Trailing Edge Flap Influence on Leading Edge Vortex Flap Aerodynamics

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A study has been conducted to explore the effects of trailing edge flaps (TEF) on leading edge vortex flap (LEVF) aerodynamics. A variety of LEVF and TEF configurations were tested on flat plate delta wings with leading edge sweep angles of 60 and 75 deg. Results indicated that the well-established vortex flowfield of the 75-deg wing was not substantially improved with the deflection of trailing edge flaps. Significant changes were seen to occur to the marginal vortices of the 60-deg wing. For the 60-deg wing with inverted constant chord LEVFs, the deflection of TEFs resulted in substantial increases in lift coefficient at low angles of attack without sacrificing other performance parameters. Also shown is the capability for eliminating the adverse longitudinal characteristics of constant chord LEVFs.

Nomenclature

C_D	= drag coefficient
C_L	= lift coefficient
$C_{L_{max}}$	= maximum lift coefficient
$C_{L_{ref}}$	= reference lift coefficient
C_m	= pitching moment coefficient
ILEVF	= inverted leading edge vortex flaps
LEVF	= leading edge vortex flaps
TEF	= trailing edge flaps
α	= angle of attack

Introduction

RECENTLY there has been considerable interest in the tactical supercruiser, an aircraft which would efficiently cruise at supersonic speeds and yet retain the transonic maneuver capabilities of today's lightweight fighters. Several configurations have been proposed, but each specified a highly swept slender wing, optimized for supersonic cruise and dependent on vortex flow for maneuver lift. It would be natural to expect that such an aircraft would also depend on vortex flow for low-speed flight. Many current generation supersonic aircraft also rely on moderate to highly swept delta wings for successful operation throughout their flight regimes.

Numerous exploratory studies[1-5] have investigated leading edge modification to highly swept delta wings and their effects on the aerodynamics of leading edge vortex flows. The most promising concept involves what is termed a leading edge vortex flap[3] (LEVF), where the vortex is forced to form on a protruding flap rather than on the wing's upper surface. If the flap is deflected in a downward direction (Fig. 1), the vortex core again produces a force vector normal to the surface, but producing a thrust rather than drag. Aerodynamic tailoring of the LEVF could permit the creation of a lift and thrust producing vortex whose circulation would induce flow reattachment at the wing-flap junction. Substantial lift increases and drag reductions could be realized for an aircraft in a takeoff and climb configuration, decreasing the time an aircraft must spend at low altitudes where noise and fuel consumption present problems.

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A slight variation of the original concept involves deflecting the flap above the plane of the wing (Fig. 2).[6] This permits the creation of stable leading edge vortices at an angle of attack which normally would not support such a flow environment. The inverted leading edge vortex flap (ILEVF) seems to be best suited to landing configurations where its high lift and drag characteristics at low angles of attack may be desirable. Lower angles of attack during landing could alleviate pilot visibility problems and possibly eliminate the need for the "drooping nose" typical of supersonic transport designs. Fighter aircraft could benefit from the increased drag and sink rates the ILEVF provide by allowing higher power settings, thus improving the aircraft's ability to maneuver and execute a go-around in the event of an aborted landing. The increased drag might also eliminate the need for speed brakes or other drag-producing surfaces necessary to slow such high performance aircraft.

One aspect of LEVF aerodynamics which has not been adequately explored concerns conventional trailing edge flaps and their effect on the aerodynamics of leading edge vortex flaps. Although LEVF research conducted by Marchman et al.[2] and Rao[1] included brief investigations, an exploratory study devoted entirely to LEVF and TEF interactions was needed. Aircraft which utilize the highly swept, low aspect ratio, delta wing typically must depend on a system of trailing edge flaps to provide adequate lift during the landing and takeoff phases of flight. Trailing edge flaps might also eliminate the longitudinal instability exhibited by several LEVF configurations.[2,6] Most importantly, the increased circulation and effective angles of attack generally associated with the deflection of trailing edge flaps might provide engineers an additional tool in the aerodynamic tailoring of a complete leading edge vortex flap system.

Description of Experiment

The primary objective of this study was to determine what effects simple, unslotted constant chord, trailing edge flaps would produce relative to the performance of leading edge vortex flaps of several different geometries. No attempt was made to optimize the performance of these trailing edge flaps, as this was to be an initial exploratory study.

Two delta wing models which had been investigated previously[2,5,6] (Fig. 3) were chosen for this study: a 60-deg symmetrical delta wing and a 75-deg flat plate delta wing. The models were of equal area (4 ft^2) and had sharp leading edges. The flap configurations to be tested were identical for the 60- and the 75-deg wings. Leading and trailing edge flaps were sheared from sheet steel, bent to the desired deflection angle,

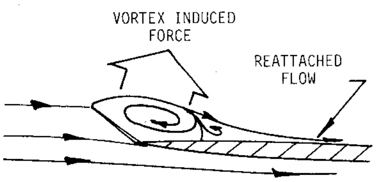

Fig. 1 Flow on a leading edge vortex flap.

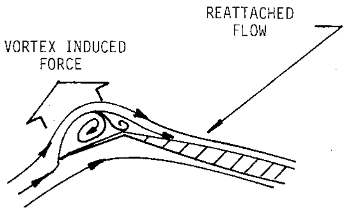

Fig. 2 Flow on an ILEVF.

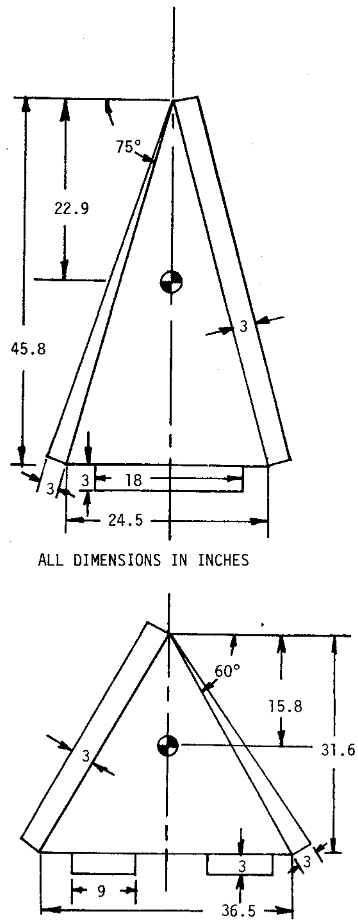

Fig. 3 Wing and flap model geometries.

and fastened to the wing model with double-sided tape and small bolts. Leading edge flap configurations (Fig. 3) were 3-in. full span, constant chord flaps deflected to ±30 deg, and full span, inverse tapered flaps deflected to ±30 deg. The tapered flaps had zero chord at the delta apex and increased linearly to a chord of 3 in. at the trailing edge. A standard leading edge vortex flap (LEVF) consisted of a flap deflected below the plane of the wing while an inverted leading edge vortex flap (ILEVF) would be deflected above the plane of the wing. Constant chord, trailing edge flaps (TEF), as shown in Fig. 3, were tested at deflection angles of 10 and 20 deg downward and were run with and without leading edge modifications on the two wings.

All configurations were tested at angles of attack ranging from 0 to 45 deg. The force and moment coefficients were based on the projected wing area plus the projected deflected flap area in order to illustrate the real aerodynamic performance of LEVF and TEF configurations. The "projected" area[1,2,5,6] has become the standard means for reducing LEVF data because direct performance comparisons may be made without interference from dissimilar flap geometries. All pitching moment measurements were taken about the mid-point of the wing root chordline which corresponds to the wing's mean chord.

All wind tunnel testing was conducted in Virginia Tech's 6×6 ft Stability Wind Tunnel. Originally designed and constructed at the NASA Langley Research Center, this single return subsonic wind tunnel maintains freestream turbulence levels of less than 0.5%. Throughout the study, a tunnel dynamic pressure of 3.00 in. of water (15.6 psf) was utilized, yielding a mean chord Reynolds number of approximately 1.1×10^6. The delta wing models were mounted on a six-component strain gage strut balance which was linked to a Hewlett-Packard data acquisition system. As data were taken, it was reduced, plotted, and recorded on magnetic and paper tapes. Virtually instantaneous data reduction and output allowed testing to be custom tailored to suit the individual performance of each model configuration.

Results

In the aerodynamic tailoring of leading edge vortex flaps, a variable flap deflection angle provides the simplest means for altering the flap's performance characteristics. The optimum deflection angle will necessarily depend on the wing's angle of attack and the flap characteristics which are to be emphasized. For standard LEVFs, the optimum deflection angle should be as large as possible in order to maximize the thrust, yet not so great as to prevent separation and vortex formation. The ILEVFs suffer similar deflection angle limitations; too small an angle will prevent vortex formation while too large an angle results in excessive drag. At moderate-to-high wing angles of attack, the local flow (upwash) is generally at a sufficient angle to the leading edge to permit some flexibility in the choice of leading edge vortex flap deflection angles. However, at low wing angles of attack, the local angle of attack at the leading edge may be small enough to prevent the formation of desirable vortex flows except in the ILEVF application. To allow direct comparison with the results of previous studies,[2,5,6] LEVF and ILEVF deflection angles of 30 deg below and above the plane of the wing, respectively, for both the 60- and 75-deg wings were used.

To provide a basis for comparison, the basic aerodynamic characteristics of each LEVF configuration are needed. It should be re-emphasized that all coefficients are based on the sum of the wing and flap projected areas. In practice, where LEVFs and TEFs are extended only for temporary use, it may be more desirable to calculate these coefficients based on the area of the wing only. In order to concentrate on the vortex aerodynamics, it is advantageous, however, for the purposes of this study to eliminate the effects of increased wing area. Also, a reference lift coefficient of 1, $C_{L_{\rm ref}} = 1.0$, will be used to simulate a design point. This value was considered representative of the landing regime where the application of TEF would most likely occur.

The effects of constant and tapered chord LEVFs on a 60-deg delta wing are illustrated in Fig. 4. The constant chord flaps provide a slight increase in $C_{L_{\max}}$, the tapered chord flaps result in a slight decrease in C_L for angles of attack below 25 deg. The primary benefit accrued from LEVFs, however, is a reduction in drag.[1-3] For lift coefficients above 0.2, the approximate point at which the leading edge vortex forms for these configurations, the suction developed by the flap bound vortex significantly increases the negative axial force, or thrust, produced by the configuration. However, the constant chord LEVFs incur a pitching moment penalty. The increased area at the apex of the delta wing and the lifting effect of the flap bound vortex result in unstable longitudinal

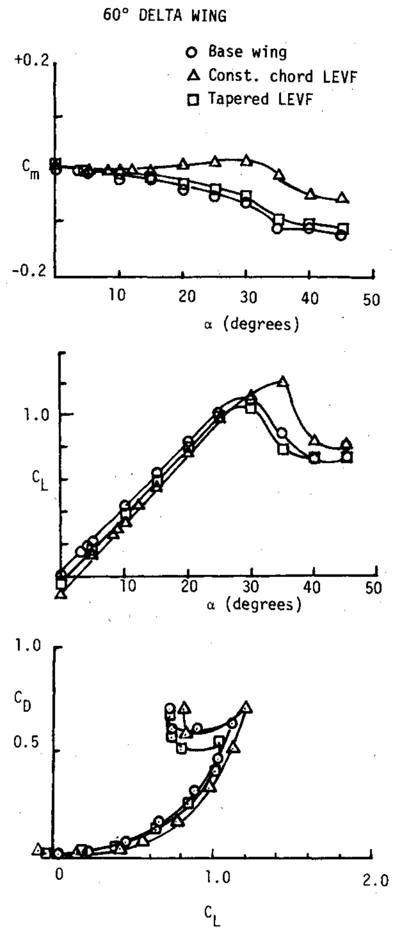

Fig. 4 LEVF effects on a 60-deg delta wing.

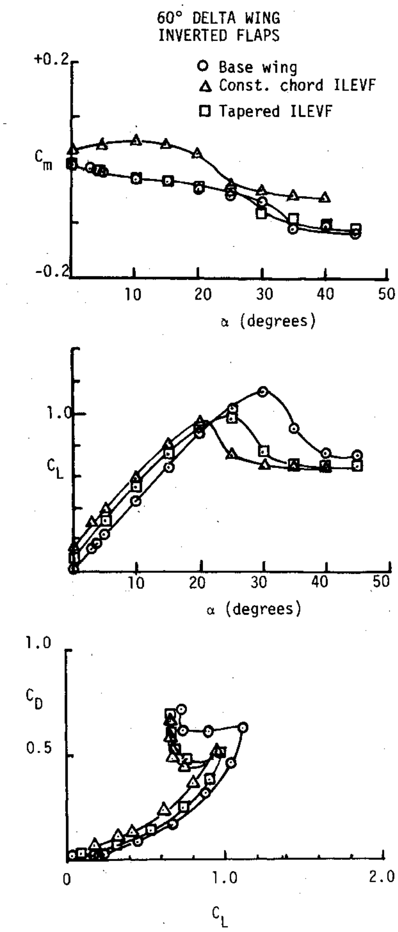

Fig. 6 ILEVF effects on a 60-deg delta wing.

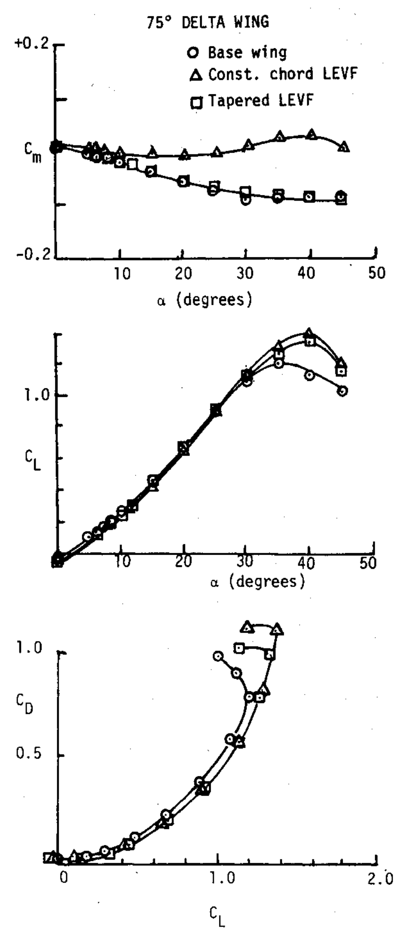

Fig. 5 LEVF effects on a 75-deg delta wing.

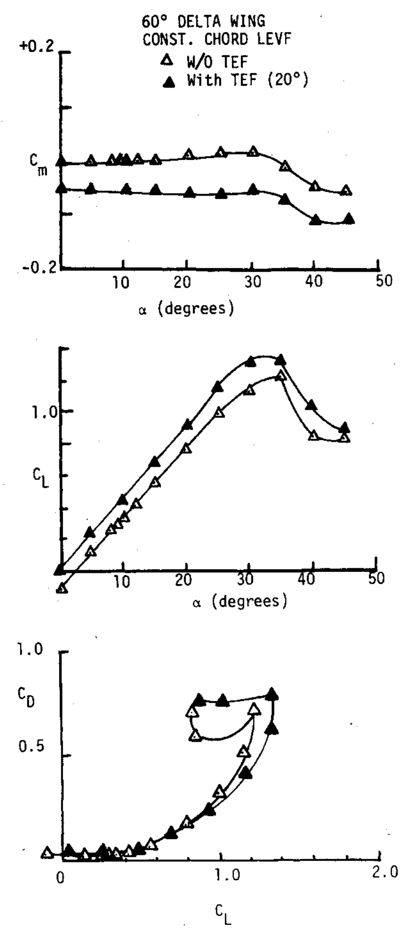

Fig. 7 TEF effects on a 60-deg delta wing with constant chord LEVFs.

characteristics.[2] The reduced forward area of the tapered flaps eliminates this instability and produces pitching moments which closely match those of the unmodified wing.[2]

The effect of constant and tapered chord LEVFs on a 75-deg delta wing are shown in Fig. 5. The basic trends for the 75-deg wing are very similar to those shown for the 60-deg case. However, owing to the increased sweep angle of the wing and the tendency to provide stronger leading edge vortices, several LEVF effects are magnified. For the 60-deg case, the nonlinearities in the lift curve are very slight, indicating that the leading edge vortex effects are relatively small. The 75-deg wing, however, exhibits a very nonlinear lift curve for both LEVF configurations due to the presence of strong leading edge vortex effects. Significant increases in C_L at high angles of attack due to the LEVF again illustrate their ability to vector the vortex lift in a beneficial direction. While the tapered chord LEVFs have little effect on the longitudinal characteristics of the wing, the constant chord LEVFs still induce unstable pitching moments.[2]

Figure 6 illustrates the effect of constant and tapered chord ILEVFs on a 60-deg delta wing. The basic effect is a leftward shift of the lift curve similar to the effect of added camber on a conventional wing: A decrease in $C_{L_{max}}$ should also be noted; however, the principal advantages of ILEVFs occur at low angles of attack. Large drag coefficients and low lift to drag ratios would be expected and have been reported[6]; however, these performance characteristics coupled with high lift at low angles of attack may be desirable for a slender wing aircraft in a landing configuration. The pitching moment characteristics follow the trends noted before; the tapered chord ILEVFs have little effect on the longitudinal stability, while the constant chord ILEVFs induce unstable pitching moments.[6]

In all tests run with trailing edge flaps, the TEFs were tested at both 10- and 20-deg deflections; however, since the results for the 10-deg case were always bracketed by the performance of the cases shown, it was felt that the presentation of results might be easier to read if only the 20-deg results were shown.

The effects of 20-deg TEFs on the 60-deg wing equipped with constant chord LEVFs are illustrated in Fig. 7. As expected, with the deflection of TEFs there is a leftward shift of the C_L vs α curve, an increase in $C_{L_{max}}$, and a negative shift in the C_m vs α curve. An interesting effect the TEFs provide for angles of attack between 15 and 30 deg is a slight increase in the lift curve slope. As noted before, a leading edge sweep angle of 60 deg is marginal in its ability to produce strong, stable leading edge vortices. The nonlinearities have increased for the TEF case, suggesting that the leading edge vortex has been strengthened. At the reference lift coefficient, $C_{L_{ref}} = 1.0$, the 20-deg TEFs offer an angle of attack reduction of 4 deg or 15%. If the angle of attack of 26 deg were desired, the TEFs provide an increase in C_L of 0.19 or 19%. For lift coefficients above 0.7, the deflection of TEF provides small decreases in drag coefficient.

As discussed earlier, one of the desired effects of TEF deflection was the correction of the unstable pitching moments that the constant chord LEVFs induce. As indicated by the slope of the C_m vs α curve, the TEFs provide, at best, marginal longitudinal stability. However, if the TEF deflection angle were proportional to the wing angle of attack, stable pitching moment characteristics could be provided.

The constant chord LEVF with 20 deg TEF is shown for the 75-deg wing in Fig. 8. Similar trends to those seen for the 60-deg wing are evident: a leftward shift of the lift curve, an increase in $C_{L_{max}}$, and a nose-down shift in the pitching moment curve. The most striking difference between the 60- and 75-deg wing sweeps is the relatively small incremental increase in lift coefficient which the TEFs provide. At low angles of attack, where the vortex is weakest, the ΔC_L is greatest; while at high angles of attack, where a strong vortex is present, the ΔC_L is small. This suggests that the stronger

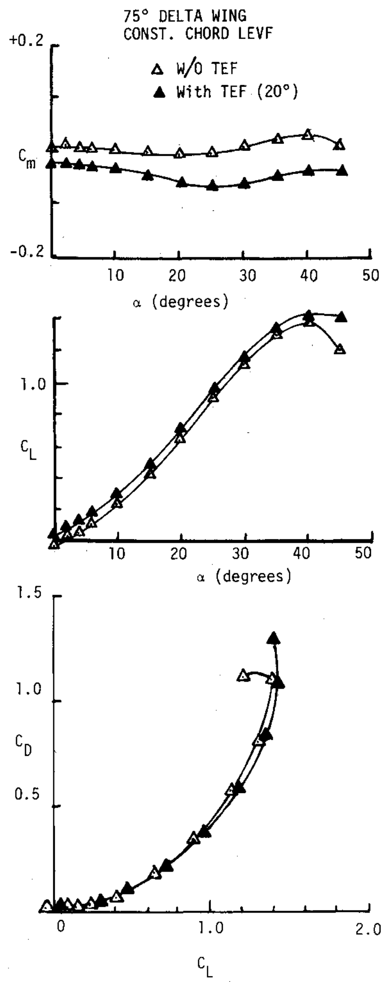

Fig. 8 TEF effects on a 75-deg delta wing with constant chord LEVFs.

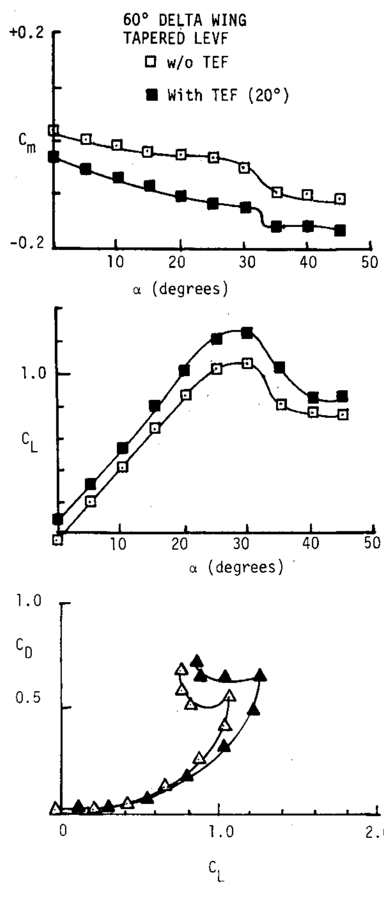

Fig. 9 TEF effects on a 60-deg delta wing with tapered LEVFs.

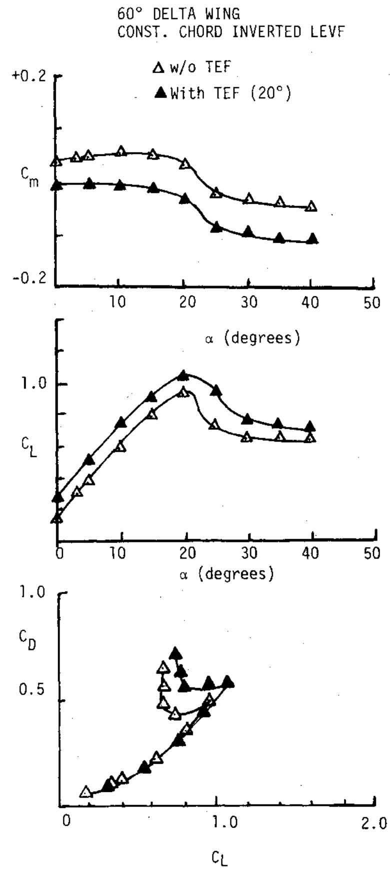

Fig. 10 TEF effects on a 60-deg delta wing with constant chord ILEVFs.

leading edge vortex of the higher sweep 75-deg wing is less susceptible to the effects of TEFs. At the $C_{L_{ref}}$, the deflection of TEF only offers a 1-deg or 4% angle of attack reduction. At 27-deg angle of attack, the increase in C_L due to TEF deflection is only 0.05 or 5%. Similarly, the deflection of TEF has only a slight effect on the configuration's drag characteristics. Small decreases in C_D can be seen for lift coefficients greater than 0.7.

Although the TEFs have only a small effect on the configuration's lift and drag performance, they do provide a significant change in the pitching moment characteristics. As was suggested for the 60-deg wing and constant chord LEVF, a TEF deflection angle schedule which would be linked to the wing angle of attack could provide a longitudinally stable configuration.

Figure 9 illustrates the effect of TEFs on the 60-deg wing with tapered chord LEVFs. The same general trends are again seen here. There is a large increment in lift coefficient provided by the TEFs which was not seen on the 75-deg swept wing. The deflection of TEF again provides an increase in the lift curve slope for high angles of attack. At the reference C_L, the TEFs offer an angle of attack reduction of 5 deg, or 20%. At an angle of attack of 25 deg, the TEFs provide an increase in C_L of 0.2 or 20%. Again, note the decreases in drag coefficient for the larger lift coefficients. Unfortunately, the deflection of TEFs introduces large nose-down pitching moments to an already stable configuration.

The effect of TEFs on the 60-deg wing with constant chord ILEVF is shown in Fig. 10. As before, there is a leftward shift of the lift curve and an increase in the configuration's $C_{L_{max}}$. Although the $C_{L_{max}}$ for the ILEVF is less than that attainable by the base wing, the addition of TEF makes this loss more tolerable. Relative to the plain wing, the TEF offers a 5-deg or 20% angle of attack reduction at $C_{L_{ref}} = 1.0$. The most attractive feature of the ILEVFs is their ability to produce significant lift at low angles of attack. At 0-deg angle of attack, where the base wing produces no lift, the addition of TEF improves on the lift coefficient of the ILEVF by 0.12 or 67%. At 5-deg angle of attack, the addition of TEF again increases C_L by 0.12 for a 30% improvement. Interestingly, there is no increase in C_D due to the deflection of TEF. As observed for the other LEVF configurations, the deflection of TEF could provide a means for correcting the adverse pitching moments of the ILEVF case.

Conclusions

The tests conducted indicated that trailing edge flaps can interact favorably with several leading edge vortex flap configurations on 60- and 75-deg sweep delta wings. Results indicated that the already strong leading edge vortex flow on a 75-deg delta wing does not substantially improve owing to the deflection of trailing edge flaps. Significant performance improvements were seen, however, on a LEVF-equipped 60-deg delta wing where the weaker leading edge vortex flow is more susceptible to the increased upwash angles and circulation rates induced by trailing edge flap deflections. A 60-deg delta wing equipped with constant chord, ILEVFs was shown to achieve large increases in lift coefficient at low angles of attack without sacrificing other performance characteristics as trailing edge flaps are deflected. In addition, adverse pitching moments generally associated with the deflection of constant chord LEVFs were eliminated through the use of trailing edge flaps. The use of trailing edge flaps best benefits the 60-deg wing with constant chord LEVF of ILEVF. The greatest advantage of trailing edge flap appears to be its ability to correct adverse pitching moments.

References

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