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Effectiveness of Leading-Edge Vortex Flaps on 60 and 75 Degree Delta Wings

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A series of wind tunnel tests were run on 60 and 75 deg sweep delta wings to examine the effectiveness of leading-edge vortex flaps. Test results showed that leading-edge vortex flaps are effective in giving large increases in lift-to-drag ratio and decreases in drag over a wide range of angle of attack. Tests on inverted flaps on the 60 deg delta wing showed substantial increases in lift and drag and may indicate a possibility of using inverted flaps on delta wings in the landing portion of flight. The 60 deg data were compared with that for a 75 deg sweep delta wing confirming that leading-edge vortex flap effectiveness is stronger as sweep is increased. Pitching moment effects due to vortex flaps use were also examined.

Nomenclature

$\mathcal{R}$	= aspect ratio of wing
C_a	= axial force coefficient
C_d	= drag coefficient
C_L	= lift coefficient
$C_{L\max}$	= maximum lift coefficient
C_m	= pitching moment coefficient
L/D	= lift-to-drag ratio
α	= angle of attack of wing
δ	= flap deflection angle

Introduction

DELTA wings and other highly swept wings are designed primarily for transonic and supersonic flight. Hence, their performance at subsonic speeds is often far from optimal. During landing, takeoff, initial climb, and many maneuvers the aircraft is operating subsonically and a penalty is paid for poor wing performance. It is often necessary to operate at high angles of attack at these speeds to generate the needed lift. Fortunately delta wings can generate large lift at low speeds due to the action of their leading-edge vortices; however, the effect of these vortices is not entirely beneficial.

On most highly swept and delta wings the leading-edge radius is not sufficiently large to prevent flow separation along the leading edge. This separation results in the formation of a vortex on the upper surface of the wing. The strength of the leading edge vortex is normally sufficient to result in flow reattachment over the wing's upper surface and, consequently, in the production of lift up to large angles of attack. The low pressure in the vortex itself adds to the lifting force on the wing; however, it also contributes a drag force due to the rearward inclination of the resulting force vector (Fig. 1a). The vortices themselves also tend to be somewhat unstable in yaw due to vortex bursting over the wing.

One means of increasing wing stability in yaw and in maintaining lift at high angles of attack is by adding leading-edge camber to the wing either by use of flaps or by building a deformation into the wing.[1] With this configuration (Fig. 1b) a leading-edge vortex does not form and some lift is lost with the absence of the low pressure in the vortex. However, drag is reduced because of the absence of the vortex and because of the leading-edge suction resulting from flow acceleration around the leading edge. The net result is a lower drag and increased stability at a cost of a reduction of $C_{L\max}$. There may also be a reduction in overall supersonic and subsonic aircraft performance due to the added weight of a complex flap system or a shape which may be less than optimum in the supersonic regime.

An alternative solution is the vortex flap. Here a leading-edge flap is used, not to prevent vortex formation, but to cause vortex formation on the flap itself rather than on the wing. If the vortex can be placed such that the flow reattachment point is at the flap-wing junction, an attached lifting flow is provided over the upper surface of the wing. A leading-edge suction due to the vortex on the flap produces a thrust, and increased roll and yaw stability should result from confining the vortices to the flaps. This concept is illustrated in Fig. 1c where the flap angle must be such that the flow separates at the edge of the flap and a vortex results. The size of the flap should be sufficient to give reattachment at the wing-flap junction.

Previous research on leading edge vortex flaps (LEVF) has concentrated on very highly swept (70 deg or more) wings[2] of the type planned for supersonic cruise aircraft. Many aircraft, however, have more moderately swept wings and it is possible that the leading-edge vortex flap would be equally useful on these wings. A wing with less sweep will not produce as strong a leading-edge vortex and vortex bursting may limit the effects of vortex lift to lower angles of attack, therefore, the advantage gained by leading-edge vortex flaps may not be as great as for more highly swept wings; however, it may still produce an improvement in the wing's performance. Hence, a series of systematic tests was conducted on a 60 deg delta wing to determine the effectiveness of vortex flaps on that wing and to compare the performance gains with those found possible on a 75 deg swept delta wing.

Test Description

Tests were conducted in the 6 × 6 ft straight flow test section of the Virginia Tech Stability Wind Tunnel. This tunnel, originally designed and constructed at Langley Research Center, is a continuous flow subsonic facility with freestream turbulence levels of less than 0.05%. Several wings were tested in the course of the research; however, most testing involved the wing shown in Fig. 2. This is a 60 deg delta wing that is one of a series of wings originally constructed and tested at Langley Research Center.[3] The sharp edge wing was chosen for a majority of the tests because it would provide a base case with no leading-edge suction; hence, all leading-edge suction found in the tests would be the result of the vortex action on the flaps. A few tests were also conducted on a 75 deg sweep flat plate delta of equal area to the 60 deg wings in order to examine the effects of sweep.

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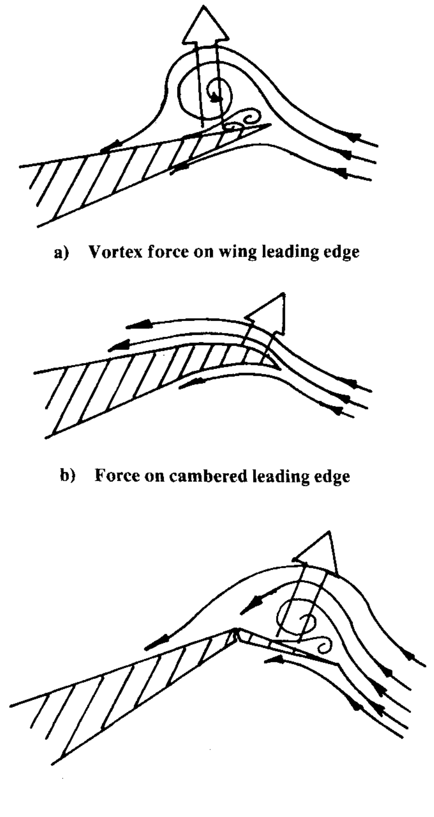

a) Vortex force on wing leading edge

b) Force on cambered leading edge

c) Force on vortex flap

Fig. 1 Effect of leading-edge shape on flow patterns and forces.

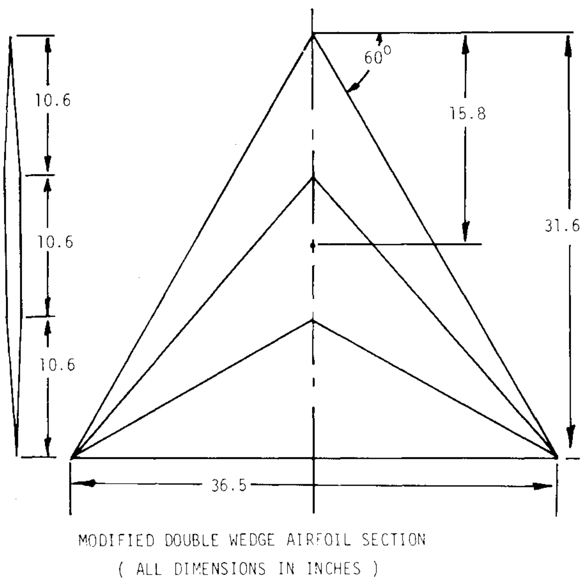

Fig. 2 Sketch of wing model used in most tests.

The primary purpose of the tests was to determine the optimum vortex flap configuration for the 60 deg delta wing being tested and to determine the resulting aerodynamic behavior of the wing-flap combinations. Most tests were conducted at a tunnel dynamic pressure of five inches of water giving Reynolds numbers of approximately 2.2×10^6 based on wing root chord. All configurations were tested over an angle of attack range from 0 to 45 deg. Most flaps tested were full span, constant chord flaps. Flaps of 1,2,3,4, and 5 in. chord were tested giving flap area-to-wing area ratios of 0.13, 0.26, 0.38, 0.51, and 0.64. All flaps were tested at deflection angles (δ) of 0, 10, 20, 30, 40, 50, and 60 deg with some tests conducted at intermediate angles. The flaps used were simply cut

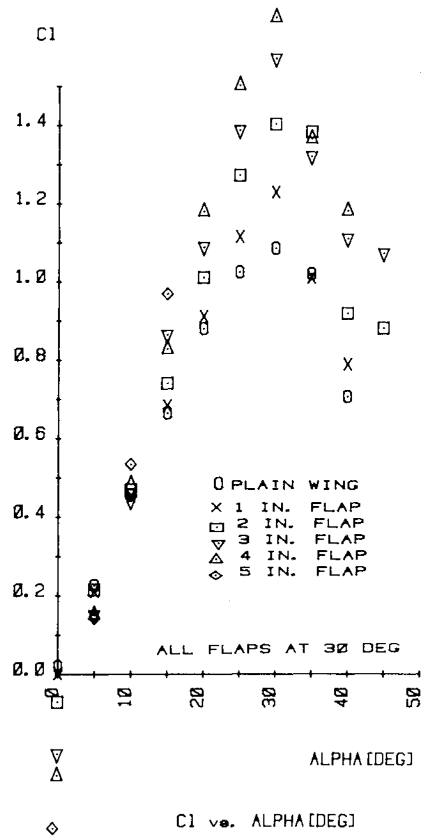

Fig. 3 Comparison of flap size effects on lift coefficient data for 60 deg delta wing; C_L based on wing area only.

from sheet metal, set at the desired angle, and attached to the wing using two-sided tape and small bolts. Using this wide range of parameters it was possible to determine optimum flap area and deflection for the 60 deg delta wing.

Additional tests were run to compare the 60 deg sweep case with a 75 deg swept delta wing. Other tests were also conducted to determine the influence of trailing-edge flaps on the performance of the vortex flaps. The leading-edge flaps were also tested on the 60 and 75 deg wings in an inverted configuration (deflected upward) which provided somewhat surprising results.

Data and Results

As previously mentioned, the 60 deg delta wing was tested with five different sizes of full span, constant chord leading-edge vortex flaps and each flap size was tested through a range of flap deflection angles from 0 to 60 deg. From this wide range of test results it was concluded that the 3 in. chord flaps at a 30 deg flap deflection angle were optimum for the wing tested. Since it is impossible to show all the data in this paper, a sample of the results will be presented.

There are two results to be expected from the use of the flaps. The added area of the flaps will obviously increase the wing's lift and drag while aerodynamic changes caused by the movement of the leading-edge vortex from the wing to the flap should reduce its drag and possibly its lift. Since both the effects of added wing area and of vortex shift aerodynamics will ultimately influence the behavior of a wing on which LEVF are deployed it is important to be aware of both effects. To get an idea of the total effect of the deployment of vortex flaps the data can be reduced with all coefficients based on only the area of the original wing. To understand the true aerodynamic effect of the flaps, the data should be based on the full projected area of both the wings and the flaps.†

†"Full or actual projected area" is the vertical projected area, which is a function of flap angle and chord.

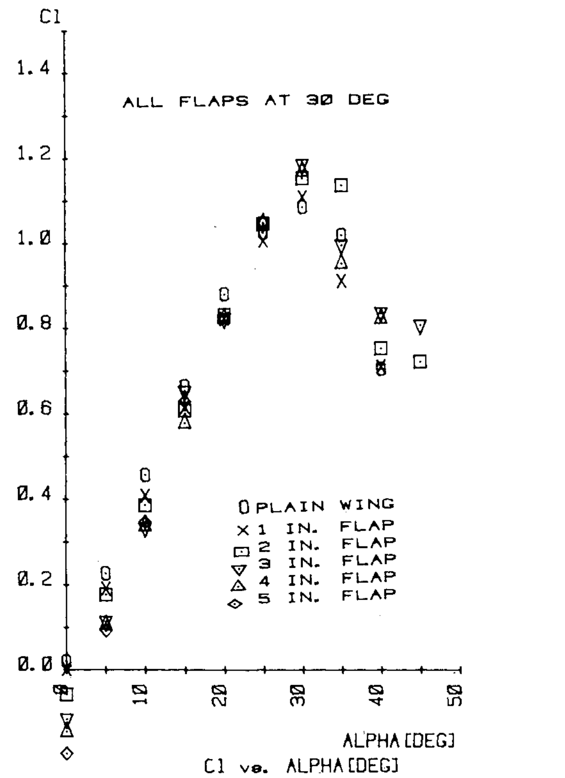

Fig. 4 Comparison of flap size effects on C_L for a 60 deg delta wing with C_L based on total projected area.

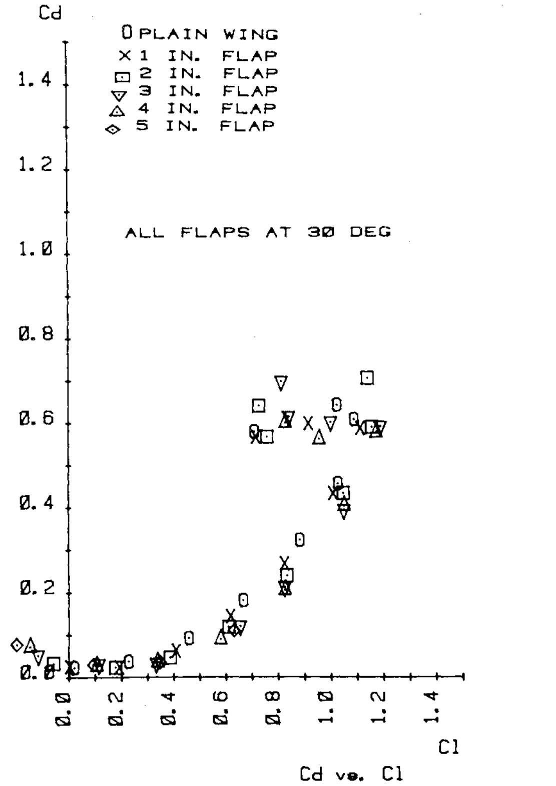

Fig. 6 Drag polar variation on 60 deg delta with flap size; C_D based on total projected area.

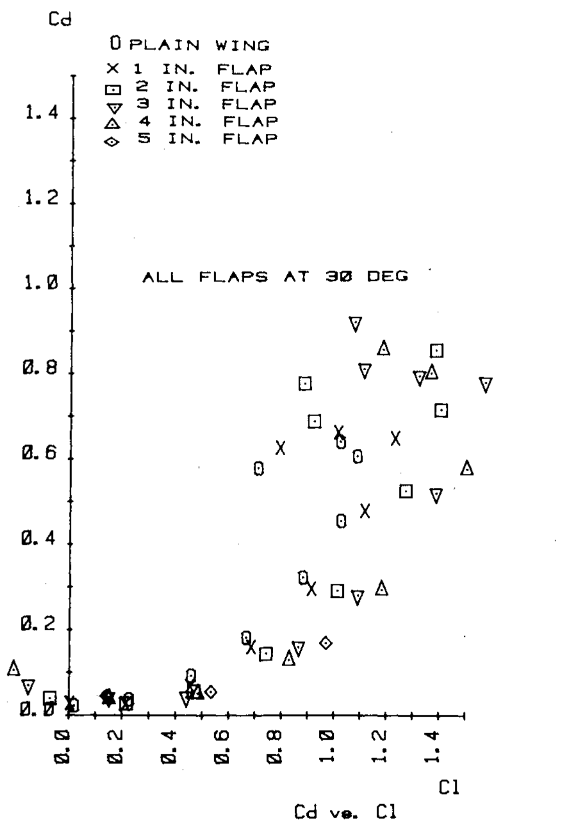

Fig. 5 Drag polar variation on 60 deg delta with flap size; C_D based on wing area only.

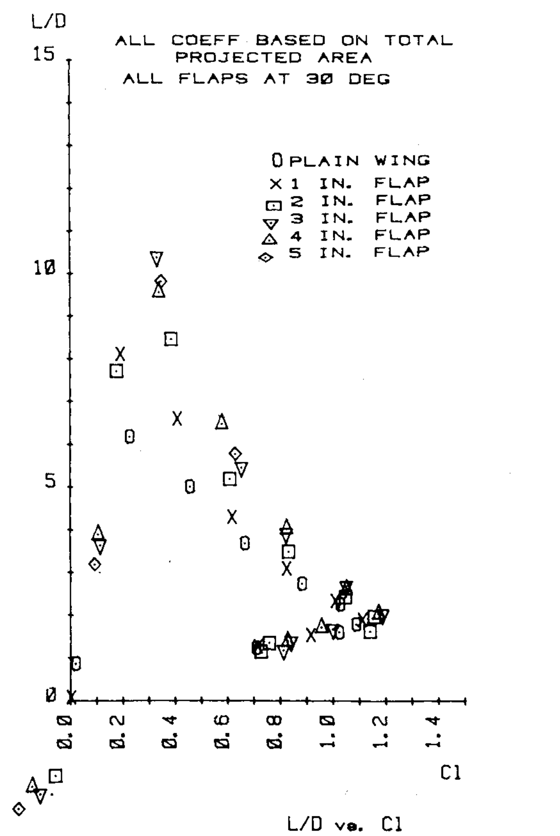

Fig. 7 *L/D* change with LEVF size on a 60 deg delta wing.

Figures 3 and 4 show the lift coefficient data for the 60 deg delta wing alone and with five different sizes of flaps with all flaps deflected at a 30 deg angle.

Figure 3 indicates that the combined effect of area and aerodynamics results in large lift increases at all angles of attack above 10 deg. $C_{L_{max}}$ is increased by 55% with 4 in. (51%) flaps when the data is presented in this manner; i.e., by adding vortex flaps, very large increases in total lift are possible because of the added wing area and the aerodynamic behavior of the flaps. Figure 4, however, puts the same data

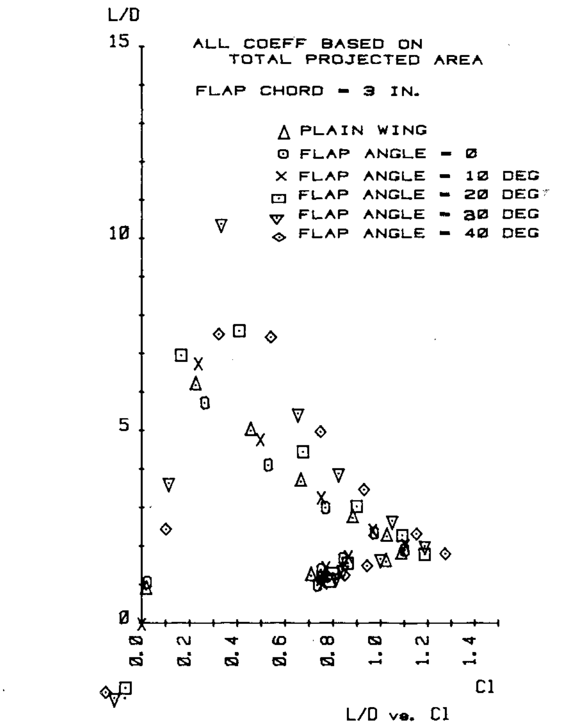

Fig. 8 Effects of LEVF angle on L/D for 60 deg delta.

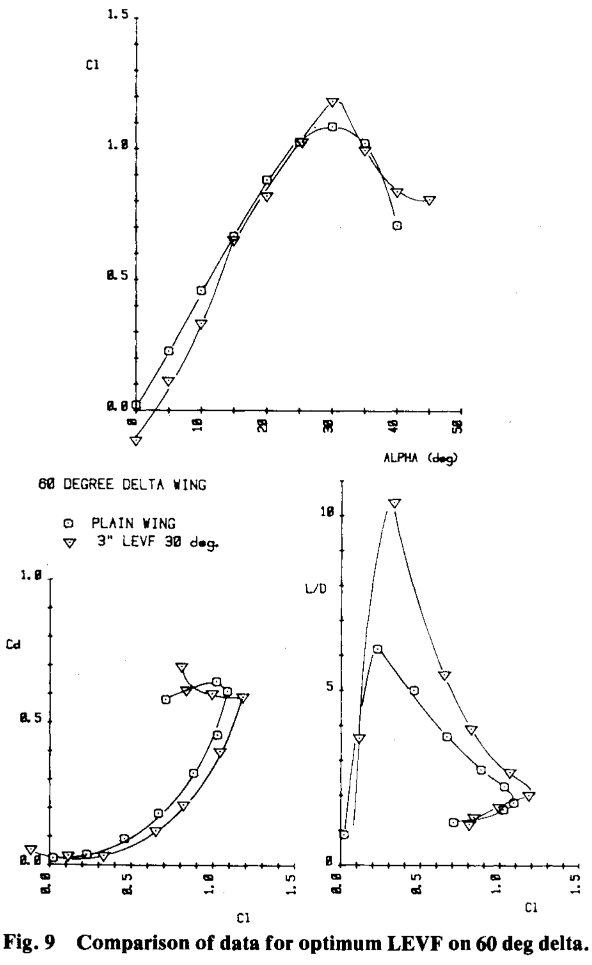

Fig. 9 Comparison of data for optimum LEVF on 60 deg delta.

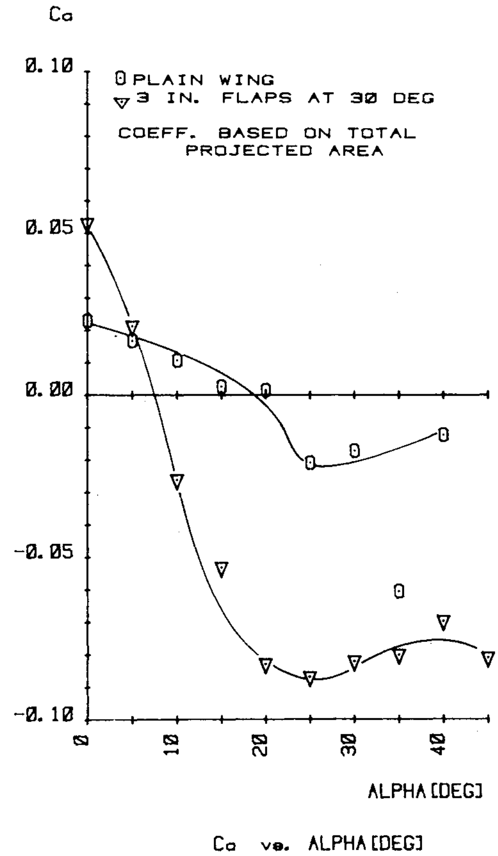

Fig. 10 Axial force change due to LEVF on 60 deg delta.

in a different perspective. Here the lift coefficients are based on the actual projected areas for each case and the real aerodynamic effects of the flap deflection can be better seen. It is seen that the use of LEVF produces a decrease in real C_L at all angles of attack below 25 deg. There is still an increase in $C_{L_{max}}$ but of less than 10%. Figure 4 confirms the assumption that the real aerodynamic benefit of LEVF use is not in increasing lift, but in reducing drag.

Figures 5 and 6 show the drag polars plotted based on wing area only (Fig. 5) and on actual projected area (Fig. 6). Both figures show the reduction in drag coefficient produced by LEVF use. The reduction of real drag is best seen in Fig. 5 which shows that at C_L of 1.0 the drag is reduced by about 50% when LEVF are used, despite the area they add to the wing. Figure 6 confirms that this drag reduction is indeed a real aerodynamic effect.

The resulting L/D comparison for the different size LEVF at a 30 deg deflection angle is shown in Fig. 7 where C_L is based on actual projected area. This figure indicates an approximately 70% improvement in maximum L/D for the 3 in. (38%) flaps. Maximum L/D occurs at a 10 deg angle of attack.

The optimum LEVF deflection angle will obviously depend on the wing's angle of attack. At very low α any flap deflection will merely decrease lift and produce drag. At moderate α small flap deflections should result in movement of the vortex to the flaps while large flap deflections will prevent vortex formation. Figure 8 shows the L/D results for the 60 deg delta wing with a 3 in. (38%) constant chord LEVF deflected to various angles. It is seen that at a C_L of about 0.2 ($\alpha = 5$ deg) the 20 deg deflection is best while around a C_L of about 0.3 ($\alpha = 10$ deg) the 30 deg flap deflection is best. At higher C_L there is a reduction in L/D but here it is apparent that a higher LEVF deflection of 40 deg is best.

The resulting comparison of the selected optimum LEVF configuration (3 in., 30 deg flaps) is shown in Fig. 9 where the aerodynamic influence of the LEVF is clearly shown to be one of reducing both C_L and C_D at small-to-moderate α such that L/D is increased.

The real effect of leading edge vortex flaps is seen more clearly in Fig. 10 where the axial force coefficient is plotted against angle of attack. For most airfoils above a moderate

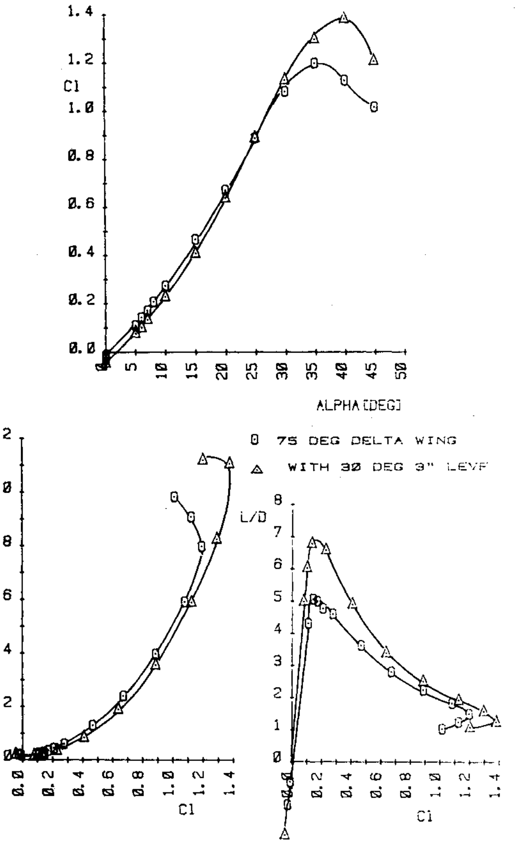

Fig. 11 Effects of 30 deg LEVF on a 75 deg flat plate delta wing.

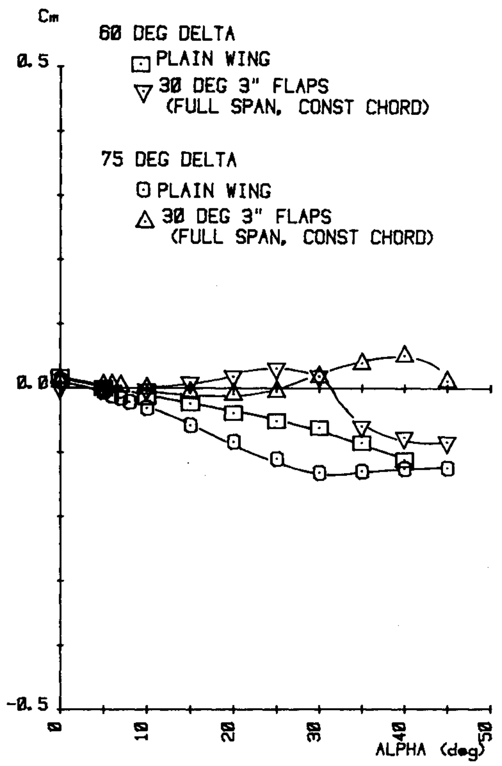

Fig. 12 Effects of vortex flaps on pitching moment.

angle of attack the axial force is negative, or forward, since the negative axial component of the lift vector outweighs the positive contribution of the drag vector. However, Fig. 10 shows that at angles of attack from 10 deg through 20 deg the LEVF equipped wing produces a strong thrust while the basic

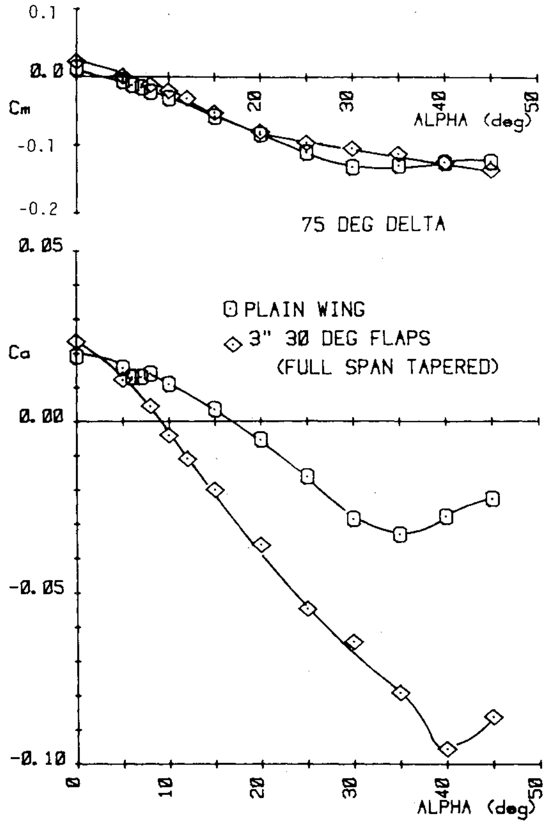

Fig. 13 Effects of tapered LEVF on pitching moment and axial force on a 75 deg delta.

wing is still producing a positive axial force. Even at higher angles of attack the wing with LEVF gives a stronger forward force.

Comparison with 75 deg Sweep Case

Since it was suspected that the effects of the leading edge vortex flap would not be as pronounced for the 60 deg swept delta wing as for a wing with a higher sweep angle, some tests were run to compare the 60 deg case to a 75 deg sweep delta wing. A simple flat plate 75 deg delta wing was constructed of ¾ in. plywood. The flat plate wing was constructed with tapered edges to eliminate any leading-edge radius effects and was made the same area as the 60 deg delta wing previously tested.

Figure 11 compares the data for the 75 deg swept flat-plate wing with that for the same wing with 3 in. constant chord full span LEVF deflected 30 deg. In Fig. 11 it is seen that the use of LEVF at this sweep angle does not result in as great a loss of C_L at low α as was the case for the 60 deg delta wing and that again C_L improved with the use of LEVF above an angle of attack of 20 deg. Drag coefficient reductions are evident over the entire range of lift coefficient and there is an increase in L/D of up to 40% over the range of operation. This data compares favorably with that of Rao[2] on a 74 deg airfoil except that Rao measured lower minimum drag values resulting in higher maximum L/D values. The higher drags measured in the present study probably result from the somewhat rougher surface of the plywood flat plate model and the different mounting used. Rao's model was sting mounted while the models in this study were strut mounted, requiring a hole in the model and a strut attachment that undoubtedly increased the drag of the wing enough to be significant at low angles of attack. Since the present research was largely unfunded, neither the time or money was available to construct a more desirable model. Such a problem does not negate the conclusions to be made from the comparisons between the data sets shown in Fig. 11.

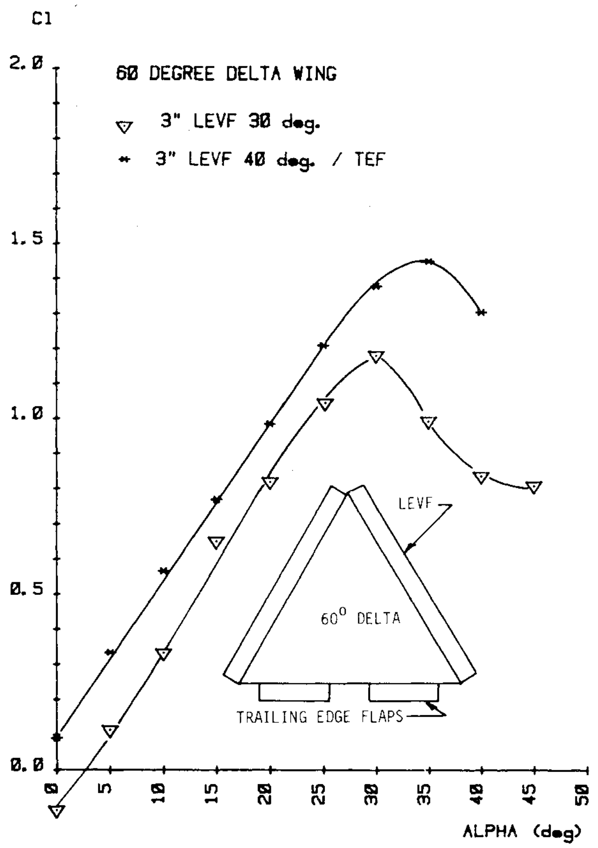

Fig. 14 Influence of trailing-edge flaps on LEVF effectiveness.

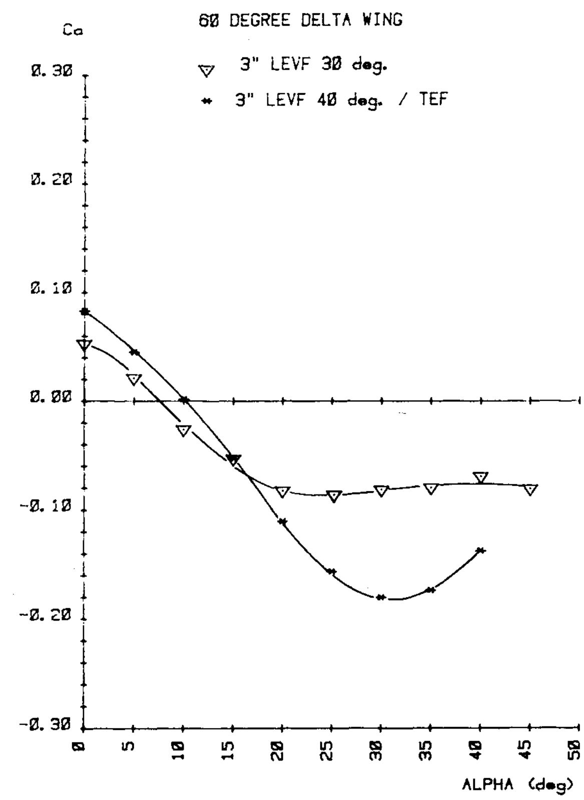

Fig. 15 Axial force improvement with trailing-edge flaps.

It is interesting to note that while there was about 9% increase in $C_{L_{max}}$ on the 60 deg sweep wing due to LEVF there was an increase of over 15% in the 75 deg case. This tends to verify the assumption that the effectiveness of the LEVF concept increases with increasing wing sweep. While the 75 deg wing stalled at about 35 deg, the same wing with LEVF does not stall until an angle of attack of 40 deg is reached.

It is an interesting historical footnote to examine the results of Ref. 4, a 1949 NACA research memorandum of Riebe and Fikes, where the leading edges of a 60 deg delta wing were deflected to study leading edge camber effects on the wing's aerodynamics. The deflection of the leading edge "flaps" resulted in a configuration that was essentially a 71 deg sweep delta wing with flaps tapered from zero chord at the wing apex to 40% of the resulting wing's wing semispan at the tips. The results of this study were quite similar to those of Rao[2] with the authors reporting 28% improvements in L/D at C_L's of 0.2-0.3 for 20 deg flap deflections. When flap deflections exceeded 40 deg a reduction of L/D occurred since a vortex was not able to form over the upper surface of the flaps, although the authors did not indicate any awareness of the vortex effect at that time.

Pitching Moments

One aspect of the test results not previously discussed is the effect of the vortex flaps on pitching moments. If strong forces are being developed on the flaps they might result in a shift in pitching moment behavior, especially at higher angles of attack where the leading-edge vortex would be stronger. Figure 12 confirms this. Pitching moments were measured about the mounting point of the wing which is at the midpoint of the wing centerline or root chord. The figure shows the results for both the 60 and 75 deg delta wings with and without 3 in. full span leading-edge flaps deflected 30 deg. Both wings exhibit a fairly stable longitudinal behavior with no flaps; however, with flaps both exhibit unstable behavior over part of the range of C_L. This is especially noticeable in the case of the 60 deg wings where C_m increases with C_L values of between 0.5 and 1.5.

This pitch instability has not been noted in previous studies[2,4] where the flaps have either not been full span or constant chord. Hence, tests were run on the 75 deg model using flaps tapered linearly from zero chord at the apex to 3 in. at the wing tip. This resulted in a more stable wing while still providing significant increases in forward axial force as shown in Fig. 13.

Trailing-Edge Flap Influence

Since trailing-edge flaps (TEF) will undoubtedly be used during some phases of flight, their influence on LEVF behavior needs to be understood. The expected effect of TEF is to increase the angle of the relative flow at the wing's leading edge allowing the LEVF to be deflected to larger angles while still producing a vortex over the flaps. This should, in turn, result in an increased thrust as the force vector on the flaps is tilted forward. To determine some of the effects of TEF on LEVF performance, two one-ft span, 3 in. chord, 30 deg trailing-edge flaps were added to the 60 deg delta wing by bolting sheet metal strips that had been cut to size and bent to angle onto the wings trailing edge as shown on the inset drawing of Fig. 14. These were tested with several LEVF deflection angles as well as on the base wing.

Figure 14 shows the effect of the TEF to be typical as far as lift is concerned with a leftward shift of the C_L-α curve. The 40 deg LEVF, TEF combination appears to produce the highest lift coefficients at most angles of attack. The use of TEF greatly reduced L/D at low angles of attack due to drag increases. Figure 15 shows the primary effect of the LEVF+TEF combination to be one of producing greatly increased thrust at high α. Here the 40 deg LEVF deflection is clearly superior to the 30 deg case indicating that the desired effect is being achieved.

Inverted Flaps

In response to a suggestion from Dr. J. F. Campbell of NASA a somewhat unusual test series was performed where

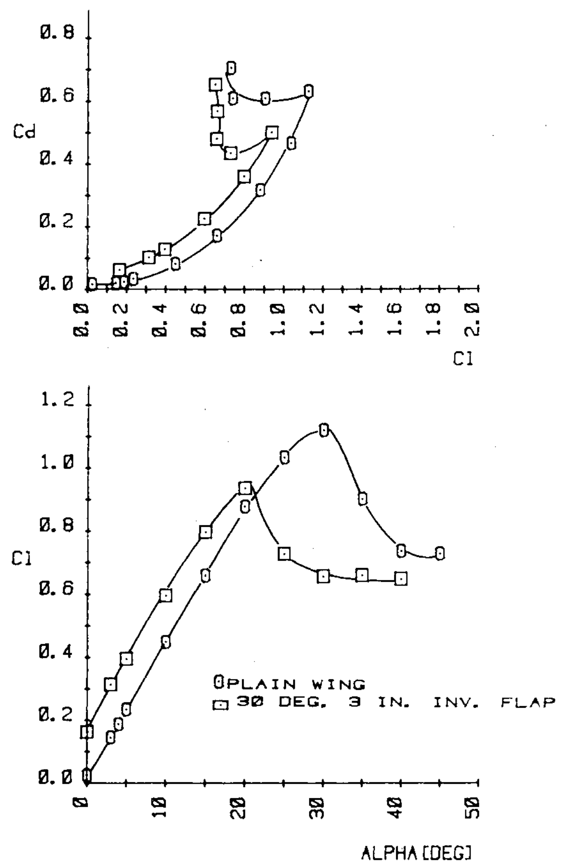

Fig. 16 Effects of inverted leading-edge vortex flaps on the 60 deg delta.

the leading edge flaps were deflected upward rather than downward. A sample result for the 60 deg delta is shown in Fig. 16 in comparison with the base wing. A substantial increase in lift coefficient is achieved up to angles of attack of 20 deg where this configuration stalls. The drag increase is also large, as might be expected, thus giving much lower L/D ratios. These results may indicate another important use for leading-edge vortex flaps during landing. They would allow an aircraft to achieve large lift at low speeds without necessitating high angles of attack and resultant control and visibility problems. In a landing situation the high drag may even be beneficial in order to slow the aircraft prior to touchdown or to provide the high sink rates needed for carrier approaches.

Without further testing, the mechanism behind the surprising performance of inverted vortex flaps cannot be fully described; however, flow visualization tests indicate that the strong vortex behind the inverted flap causes increased lift and flow reattachment, thus shifting the C_L-α curve to the left in a typical camber increase fashion. This phenomenon warrants further investigation since it may prove valuable in many applications.

Conclusions

The results indicate that the concept of the leading-edge vortex flap is sound for both 60 and 75 deg delta wings. The vortex action on the 60 deg wing with constant chord flaps of size 38% of the wing area deflected 30 deg is sufficient to produce strong thrust directed axial forces on the wing, leading to drag coefficient reductions up to 50% and up to 70% increase in L/D at moderate angles of attack. While, aerodynamically speaking, lift coefficient is reduced by deployment of vortex flaps at most angles of attack, the actual lift will probably increase due to the added flap area; thus, interpretation of the data regarding actual lift and drag magnitudes is dependent upon the method of accounting for flap area in the coefficient calculation.

The effect of LEVF and their sizing and placement on pitching moment and longitudinal stability need further study. Proper flap design can probably result in desired improvements in lift and drag performance without penalizing longitudinal stability.

The use of LEVF with trailing-edge flaps allows the deflection of the LEVF to larger angles giving even greater thrust improvement. Research needs to be continued to determine the optimum leading- and trailing-edge flap combinations to take advantage of this effect. Inverted, or upward deflected LEVF appear to have application in the approach and landing phases of flight, giving 70% increases in lift coefficient at 5 deg angle of attack on a 60 deg delta wing for the case tested. Again, more work will be needed to optimize the inverted LEVF concept.

Considerable further research is needed to determine the full consequences of LEVF use. Studies need to be conducted to determine the flow patterns and their resulting pressures over the flaps. The effects of yaw on LEVF effectiveness and on vortex stability are as yet unknown. Numerical analytical techniques need to be developed to predict and describe LEVF flows and their effects on wings.

The leading-edge vortex flap appears to be a promising tool for improving the performance of supersonic cruise wing designs in the subsonic flight regime. It can be deployed temporarily where needed, thus avoiding any compromise of supersonic cruise aerodynamics. Its use could decrease drag on take off and climb and thus reduce fuel consumption and noise in this critical portion of the flight envelope of a supersonic aircraft.

Acknowledgments

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