An Exploratory Study of Area-Efficient Vortex Flap Concepts

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The potential of planform modification and hinge-line relocation to improve the thrust efficiency of vortex flaps was experimentally investigated on a 60-deg cropped delta wing model. Spanwise segmentation of the flap, together with chord-tailoring of the segments, allowed the vortex to be maintained on the outboard flap surfaces to higher angles of attack. In addition, location of the flap hinge aft of and underneath the wing leading edge generated substantial thrust from the vortex suction acting on the leading-edge lower surface. A combination of these beneficial effects allowed the flap/wing area to be reduced from 11.4% of the continuous flap to 6.3% of segmented flap, essentially without detriment to the $\Delta(L/D)$ in C_L range 0.5 to 0.7.

Nomenclature

A_F	= flap area
A_W	= basic wing area
$C_{D,B}$	= basic wing drag coefficient
C_L	= lift coefficient based on A_W
$C_{L,B}$	= basic wing lift coefficient
C_P	= static pressure coefficient
$C_{P,\text{LE}}$	= leading-edge pressure coefficient
$C_{t,\text{LE}}$	= local chord-plane thrust coefficient from leading-edge pressure integration
C_m	= pitching moment coefficient
L/D	= lift-to-drag ratio
ΔC_D	= incremental drag coefficient due to flap addition
ΔC_L	= incremental lift coefficient due to flap addition
$\Delta(L/D)$	= incremental lift-to-drag ratio due to flap addition
α	= angle of attack
α_s	= angle of attack for local vortex spillover
η	= spanwise coordinate normalized by semispan

Introduction

THE leading-edge vortex flap concept for drag reduction of slender wings at high lift coefficients[1] has been validated extensively in recent wind tunnel tests on generic wings and also aircraft configuration models.[2-9] By concentrating the suction of a controlled vortex on its upper surface, the vortex flap produces a thrust component, as well as attached flow on the wing downstream of the hinge line. Although mechanically they are much simpler than the conventional leading-edge droop for highly swept wings, the vortex flaps used in the studies thus far have been relatively large (e.g., 15-25% of the wing area). A reduction of the flap size is desirable not only for ease of actuation but also to avoid excessive forward shift of the aerodynamic-center, which may be critical on relaxed static stability vehicles. Thus, more efficient vortex flap concepts are needed to allow area reduction of the flap without unduly sacrificing its aerodynamic benefits.

This paper explores two distinct approaches, each aimed at improving the flap thrust effectiveness, one resting on planform modification and the other on the hinge location. The idea of flap segmentation (Fig. 1) is essentially to terminate the flap at a semispan position where the suction footprint of the expanding vortex has become too broad, or is beginning to spill over to the wing, and to start a new vortex from that position by means of a new flap surface.[2] A more concentrated suction under the newly generated vortex should allow the chord to be reduced toward the outboard sections of the flap without sacrificing thrust. The consecutive flap segments may also be independently actuated to different deflection angles in accordance with the spanwise varying upwash angle, thus providing an additional means of fine-tuning the overall thrust performance.

The second idea is to move the flap hinge underneath and aft of the wing leading edge (Fig. 2), in order to place the vortex at the mouth of the cavity formed between the flap and the wing. This exposes an additional frontal area, namely, that of the leading-edge undersurface to vortex suction, thereby increasing the thrust per unit flap area. Note that this additional thrust area increases with angle of attack, whereas the flap frontal area itself (at constant deflection) reduces; increasing flap deflection weakens the vortex and therefore the thrust improvement is not in proportion to the frontal area gained.[7] Apart from the anticipated aerodynamic benefit, the aft hinge location at a deeper section of the wing also is structurally advantageous.

The above two ideas were integrated into an exploratory subsonic wind-tunnel investigation using a 60-deg cropped delta wing model with blunt leading edges, fitted in turn with continuous and segmented flaps. The paper begins by examining the effects of segmentation and planform shaping in delaying the spillover of the vortex. Then, the leading-edge suction and thrust performance due to the setback position of the vortex flaps are addressed. Finally, the longitudinal stability characteristics as affected by flap segmentation are noted.

Experimental Details

The geometry and major dimensions of the wing model are presented in Fig. 3. A noteworthy feature is the relatively blunt leading edge which, while not essential for the purpose of demonstrating the vortex flap concepts of this study, was conveniently pressure-instrumented to permit evaluation of the leading-edge thrust characteristics. Static pressure taps were installed in chordwise rows around the semielliptic leading edge, both on the upper and lower surfaces nearly to the maximum thickness position, at six semispan stations. A pressure scanning valve was housed in the lower centerbody while the upper centerbody contained a six-component strain-gage balance.

The various vortex flap test configurations are illustrated in Fig. 4. The uninstrumented flaps were constructed from a thin aluminum plate and bent downward at a 30-deg angle normal

Received March 14, 1983; revision received July 19, 1983.
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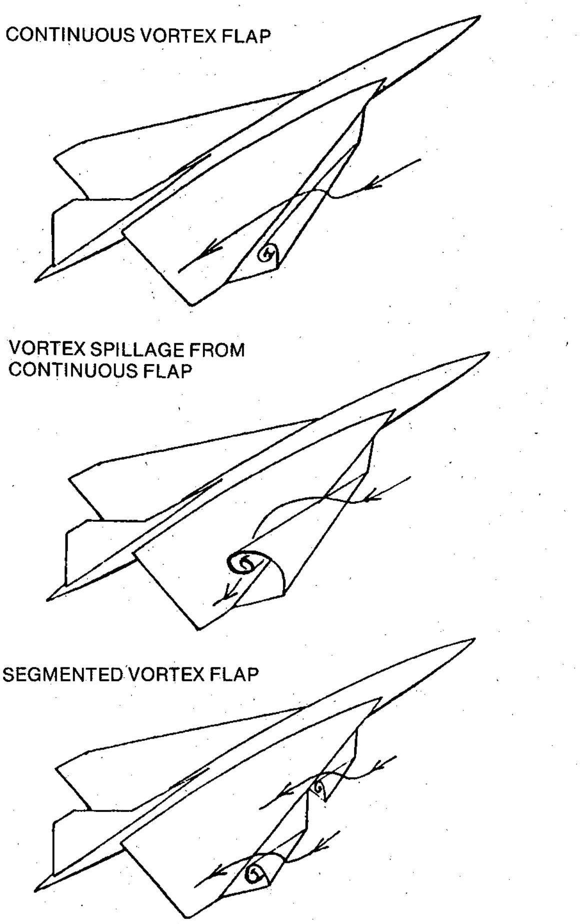

Fig. 1 Concept of vortex spillage control by means of flap segmentation.

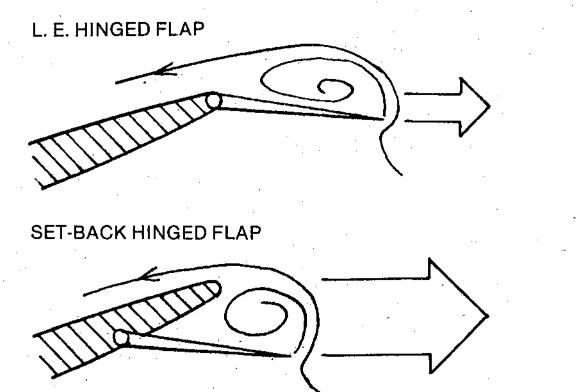

Fig. 2 Concept of increasing effective thrust area by means of setback hinge vortex flap.

to the bend line. The part inboard of the bend was attached to the flat undersurface of the wing immediately aft of the lower-surface curvature (see sketch in Fig. 4), the bend line being coincident with the leading-edge vertical projection. This mode of flap attachment was intended to simulate the setback hinge arrangement without interfering with the lower-surface pressure taps. The flap area (i.e., area of the bent portion forward of the wing leading edge) ranged from 11.4% (continuous flaps) to 6.3% (delta-segmented flaps) relative to the wing area. The tests were conducted in the NASA Langley 7×10 ft high-speed wind tunnel a at Mach number of 0.16 and Reynolds number of 2 million based on the wing mean geometric chord. Additional experimental details and a compilation of the balance and pressure data are available in Ref. 10.

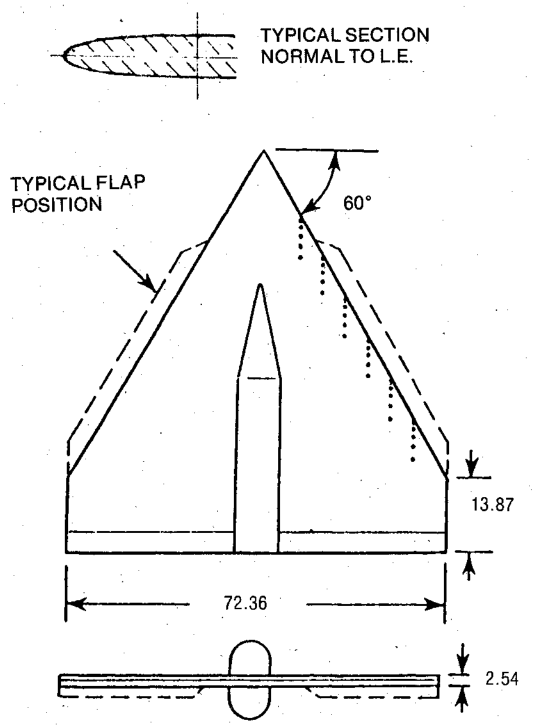

Fig. 3 Delta wing model geometry for modified vortex flap tests (dimensions in centimeters).

Discussion of Results

Vortex Spillover Boundary

The present definition of vortex spillage is based on the characteristic variation of leading-edge static pressure coefficient ($C_{P,\mathrm{LE}}$) with angle of attack at a given semispan location, an example being given in Fig. 5. At vortex onset, reattachment occurs initially on the flap surface (see sketch A) and then approaches the leading edge as a result of vortex growth. The $(-C_{P,\mathrm{LE}})$ drops to a minimum when the reattachment impinges on the leading edge (sketch B), followed by a rapid increase as the vortex core moves inboard across the leading edge in the process of spilling over to the wing (sketch C). Thus the $(-C_{P,\mathrm{LE}})$ minima is an easily identifiable and consistent indicator of the incipient angle of attack for local spillover, which will be designated α_s.

From similar $C_{P,\mathrm{LE}}$ vs α plots for a number of semispan positions (in addition to the six pressure stations shown in Fig. 3), a vortex spillover boundary of α_s vs η may be constructed, as shown in Fig. 6 for the constant-chord continuous flap. In this instance, the spillover initiates at about $\alpha = 10$ deg near the tip, and at progressively higher angles of attack at inboard stations because of the decreasing upwash toward the wing root. At $\alpha = 14$ deg (or $C_L \cong 0.5$, the assumed lift coefficient at which drag reduction is to be maximized), the outboard half of this flap has already "lost" the vortex, whereas the inboard half lies well below the spillover boundary, implying a relatively small vortex (or a surplus of flap chord).

It follows that a more efficient vortex flap would be characterized by a horizontal α_s boundary located at $\alpha = 14$ deg. In principle, such a boundary might be achieved by twisting the flap for uniform local incidence spanwise. Apart from the question of practicality, this approach does not allow a reduction in the flap area. Alternatively, a planar flap may be chord-tailored to match the spanwise growth of the reattachment distance. A simple chord-tailored geometry is the inversely tapered flap with linearly increasing chord toward the tip, which the early studies[1] had already shown to be more area efficient. The spillover boundary of the present inverse-taper flap (Fig. 7) shows the improvement as expected over the constant-chord flap. At equal flap area, however, the

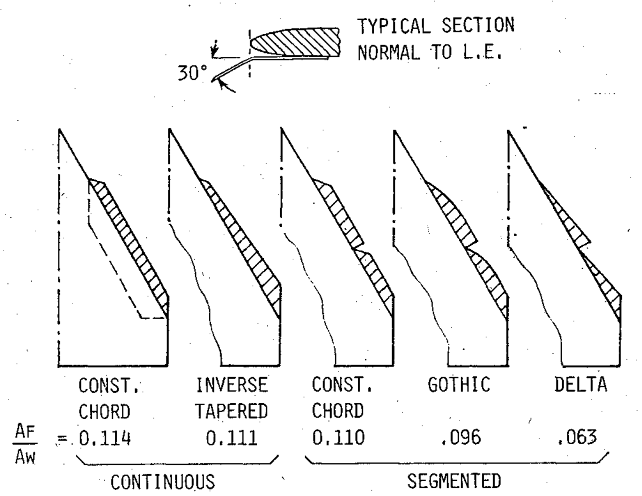

Fig. 4 Geometry of vortex flap test configurations.

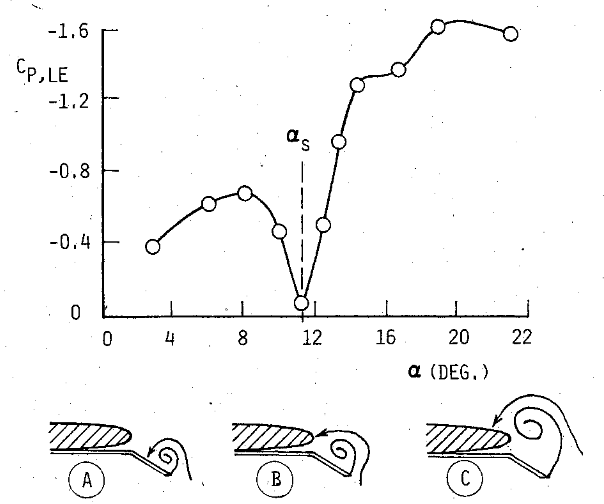

Fig. 5 Definition of local vortex spillover from typical leading-edge pressure variation with angle of attack ($\eta = 0.66$, constant-chord continuous flap).

tip chord of the inverse-taper flap is nearly 45% greater, which is structurally undesirable.

Effect of Segmentation

To isolate the aerodynamic benefit of segmentation (i.e., without also altering the flap planform), a narrow chordwise slit was cut into the constant-chord flap at $\eta = 0.625$. The natural flow through this slit was intended to disrupt the feeding of the prevailing vortex and allow a new flap vortex to form on the outboard side. As shown in Fig. 8, this segmentation mechanism is successful in delaying vortex spillover outboard of $\eta = 0.625$ (with little change on the inboard side).

Modification of the slit into a 45-deg swept apex (i.e., identical to the apex of the inner flap segment) leads to a further improvement of the outer spillover boundary (Fig. 9). Since the planform change was minimal, this improvement probably resulted from elimination of the jet turbulence interference with the new vortex. This segmented constant-chord flap has an even higher η_s boundary outboard than the inverse-tapered flap, with no increase in the tip chord. Indeed, the spillover boundary is now well in excess of the target level of $\alpha_s = 14$ deg, suggesting the possibility of some flap area reduction through chord-tailoring of the outboard segment in conjunction with similar treatment of the inboard flap.

The gothic and delta flaps were shaped as more efficient vortex generators, while at the same time reducing A_F/A_W to

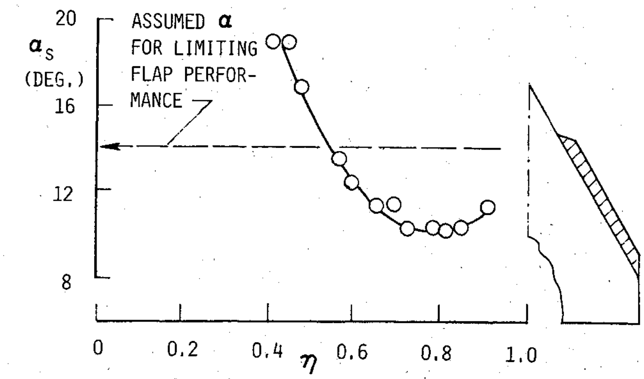

Fig. 6 Vortex spillover boundary for constant-chord continuous flap.

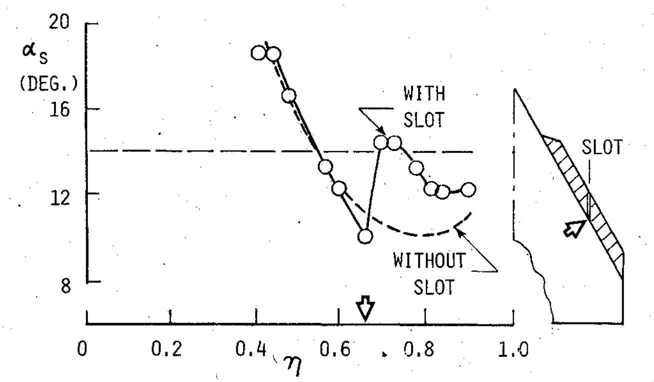

Fig. 7 Vortex spillover boundary for inversely tapered continuous flap.

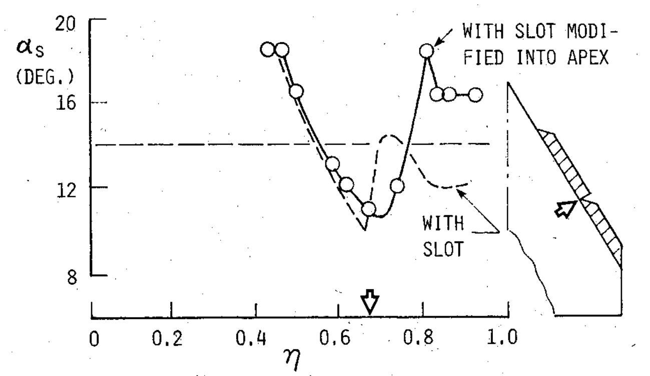

Fig. 8 Segmentation effect due to a chordwise slot on the vortex spillover boundary of constant-chord continuous flap.

9.6 and 6.3%, respectively. The spillover boundaries presented in Fig. 10 indicate that the gothic flap achieved the goal of $\alpha_s = 14$ deg on the outer segment. Clearly, there remains much scope for optimization beyond this first trial at flap shaping, considering that the two flap segments need not necessarily be identical, either in geometry or in dimensions. In the case of the delta flaps, the $C_{P,\mathrm{LE}}$ behavior with angle of attack was characteristically different and a distinct spillover was not identifiable. The spillover boundary for this case must therefore be regarded with reservations. Nevertheless, the performance of delta flaps was comparable to the other flaps, as will be shown in the next section.

Lift/Drag

The lift-to-drag ratio (L/D) at a lift coefficient of 0.5 (based on wing area only) are presented in Fig. 11. The indicated theoretical limits correspond to 100% leading-edge

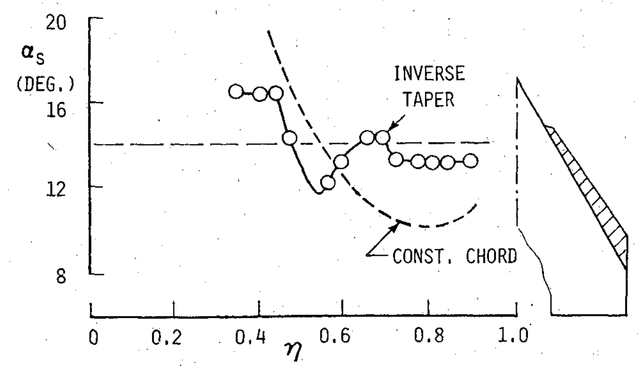

Fig. 9 Vortex spillover boundary for segmented constant-chord flaps.

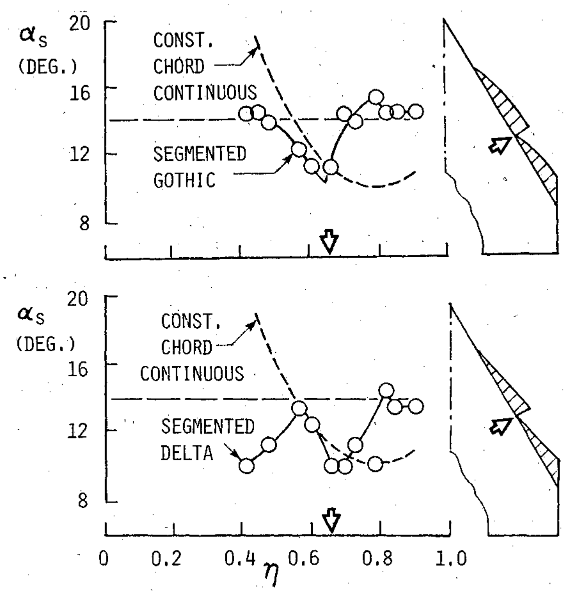

Fig. 10 Vortex spillover boundaries for segmented gothic and delta flaps.

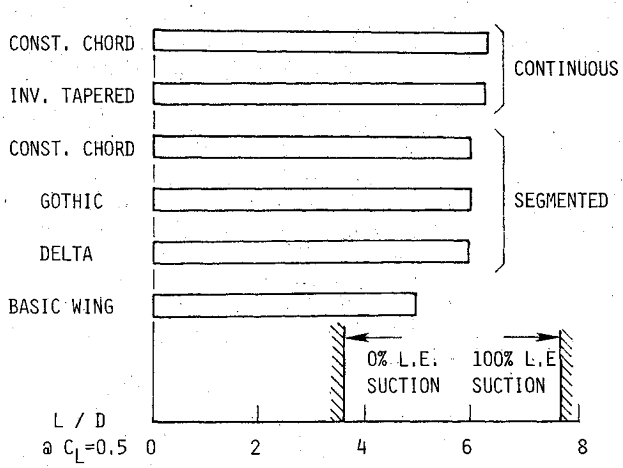

Fig. 11 Comparison of L/D increments at $C_L = 0.5$.

suction (i.e., potential flow), and 0% suction with fully developed leading-edge separation and associated vortex lift on the basic planform. The zero-lift drag value from experiment was used in both cases. Relative to these theoretical limits, the measured L/D of the basic wing implies a significant residual suction (even with largely separated flow) because of the relatively blunt leading edges, a factor to be borne in mind when evaluating the incremental (L/D) due to

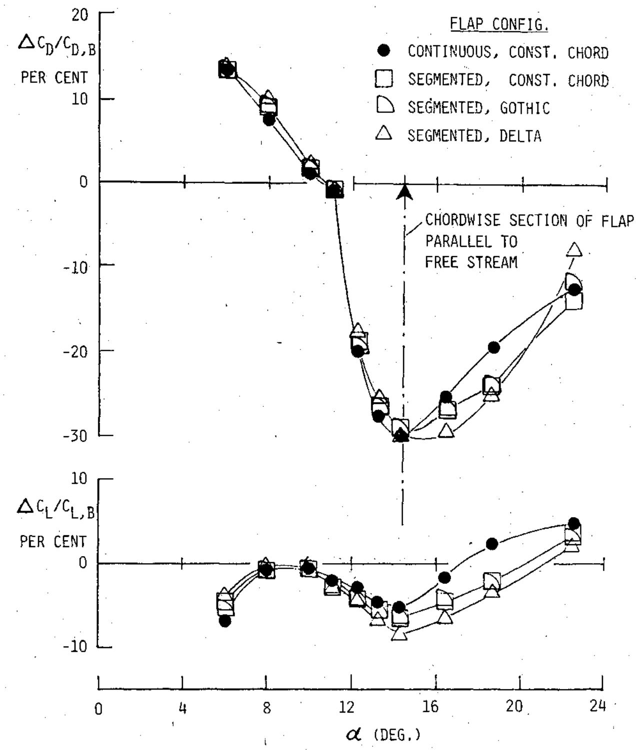

Fig. 12 Incremental drag and lift characteristics of various vortex flaps.

vortex flaps. Among the various flaps tested, the $\Delta(L/D)$ at $C_L = 0.5$ is seen to decrease only slightly in spite of a 50% area reduction from the continuous flaps to the segmented delta. This result contrasts previous vortex flap investigations, where a reduction of the leading-edge hinged flap area generally led to progressive loss of performance.

An analysis of the incremental lift and drag relative to the basic wing, presented in Fig. 12, is helpful toward understanding the $\Delta(L/D)$ results. The drag reduction due to flaps beginning at $\alpha = 11$ deg (i.e., as the basic wing approaches full separation), rapidly reaches a maximum of 30% near $\alpha = 14$-15 deg in all cases. Beyond this angle of attack, the differences among the various flaps become apparent; the drag reduction of segmented flaps drops off less rapidly than that of the continuous flaps, the segmented delta performing best to $\alpha = 18$ deg. Simultaneously there is a loss of lift, inherent to the vortex flap concept, where part of vortex lift is traded for thrust, although at a much smaller percentage than the drag reduction. Using $(-\Delta C_L)$ as an independent measure of the vortex-retention capability, the segmented flaps are again seen to be more effective than the continuous flap.

It is worth noting that the angle of attack for maximum drag reduction coincides with the flap becoming nearly parallel to the freestream direction, that is, when the flap angle in the chord plane equals the angle of attack. In this condition, the flap normal force has no thrust component; therefore, the drag reduction is wholly due to the distributed suction around the wing leading edge as modified by the flap vortex. This fact serves to explain the relative insensitivity of $\Delta(L/D)$ to flap area variation and is of particular significance to the setback hinge concept.

Leading-Edge Suction/Thrust

Static pressure distributions around the leading edge are presented in Figs. 13 and 14 for two semispan stations representing chord sections inboard and outboard of segmentation, respectively. At the angle of attack shown (16.5 deg), the thrust force still is generated primarily from leading-edge suction rather than from the negligibly small projected frontal area of the flap. It is noted that the leading-edge

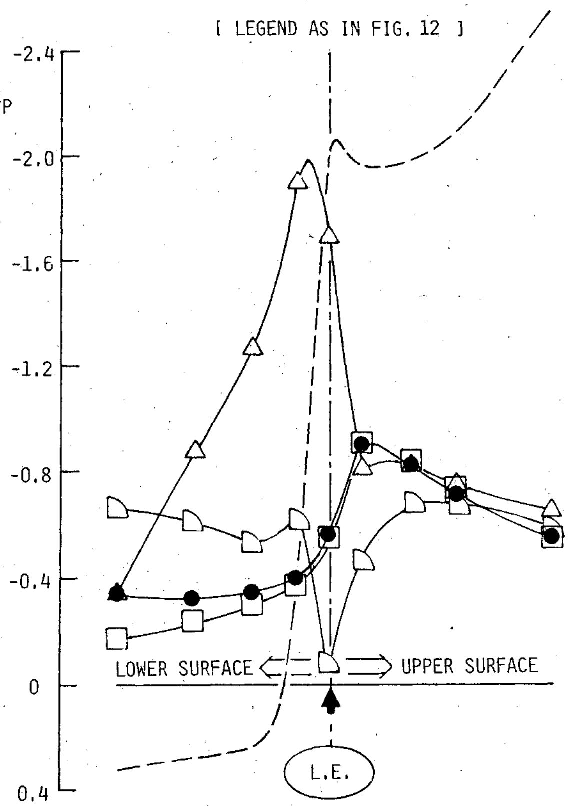

Fig. 13 Pressure distributions around leading edge at $\alpha = 16.5$ deg with various vortex flaps, inboard of segmentation ($\eta = 0.45$).

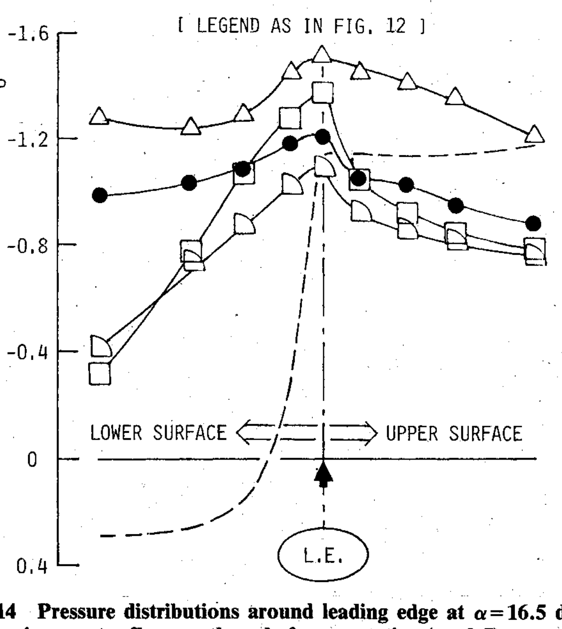

Fig. 14 Pressure distributions around leading edge at $\alpha = 16.5$ deg with various vortex flaps, outboard of segmentation ($\eta = 0.7$).

pressure distributions of the basic wing are modified by the vortex flaps in two important respects:

1) The positive pressures acting on the forward-facing surface elements near the chin of the leading edge are changed to negative pressures, at both semispan stations but particularly outboard.

2) The prevailing negative pressures on the aft-facing upper surface at the inboard section are considerably reduced in magnitude.

While both of these effects are favorable, the more important contributor toward drag reduction is the vortex-

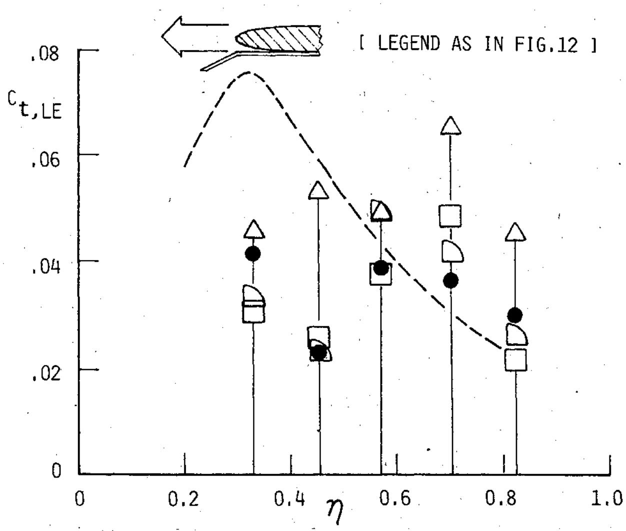

Fig. 15 Spanwise distribution of pressure-integrated local leading-edge thrust at $\alpha = 16.5$ deg with various vortex flaps.

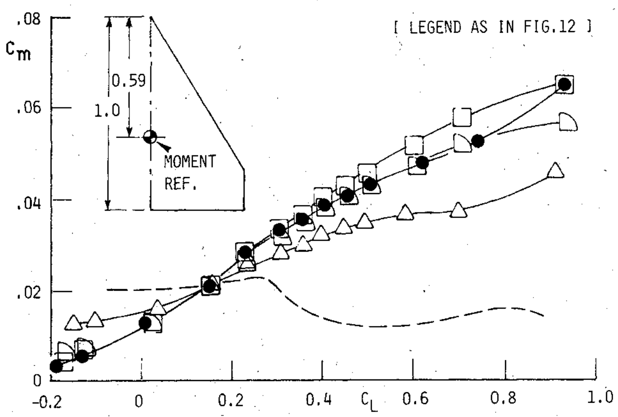

Fig. 16 Pitching moment characteristics with various vortex flaps.

induced suction in the leading-edge region where the local surface elements are oriented largely normal to freestream. In this respect, the segmented delta stands out as the most effective of the flaps tested. Evidently, the chord tailoring in this case favored vortex formation closely underneath the leading edge over most of the segment span, generating the observed high-suction levels on the leading-edge frontal area.

The integrated chord force resulting from such pressure measurements at the various semispan stations is shown in Fig. 15, which confirms the overall superiority of the segmented delta over the other flaps. From this figure, it is also seen that the thrust over the inner half of semispan is higher with the flaps off, because at this angle of attack ($\alpha = 16.5$ deg) the blunt leading edge remains attached to $\eta = 0.3$. Therefore, deletion of the inboard flap segment on this wing may actually improve the performance. On a more typical supersonic wing with sharp leading edges, however, the inner flap segment should still be beneficial for drag reduction.

Pitching Moment

As mentioned in the Introduction, an excessive forward shift of aerodynamic center resulting from flap extension can be of concern, particularly on vehicles flying with relaxed static stability. The pitching moments presented in Fig. 16 show that the delta-segmented flaps, mainly because of the considerable area relief forward of the center of gravity, are able to significantly reduce the aerodynamic center shift. At the same time, the pitchup of the basic wing is postponed to a higher lift coefficient.

Concluding Remarks

A pressure and force investigation on a 60-deg cropped-delta wing model has shown that segmented and chord-tailored vortex flaps are able to retain the vortex in the outboard region to higher angles of attack. Further, an arrangement simulating the flap hinge located under and aft of the wing leading edge generated substantial thrust from the vortex suction acting on the chin region of the leading edge at the angles of attack of interest when the flap frontal area itself was negligibly small. This approach of positioning the vortex optimally with respect to the wing leading edge at a prescribed angle of attack, thereby augmenting the effective frontal area under the vortex suction, appears to result in a more efficient vortex flap. In combination with segmentation and chord tailoring, the setback hinge offers improved potential for thrust per unit flap area as indicated by the present results on delta flaps. The flap area reduction forward of the center of gravity also is helpful in restricting the aerodynamic center shift accompanying flap deployment. In view of the model limitations of this exploratory study, further investigations appear worthwhile to more fully assess the potential of the proposed approach in comparison with the standard type of vortex flaps.

Acknowledgments

This research was supported by NASA Langley Research Center. The experimental work was performed by S.A. Tingas as part of his graduate research requirements of North Carolina State University.

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