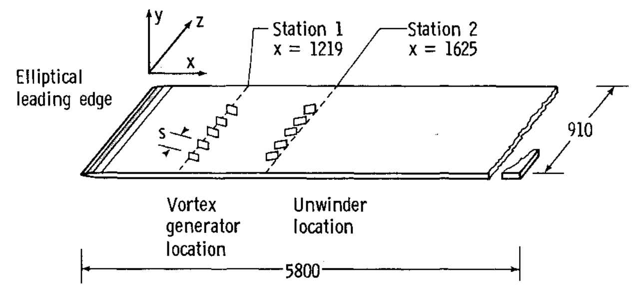

Fig. 1 Splitter plate showing generator/unwinder arrangement (all dimensions in millimeters).

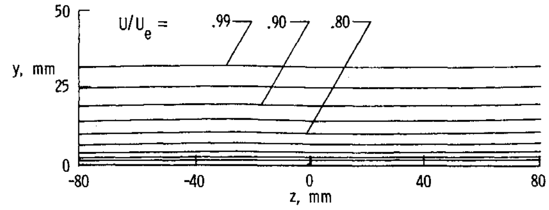

Fig. 2 Spanwise isotachs of undisturbed boundary layer, $x = 2438$ mm.

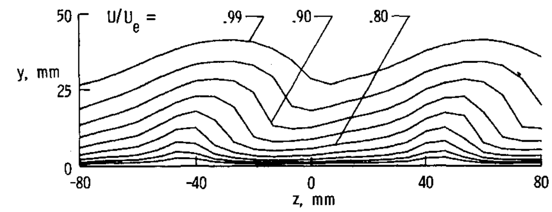

Fig. 3 Spanwise isotachs with vortex generators, $x = 2438$ mm.

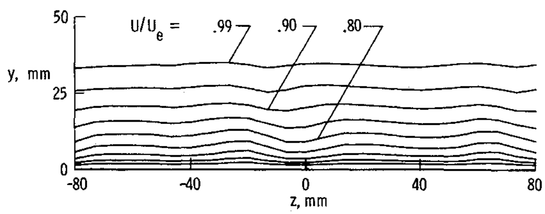

Fig. 4 Spanwise isotachs with generators and unwinders, $x = 2438$ mm.

Although this configuration was not a true optimum (in that the isotachs in Fig. 4 are not identical to the nominally two-dimensional case), the optimization process was halted for several reasons. Primarily, the major improvement in the boundary-layer variation is believed to be a sufficient indication of the feasibility of vortex unwinding in this situation. Several of the points raised in Ref. 2 were found to apply in the boundary layer, e.g., correct spanwise position is important and various levels of unwinding can be achieved depending on unwinder strength. In fact, in this experiment, the initial unwinder angle of -3 deg actually reversed the entire spanwise flowfield. Second, any further optimization will require more detailed measurements of the vortices strengths and positions. In contrast to Ref. 2, where the unwinder angle needed to be accurate only to within 1 deg, the present configuration showed sensitivity to changes of at least 0.25 deg. The final unwinder configuration, while close to the true optimum, was actually slightly overpowering. However, since this setting so greatly reduced the spanwise variations, it is reasonable to assume that given time, and perhaps more detailed measurements, the vortices could be completely removed.

Conclusion

In this Note, the feasibility of vortex unwinding in a turbulent boundary layer has been demonstrated. While the true optimum unwinding configuration was not reached (i.e., the return to the nominally two-dimensional case), sufficient reduction in the isotach variation was achieved to verify the usefulness of this technique in turbulent boundary-layer vortex control. It is suggested that more detailed measurements of vortex strength and position will improve the optimization process and increase the amount of vortex unwinding. It should be noted that most of the applications suggested in this Note will benefit from vortex reduction as well as from complete vortex unwinding.

References

[1]McGinley, C.B. and Beeler, G.B., "Large-Eddy Substitution via Vortex Cancellation for Wall Turbulence Control," AIAA Paper 85-0549, March 1985.

[2]Schaffer, A., "A Study of Vortex Cancellation," *Journal of the Aerospace Sciences,* Vol. 27, March 1960, pp. 193-196.

[3]Rossow, V.J., "Experimental Investigation of Wing Fin Configurations for Alleviation of Vortex Wakes of Aircraft," NASA TM 78520, Nov. 1978.

[4]Furuya, Y., Nakamura, I., Osaka, H., and Shimizu, T., "The Spanwise Non-uniformity of Nominally Two-Dimensional Turbulent Boundary Layer," *Bulletin of the JSME,* Vol. 19, No. 134, Aug. 1976, pp. 922-929.

[5]Taylor, H.D., "Application of Vortex Generator Mixing Principle to Diffusers Concluding Report," United Aircraft Corp. Research Dept., East Hartford, CT, Rept. R-15064-5, 1948.

[6]Pearcey, H.H. and Stuart, C.M., "Methods of Boundary-Layer Control for Postponing and Alleviating Buffeting and Other Effects of Shock-Induced Separation," Paper FF-22, presented at IAS National Summer Meeting, Los Angeles, June 1959.

Spanwise Pressure Distribution on Delta Wing with Leading-Edge Vortex Flap

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Nomenclature

A	= aspect ratio
$b(x)$	= local wing span
$\bar{c}$	= aerodynamic mean chord
c_r	= root chord
C_D	= drag coefficient
C_L	= lift coefficient
C_m	= pitching moment coefficient
D	= drag
FVS	= free vortex sheet
L	= lift
x,y,z	= body axis coordinates
α	= angle of attack
δ	= flap angle normal to hinge
Λ	= leading-edge sweep angle

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Introduction

MOST of the present-day aircraft and missiles designed for supersonic speeds employ highly swept-back and low-aspect-ratio wings with sharp edges. However, such wings are inefficient in subsonic and high-lift flight regimes such as climb to cruise, maneuver, and approach to landing and have serious performance, stability, and control deficiencies. Flow separation occurs near the leading edges of such wings at moderate-to-high angles of attack. The separation produces vortex sheets that roll up into strong vortices that generate additional lift at the cost of increasing the drag due to the loss of leading-edge suction. The forward movement of the center of vortex lift with increasing angle of attack causes longitudinal instability. Generally, the formation of concentrated vortices on the wing surface induces undesirable stability and control problems.[1]

Leading-edge flaps may be used to maintain attached flow even at higher angles of attack in case of the wings with moderate sweep angles. Such an approach, however, is less practical in the case of highly swept-back wings typically employed in supersonic aircraft because of the difficulties involved in complete suppression of the separation.

A leading-edge vortex flap may physically resemble a conventional leading-edge flap, but its aerodynamic function is quite different. Unlike the latter whose function is to maintain a smooth on-flow, the former's function is to force the separation to take place on the flap and thereby produce a significant thrust component in the flight direction. Depending upon the flap deflection in the upward or downward direction, the thrust component generated owing to the vortex formation on the flap can be exploited to increase or decrease the drag. This type of vortex management can be profitably used in different flight regimes of an aircraft. A good account of the leading-edge vortex flap concept can be found in the recent works by Rao.[2,3]

In this Note, the aerodynamic characteristics of a highly swept-back planar delta wing with leading-edge flap are numerically investigated. The spanwise pressure distributions at different angles of attack and various chordwise stations are also estimated. The numerical code used for this purpose and the results obtained are discussed in the following sections.

Method

The method employed for studying the aerodynamic performance of the delta wing with leading-edge flap is the free vortex sheet (FVS) method.[4,5] The method is based on a three-dimensional inviscid flow model. This is an advanced panel method using quadratic doublet distributions to represent the wing surface and the rolled-up vortex sheet and wake. It is capable of computing forces, moments, and surface pressures. It has been tested and found to predict the aerodynamic results satisfactorily up to moderate angles of attack for various configurations, especially delta wings.[6-8]

Results and Discussion

The wing investigated is a 74 deg planar delta wing with 50 mm (2 in.) conical leading-edge vortex flap that can be deflected upward or downward. The reference area used here is the area of the basic wing plus the projected area of the flap with no deflection ($\delta = 0$) in all cases except in Fig. 1, where it is the basic wing area only. The longitudinal aerodynamic characteristics of the delta wing predicted by the FVS method are compared with unpublished experimental data provided by Rao in Fig. 1 for an upward flap deflection of 130 deg. As the figure indicates, the agreement between them is fairly good. Figure 2 shows the converged vortex sheet shapes at two chordwise stations for an angle of attack of 5 deg. The end of the vortex sheet represents the location of the vortex core. The vortex is larger in the aft portion as expected.

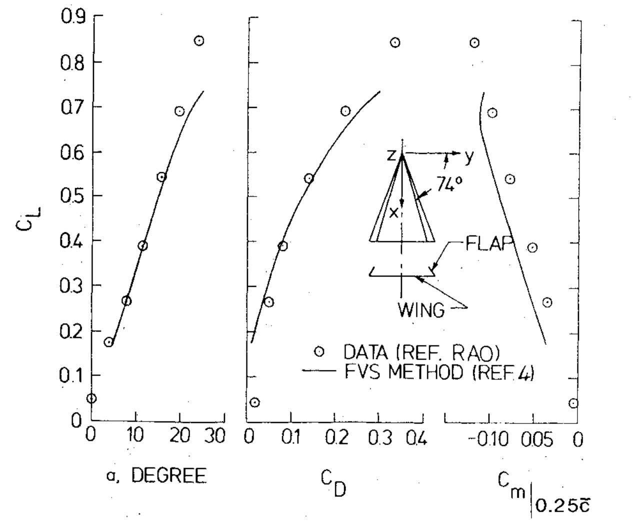

Fig. 1 Longitudinal aerodynamic characteristics of planar delta wing with leading-edge vortex flap ($A = 1.5$, $\Lambda = 74$ deg, $\delta = 130$ deg, and $M \approx 0$).

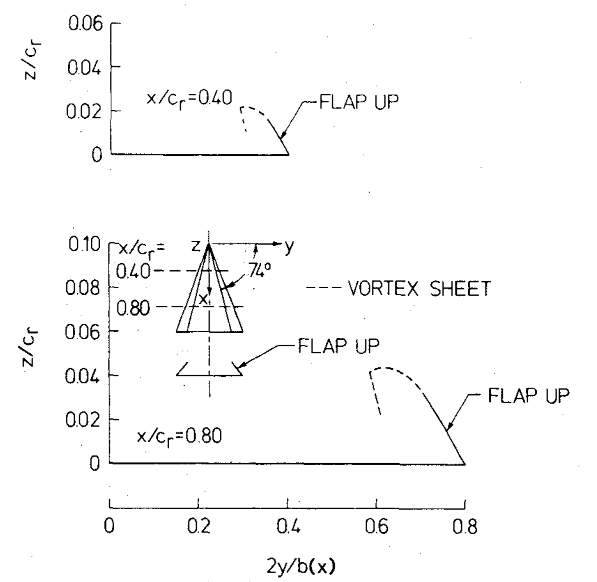

Fig. 2 Converged vortex sheet shapes at $\alpha = 5$ deg, $\delta = 130$ deg, and $M \approx 0$.

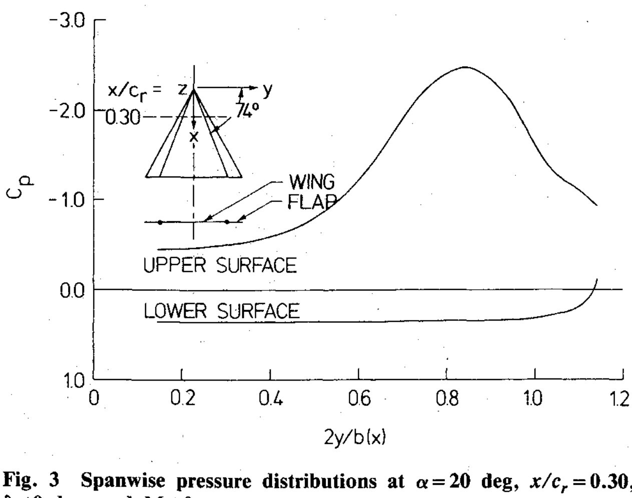

Fig. 3 Spanwise pressure distributions at $\alpha = 20$ deg, $x/c_r = 0.30$, $\delta = 0$ deg, and $M \approx 0$.

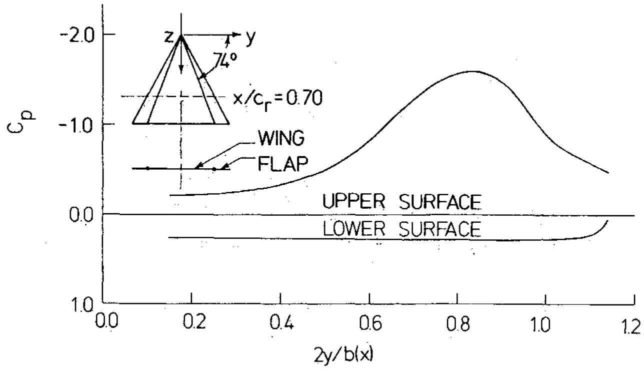

Fig. 4 Spanwise pressure distributions at $\alpha = 20$ deg, $x/c_r = 0.70$, $\delta = 0$ deg, and $M \approx 0$.

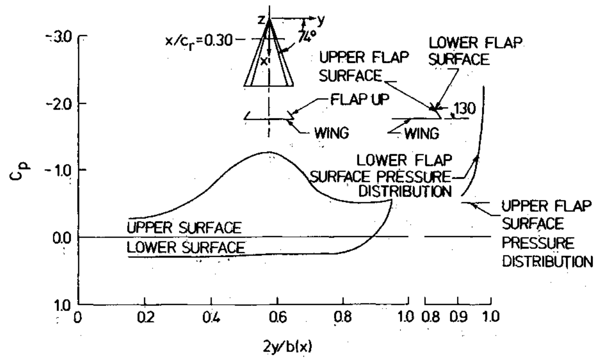

Fig. 5 Spanwise pressure distributions at $\alpha = 20$ deg, $x/c_r = 0.30$, $\delta = 130$ deg, and $M \approx 0$.

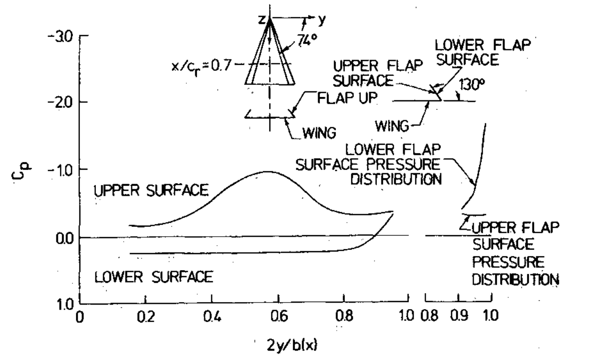

Fig. 6 Spanwise pressure distributions at $\alpha = 20$ deg, $x/c_r = 0.70$, $\delta = 130$ deg, and $M \approx 0$.

Spanwise pressure distributions for the delta wing are shown in Figs. 3–6 at different chordwise stations and flap and attack angles. In plotting these pressures, the spanwise distance is nondimensionalized by the local span of the basic wing only. Figures 3 and 4 illustrate the pressures for the wing with no flap deflection and at a 20-deg angle of attack. The pressure peak occurs under the vortex at about 90% of the span at 30% chordwise location, whereas at 70% chordwise location it occurs slightly inboard at about 80% of the span. The lower surface pressures are almost constant in the spanwise direction. For the cases shown in Figs. 5 and 6, the leading edge flap is deflected upward at 130 deg. In these figures, the pressures on the basic wing and flap are shown separately for clarity. These pressures are very significant, especially those on the lower flap surface that faces the sky as depicted by Figs. 5 and 6. An examination of the figure pairs 3 and 5 or 4 and 6, which correspond to the same angle of attack and chordwise station but different flap deflections, reveals that the magnitude of the pressure peak on the basic wing is much smaller. It also occurs more inboard in the case where the flap is deflected upward compared to the instance where there is no flap deflection. The large suction produced on the lower surface of the flap deflected upward will have a thrust component in the direction of the flight, thereby reducing the overall drag.

Conclusions

A 74-deg planar delta wing with a conical leading-edge flap was numerically investigated. Its longitudinal aerodynamic characteristics were predicted and compared to the experimental data and found to agree favorably. The effects of flap deflection on the spanwise pressure distributions at different angles of attack and chordwise locations were studied. The deflection of the conical flap upward shifts the negative pressure peak inboard on the basic wing and develops significant suction pressure on the flap that then produces thrust component in the direction of the flight, thereby reducing the overall drag. Leading-edge vortex flaps are very effective flow manipulating devices that can profoundly influence the performance ang maneuverability of highly swept-back wings operating in the regimes of leading-edge flow separation and vortex formation.

Acknowledgments

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References

[1]Coe, P. L. Jr. and Graham, A. B., "Results of Recent NASA Research on Low-Speed Aerodynamic Characteristics of Supersonic Cruise Aircraft," NASA CP-001, 1976.

[2]Rao, D. M., "Leading-Edge Vortex Flaps for Enhanced Subsonic Aerodynamics of Slender Wings," *Proceedings of 1980 International Council of Aeronautical Sciences,* Oct. 1980.

[3]Rao, D. M., "Leading Edge Vortex Flap Experiments on a 74° Delta Flap Wing," NASA CR-159161, 1979.

[4]Johnson, E. T., Lu, P., Tinoco, E. N., and Epton, M. A., "An Improved Panel Method for the Solution of Three-Dimensional Leading-Edge Vortex Flows," Vol. I, NASA CR-3278, 1980.

[5]Johnson, E. T., Lu, P., Tinoco, E. N., and Epton, M. A., "An Improved Panel Method for the Solution of Three-Dimensional Leading-Edge Flows," Vol. II, NASA CR-3279, 1980.

[6]Reddy, C. S., "Analytical Investigation of Aerodynamic Characteristics of Highly Swept Wings with Separated Flow," *Journal of Aircraft,* Vol. 17, Jan. 1980, p. 58.

[7]Reddy, C. S., "Theoretical Study of Aerodynamic Characteristics of Wings Having Vortex Flow," NASA CR-159184, 1979.

[8]Kuhlman, J. M., "Analytical Studies of Separated Vortex Flow on Highly Swept Wings," NASA CR-3022, 1978.