# An Investigation of the Tabbed Vortex Flap

Keith D. Hoffler* Dhanvada M. Rao†
*Vigyan Research Associates Inc., Hampton, Virginia*

**Subsonic wind tunnel investigations were conducted on delta wings with tabbed vortex flaps. The tab comprises an up-deflected leading-edge portion of the flap intended to augment the vortex-induced thrust on the down-deflected flap. Balance and pressure measurements on a 74-deg delta model compared plane and tabbed vortex flaps of equal total area; tab modifications intended to improve the L/D over plane flaps were evaluated. In a parallel investigation, detailed spanwise pressures were measured on a 65-deg delta wing model from which sectional lift and drag contributions of the individual wing, flap, and tab surfaces were obtained by integration. Theoretical solutions using the free vortex sheet code with several flap/tab deflections on the 65-deg delta were compared with experimental pressures and vortex core positions. The results of this exploratory study showed that while the tab can augment the flap vortex thrust considerably, an excessive tab drag component may cancel this benefit. Preliminary guidelines toward more efficient tab configurations have been suggested.**

## Nomenclature

| | |
|---|---|
| $C_A$ | = axial force coefficient |
| $C_D$ | = drag coefficient |
| $C_L$ | = lift coefficient |
| $C_m$ | = pitching moment coefficient |
| $C_N$ | = normal force coefficient |
| $C_{P,U}$ | = upper-surface pressure coefficient |
| $C_R$ | = wing root chord |
| $L/D$ | = lift-to-drag ratio |
| $x$ | = chordwise distance from apex |
| $y$ | = spanwise distance from wing root |
| $\alpha$ | = angle of attack |
| $\Delta$ | = increment over planar case |
| $\delta_F$ | = flap deflection angle relative to wing center plane, normal to hinge line (positive downward) |
| $\delta_T$ | = tab deflection angle relative to flap center plane, normal to hinge line (positive upward) |
| $\eta$ | = spanwise distance from wing root as a fraction of semispan |
| $\Lambda$ | = sweepback angle |

*Subscripts*

| | |
|---|---|
| $F$ | = flap |
| HL | = hinge line |
| LE | = leading edge |
| $T$ | = tab |
| $W$ | = wing |

## Introduction

RECENT studies have demonstrated considerable potential of the vortex flap concept for subsonic-transonic maneuver enhancement of supersonic tactical aircraft. Several variants of the basic vortex flap have been proposed for augmenting its thrust efficiency over a wider range of lift coefficients. One such device is the vortex tab,[1] comprised of a secondary leading-edge portion of the flap which is deflected upward, i.e., counter to the down-deflection of the main flap (Fig. 1). The purpose of the tab is to control and augment the vortex suction on the flap frontal area for increased thrust. Although early flow-visualization studies on the vortex tab[2] confirmed its vortex enhancement capability, few balance measurements have been published. In a NASA Langley investigation,[3] the vortex tab on a cranked-arrow planform was found to perform better than the plane flap with respect to $L/D$ as well as lateral stability at high angles of attack; however, differences in geometry and size between the two types of flaps introduced an uncertainty in that comparison

A valid aerodynamic comparison would require the total flap area (inclusive of the tab) to be maintained constant within the same basic wing planform; i.e., tab deflection should be evaluated with respect to the same tab used as a planar extension of the flap surface. This was a basic consideration in planning the present investigation. In addition, details of the induced suction and vortex flow characteristics were desired to aid a basic understanding of the tab aerodynamics. Also of interest was the evaluation of the free vortex sheet code, applied extensively in previous vortex flap

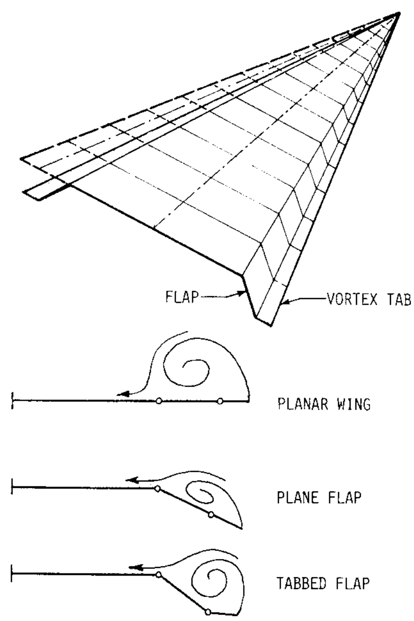


**Fig. 1 Tabbed vortex flap.**

Presented as Paper 84-2173 at the AIAA 2nd Applied Aerodynamics Conf., Seattle, Wash., Aug. 21-23, 1984; received Sept. 27, 1984; revision received March 15, 1985. 

*Research Engineer, Member AIAA.
†Vice President, Associate Fellow AIAA.

studies, for predicting the aerodynamic load characteristics of a vortex tab configuration.

The first part of this investigation consisted of balance and upper-surface pressure measurements on a 74-deg delta wing/body configuration model used in previous NASA Langley vortex flap research. This model was tested with a series of tab attachments at $M=0.3$ in the Langley $7\times10$ ft High-Speed Tunnel. In a parallel study conducted in the North Carolina State University (NCSU) $32\times45$ in. Subsonic Tunnel, detailed upper-surface pressure distributions were measured at a single spanwise section across the wing, flap, and tab surfaces on a 65-deg delta semispan model. The integrally hinged flap and tab segments were deflected to various flap-down and tab-up combinations starting from an uncambered basic delta wing, the total surface area thus remaining constant throughout. Flow-visualization studies using oil-flow, tuft, and helium-bubble techniques supplemented the pressure measurements. This essentially conical model geometry also was the subject of free vortex sheet computations.

## Models and Experimental Details

### 74-Deg Delta Wing

The configuration and principal dimensions of this NASA Langley force-cum-pressure vortex flap research model are presented in Fig. 2. Thin sheet-metal tabs of different shapes, as depicted in Fig. 3, were added to the existing constant-chord (c.c.) leading edge flaps of this model. The tabs varied from full-span constant chord, to segmented, part-span, and inverse-taper variants. The full-span tabs initially were tested at zero tab deflection, i.e. as planar flap extensions, providing a baseline for evaluating the tab effects. The aerodynamic coefficients from these tests were based on the total wing area which included the flap and tab surfaces. The tests were conducted in the Langley $7\times10$ ft High-Speed Tunnel at a Mach number of 0.3 and mean-chord Reynolds number of $5.2\times10^6$.

### 65-Deg Delta Wing

Shown in Fig. 4, this semispan model of composite construction incorporated hinged flap and tab segments. The flap and tab hinge lines were located along rays from the apex swept at 74 and 68 deg, respectively, and the trailing edge was left blunt. These geometrical features were intended to promote an essentailly conical leeward flowfield. A minor deviation from conical geometry occurred in the apex region where the very narrow flap and tab surfaces were deleted for structural reasons. A spanwise row of upper-surface pressure taps extending to $\eta=0.946$ was provided at $x/C_R=0.7$, with a close spacing between taps maintained across the hinged surfaces.

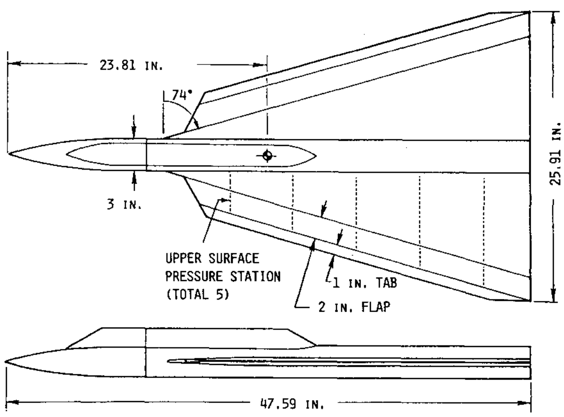


Fig. 2 NASA Langley 74-deg delta balance and pressure model.

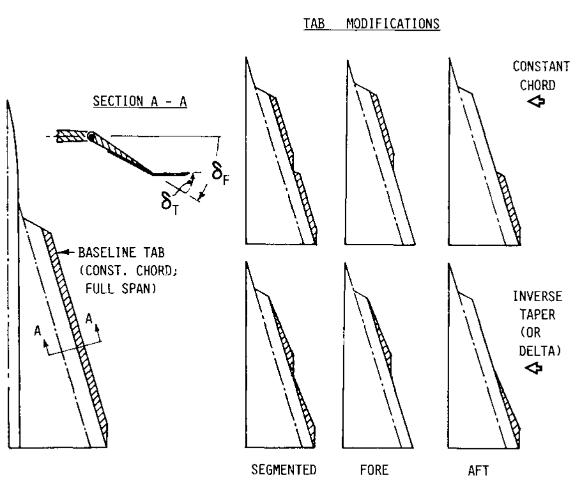


Fig. 3 Baseline and modified tabs tested on 74-deg delta.

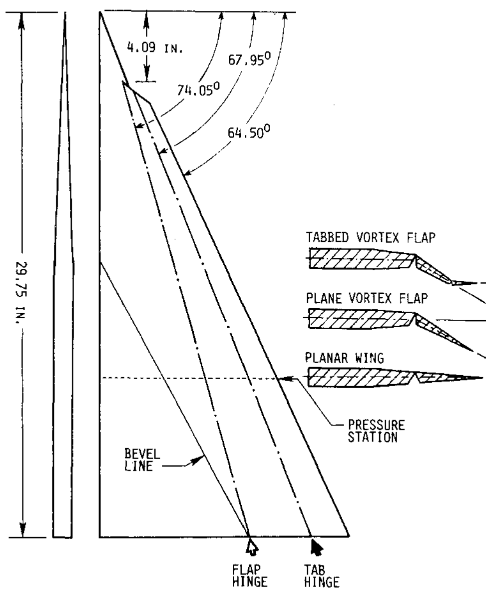


Fig. 4 NCSU 65-deg delta semi-span pressure model with integral "conical" flap and tab.

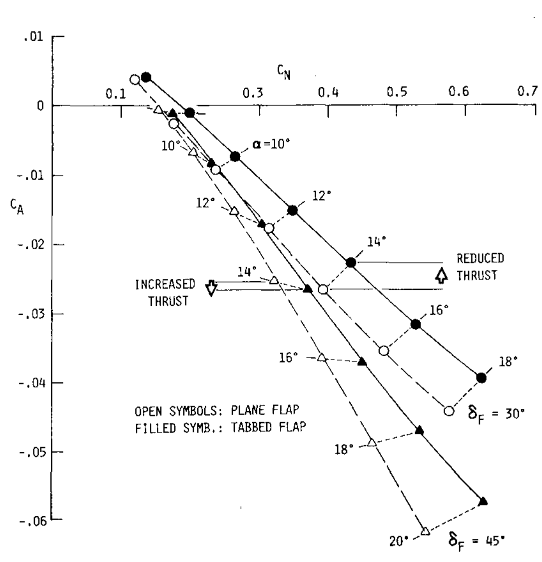


Fig. 5 Tab deflection effects on 74-deg delta axial vs normal force.

The flap-down and tab-up deflections (both defined as positive angles) could be varied continuously between 0 and 60 deg measured normal to the respective hinge lines. The angle of attack measured from the wing center plane ranged from 0 to 20 deg. The tests were conducted in the NCSU Subsonic Wind Tunnel at a velocity of 88 fps corresponding to a mean chord Reynolds number of $0.87 \times 10^6$. For helium-bubble experiments the velocity was reduced to approximately 20 fps (Reynolds number of $0.2 \times 10^6$ based on mean aerodynamic chord).

## Results and Discussion

### 74-Deg Delta Wing

*Baseline Tab*

In the majority of deflected-tab tests on this model, the tab angle was set equal to the flap angle. While this might appear unduly restrictive to the vortex tab concept, it did provide a convenient reference case when investigating the tab planform modifications to be discussed subsequently.

When $\delta_T = \delta_F$, the flap thrust is seen directly in the balance axial force data unaffected by the tab load component, because the tab lies parallel to the wing center plane as a consequence of parallel hinge lines on this model. The coefficients of axial force vs normal force (based on total area) are plotted in Fig. 5. At both flap angles, tab deflection increases $C_N$ at constant angles of attack due to the vortex lift on the tab surface. However, the effects on axial force are opposite; tab deflection reduces the flap thrust $(-C_A)$, at $\delta_F = 30$ deg, but increases it at $\delta_F = 45$ deg. This contrasting behavior may be understood by inspecting the corresponding spanwise pressure distributions on the wing and flap upper surfaces shown in Fig. 6. Tab deflection augments the flap suction (see shaded area) in both cases but even more so on the 45-deg flap. At $\delta_F = 30$ deg, the relatively moderate suction increment due to tab deflection was insufficient to compensate for the reduction in flap frontal area, as may be inferred from the net loss of thrust seen in the corresponding axial force characteristics. On the other hand, the significantly increased flap suction at $\delta_F = 45$ deg evidently overcomes the frontal area reduction to yield a net thrust increase. The conflicting effects of flap suction enhancement and frontal area reduction require careful proportioning of the tab and flap to derive a performance benefit.

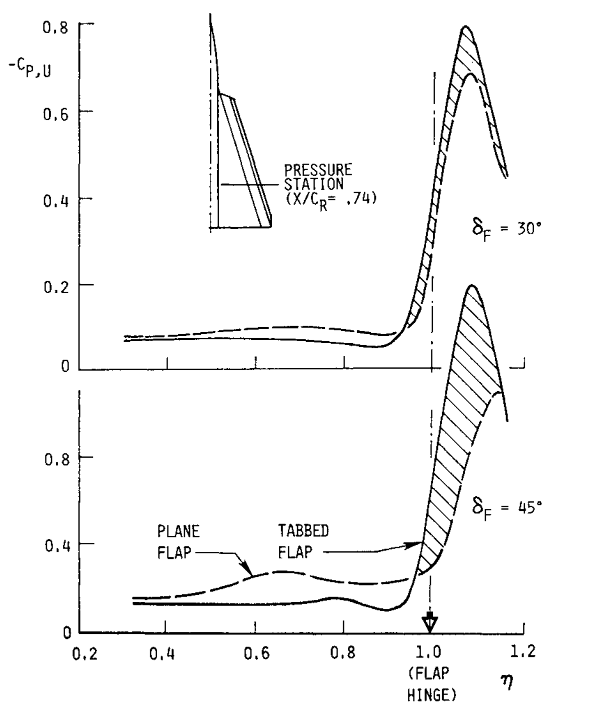


**Fig. 6 Tab deflection effect on 74-deg delta upper-surface pressures ($\alpha = 16$ deg).**

A noteworthy feature in the pressure distributions with the plane flap at $\delta_F = 45$ deg (Fig. 6) is a minor suction peak appearing on the wing, interpreted as flow separation at the flap hinge line which rolls up into a separate vortex. This hinge-line separation, which is an evident source of drag, is practically eliminated by tab deflection. Vortex augmentation due to tab deflection apparently induces a more vigorous turning of the external streamlines, with the associated downwash leading to reduced suction level inboard of the flap hinge. Thus, the tab makes larger flap deflections feasible without the risk of hinge-line separation.

The $L/D$ vs $C_L$ for the preceding flap/tab combinations are presented in Fig. 7. The opposite effects of tab deflection found in the two cases, viz., adverse at $\delta_F = 30$ deg but favorable at $\delta_F = 45$ deg, are in accord with the corresponding axial force increments discussed previously. Note, however, that although tab deflection improves the 45-deg flap thrust, it is the 30 deg plane flap that provides higher $L/D$, indicating that the drag due to high suction on the tab may cancel most of the flap thrust improvement.

*Tab Modifications*

In order to alleviate the adverse effect of tab drag, preliminary attempts were made toward tab area reduction by limiting its spanwise extent, as well as by tab planform shaping. The full-span, constant-chord baseline tab was modified accordingly in two stages: 1) the tab length was bisected to produce a two-segment constant-chord tab, and 2) the segments were shaped into inverse-taper (or delta) tabs. The part-span tabs also were tested alternately in the forward and aft positions (see Fig. 3 for the modified tab test configurations).

The $L/D$ results for the modified tabs on a 30-deg flap are summarized as a bar chart in Fig. 8. The $L/D$ increments (shaded area) are relative to the planar wing containing the baseline tab (planar configurations corresponding to the modified tabs were not tested). This comparison shows a distinct aerodynamic advantage of the part-span aft tabs, which generate nearly the same $(L/D)_{max}$ and a better $(L/D)$ at $C/_L = 0.5$ than the plane flap although the ratio of tab to total (wing + flap + tab) area has reduced from 10.1 to 2.73%.

The reason for better $(L/D)$with part-span aft tabs is found in the spanwise upper-surface pressure distributions at four axial stations by comparing the full- and part-span aft tabs at

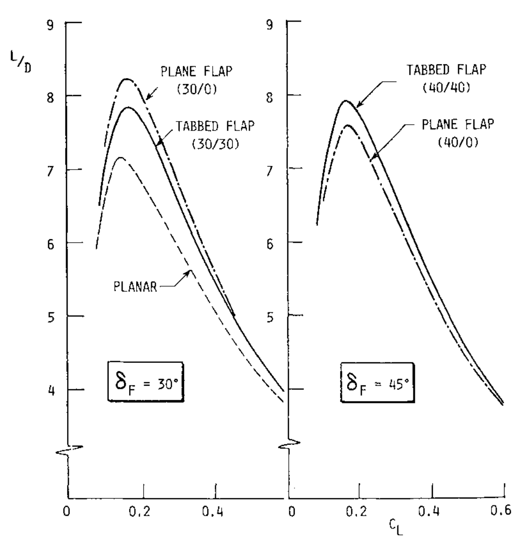


**Fig. 7 Tab deflection effect on 74-deg delta lift/drag characteristics.**

$\delta_F = 30$ deg and $\alpha = 16$ deg in Fig. 9. The tab is clearly detrimental at the forward station where the vortex suction peak occurs on the tab rather than on the flap surface. By removing the forward half of the tab the vortex is allowed to move to the flap improving its thrust, while the tab drag penalty is reduced almost by one-half. Undoubtedly, there is potential for further optimization of the part-span tab than could be accomplished within the limited scope of this study.

*Pitching Moment*

The effect of full-span tab deflection on the pitching moment characteristics for $\delta_F = 30$ deg (which is typical of other flap angles) is shown in Fig. 10. The existing moment reference on the model resulted in a relatively high static margin which is not representative of an actual aircraft of this class; the pitch characteristics, however, are presented mainly for a qualitative evaluation of the effects of flap and tab deflection. The planar wing exhibits a distinct pitch-up behavior; in contrast, the plane flap configuration remains stable throughout the $C_L$ range of the data. The effect of tab deflection is to further improve the static stability toward higher lift coefficients; certainly, no adverse effects are noted.

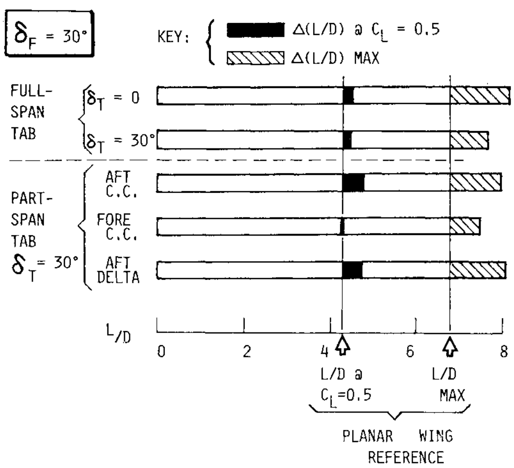


Fig. 8 Tab modification effects on 74-deg delta lift/drag.

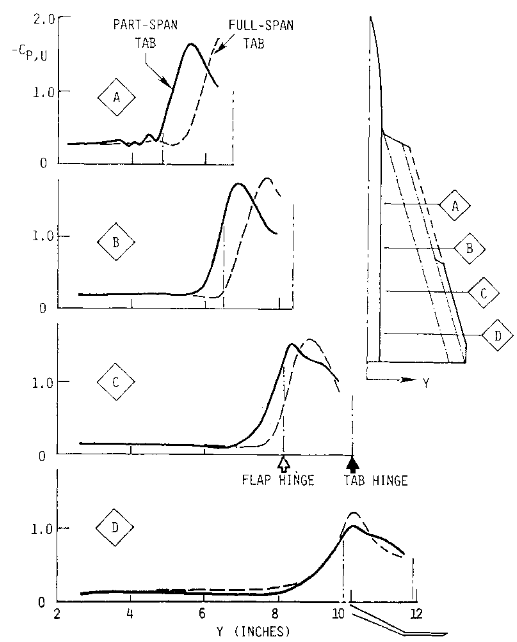


Fig. 9 Upper-surface pressures on 74-deg delta—part-span aft tab vs baseline tab ($\delta F = 30$ deg, $\delta T = 30$ deg, $\alpha = 16$ deg).

**65-Deg Delta Wing**

This semispan model was used to generate detailed spanwise upper-surface pressure distributions on the wing, flap, and tab at a fixed axial distance from the apex. Flow visualizations using oil-flow, tuft, and helium-bubble techniques also were conducted to assemble a consistent description of the tab vortex-induced effects. The upper-surface oil patterns were found to be conical in major respects, all the way to the trailing edge in the test range of $\delta_F$ and $\delta_T$.

Typical pressure distributions presented in Fig. 11 show the effects of flap and tab deflections. Of particular interest is the augmentation of the flap surface suction when the tab is deflected, together with the appearance of a suction peak on the tab itself. Corresponding oil-flow and helium-bubble visualizations suggested a single augmented vortex responsible for the suction peaks on adjacent flap and tab surfaces. A concave corner separation occurs as the boundary layer is swept from the primary attachment line outwards across the tab hinge, followed by secondary separation on the tab (interpreted as usual by the formation of an oil-accumulation line).

A small increment in the angle of attack from 16 to 18 deg raises the suction level on the plane 30-deg flap but reduces the suction peak with deflected tab, suggesting vortex breakdown in the second case as confirmed by the helium-bubble visualizations at $\alpha = 18$ deg presented in Fig. 12. For reference,

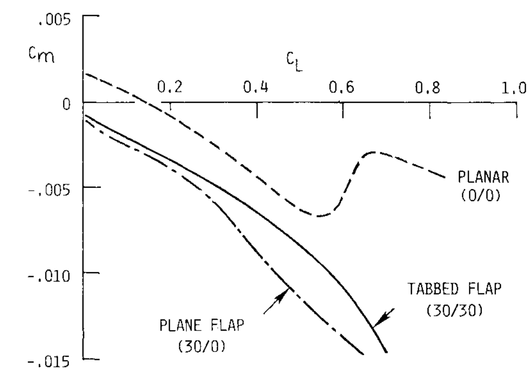


Fig. 10 Plane flap and baseline tab effects on pitch characteristics of 74-deg delta.

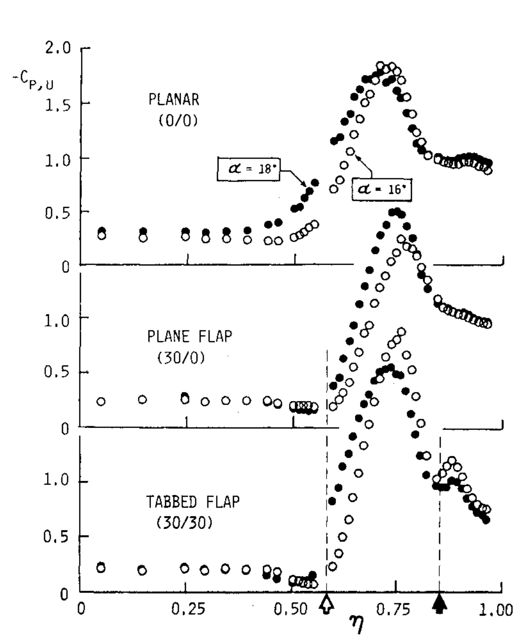


Fig. 11 Spanwise upper-surface pressure distributions on 65-deg delta.

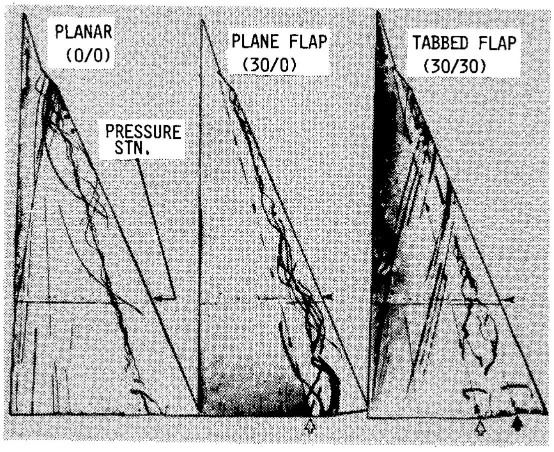


**Fig. 12 Helium-bubble visualizations on 65-deg delta ($\alpha = 18$ deg).**

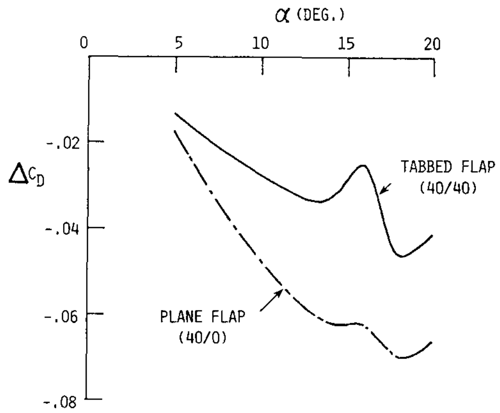


**Fig. 14 Total drag increment due to plane flap and flap plus tab deflections.**

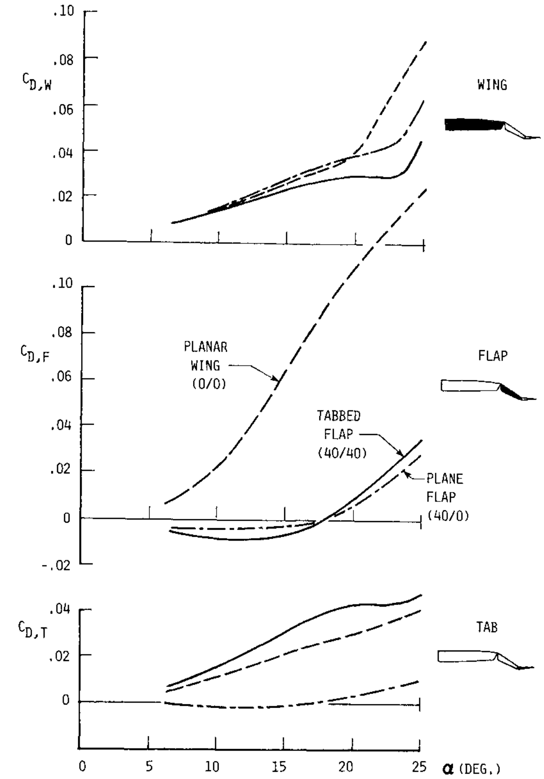


**Fig. 13 Wing/flap/tab drag contributions showing effect of plane flap and flap plus tab deflections ($\delta F = 40$ deg).**

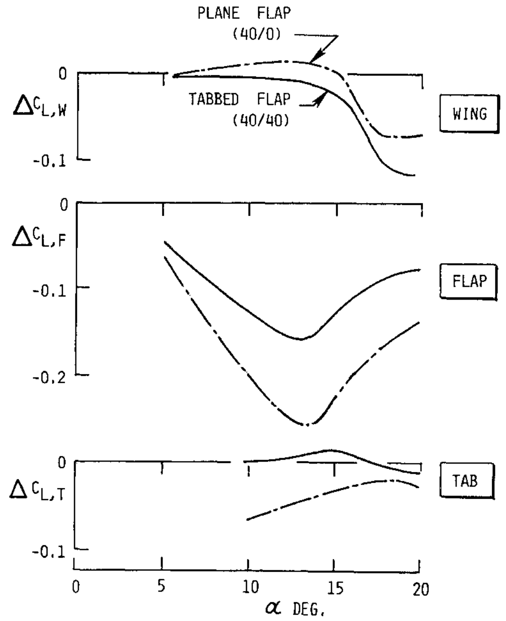


**Fig. 15 Tab effect on lift increments on 65-deg delta with 40-deg flap.**

vortex breakdown on a planar 65-deg delta wing crosses the trailing edge at $\alpha = 18.5$ and reaches the 70% center-chord station at $\alpha = 20.5$ deg.[4]

The high resolution of pressure distributions obtained on the 65-deg delta model made it possible to evaluate the local (or sectional) load characteristics accurately by integration, separately on the wing, flap, and tab surfaces. Although the lower-surface pressure data were lacking, the vortex-dominated flow, particularly over the flap and tab regions, implied that their loading was determined largely by the upper-surface suctions. This offered a convenient means of surveying the main aerodynamic trends with respect to the tab effects, covering a range of flap/tab deflection combinations.

From pressure-integrated local loads, sectional lift and drag contributions of the wing, flap, and tab were determined. The drag coefficient vs angle of attack for a typical case of a 40-deg flap are compared with the planar wing in Fig. 13. On the wing portion an initial, small drag increase due to flap deflection is attributable to hinge-line separation. On the other hand, at higher angles of attack, flap deflection results in a substantial drag reduction of the wing due to a delayed vortex migration. This high-$\alpha$ drag reduction is further accentuated by tab deflection because the augmented vortex-induced downwash decreases the average suction level over the wing.

Considering next the flap component, the characteristic thrust (or negative drag) feature is evident below $\alpha = 14$ deg, i.e., as long as the flap upper surface remains sloped forward. Up to that angle of attack the increased suction generated by the tab vortex is beneficial to flap thrust, but the same effect becomes a liability at higher $\alpha$ when the flap begins to slope aft. Then, the reduced suction on the wing due to tab-augmented downwash becomes the dominant drag-reduction mechanism.

With regards to the tab when deflected from 0 to 40 deg, its own contribution changes from thrust to drag; the resulting drag increment exceeds the combined drag reductions induced on the wing and flap surfaces. Consequently, the total configuration sectional drag is higher throughout with the tab deflected (Fig. 14).

The lift increments relative to planar wing on the three elements are shown in Fig. 15. The lift contributions of the flap and tab are both improved significantly by tab deflection. This essentially reflects a partial recovery of the planar wing vortex lift that was lost as a result of plane flap deflection.

The overriding adverse effect on tab drag found on the 40-deg flap/40-deg tab configuration prompted a study of smaller tab deflections, i.e., $\delta_T < \delta_F$, as a possible means of reducing the tab drag while retaining some of its beneficial effect on the flap thrust. The separate drag contributions of wing, flap, and tab surfaces as a function of tab deflection (at a constant $\alpha = 10$ deg) are shown in Fig. 16. While the flap thrust increases linearly with tab deflection, the tab contribution reverses from thrust to drag at a relatively small tab angle of approximately 7 deg, which coincides with the tab becoming aligned with freestream direction. Accordingly, the sectional $L/D$ reaches a maximum at $\delta_T = 5$ deg to a value about 15% higher than the $L/D$ with an undeflected tab. If these sectional characteristics derived from upper-surface pressures are representative of the overall configuration aerodynamics, the $\delta_T < \delta_F$ cases would appear to deserve more detailed investigation.

**Free Vortex Sheet Computations**

The free vortex sheet (FVS) theory[5] has been used extensively in recent years to analyze vortex flows on highly swept configurations. This fully three-dimensional theory predicts pressure distributions on wings with leading-edge separation vortices; vortex sheet shape and vortex core location are obtained as well.

Achieving convergence with the FVS code, while relatively easy for planar wings, has proven more difficult with vortex control devices such as vortex flaps, and was not possible with conical flow-starting solutions. This problem was alleviated to some extent by the development of a "partial restart" procedure,[6] which employs free sheet geometries from previous computations as starting solutions for new computations. Although applied successfully on a variey of configurations,[6,7] the method has been limited to small increments in $\alpha$ and $\delta_F$ for vortex flap applications. With the "partial restart" procedure and some "user-manipulation" of the vortex sheet shape, convergence has been obtained for more difficult cases.[8]

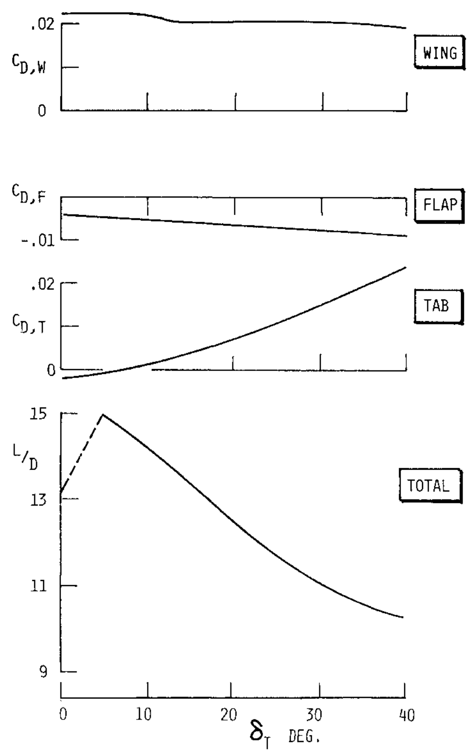


**Fig. 16 Wing/flap/tab drag contributions and $L/D$ showing effect of tab angle on 40-deg flap ($\alpha = 10$ deg).**

Modifications were made to the FVS code during this investigation to allow the user to easily rotate and/or radially scale the entire or any column of the free and fed sheets about the leading edge (Fig. 17). This procedure ("modified partial restart") provided convergence for the flap-deflected cases, requiring considerably less user and CPU time than needed previously.

Figure 18 shows the geometry used to validate the FVS solutions against the 65-deg delta wing experimental results. The computational model geometry was of zero thickness, and also had the flap and tab surfaces continued to the apex. These presumably minor deviations from the experimental geometry were accommodated to simplify modeling and promote convergence. A spanwise row of control points was located at $x/C_R = 0.7$ for direct comparison of the upper-surface pressures between FVS and experiment.

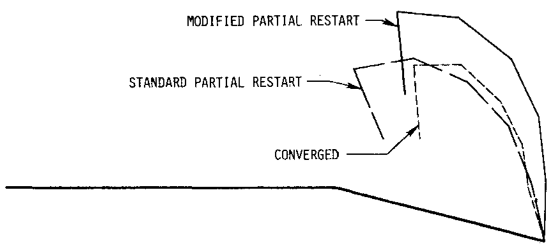


**Fig. 17 Modification to free vortex sheet starting free/fed sheet geometries and converged solution.**

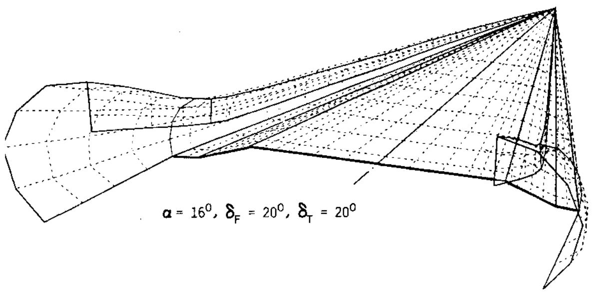


**Fig. 18 Free vortex sheet model geometry.**

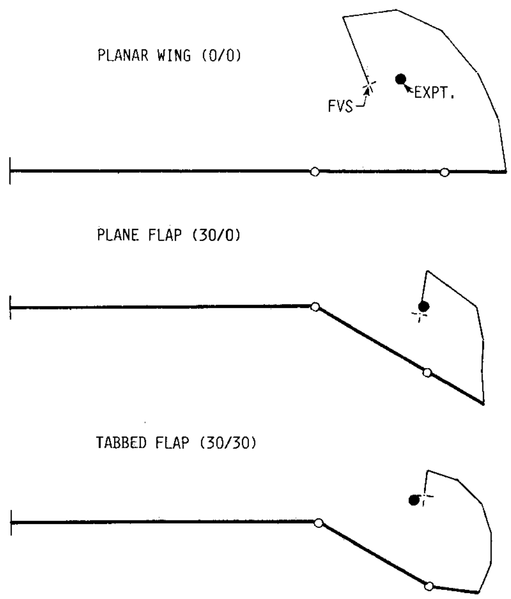


**Fig. 19 Experimental and theoretical vortex core locations on 65-deg delta ($\alpha = 16$ deg).**

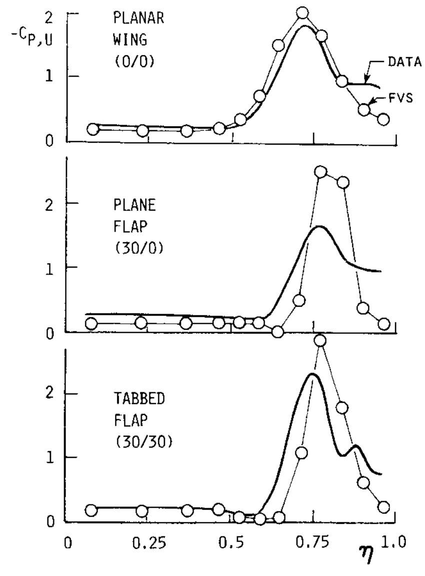


**Fig. 20 Upper-surface pressure distribution on 65-deg delta—theory vs experiment ($\alpha = 16$ deg).**

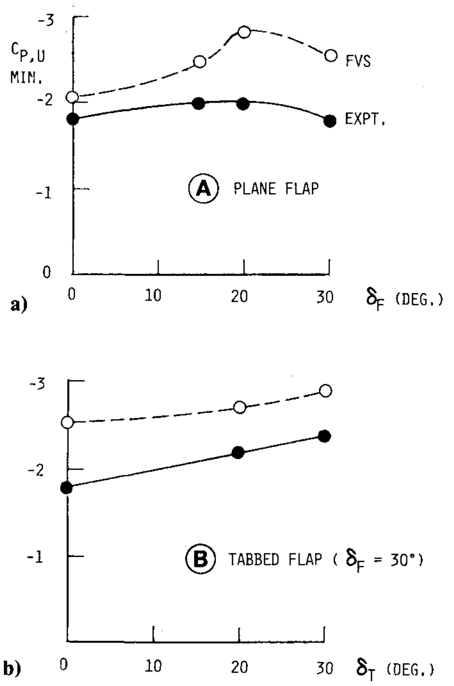


**Fig. 21 Suction peak ($CP$, $U_{min}$) as influenced by plane flap and flap plus tab deflections—theory vs experiment ($\alpha = 16$ deg).**

Typical results showing the theoretical and experimental vortex core locations are shown in Fig. 19. Overall, the vortex core movement trends with flap and tab deflections are found to be predicted fairly well. The core moved outboard and closer to the flap surface as the flap was deflected downward; tab deflection at a given $\delta_F$ brought the core back inboard and raised it further above the flap surface.

Representative comparisons between experimental and computed $C_{P,U}$ distributions for the planar wing, plane flap, and tabbed flap at a constant $\alpha = 16$ deg are presented in Fig. 20. In all cases, the vortex-induced suctions are overpredicted by FVS. Cited as primary reasons for the theoretical overprediction are discrepancy between experimental and numerical model geometries and viscous effects, including secondary separation, which are not modeled by theory.

An overall assessment of FVS capability in prediction of the load trends, using the upper-surface peak suction characteristics due to flap and tab deflection at a constant angle of attack, is presented in Fig. 21. Plane flap deflections (Fig. 21a) initially raises the peak suction; however, at higher flap angles the peak suction begins to drop. This FVS trend suggests that initially, the effect of vortex core movement towards the flap dominates, giving way to the opposite effect of vortex weakening dominating at the higher flap deflections. The experimental trend appears to be similar but less pronounced, possibly due to a softening effect of secondary separation.

The effect of tab deflection (Fig. 21b) is to steadily increase the peak suction, on which both FVS and experiment agree. Since the vortex core is moving away from the flap with increasing $\delta_T$, the increase in $-C_{P,U_{min}}$ on the flap reflects a high rate of vortex intensification due to tab deflection.

## Concluding Remarks

The present study has attempted assess the vortex tab relative to a plane vortex flap; the two flap systems having equal total area and being integral to the basic wing planform. The results indicate that although the augmented vortex from an integral tab definitely enhances the flap thrust in spite of the diminished frontal area, the drag component of the tab can more than nullify that benefit. Means to reduce the tab drag while retaining its positive influence on the flap thrust, such as part-span and tailored-planform tabs as well as tab deflections much smaller than the flap angle, showed promise. However, on the basis of (L/D) improvements achieved within the limited scope of this study, it cannot be asserted that the potential benefits over properly designed plane vortex flaps of equal area will be such as to justify the added mechanical complexity of the tabbed flap. Certain incidental advantages of the vortex tab are noted, viz, a partial recovery of the vortex lift lost by plane flaps which may help to reduce the angle of attack at landing, and the possibility of longitudinal trimming through segmented tab adjustment. In light of the present findings, other vortex tab arrangements aimed at minimizing the tab drag at a design condition are worthy of investigation. In such a future investigation, the FVS code could be a useful analytical tool for providing the correct tab-vortex trends.

## Acknowledgments

The considerable assistance received from Messrs, Robert Vess, Cary Moskovitz, and Jay Al-Saadi in wind tunnel testing at NCSU, and from the staff of the NASA Langley 7×10 ft High-Speed Tunnel in the course of this work, is gratefully acknowledged. This research was supported by NASA Langley Research Center.

## References

[1]Tinoco, E. N. and Yoshihara, H., "Subcritical Drag Minimization for Highly Swept Wings with Leading Edge Vortices," AGARD-CP-247, Oct. 1978.

[2]Runyan, L. J., Middleton, W. D., and Paulson, J. A., "Wind Tunnel Test Results of New Leading Edge Flap Design for Highly Swept Wings—A Vortex Flap," NASA CP-2108, Pt. 1, Nov. 1979, pp. 131-147.

[3]Yip, L. P. and Murri, D. G., "Effects of Vortex Flaps on the Low-Speed Aerodynamic Characteristics on an Arrow Wing," NASA TP-1914, 1981.

[4]Wentz, W. H. Jr. and Kohlman, D. L., "Wind Tunnel Investigations of Vortex Breakdown on Slender Sharp-Edged Wings," NASA CR-98737, Nov. 1968.

[5]Tinoco, E. N., Lu, P., and Johnson, F. T., "An Improved Panel Method for the Solution of Three-Dimensional Leading-Edge Vortex Flows, Volume II—User's Guide and Programs Document," NASA CR 3279, 1980.

[6]Luckring, J. M., Schoonover, W. E. Jr., and Frink, N. T., "Recent Advances in Applying Free Vortex Sheet Theory for the Estimation of Vortex Flow Aerodynamics," AIAA Paper 82-0095, Jan 1982.

[7]Frink, N. T., "Analytical Study of Vortex Flaps on Highly Swept Delta wings," 13th Congress of the International Council of the Aeronautical Sciences/AIAA Aircraft Systems and Technology Meeting, Aug. 1982.

[8]Erickson, G. E., "Application of Free Vortex Sheet Theory to Slender Wings with Leading-Edge Vortex Flaps," AIAA Paper 83-1813, July 1983.