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Aerodynamics of Inverted Leading-Edge Flaps on Delta Wings

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Subsonic wind-tunnel tests were conducted to determine the aerodynamic effects of leading-edge flaps deflected upward from 60- and 75-deg sweep delta wings. Leading-edge flaps of various sizes and shapes were tested at a range of flap deflection angles. It was found that inverted flaps cause a strong vortex lift at low-to-moderate angles of attack and give large increases in C_L at those angles. Examination of pitching moment data reveals that the lift increases due to inverted flap use are not necessarily accompanied by the large changes in pitching moment which are associated with trailing-edge flap deployment. With a properly shaped leading-edge flap, a negative flap deflection can give substantial increases in C_L with no change in longitudinal stability.

Nomenclature

AR	= aspect ratio of wing
C_D	= drag coefficient
C_L	= lift coefficient
$C_{L_{max}}$	= maximum lift coefficient
C_m	= pitching moment coefficient (about centerline midchord)
L/D	= lift-to-drag ratio
α	= angle of attack of wing
δ	= flap deflection angle (measured downward from chord line)

Introduction

IT is well known that the aerodynamic behavior of highly swept delta wings is considerably different from conventional wings at subsonic speeds. At moderate angles of attack the vortex which forms as the flow separates around the wing's leading edge becomes the dominant factor in the wing's aerodynamics, producing a lift due to the low pressure in the vortex core (Fig. 1). While the leading-edge vortex allows the delta wing to produce lift at high angles of attack (up to 40 deg or more), it also produces a high drag.

Many recent studies[1-4] have explored the effects of wing leading-edge geometry modification on the vortex and on the wing's aerodynamics. Among these concepts the most promising appears to be that of the leading-edge vortex flap (LEVF), where the vortex forms on a leading-edge flap such that a vortex lift is still produced but the drag force resulting from the vortex is tilted forward to give a thrust.[2,4] The optimum leading-edge vortex flap would be designed such that the flap is deflected as far as possible while still maintaining separation and the resulting vortex, and such that the flap chord is sufficient to result in flow reattachment at the wing flap junction (Fig. 2).

In the course of investigating leading-edge vortex flaps[4] another interesting flap application was found, that of the inverted leading-edge flap. This is simply a leading-edge flap which is deflected upward relative to the chord line instead of downward in the usual manner. These tests were undertaken at the suggestion of Dr. J.F. Campbell of NASA Langley Research Center.

Normally, one would expect that adding negative camber at the wing's leading edge via inverted leading-edge flaps or any other means would have the effect of a leading-edge spoiler, causing separation and wing stall. However, since leading-edge separation is a primary lift producing mechanism for highly swept wings, it was felt that adding negative camber at the leading edge might result in the introduction of vortex lift at lower angles of attack than normal, giving greatly improved lift at low-to-moderate angles of attack. Optimum flap angle and size needed to be determined if indeed, the scheme proved workable.

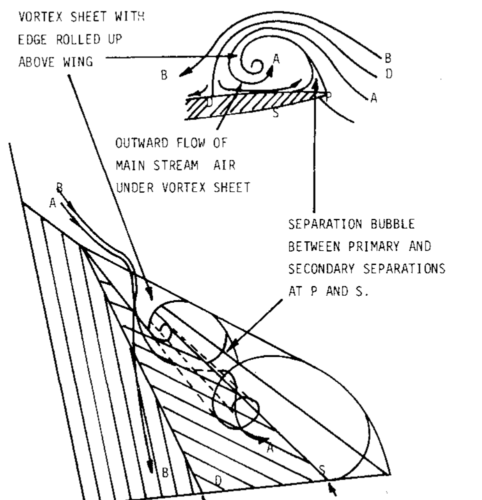

Fig. 1 Leading-edge vortex on a delta wing.

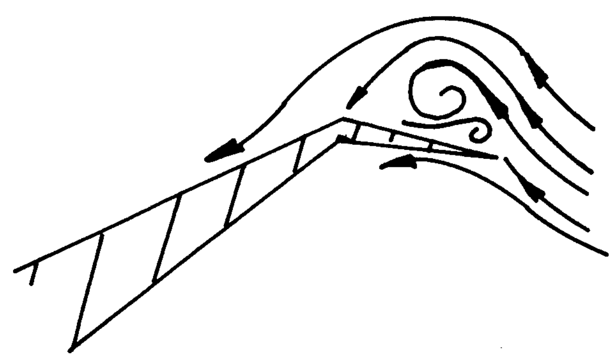

Fig. 2 Vortex on leading-edge vortex flaps.

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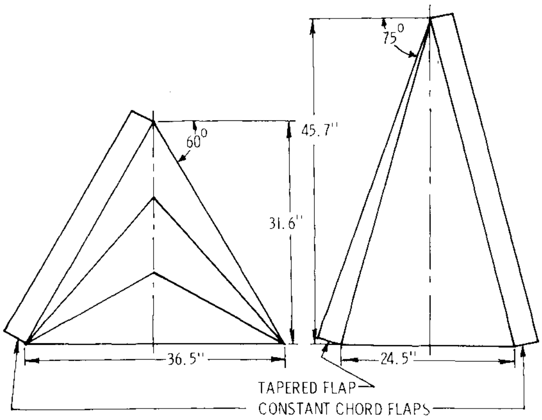

Fig. 3 Wing and flap models tested.

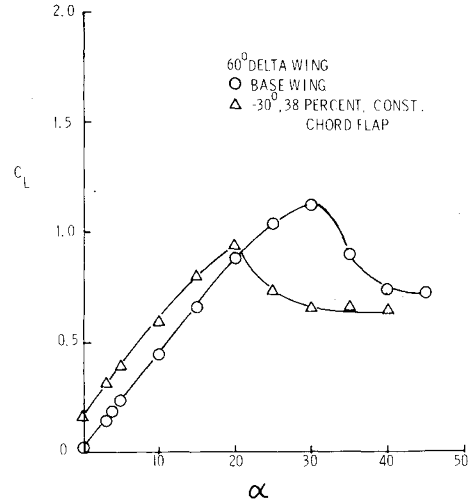

Fig. 4 C_L results for 60-deg delta with inverted flaps.

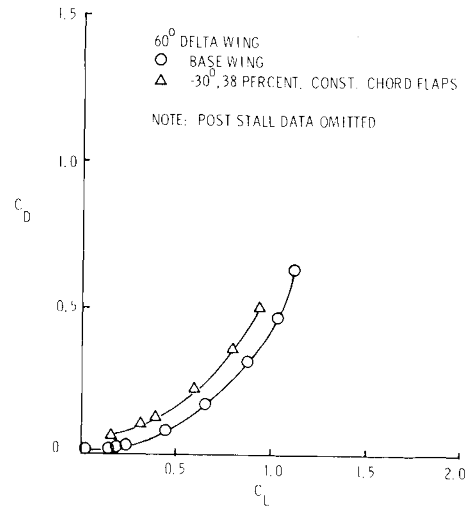

Fig. 5 C_D results for 60-deg delta with inverted flaps.

Description of Experiment

Tests were conducted in the Virginia Tech 6×6 ft Stability Wind Tunnel, a continuous flow subsonic facility with freestream turbulence less than 0.05%. Tests were run on 60- and 75-deg sweep delta wing models shown in Fig. 3. Both models had a projected area of 4 ft^2, sharp leading edges, and were used in earlier tests of leading-edge vortex flaps reported in Ref. 4. The 60-deg wing was originally built and tested at NASA Langley Research Center[5] and the 75-deg model was a flat plate wing with beveled edges constructed at Virginia Polytechnic Institute (VPI) of ¾-in. plywood.

All tests were run at a Reynolds number of approximately 2×10^6 based on wing mean chord. The models were strut mounted from below, using a six component strain gage strut balance. Data were taken by a Hewlett-Packard data acquisition system which reduced, plotted, printed, and tape recorded all results. The data acquisition system was later used to make selected plots of the data for presentation purposes.

Initial tests were run on the 60- deg delta wing with constant chord, full-span leading-edge flaps of three sizes and at four flap angles (Fig. 3). Flaps of 1-, 2-, and 3-in. chord were investigated, giving flap area-to-wing area ratios of 0.12, 0.25, and 0.38. Flaps were tested at upward deflection angles of 10, 20, 30, and 40 deg from the plane of the wing chord. All flaps were sheared from sheet metal, bent to the desired angle, and attached to the wing via tape and bolts. Similar tests were run on the 75-deg delta wing. Each configuration was tested over a range of angle of attack from 0 to 45 deg.

Some additional tests were also run on the 75-deg wing using flaps which were inversely tapered from zero flap chord at the wing apex to 3 in. at the trailing edge, giving a flap area-to-wing area ratio of 25% (Fig. 3).

Results and Conclusions

The general results for the tests are shown in Figs. 4-6, which compare C_L, C_D, and L/D data for the 60-deg delta wing with inverted flaps to the results for the same wing without flaps. The flaps used to obtain this data comparison were constant chord, 3- in. flaps deflected 30 deg upward, giving a flap area-to-wing area ratio of 38%. All coefficients shown are based on projected wing area plus projected flap area; hence the effect of flap area is divided out, giving only the real aerodynamic effects of the flaps.

As is seen in Fig. 4, the effect of inverted vortex flaps on lift coefficient is to shift the lift curve to the left, much as a camber effect would shift the curve; however, $C_{L_{max}}$ is reduced by about 16%. Since the lift coefficient on a highly swept wing is strongly affected by the action of the leading-edge vortex, this shift must be discussed in terms of the flaps' effect on the vortex. The inverted flaps give the leading edge of the wing an angle of attack 30 deg more than the nominal angle of attack of the wing, i.e., when the wing is at $\alpha = 0$, the flow sees a leading edge at $\alpha = 30$ and the leading-edge vortex is formed accordingly. Hence a strong vortex lift occurs which would not be present on the basic wing at $\alpha = 0$. The basic mechanism of the inverted vortex flap is then to create vortex lift at low angles of attack where it would not normally exist; thus enhancing the lift at low α. As can be seen in Fig. 4, the result is a ΔC_L of about 0.16 at low-to-moderate angles of attack, which represents a 70% lift increase of 5-deg angle of attack.

Because of the strong vortex which forms, stall does not occur until an angle of attack of 20 deg, even though the leading-edge angle of attack is 50 deg at that point. This represents a 10-deg decrease in stall angle of attack and a 16% reduction in $C_{L_{max}}$ when compared to the base wing. Therefore one does pay a penalty for the C_L increase at moderate angle of attack; but, properly applied, the results may be worthwhile.

As would be expected, the drag is increased by use of inverted vortex flaps as shown in Fig. 5. The low pressure in the vortex acting on the top of the flap results in a force vector tilted in the drag direction which increases the drag even though the flow reattachment behind the vortex would prevent any large increase in conventional wake or form drag at moderate α.

At first glance it would appear that the very large increase in drag at low angles of attack (about 300%) would negate

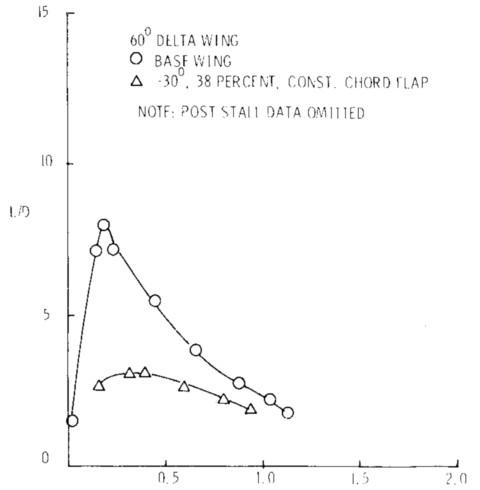

Fig. 6 L/D results for 60-deg delta with inverted flaps.

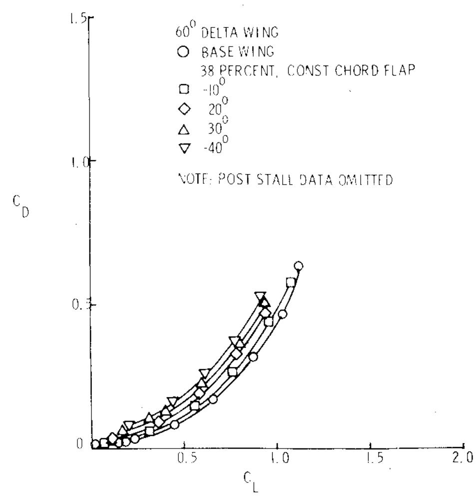

Fig. 8 Effect of inverted flap deflection on C_D.

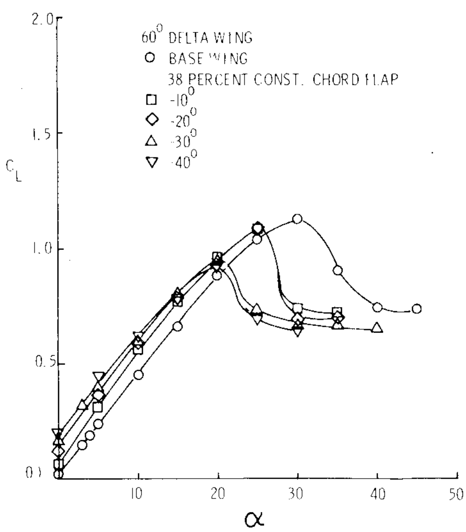

Fig. 7 Effect of inverted flap deflection on C_L.

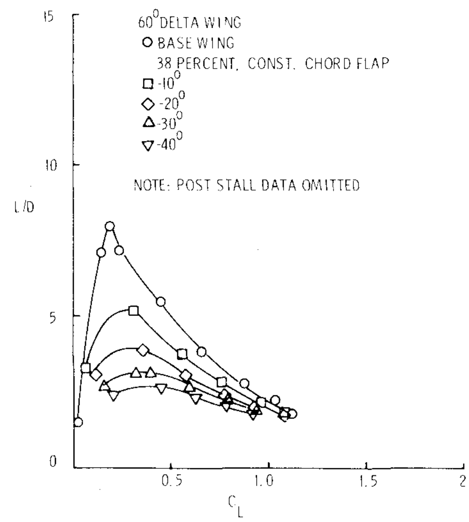

Fig. 9 Effect of inverted flap deflection on L/D.

any advantage given by the lift increase. This is particularly true when one looks at the L/D result shown in Fig. 6, which indicates a large drop in performance at low-to-moderate angles of attack. However, there are cases where the combination of increased lift and drag are advantageous. One such case is that of landing a high-speed aircraft where it is desirable to maintain sufficient engine power to allow an aborted landing and go-around. The high lift provided by the inverted vortex flap allows a lower-speed approach at a lower angle of attack (thus improving pilot visibility). The high drag both serves to brake the aircraft and to provide high sink rates. The result is an aircraft which is more responsive in landing. Further study is underway to determine the lateral/directional stability of the wing flap system.

In addition to examining the basic effects of inverted vortex flaps, the object of the study was to investigate the effects of flap size and deflection on inverted vortex flap performance. A 3-in. chord leading-edge flap was chosen as a starting point primarily because this size was found to be optimum for the 60-deg delta wing model in the previous study of leading-edge vortex flaps.[4] This flap was tested at flap angles of -10, -20, -30, and -40 deg to see the effect of flap angle on the results. The primary results are seen in Figs. 7-9. In general, it is seen that as flap deflection increases, both lift coefficient and drag coefficient increase and the lift-to-drag ratio decreases. It is interesting that in the cases of 10- and 20-deg inverted flap deflection there is very little degradation in $C_{L_{max}}$ compared to the basic wing case and only a 5-deg change in the stall angle.

Looking at the -20-deg flap deflection case it is seen that the C_L improvement over the base wing is almost identical to that for the -30-deg deflection and that $C_{L_{max}}$ is almost identical to that for the base wing, suggesting that, of the flap angles tested, 20 deg may be the best. The 20-deg flap deflection case also gave somewhat better L/D results than the 30-deg case. Based on this apparent superiority in $C_{L_{max}}$ and L/D of the -20-deg flap deflection, testing proceeded with the examination of various sizes of flaps deflected at -20 deg.

Figures 10-12 show the effect of flat size on the lift and drag aerodynamics of the 60-deg wing with 20-deg inverted flaps. The general results are somewhat predictable. As flap size decreases, the drag coefficient and lift coefficient decrease and L/D increases, since the resulting wing flap configuration approaches the basic wing shape. These results also suggest that as flap size increases, the angle of attack for stall decreases slightly.

Some similar tests were also run on the 75-deg flat plate delta wing model. These gave results quite similar to those for the 60-deg delta, as is seen in Figs. 13-15. Lift coefficient increased by up to 100% at lower angles of attack with a 14% decrease in $C_{L_{max}}$ due to the use of 3-in. constant chord flaps deflected upward to 30 deg. The drag coefficient increase was not as great as observed for the 60-deg delta wing and hence

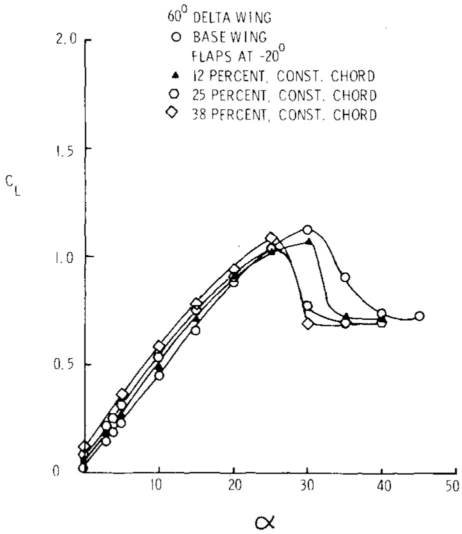

Fig. 10 Effect of inverted flap size on C_L.

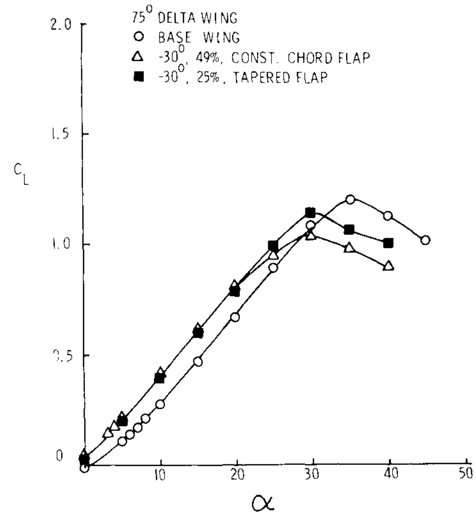

Fig. 13 C_L results for 75-deg delta with tapered and constant chord inverted flaps.

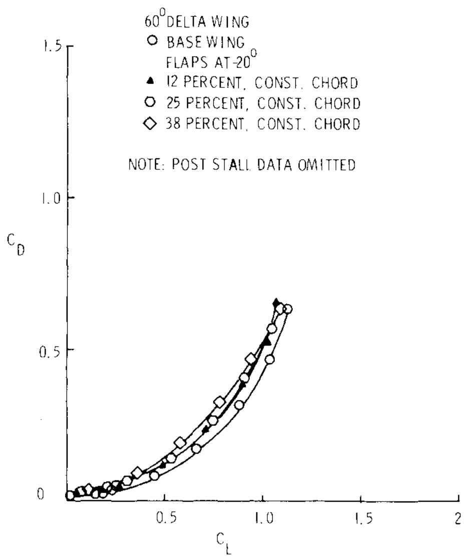

Fig. 11 Effect of inverted flap size on C_D.

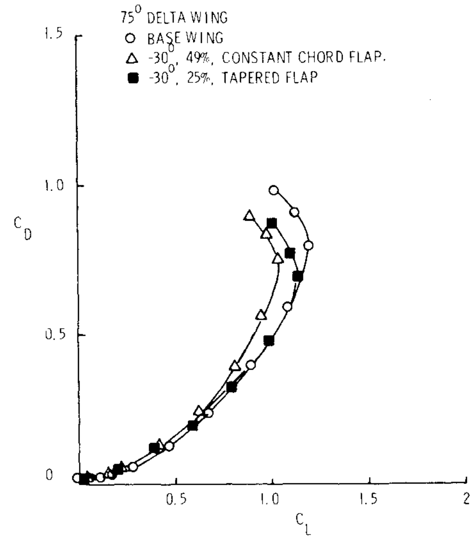

Fig. 14 C_D results for 75-deg delta with tapered and constant chord inverted flaps.

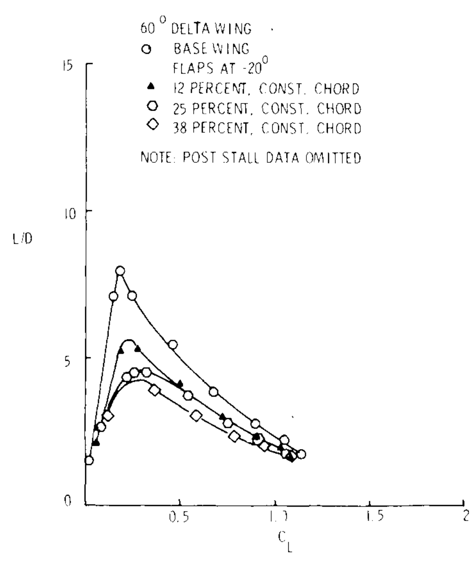

Fig. 12 Effect of inverted flap size on L/D.

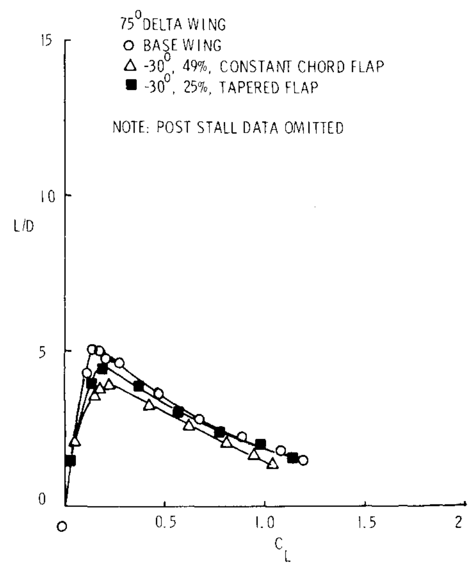

Fig. 15 L/D results for 75-deg delta with tapered and constant chord inverted flaps.

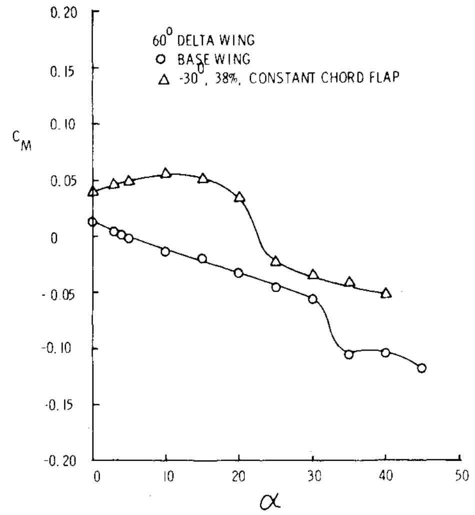

Fig. 16 Pitching moment for 60-deg delta with inverted flaps.

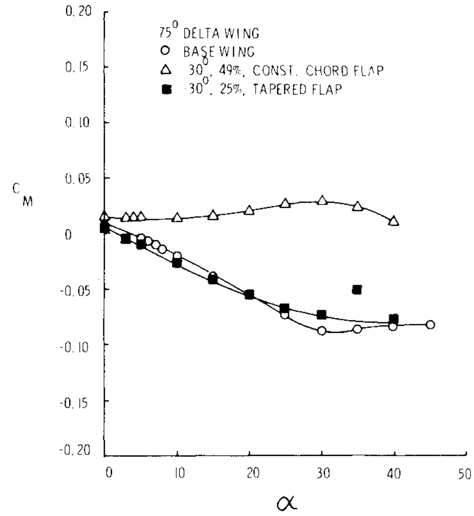

Fig. 18 Comparison of tapered and constant chord inverted flap effects on pitching moment for 75-deg delta wing.

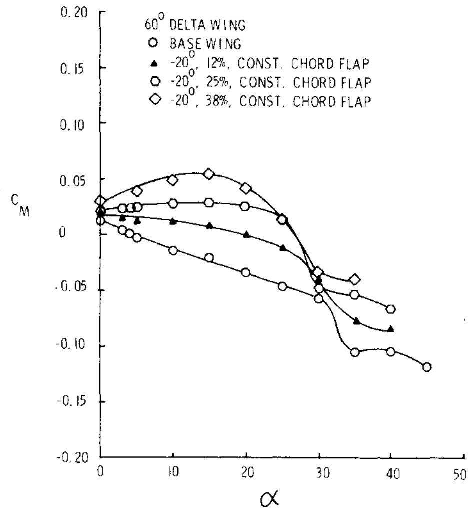

Fig. 17 Effect of inverted flap size on pitching moment for 60-deg delta wing.

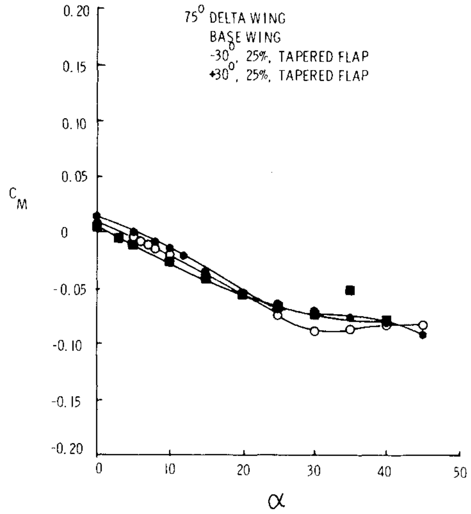

Fig. 19 Comparison of downward and upward deflected tapered LEVF on 75-deg delta pitching moments.

the lift-to-drag ratio was not reduced nearly as much as in the previous case.

Also shown on Figs. 13-15 are the results from tests run on the 75-deg wing with tapered chord flaps, where the flap chord increased linearly from 0 at the wing's apex to 3 in. at the wing tip. This flap is seen to produce C_L increases almost as great as the constant chord flap and a $C_{L_{max}}$ only 2% lower than that for the constant chord flap and the resulting lift-to-drag ratio is close to that for the base wing. This indicates that, unless the higher drag of the constant chord flap is desired, the tapered flap is superior in both lift and drag.

One problem which must be considered with leading-edge vortex flaps is their effect on pitching moment. Past tests[4] showed that constant chord LEVF's produced strong positive pitching moments and longitudinal instability at moderate angles of attack, owing primarily to the large added wing area near the wing apex and the strong vortex action there. The use of tapered LEVF's resulted in a pitching moment behavior much closer to that of the basic wing.[4] Figure 16 indicates that the inverted constant chord flap has similar problems on the 60-deg delta wing. The wing exhibits longitudinal stability at angles of attack above 10 deg but is unstable below that angle. Tests of various inverted flap sizes and angles showed similar tendencies; however, the unstable region did flatten out for the smaller size flaps at a −20-deg flap deflection, as shown in Fig. 17. At these smaller flap sizes the wing is more stable at low-to-moderate angles of attack and the smaller slope of the curve may indicate that less stick force would be necessary to hold the aircraft at a desired angle of attack during approach and landing. This would most certainly be the case when compared with the large nose-down moments created by the use of trailing-edge flaps to increase C_L for landing.

Figure 18 shows some of the pitching moment results for the 75-deg delta wing where the constant chord flaps produce a neutral-to-unstable response over most of the angle-of-attack regime. When tapered inverted flaps were tested the moment curve almost matched that of the base wing. Since the lift and drag results for the tapered flaps were equal to or better than the constant chord flap results, the moment data may suggest that tapered flaps could have an advantage in that the pitching stability with flaps would change little from that for the basic wing. This could be of benefit in the control system where use of the inverted leading-edge flaps would not require additional control power to hold the desired angle of attack. It is also interesting to note that a downward deflection of the tapered leading-edge flaps to 30 deg produces an almost identical pitching moment curve to that of either the basic wing or the inverted tapered flaps; i.e., with tapered leading-edge vortex flaps, flap use does not change

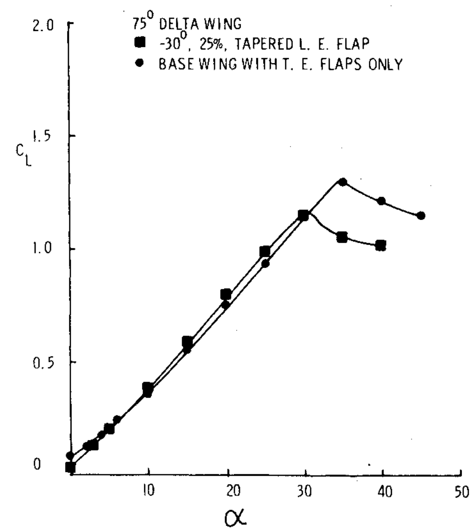

Fig. 20 Comparison of C_L for inverted LEVF and trailing-edge flaps on 75-deg delta.

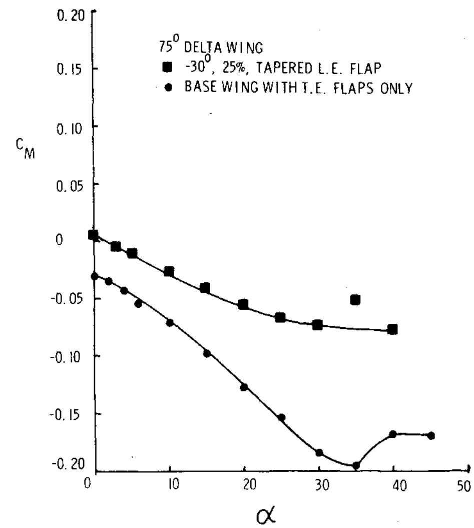

Fig. 22 Comparison of C_M for inverted LEVF and trailing-edge flaps on 75-deg delta.

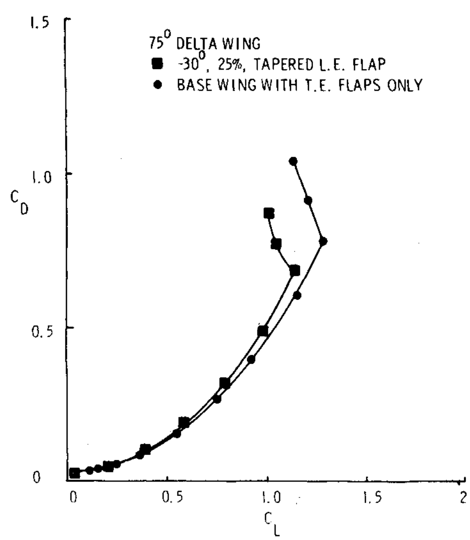

Fig. 21 Comparison of C_D for inverted LEVF and trailing-edge flaps on 75-deg delta.

the trim requirements for the aircraft at a given angle of attack (Fig. 19).

In looking at the overall concept of using inverted leading-edge vortex flaps to increase lift for landing vs the conventional method of using trailing-edge flaps, inverted LEVF appear to deserve consideration. A comparison of the 75-deg delta wing model tested with inverted LEVF with the same wing tested with a pair of trailing-edge flaps is revealing, as seen in Figs. 20-22. The 75-deg delta wing was tested with trailing-edge flaps with an area 12.5% of the base wing area deflected to 20 deg. Figure 20 indicates that while $C_{L_{max}}$ for the tapered inverted flaps is slightly (about 12%) lower, the lift coefficient at most angles of attack exceeds that for the same wing with conventional trailing-edge flaps. Figure 21 shows that the drag is slightly higher for the inverted flap case, which will help slow the aircraft for landing and Fig. 22 shows that the inverted flaps produce longitudinal stability and would require much less longitudinal control force in maintaining a landing attitude. Lateral/directional stability must also be investigated to determine effects of yaw on leading-edge vortex flap operation.

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