pressure gradient, transpiration through the surface, and motion of the surface itself. On a delta wing, the amount of vorticity rollup into the vortex depends on the condition of the boundary layer at the leading edge prior to separation because the local curvature determines the pressure gradient.

Next, let us look at the effects of vorticity convection. On a two-dimensional airfoil, separation from the leading edge does not lead to

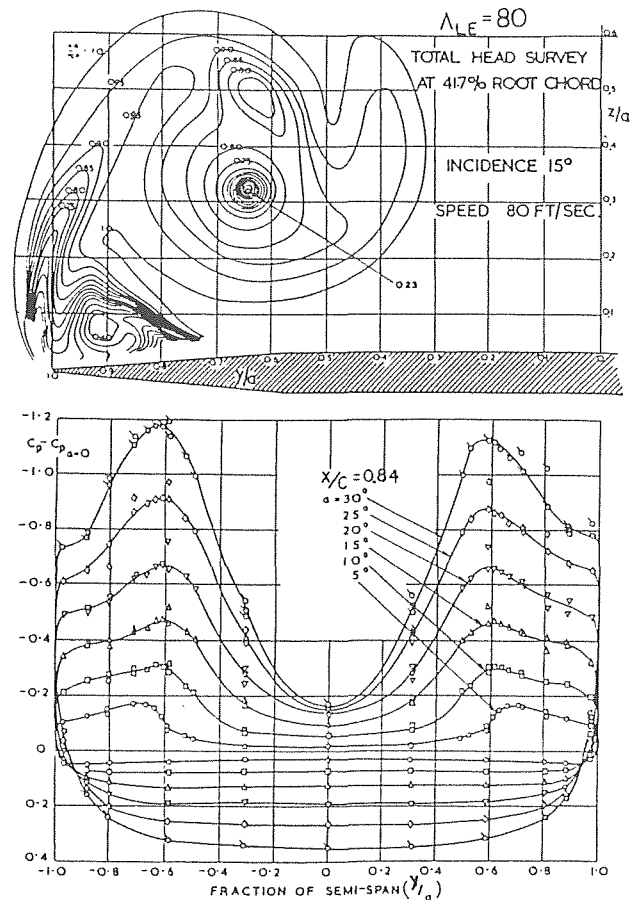


FIG. 2. (a) Total head measurement of the L E vortices; (b) surface pressure measurements (Fink and Taylor, 1967).

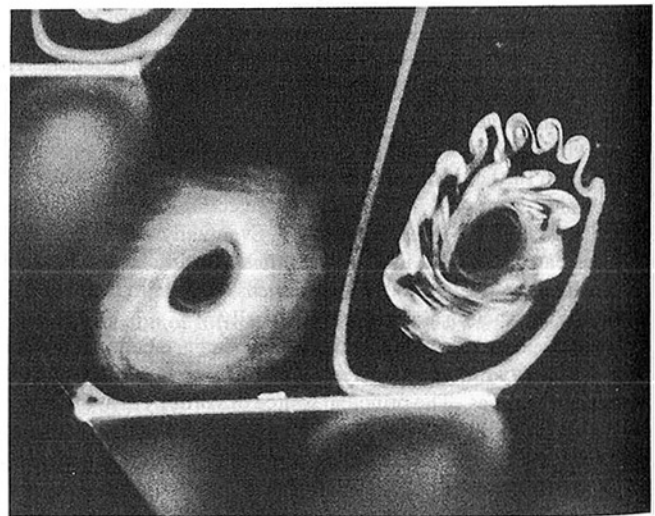


FIG. 3. Secondary vortices superimposed on L E separation vortices (Payne, 1987).

a stationary vortex. The free stream velocity is normal to the leading edge and there is no intrinsic convection to remove vorticity. All the vorticity is simply convected with the vortex by the free stream as a whole. Shih (1988) has shown that the time spent by the vortex on the chord is an intrinsic time scale in determining the aerodynamic properties of a wing. Rossow (1978) tried to stabilize the vortex on a two-dimensional wing by providing artificial suction from the side and

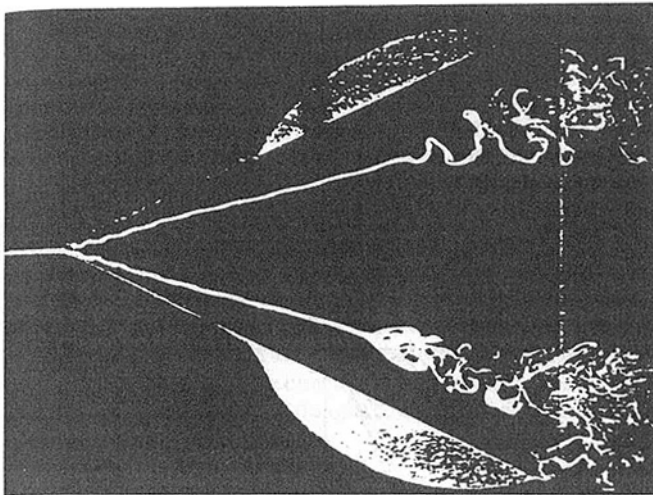


FIG. 4. Patterns of vortex breakdown, Lambourne and Bryer (1961)

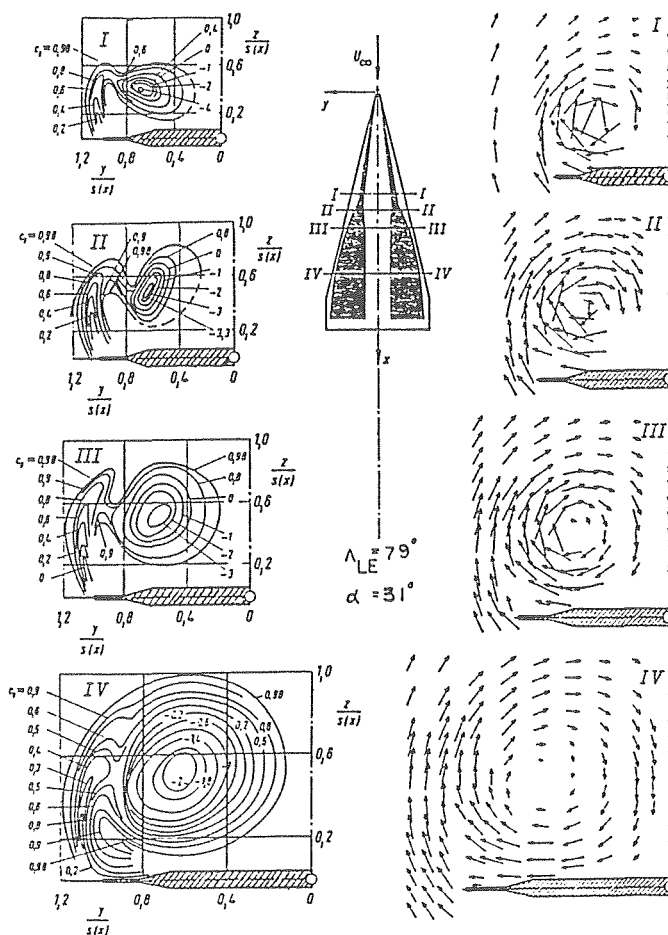


FIG. 5. Velocity distributions before and after vortex breakdown (Hummel, 1965).

using a vertical fence to shield the vortex from the free stream. He found that the vortex was too sensitive to stay stationary, and an inclination of  $10\text{--}20^\circ$  from the leading edge was observed. This shows that axial convection along the core is essential in maintaining a stationary vortex. On the delta wing, a stationary leading edge vortex is possible due to the slanted leading edge. The swirl in the core depends on the amount of bounded vorticity fed through the shear layer

and the magnitude of axial convection along the vortex core. The convected vorticity is determined by the component of the free stream velocity in the direction parallel to the leading edge. This component of the free stream velocity is a function of the angle of attack,  $\alpha$ , angle of sideslip,  $\beta$ , and sweepback angle,  $\Lambda_{LE}$ , as shown in Fig. 6. The swirl produces suction on the surface. Therefore, lift is a function of these parameters. Based on the above reasoning, the swirl angle  $\psi$  between the perpendicular and axial velocity components along the leading edge would reflect the vorticity balance necessary for a stationary vortex. Lambourne and Bryer (1961) suggested that  $\psi$  is important in determining the location of vortex breakdown over a delta wing. The evidence supporting this view will be provided in section 3. A more detailed review of the theories relating to swirl angle at the edge of the viscous core and breakdown has been given by Leibovich (1984).

### 2.3. Lift Prediction

The purpose of this paper is mainly to survey the experimental studies on the lift of delta wings. Review of theoretical or numerical prediction methods is not within the scope of the present paper. A review of various lift prediction methods was provided by Parker (1976) as well as Ericsson and Reding (1987). However, a simple and effective theory developed by Polhamus (1971) will be referred to in order to understand the effects of several parameters on the lift forces generated by vortices and the potential effect.

Based upon the leading edge suction analogy, Polhamus predicted the total lift on a delta wing by separating the normal force into potential and vortex components. The potential lift term is based on the lifting-surface theory, taking into account the Kutta condition at the trailing edge. The vortex lift term is modeled by the suction force generated by the equivalent attached flow around the edge. The only condition necessary for the analogy to hold is that the separation must reattach on the upper surface. No detailed knowledge of the shape, strength, and position of the vortex is required. It is interesting to note that the vortex lift term is sensitive only to angles of attack. The sweepback angle dependence comes solely from the potential lift term (Fig. 7). According to this theory, the airfoil depends more and more on the vortex for lift as the sweepback angle increases, and it can offer reasonable predictions on the lift of delta wings until vortex breakdown occurs over the wing surface. The Kutta condition most likely will not be held when high levels of fluctuation become dominant in flows with vortex bursting. The assumption in the theory breaks down and the predictions are of course invalid. Campbell (1976) compiled the lift coefficients for wings with different swept back angles (Fig. 8) and showed that vortex breakdown limited the application of Polhamus' prediction.

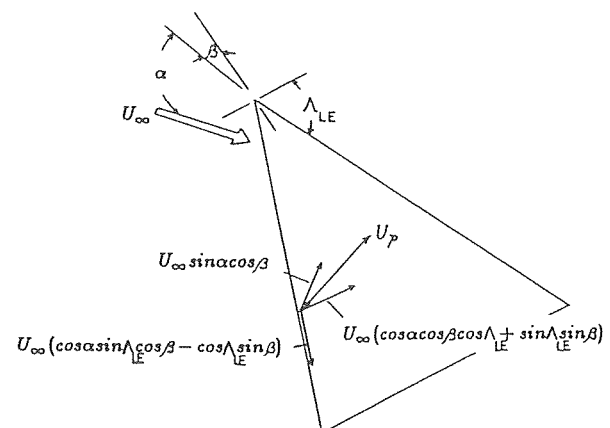


FIG. 6. Geometric relation of velocity and delta wing.

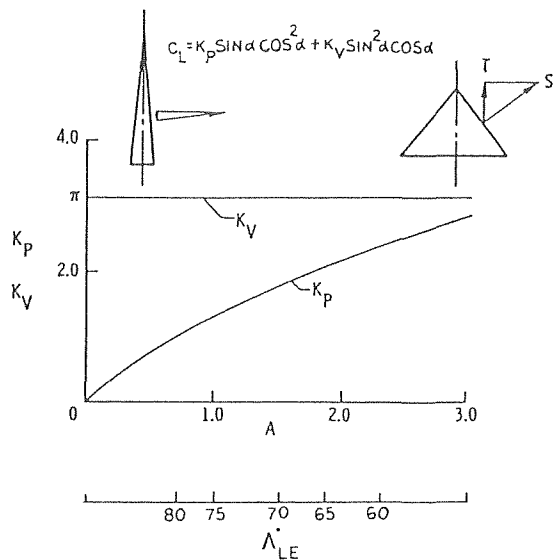


FIG. 7. Vortex and potential lift (Polhamus, 1971).

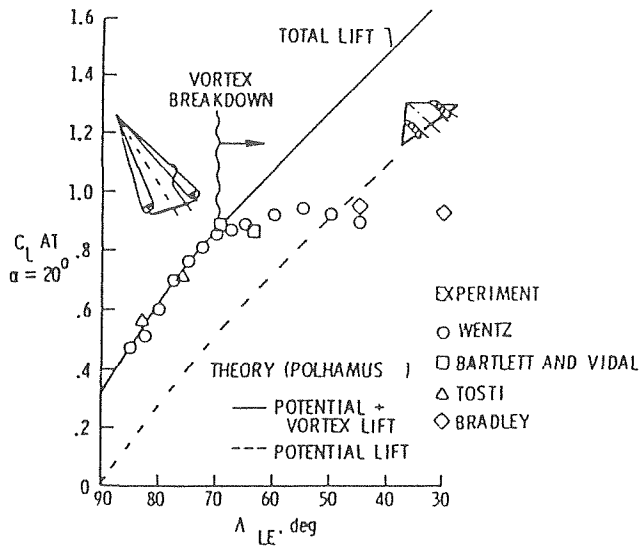
Lift capability of delta wings at  $\alpha = 20^\circ$ .

FIG. 8. Vortex breakdown and the leading edge suction analogy (Campbell, 1976).

### 3. LIFT OF STEADY DELTA WINGS

Parameters which affect steady flow over a delta wing include angle of attack, sweepback angle, angle of sideslip, leading edge profile, trailing edge geometry, Reynolds number, Mach number, and free stream turbulence. In the following sections, we will examine the measured lift as a function of these parameters.

#### 3.1. Effects of Angles of Attack, Sweepback, and Sideslip

The effects of sweepback angle,  $\Lambda_{LE}$ , on lift are shown in Fig. 9 as a function of the angle of attack,  $\alpha$  (Earnshaw and Lawford 1964). The wings used are slightly cambered and therefore the  $C_L$  does not pass zero at  $\alpha = 0^\circ$ .  $C_L$  increases with the angle of attack until reaching a maximum value. The delta wings with  $\Lambda_{LE} = 65^\circ$  and  $70^\circ$  produced the best performance in terms of maximum lift coefficient. For airfoils with smaller sweepback angles, the maximum lift coefficients de-

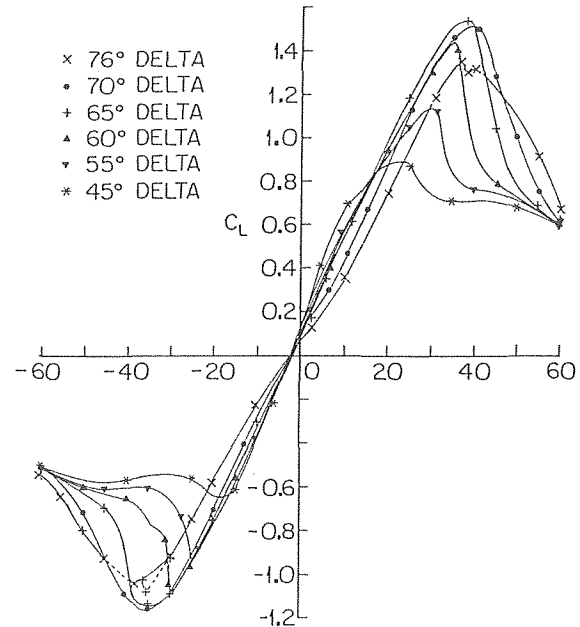


FIG. 9. Lift coefficient vs angle of attack (Earnshaw and Lawford, 1964).

creased significantly. A comparison between the measurements and the predictions by the leading edge suction analogy is shown in Fig. 10. The breakdowns of the vortices at the trailing edge and the apex are also indicated in the figure. For wings with large sweepback angles,  $\Lambda_{LE} = 70^\circ$  or  $75^\circ$ , the measured  $C_L$  curves show that the theoretical lift coefficients have been achieved. The angle of attack at the maximum  $C_L$  corresponds to that of vortex breakdown occurring at the trailing edge. For wings with smaller sweepback angle, measured  $C_L$  is always lower than that of the predicted value. No obvious correlation between the vortex breakdown and the change of the lift coefficient curve can be observed [Fig. 10(a)]. This is different from wings with larger sweepback angle [Fig. 10(b)] because a major portion of the lift of the wing with the large sweepback angle is contributed by the vortex (Fig. 7) and hence the vortex breakdown has a strong effect on the lift. For  $\Lambda_{LE} > 75^\circ$ , the projection of a wing at a high angle of attack in the direction perpendicular to the flow is close to a three-dimensional slender body. The sinus mode instability dominates in the wake and vortex asymmetry occurs before breakdown. The full vortex lift cannot be achieved.

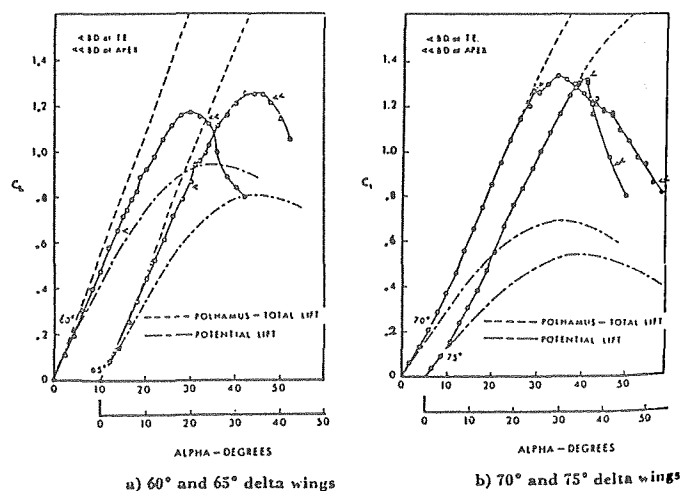


FIG. 10. Comparison between experiments and Polhamus' prediction, (Wentz and Kohlman, 1971).

The effects of yaw angle,  $\beta$ , on the position of vortex breakdown is shown in Fig. 11 from the data of McKernan and Nelson (1983). The vortex would burst closer to the apex on the windward side and farther away on the leeward side. The pressure measurements of Hummel (1965) in Fig. 12 shows the corresponding shift. However, the normal force measured by Harvey (1958) in Fig. 13 shows only a weak dependence on yaw. Ericsson and Reding (1977) suggested that the effect of  $\beta$  can be included in an effective  $\Lambda_{LE}$  for a small angle of attack. Hence, the normal force does not change much with  $\beta$ .

The variation of the vortex bursting position described above can be traced to an effective change in the balance between vorticity surface flux and convection. The vorticity is generated along the leading edge and convected away from the leading edge. The velocity component in the streamwise direction and the sweepback angle of the leading edge determine the swirl angle,  $\psi$ , which indicates the direction

of the vorticity transport. An increase in the angle of attack, a decrease in the sweepback angle or an increase in the yaw would increase the ratio between circumferential to axial flow (Fig. 6). Sforza et al. (1978) measured the flow over a  $\Lambda = 75^\circ$  delta wing and showed that the circumferential velocity at the core increases with the angle of attack. The swirl angle will increase accordingly. Figure 14 shows a summary of leeside vortex breakdown locations vs swirl angle  $\psi$  for different

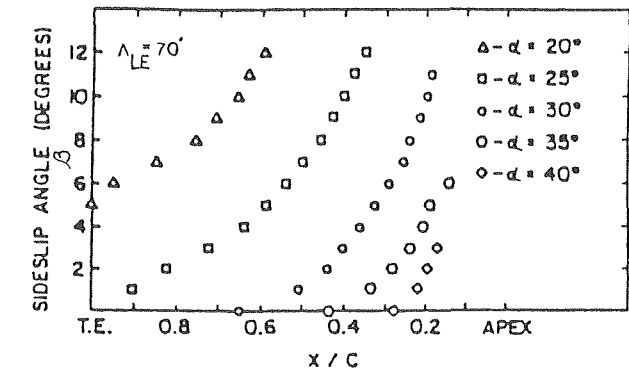


FIG. 11. Effect of yaw on the vortex breakdown position (McKernan and Nelson, 1983).

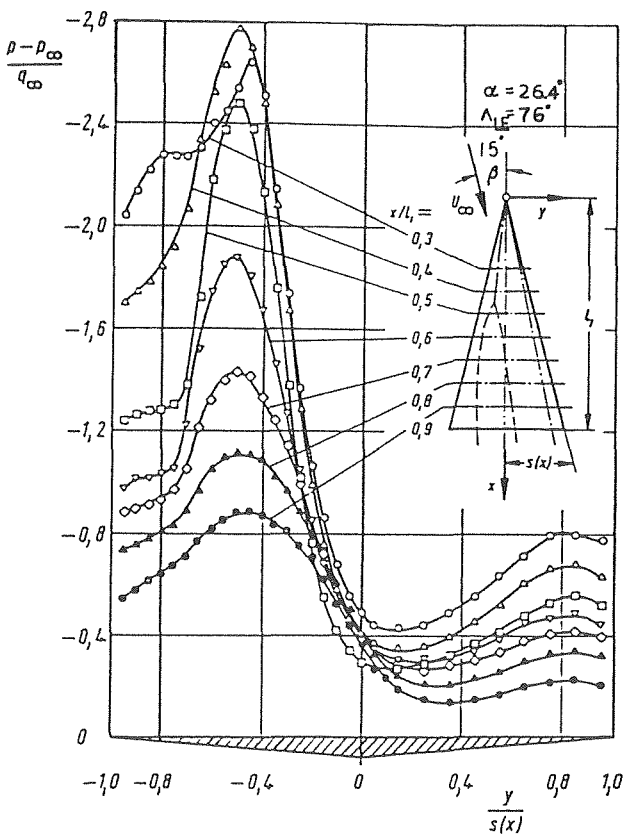


FIG. 12. Surface pressure measurement of a yawed delta wing (Hummel, 1965).

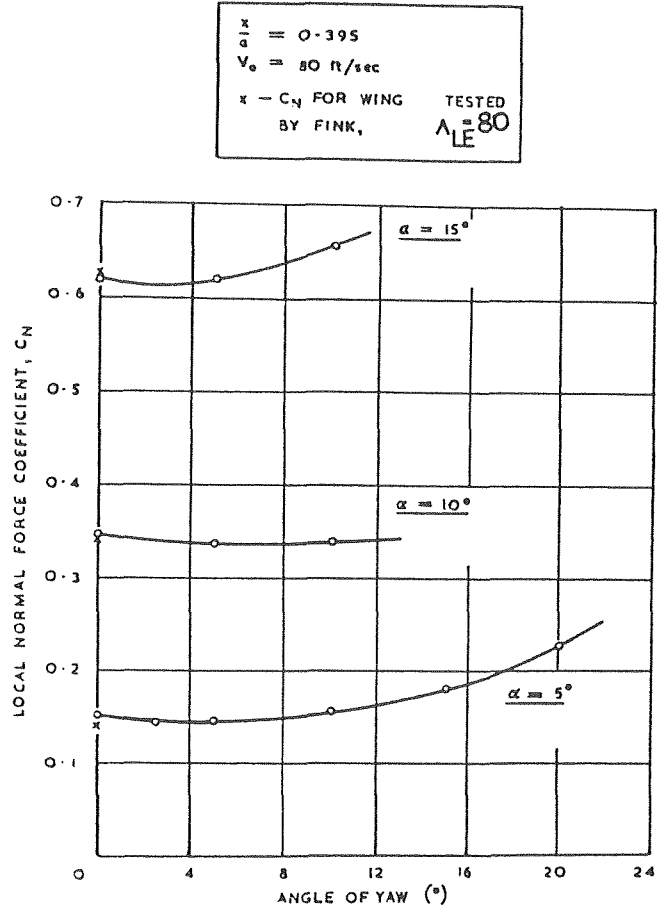


FIG. 13. Normal force of a yawed delta wing (Harvey, 1958).

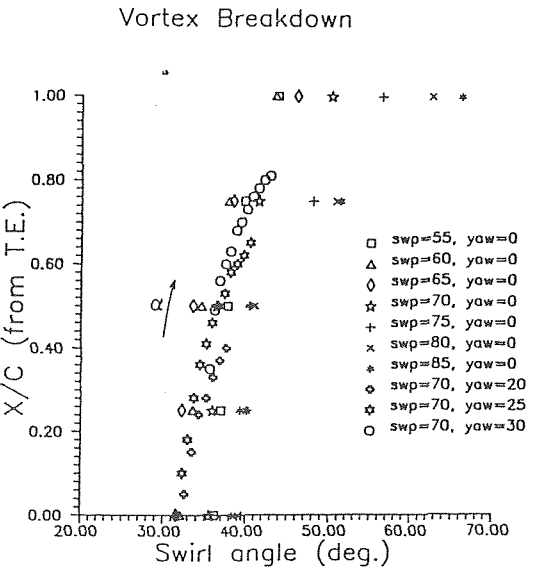


FIG. 14. A scaling law of the vortex breakdown positions.

angles of attack, sweepback, and yaw angles. The collapse of the breakdown positions in the swirl angle suggests that all three parameters affect the stability of the vortex through the same mechanism, ie, the vorticity balance. For large sweepback angles,  $\Lambda_{LE} = 75^\circ, 80^\circ$  and  $85^\circ$ , the collapse is not very good because the interaction of two vortices become important at these angles.

Payne (1987) surveyed the measurements made of the swirl angle at the edge of the viscous core upstream of vortex breakdown in vortex tube experiments. He reported that the angle varied from  $38^\circ$  to  $55^\circ$  for a spiral breakdown. Payne's own measurements over a delta wing ( $\Lambda_{LE} = 85^\circ$ ) was  $44^\circ$  at  $\alpha = 40^\circ$  while Hummel (1965) measured  $53^\circ$  ( $\Lambda = 79^\circ$ ) at  $\alpha = 31^\circ$ . These values are in the same range of the present data (Fig. 14) which varies from  $32^\circ$  to  $66^\circ$ , even though the angles in Fig. 14 are deduced based on geometry at the leading edge.

### 3.2. Effects of Leading Edge Profile

Bartlett and Vidal (1955) studied the effects of leading-edge sharpness on three wings with different symmetric cross sections and thickness-to-cord ratios. They found that the wing with beveled edges produced the maximum slope for  $C_L$  vs  $\alpha$  (Fig. 15), because the flow separated right at the sharp edge and produced a high suction. On the wings with elliptic or round edges, separation occurred downstream from the leading edge. The position of separation depended on the Reynolds number and the local curvature which determined the pressure gradient. Vortex formation was delayed and the lift was lower. The effect of local curvature was investigated by Wentz (1972). He examined a wing with spanwise camber and measured a slightly lower lift coefficient than that of conical and apex cambered wings up to  $\alpha = 35^\circ$ . However, maximum lift was somewhat increased. Based on the pressure measurements, the camber near the apex significantly modifies the pressure distributions, but not elsewhere along the leading edge. The smaller adverse pressure gradient at the apex of the spanwise camber wing postponed the separation further inboard onto the convex surface. This delayed the rollup of the vortex and resulted in less lift. Other experiments by Lamar (1977) with a linearly twisted bat wing (Fig. 16) showed that a gain in lift was achieved when a convex surface was placed on the suction side of the airfoil. This gain in lift is due to a longitudinal camber effect as indicated by the nonzero lift generated at a zero angle of attack. When the wing was inverted, the lift decreased. Earlier, Lambourne and Bryer (1961) demonstrated through flow visualizations that longitudinal camber with a convex upper surface can delay vortex breakdown.

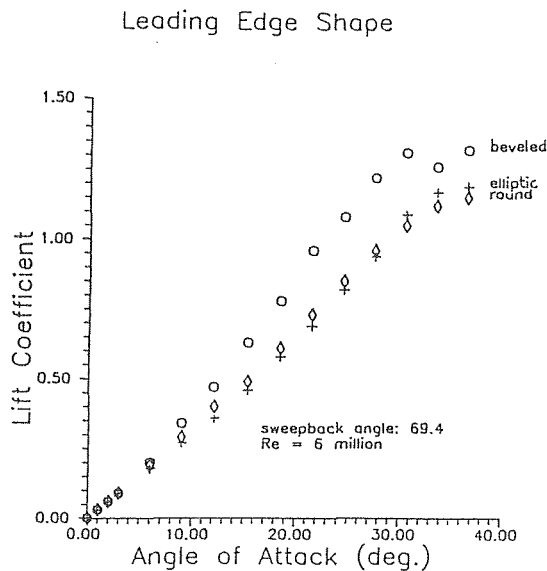


FIG. 15. Effect of leading edge profile on the lift coefficient (Bartlett and Vidal, 1955).

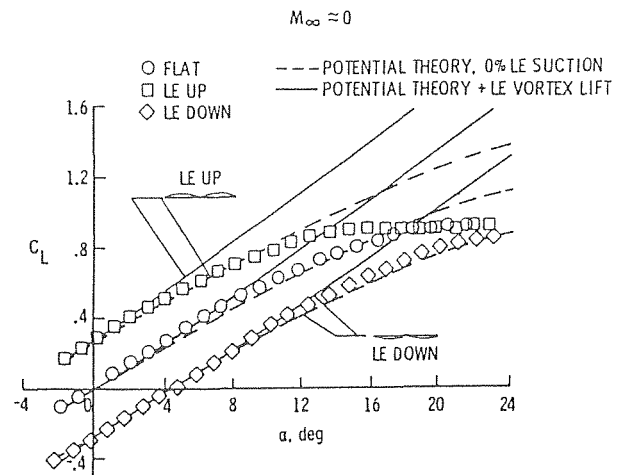


FIG. 16. Lift coefficient of linearly twisted wings (Lamar, 1977).

### 3.3. Effects of Trailing Edge Geometry

Wentz and Kohlman (1971) measured the lift coefficients of delta wings with modified trailing edge. The trailing edge of one of the wings was extended to become diamond-shaped. The trailing edge portion of the other wing was cut to form an arrow-shaped wing. The lift coefficient of the arrow wing is higher than the diamond wing over the whole range of the angles of attack (Fig. 17). Through the trailing edge boundary condition and aspect ratio effects for both vortex and potential lift terms, Polhamus (1971) predicted higher lift coefficients for an arrow wing compared with a diamond wing. The theory overpredicts the arrow wing and underpredicts the diamond wing. The difference can be corrected by using the argument of equivalent delta wings (Ericsson and Reding 1977). Wentz and Kohlman (1971) also found that the trailing edge apparently has no effect on the vortex breakdown location. This is reasonable since the trailing edge does not affect the vorticity balance, which is dictated by the swirl angle between the perpendicular and parallel velocity along the vortex. However, trailing edge flap deflected upward and downward can advance or retard vortex breakdown. The presence of the flap changes the circulation and modifies the pressure gradient over the whole wing. The axial vorticity convection which influences the vortex breakdown is then modified.

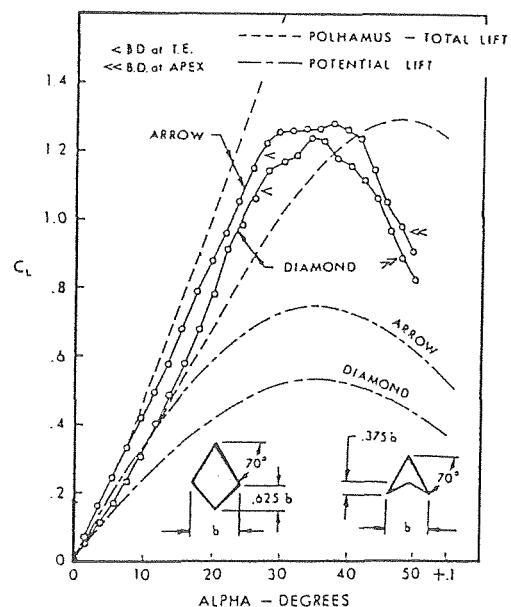


FIG. 17. Trailing edge geometry and its effects on lift (Wentz and Kohlman, 1971).

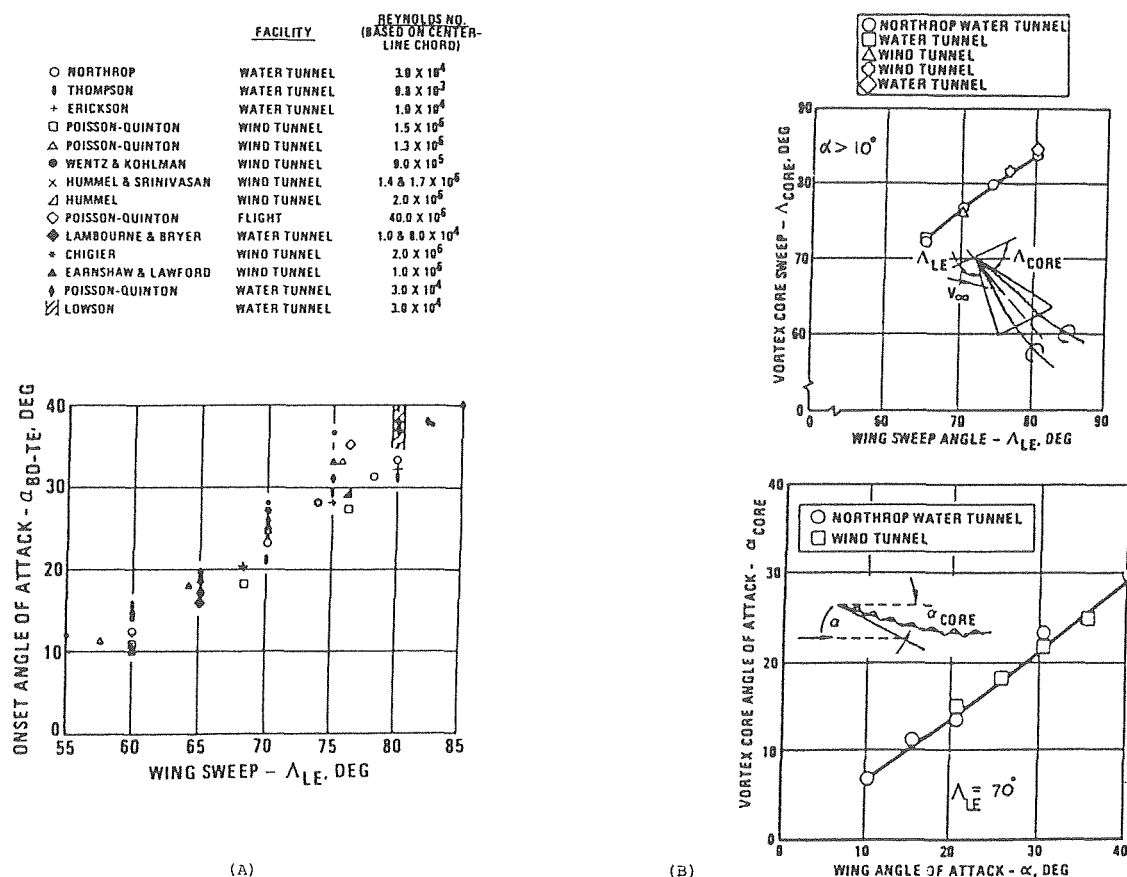


FIG. 18: Effects of Reynolds number on the vortex breakdown and vortex positions (Erickson, 1982).

### 3.4. Reynolds Number

Elle (1961) studied the location of a vortex over sharp edged delta wings in both water and air and concluded that the flow is insensitive to Reynolds number. Figure 18 shows a compilation of data by Erickson (1982) taken from water and wind tunnels and in flight. The Reynolds numbers range from  $9.8 \times 10^3$  to  $4.0 \times 10^7$ . These results confirmed previous experiments which showed that vortex location and breakdown are governed by an inviscid mechanism. The lift data (Fig. 19) taken by Lee, Shih, and Ho (1987) further showed that Reynolds number insensitivity extends to aerodynamic forces acting on delta wings. They also show that the vortex breakdown location is not a function of the Reynolds number for sharp-edged wings. However, Erickson (1982) suggested that the flow is insensitive to Reynolds number for sharp-edged wings only because the separation is fixed along the edge. He reasoned that boundary layer laminar/turbulent transition on wings with round leading edges and flaps would still be sensitive to the Reynolds number. Erickson's arguments were substantiated by Lee (1955), who showed variations in the secondary separation line on the surface through oil-film visualizations from  $Re = 5 \times 10^5$  to  $2 \times 10^6$ . The separation location is known to be dependent on the turbulent/laminar state of the boundary layer. Hence the vortex formation and the local pressure distributions will be functions of the Reynolds number. The effects discussed in the section of leading edge profile (section 3.2) must be a combination of local curvature and viscous effect. In addition, the strength and location of the secondary separation on the surface induced by the primary vortex would also be affected since this phenomenon is also viscous in nature.

The size of the LE vortex is independent of the Reynolds number. As the free stream velocity increases, the viscous core decreases in size due to a thinning of the boundary layer at the leading edge. This effect by itself, apparently, is not strong enough to affect the vorticity balance which is governed by the swirl angle and pressure gradient. A more in-

depth discussion of Reynolds number sensitivity over delta wings is given by Payne (1987). In vortex tube experiments (Escudier and Zehnder 1982), the Reynolds number was a dominating parameter. It should be noted that there are fundamental differences between vortices generated in a tube and over a delta wing. As pointed out by Leibovich (1984), vorticity is shed into the center of the tube by a vane type generator producing a spiral vortex with constant vorticity. On a delta wing, vorticity is constantly fed into the core from the leading edge, resulting in an almost linear increase of vorticity along the vortex. Wedmeyer (1982) found that velocity profiles measured in

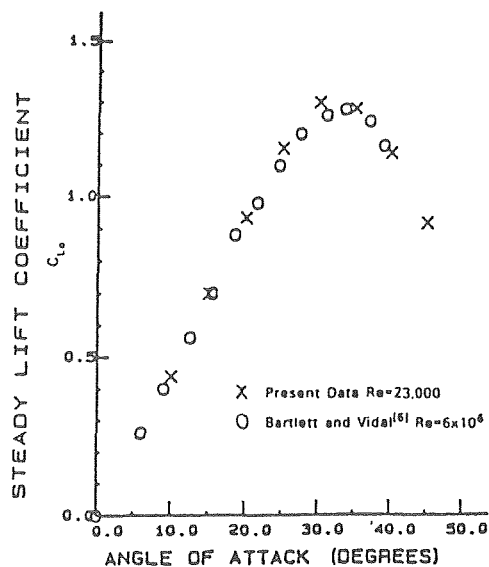


FIG. 19: Effects of Reynolds number on lift coefficient (Lee, Shih, and Ho, 1987).



vane type generators did not compare well with those measured over delta wings.

### 3.5. Mach Number Effects

In the supersonic regime, the separated leading edge vortex is replaced by a series of attached shock waves and Prandtl–Meyer type expansions depending on Mach number, angle of attack, and wing geometry. Stanbrook and Squire (1964) showed that the important parameters in supersonic flow are the angle of attack and Mach number perpendicular to the leading edge. They found that the flow can take on three different forms as illustrated by Squire (1976) in Fig. 20. Later on, Wood and Miller (1985) further classified the flow into six regimes depending on the existence and nature of shock induced separation on the top surface. It is interesting to note that the leading edge separation reappears at large enough angles of attack regardless of Mach number. Rizzetta and Shang (1986) used a Navier–Stokes code to simulate supersonic flows over a delta wing. The predicted pressure distribution matched experimental data very well. Leading edge vortices can be observed from the numerical results.

A drop of lift coefficient with increasing Mach number will happen (Polhamus 1971) because the separation line on the pressure surface would gradually move outboard toward the leading edge, resulting in a weaker vortex. The vortex totally vanished when the stagnation line reached the leading edge where no flow reversal occurred. This corresponds to the situation when the Mach cone coincides with the leading edge at the Stanbrook–Squire boundary between regions A and B in Fig. 20. Therefore, this effect would be more severe for delta wings with smaller sweepback angles. In addition, Squire, Jones, and Stanbrook (1961) pointed out that the lift would be further lowered at large angles of attack and high Mach numbers when the low pressure region in the vortex core reaches the vacuum limit.

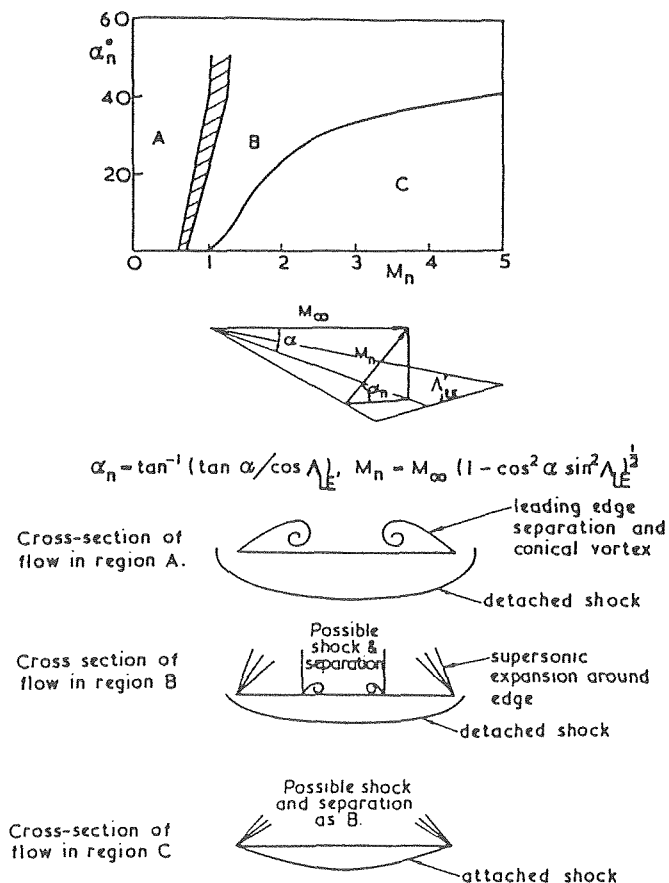


FIG. 20. Flow field of a supersonic delta wing (Squire, 1976).

### 3.6. Effects of Free Stream Disturbances

Very little work is reported in the literature concerning free stream effects on the vortex. Lambourne and Bryer (1961) found no effect on the vortex when a spoiler was placed either at or in front of the apex. However, Lee, Shih, and Ho (1987) found that the breakdown location became very unstable when the free stream turbulence was increased from 0.5% to 1.5%. The result suggests that the breakdown location is sensitive to the transverse velocity disturbances but not to the streamwise velocity perturbations. It appears that more work is required in this area.

## 4. FLOW OVER UNSTEADY WINGS

### 4.1. Time Scales

When a delta wing is placed in an unsteady environment, many types of time scales exist; the period of the unsteady motion, the response time for the stationary leading edge vortices to perturbations, and the convection time of the shedding leading edge vortices. The first one is an externally imposed time scale. The latter two are intrinsic to the flow field.

The response time of the unsteady wing depends on the mechanism governing the stability of the leading edge vortex. The vorticity balance concept determines two time scales. First, changes in the vorticity generation along the leading edge are transmitted to the core in one local turnover time. This time is maximum at the trailing edge and decreases towards the apex due to the difference in transverse lengths. Therefore, the vortex around the apex is more sensitive to disturbance than any other place along the leading edge. Second, upstream disturbances are convected throughout the vortex core in a time,  $C/U$ , which scales with the streamwise velocity along the vortex. Since the latter time is always longer, streamwise convection becomes the limiting factor for the vortex to respond to any imposed disturbance. In the following sections, we will look at how these time scales play their roles in different types of unsteady motion.

The external perturbation produces a time-varying pressure gradient. The surface vorticity flux will change accordingly. In the case of a wing with small sweepback angle, the leading edge vortices may not be able to hold to their positions due to excess vorticity diffusion and low level vorticity convection. The vortices will convect from the apex to the trailing edge. After the vortices leave the trailing edge, the lift drops. The time of the convecting vortices spent on the delta wing becomes another intrinsic time scale. This is similar to the flow over a 2D wing.

Obviously, the aerodynamic properties of the wing are dictated by the relative importance and the ratio of these time scales. We will discuss this aspect in the following sections.

### 4.2. Types of Unsteady Flows

Experimental investigation of unsteady delta wing aerodynamics has been limited due to the difficulty in producing well controlled time-varying free streams in the laboratory. The unsteady free stream needs to be produced by accelerating or decelerating the whole fluid mass in the test section. The interaction between the control device and nonlinear characteristics of the pump or the blower is nontrivial. In a vertical water channel, Shih, Lee, and Ho (1987) were able to achieve various velocity waveforms by operating it in a constant head mode. In this case, the nonlinear feature of the pump is isolated. The velocity in the test section is a function of the flow resistance governed by the opening area of the gate at the exit of the test section. By properly controlling the opening area, the test speed can be varied as a function of time.

Most other experiments subject the wing to some form of periodic motion in a steady free stream. Pitching involves varying the angle of attack by pivoting the wing about a certain chordwise location. This



motion produces a continuous change not only in the angle of attack, but also in the effective free-stream velocity approaching the wing. Other modes are the plunging and heaving motion, where the airfoil is in up-down or forward-back movements. Both modes can produce stepwise or continuous change of the effective angle of attack. Wing rock, another unsteady phenomenon which involves back and forth rolling about the centerline axis, has been observed in real flight. This and other unsteady effects can drastically influence the performance of delta wings. For a review on unsteady separated lifting surfaces, the paper by Ericsson and Reding (1987) provides a detailed reference.

#### 4.3. Pitching, Plunging, and Heaving

In a flow visualization experiment with a pitching delta wing (Gad-el-Hak and Ho 1985, Gad-el-Hak 1987), the two leading edge vortices first rolled up at the trailing edge tip and then migrated toward the apex. A well-organized wake behind the wing was formed when the reduced oscillating period,  $UT/C$ , equaled 1, where  $T$  is the period of external unsteady motion. In a series of plunging experiments, Lambourne, Bryer, and Maybrey (1969) also found that the vortex required a time period  $UT/C = 1$  to reach its new equilibrium position. Similar results by Maltby et al (1963) were reported for a heaving delta wing. These experiments suggest that the slow convection along the vortex limits the response time of the flow such that all periodic disturbances should scale with the characteristic time of  $C/U$  as discussed above. In a related experiment, Patel (1980) subjected the delta wing to vertical gusts generated by a movable section of his wind tunnel. Figure 21 shows the measured lift amplitude and phase as a function of the oscillating periods. The tested range of  $T$  is about 1 order of magnitude longer than the convection limit,  $C/U$ . The measured data are not very sensitive to the oscillating frequency. It suggests that the vortex delay effect was not important in this frequency range and that the potential flow dominated. The constant phase lag which appeared in the data was probably due to the difference between the convection speed of the vertical disturbance and the free-stream velocity as mentioned by the author.

#### 4.4. Unsteady Freestream

Freymuth (1987) used titanium tetrachloride to visualize the response of a delta wing in a flow starting from zero speed. The sequence of pictures showed the formation of leading edge vortices of a delta wing at constant angle of attack in an accelerating flow. The vortex breakdown location was observed to move upstream when the flow in the wind tunnel was accelerating and vice versa during deceleration (Lambourne and Bryer 1961). When the freestream returned to a steady speed, the bursting point returned to its average position. This result was confirmed by Lee, Shih, and Ho (1987). To explain these observations, we recall that a favorable pressure gradient increases surface flux of vorticity in the boundary layer at the leading edge

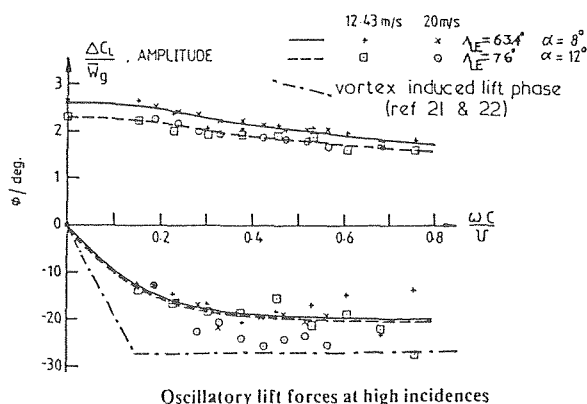


Fig. 21: Amplitude and phase angle of lift coefficient as the function of gust frequency, Patel (1980)

resulting in an increase in peak vorticity in the core. This increase in surface flux of vorticity produces a larger swirl angle. Furthermore, Lambourne and Bryer (1961) showed in their analysis that any pressure gradient in the freestream is magnified in the vortex core. A large swirl angle causes the breakdown to migrate upstream (Fig. 14). During deceleration, the adverse pressure gradient disturbs the vortex by locally reducing the convection of vorticity along the core, thereby disrupting the vorticity balance and affecting the vortex burst.

When Lee, Shih, and Ho (1987) imposed a free-stream velocity oscillation in the water tunnel, the vortex breakdown occurred at the midchord region and no significant change in the vortex breakdown location was observed. Gursul and Ho (1989) studied this problem for wings with different aspect ratios and in a wide range of angles of attack. They found that the vortex breakdown position could be very sensitive to the free stream variation, if the averaged breakdown location was near the trailing edge. The lift of the delta wing was also measured by them. For the cases of small angle of attack, the phase-averaged  $C_L$  is not a function of the reduced frequency and can be scaled by the period of the freestream variation (Fig. 22). These results again indicated that unsteady vortex effects have not come into play since the vortices have ample time to respond to the imposed distur-

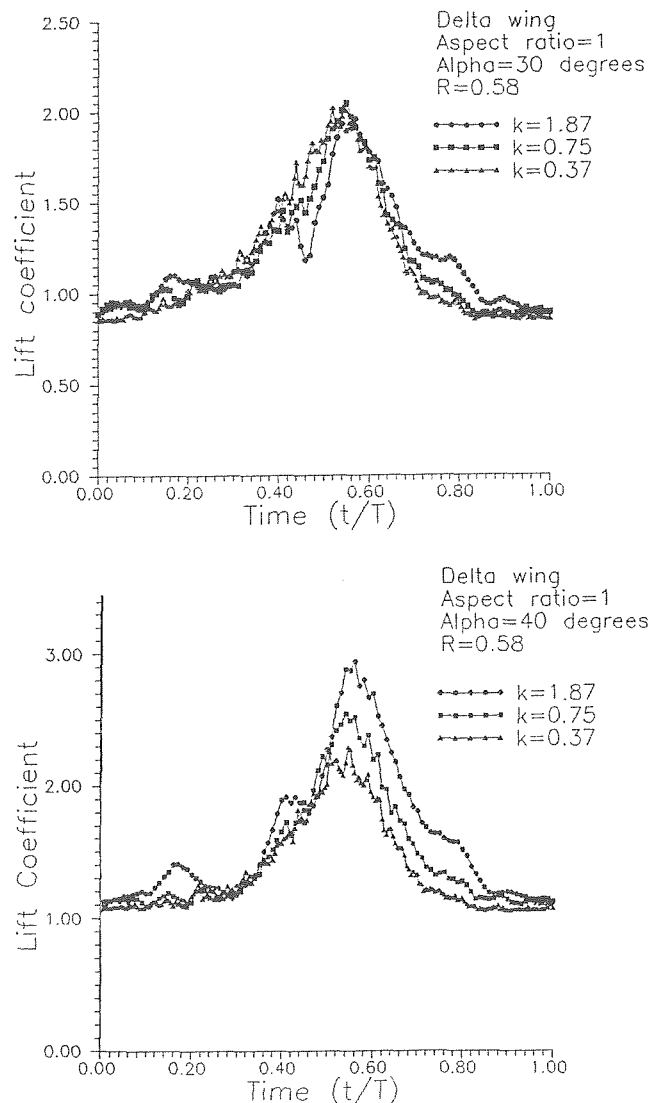
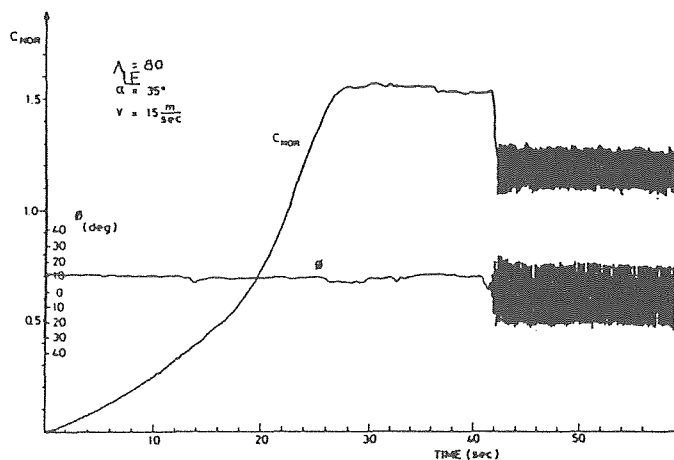


FIG. 22. Unsteady lift coefficient (Ho, Gursul, Shih, and Lin, 1990): (a) Cases for stationary leading-edge vortices; (b) Cases for convecting leading-edge vortices

bances. At a large angle of attack, the leading edge vortices do not stay stationary. The time of vortices convection from the apex to the trailing edge becomes an important scale in dictating the change of  $C_L$ . The period of the free stream variation is not the only governing time scale and the  $C_L$  curves do not collapse as those in Fig. 22.

#### 4.5. Wing Rock

The phenomenon of wing rock has been observed during flights of the aircraft with a delta wing platform marked by a sustained large amplitude oscillatory motion (Hwang and Pi 1979). A time history of the normal force and roll angle of an  $80^\circ$  delta wing tested in the wind tunnel is shown in Fig. 23 by Levin and Katz (1984). The average normal force experiences a sudden drop when the rock starts. Whether a delta wing will exhibit wing rock behavior or not depends on the initial roll and angle of attack (Fig. 24). The roll amplitude and oscillation frequency were observed to depend on the angle of attack and free-stream velocity (Levin and Katz 1984). Ericsson (1984) suggested that asymmetric vortex shedding rather than vortex breakdown is the key mechanism leading to wing rock. He argued that vortex breakdown cannot produce wing rock because Levin and Katz



Development of "wing rock."

FIG. 23. Time history of normal force and roll angle at the onset of wing rocking (Levin and Katz, 1984).

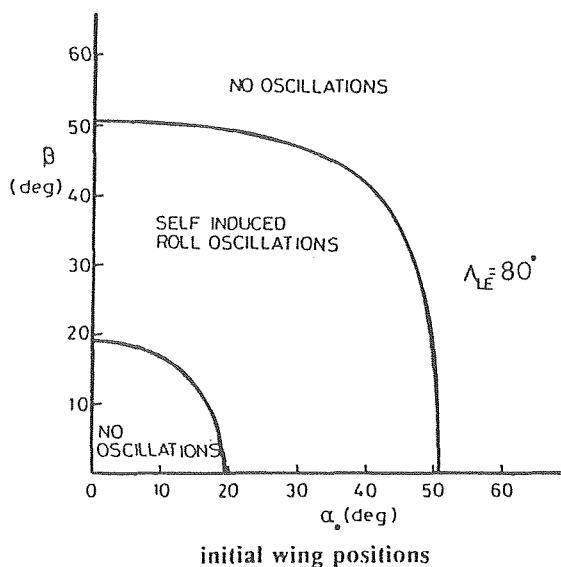


FIG. 24. Wing rocking as a function of its initial condition (Levin and Katz, 1984).

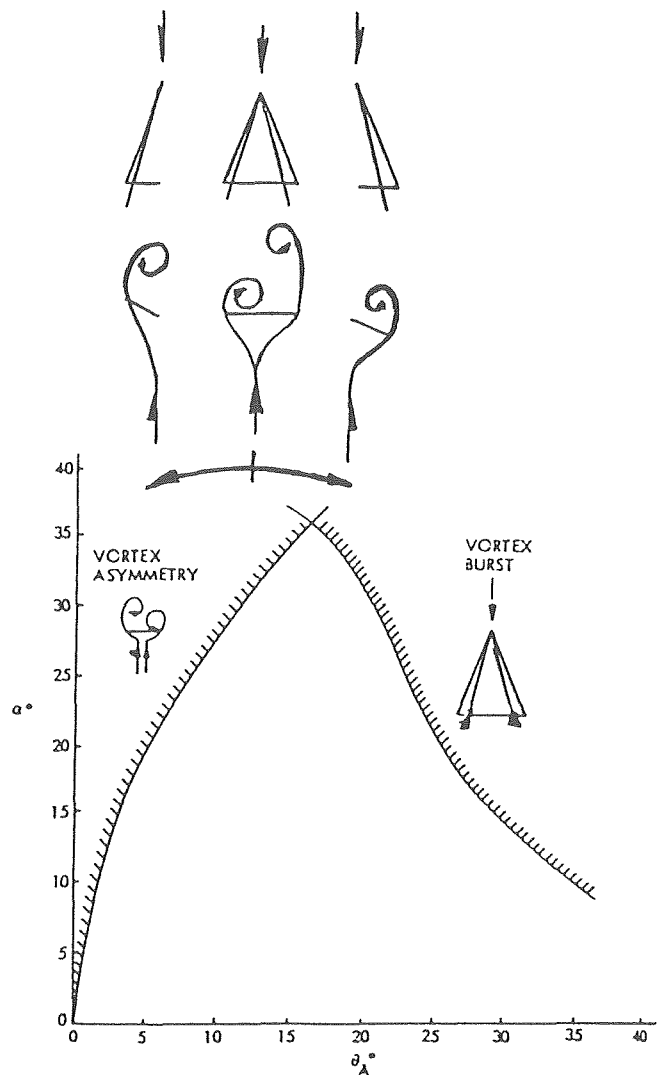


FIG. 25. Boundaries for vortex asymmetry and vortex burst (Ericsson, 1984).

(1984) observed wing roll before vortex breakdown and that the phenomenon is known to occur only on very slender wings. In addition, a loss of lift over the side of the wing with vortex breakdown produces a roll which increases the effective angle of attack. Consequently, the breakdown location is advanced farther upstream resulting in no restoring moment. In the case of asymmetric vortex shedding, a limit cycle mechanism is produced when the wing rolls to one side, resulting in an increase in the effective apex angle based on the regime chart in Fig. 25. This motion momentarily reduces the tendency for the vortex to shed asymmetrically. The leading edge vortex re-forms on the wing at a later time due to the vortex time lag effect discussed earlier and then produces the necessary restoring rolling moment.

Another way of looking at the vortex shedding mechanism based on vorticity balance is as follows. When the side of the wing tilts downward due to roll, the vorticity generation is increased due to an increase in the local pressure gradient at the leading edge as the stagnation point shifts in the opposite direction. This leads to the formation of a stronger vortex which can resist convection downstream. The formation time is again determined by  $C/U$  which sets a limit of oscillation frequency of  $C/UT = 1$ . On the other side of the airfoil, the vortex is washed downstream due to an increase in the convection as the leading edge vortex is exposed more to the freestream. This cycle is repeated when the wing rolls again in the opposite direction.

## 5. CONTROL OF LIFT

Most of the different schemes used to control the flow over delta wings reported here attempt to modify the leading edge vortex. The methods can be classified under blowing, suction and mechanical flaps applied at strategic locations on the suction surface either in a steady or in an unsteady fashion. A discussion on potential applications of vortex flaps is given by Lamar and Campbell (1984). Another scheme which does not fall in the categories mentioned above is the effect of density and viscosity variations through heating. These methods discussed here are effective in many aspects, but also have drawbacks. It is clear that the future trend of research will be the development of efficient control techniques through fundamental understanding of the physical mechanisms governing the aerodynamics.

### 5.1. Blowing

Various attempts have been made to alter the separation vortex by blowing along the leading edge in different directions. Trebble (1966) was able to enhance the lift by blowing outward away from the wing along the edge. The effect of blowing produced a stronger vortex located further outboard. An increase in drag was also measured due to the reverse thrust generated by a part of the high momentum fluid directed upstream. Bradley and Wray (1974) and Campbell (1976) achieved higher lift, a delay in stall, and better drag polar as a result of the spanwise blowing along the leading edge. The spanwise blowing could be due to an increase of the effective wing area instead of the modification of the vortices. Flow visualization pictures taken by Bradley and Wray (1974) of the vortex exhibited a more coherent core and delay in breakdown which is due to the increase in axial convection. When compared with Polhamus' theory, full vortex lift was achieved beyond the normal angle of attack for maximum lift (Fig. 26). Favorable results were also achieved by Wood and Roberts (1987), who directed the fluid tangentially upward past the round leading edge of a half delta wing. The pressure measurements shown in Fig. 27 suggest that leading edge separation was delayed for a small angle of attack and that the vortex was strengthened and localized at large angles. The reason for this is the increase in vorticity generation prior to separation due to changes in the local pressure gradient. Another method was attempted by Gad-el-Hak and Blackwelder (1987), who applied periodic blowing and suction at the leading edge. Although flow visualizations showed that the secondary vortices on the shear layer were more organized, no pressure data were available to deduce the effects on the aerodynamic forces acting on the wing.

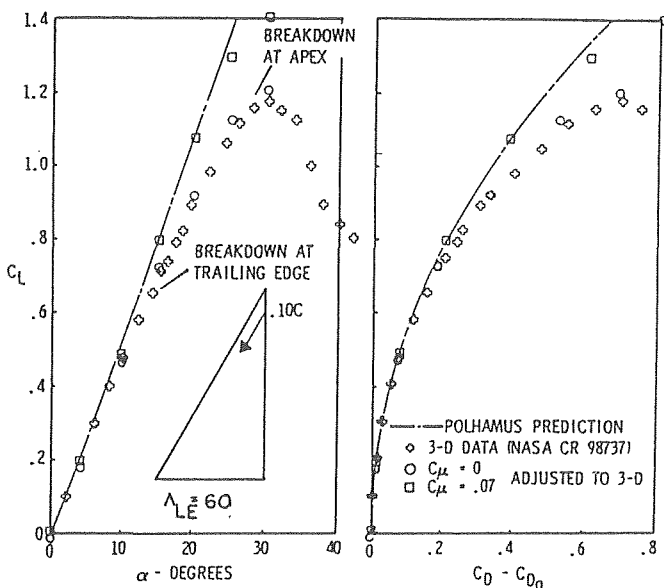


FIG. 26. Measurements of lift coefficient with axial blowing (Bradley and Wray, 1974).

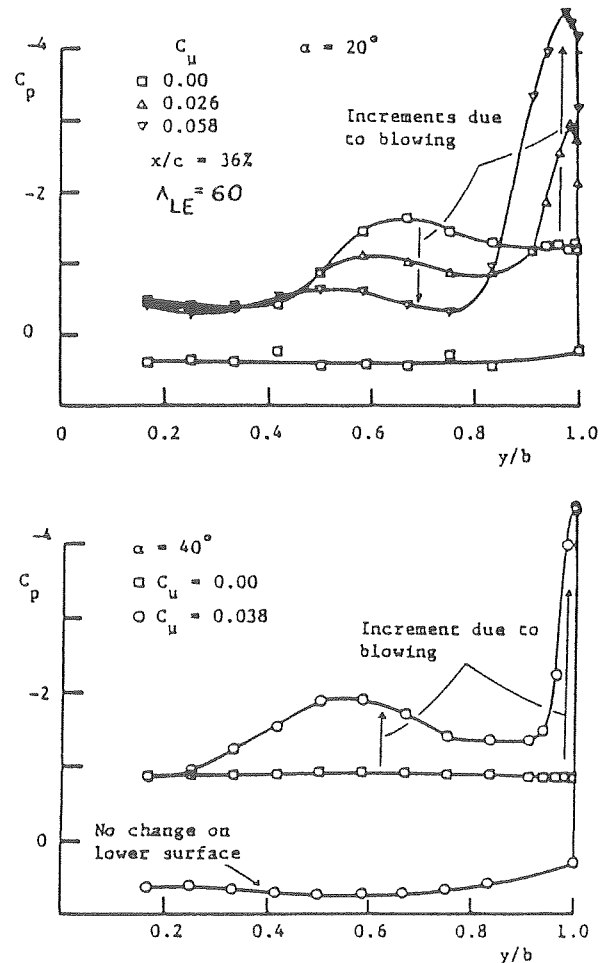


FIG. 27. Pressure distribution of delta wing with tangential blowing (Roberts, 1987).

### 5.2. Suction

Hummel (1967) investigated the effect of applying suction at the trailing edge and measured an increase of suction on the top surface while the bottom pressure profiles were not altered. A general increase in lift at a high angle of attack was observed with no gain at small to moderate angles of attack (Fig. 28). This is reasonable since suction only affects the vortex, which contributes only a small portion of the

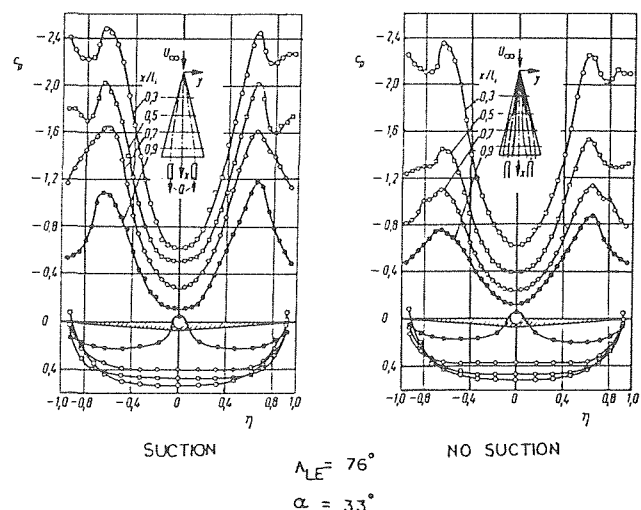


FIG. 28. Surface pressure distribution with trailing edge suction (Hummel, 1967).

lift at small angles of attack. At larger angles, suction at the trailing edge reduces the local adverse pressure gradient and increases axial convection along the vortex. As a result, a delay in vortex breakdown can be expected resulting in higher lift.

### 5.3. Flaps

Both stationary and moving flaps of different shape and size have been placed at or near the leading edge in an attempt to modify the evolution of the separation vortex. An experiment with stationary flaps was performed by Wahls, Vess, and Moskovitz (1986), who placed triangular shaped vertical fences at various locations close to the apex. Their flow visualizations showed the generation of streamwise vortices from the top of the fence. The new vortex eventually intertwined around the original vortex which was shed from the leading edge resulting in premature bursting. Rao and Buter (1983) also generated two pairs of streamwise vortices when they created an apex flap through upward deflection of the apex at 25% chord. Lift was increased for small angles of attack due to the new leading edge vortices which were generated on the apex and normally would not exist at this angle. At moderate to high angles of attack, lift was lower than the basic wing. Although no visualizations were provided, this loss of lift was probably due to premature bursting of the main vortex as a result of the interaction with the apex vortex, as has been observed by Wahls, Vess, and Moskovitz (1986). In another attempt, Marchman (1981) investigated the effects of upward deflection of a leading edge flap. The measurements in Fig. 29 show an increase of lift at low angles of attack but a loss of maximum lift. This is due to an effective increase in the swirl angle as a result of the deflected flaps. In addition to the lowered peak lift, an increase in drag was measured for all angles of attack reported. This type of flow control is probably more useful in conjunction with additional leading edge devices which can reduce the drag penalty. Of the ones tested by Rao and Johnson (1981) for this purpose, the combination of vortex plates and vertical fences produced the most drag reduction by creating a separation zone at the leading edge.

A concept borrowed from insect flight was the flapping delta wing experiment of Spedding, Maxworthy, and Rignot (1987). Two triangular shaped extensions hinged along the leading edge were allowed

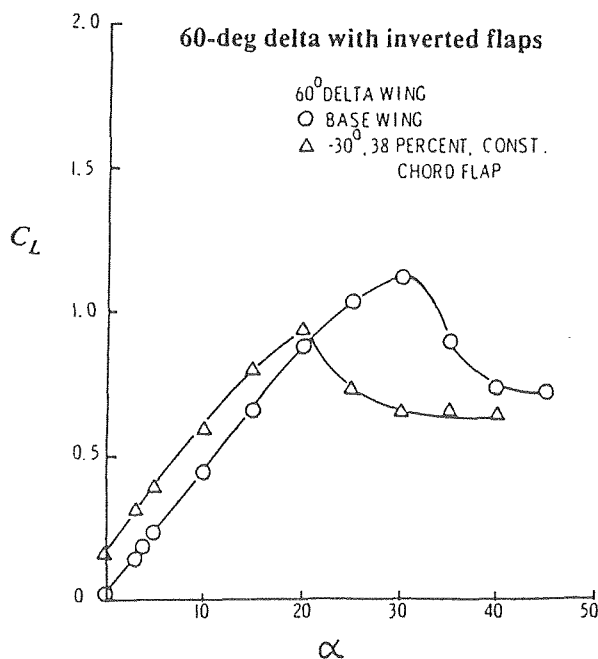


FIG. 29. Lift coefficient of a wing with steady inverted flaps (Marchman, 1981).

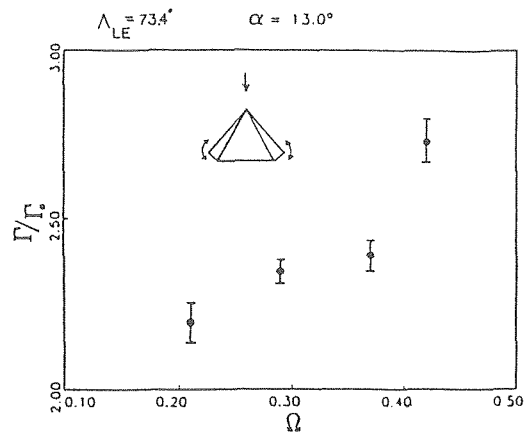


FIG. 30. Changes in circulation by unsteady flap (Spedding, Maxworthy, and Rignot, 1987).

to flap continuously at a frequency much faster than the response time of the original vortex. The idea was to generate a much stronger unsteady vortex through the flapping motion to enhance lift. Figure 30 shows the increase in circulation over nonflapping delta wings as a function of the flapping frequency. Note that the reduced frequency was based on average radian frequency measured at the mean flap width located at  $x/c = 0.5$ .

### 5.4. Heating

Marchman (1975) looked at the effects of heating on delta wing performance. The surface was heated close to twice the free-stream temperature. Their measurements showed that heating has virtually no effect on the lift and pitching moment, suggesting that variations in density and viscosity do not play an important role in the generation of the leading edge vortex. However, an increase of up to 25% in drag was recorded at large angles of attack. This is probably due to a combination of an earlier transition of the thermally stratified unstable boundary layer and the increase of viscosity.

## 6. CONCLUDING REMARKS

A review of experimental data for delta wings under both steady and unsteady conditions was presented from a vortex dynamics point of view. Vorticity balance provides the framework for understanding the effects of different parameters on the wing lift; stationary leading edge vortices result from the balance between vorticity surface flux and free-stream convection. The surface flux of vorticity depends on the condition of the boundary layer on the leading edge prior to separation, while vorticity convection depends on the component of the free-stream along the vortex. These vortices on the suction surface provide an important contribution to the lift of a delta wing, especially for the wings with large sweepback angle. Methods of either altering the vorticity generation near the leading edge or changing the vorticity convection along the cores can be effective in controlling the lift.

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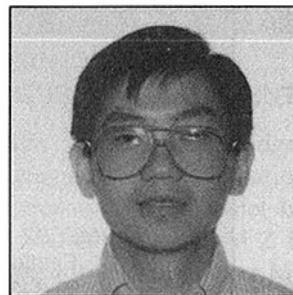
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