References

[1]MacCormack, R. W., "The Effect of Viscosity in Hypervelocity Impact Cratering," AIAA Paper 69-354, April 1969.

[2]Anderson, J. D., *Modern Compressible Flow with Historical Perspective*, McGraw-Hill, New York, 1984, p. 255.

[3]Anderson, J. D., *Modern Compressible Flow with Historical Perspective*, McGraw-Hill, New York, 1984, pp. 251–277.

[4]Anderson, J. D., *Fundamentals of Aerodynamics*, McGraw-Hill, New York, 1984, pp. 370–380.

[5]Hankey, W. L., *Re-Entry Aerodynamics*, AIAA Education Series, AIAA, Washington, DC, 1988, pp. 62–64.

[6]Anderson, J. D., *Fundamentals of Aerodynamics*, McGraw-Hill, New York, 1984, pp. 483–487.

Aerodynamic Characteristics of Vortex Flaps on a Double-Delta Planform

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Introduction

NUMEROUS investigations have shown the leading-edge vortex flap[1–6] (LEVF) concept to be effective in reducing drag. The LEVF works by concentrating the suction of the leading-edge vortex on the flap, which may with suitable orientation, result in a thrust force. Thus, cruise and maneuver performance may be improved. For full thrust recovery, flow reattachment should ideally occur at the flaps hinge line. Recent studies of vortex flaps include improvement in area efficiency and planform,[4] hinge-line sweep, and flap deflection angle,[6] etc. Various flap types have also been investigated, e.g., upper and lower surface, folding or hinged, cavity vortex flaps, as well as apex fences,[6] etc. Tabbed vortex flaps have also been examined as a means to augment vortex induced thrust on the flap.[5] The interaction of LEVFs and trailing-edge flaps has also been studied.[3]

Double-delta or slender cranked wings received considerable attention in the mid-1970s with the development of the "supercruiser" fighter. This aircraft was to have efficient supersonic performance coupled with competitive subsonic maneuverability. The purpose of the double delta was to provide a highly swept inboard panel to meet the supersonic cruise requirement, while the outer lesser swept panel increased the wingspan and improved the subsonic aerodynamic efficiency, as well as handling.[7] Vortex flaps have been tested on some of the proposed supercruiser double-delta configurations.[8] The present investigation is concerned with LEVF effects on a double-delta (or simplified strake-wing) planform.

The model configuration and dimensions are shown in Fig. 1. A LEVF was formed by rotating a 1.1-mm-thick aluminum plate through an angle δ_{FSW} (a downward flap deflection being defined as positive). The vortex flaps were attached to a flat aluminum plate 4.5 mm thick, on which the edges were beveled (Fig. 1). The model had a planform area of 0.13 m^2 (including the flap area), and an aspect ratio of 1.37 with the vortex flaps planar. Only the constant chord vortex flaps as

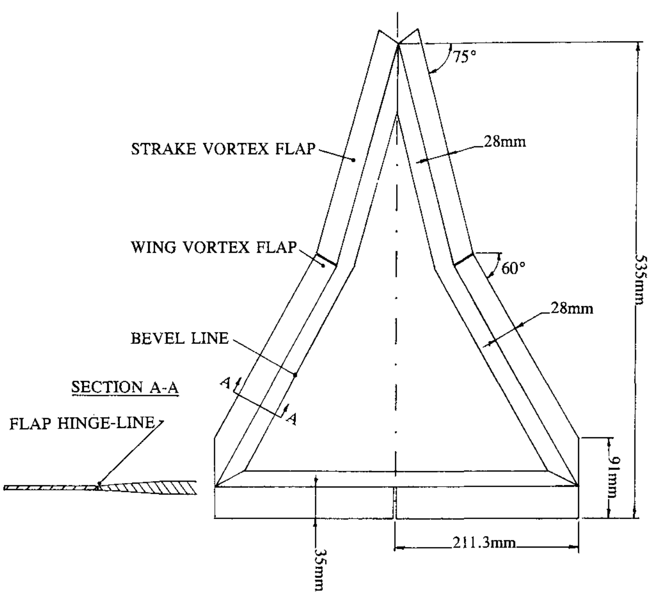

Fig. 1 Model configuration and dimensions.

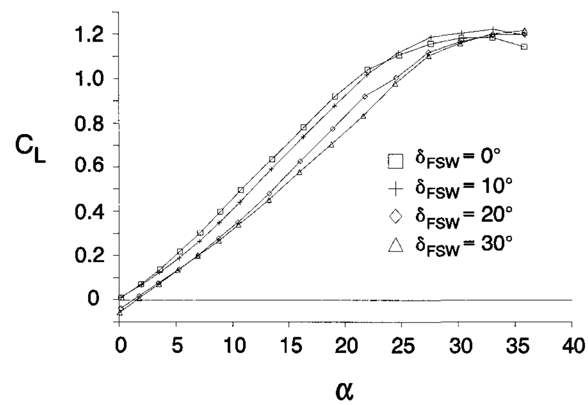

Fig. 2 Effect of vortex flap deflection angle on lift coefficient.

shown in Fig. 1 were tested. The vortex flaps on the strake and wing had an equal planform area of 0.0074 m^2. To facilitate matching the flap areas, the rear delta wing was cropped slightly. The tests were run in the University of the Witwatersrand's low-speed continuous wind tunnel. A freestream velocity of approximately 47 m/s was used. The corresponding Reynolds number based on the wing's root chord was 1.38 $\times 10^6$. The wind-tunnel balance repeatability for lift, drag, and pitching moment was estimated to be $\Delta C_L = \pm 0.0015$, $\Delta C_D = \pm 0.0008$, $\Delta C_m = \pm 0.0022$.

For each respective configuration, the forces and moments were nondimensionalized by the strake-wing area plus the projected vortex flap area. Moments were taken about a point located at 58% of the total root chord (535 mm). All the coefficients were corrected for blockage and interference effects using the procedure detailed in Ref. 9.

In the investigation the vortex flaps both on the strake and on the wing were deflected to 0, 10, 20, and 30 deg. Figure 2 shows that there is generally a reduction in lift with increasing flap angle as would be expected.[2] This is due mainly to a partial suppression of leading-edge vortex formation as a result of flap deflection,[10] and to a lesser extent the result of vortex being traded for thrust.[4] Increasing flap angle also results in a moderate reduction in the attached flow lift component.[10] Suppression of vortical formation, and the concomitant reduction in vortex strength and, hence, suction, manifests itself in a reduction of the nonlinearity of the lift curve with increasing flap deflection (see Fig. 2). Within the angle-

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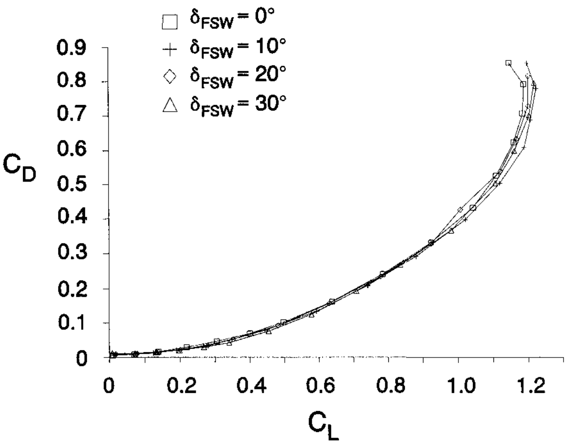

Fig. 3 Effect of vortex flap deflection angle on drag coefficient.

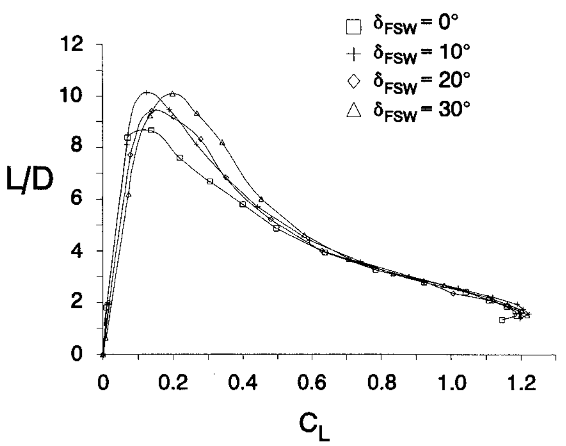

Fig. 4 Effect of vortex flap deflection angle on lift-to-drag ratio.

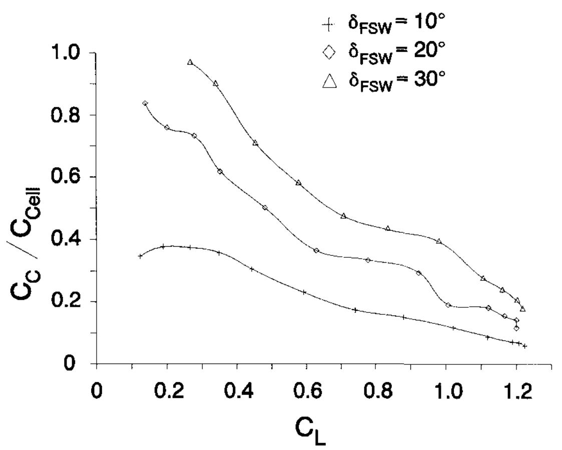

Fig. 5 Effect of vortex flap deflection angle on attainable thrust coefficient.

of-attack range tested, all the LEVF deflection variations appear to have only a minor effect on the maximum lift coefficient.

The drag as a function of lift is shown in Fig. 3, and the lift-to-drag ratios (L/D) are shown in Fig. 4. The results in Fig. 4 show that all flap deflection angles improve performance for $0.1 < C_L < 0.6$. Figure 5 shows the attainable thrust ratio $C_C/C_{C\text{ell}}$ as a function of lift coefficient. This ratio is defined[11,12] as the measured chordwise thrust C_C divided by the theoretical chordwise thrust $C_{C\text{ell}}$, which was calculated

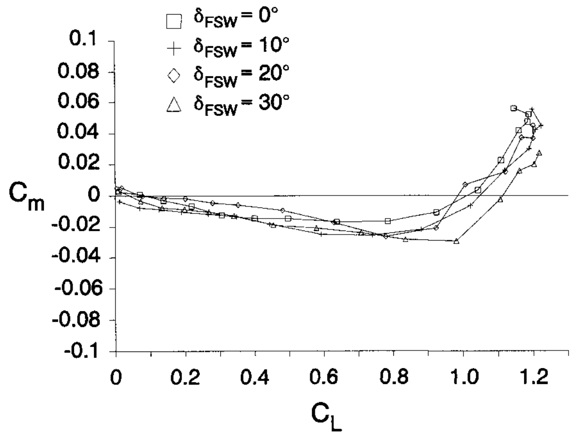

Fig. 6 Effect of vortex flap deflection angle on pitching moment coefficient.

as being equal to the maximum thrust attainable with 100% leading-edge suction, and thus, elliptic loading. As would be expected, there is an increase in attainable thrust with increasing flap angle. The flap angle of 30 deg is seen to generate almost full thrust at $C_L < 0.3$. There is a marked reduction in $C_C/C_{C\text{ell}}$ with increasing C_L. However, this does not indicate a decrease in the actual magnitude of the thrust force.

Rotating the strake and wing LEVFs to 20 and 30 deg results in an increase in the extent of the stable negative slope (Fig. 6) of the $C_m - C_L$ curve compared to the planar planform. The pitch-up, however, seems to be more extreme for both $\delta_{FSW} = 20$ deg and $\delta_{FSW} = 30$ deg than for the planar configuration.

In conclusion, the investigation confirmed the effectiveness of vortex flaps on the double-delta configuration. Significant increases in $(L/D)_{max}$ compared to the planar configuration were obtained for all vortex flap settings, with the highest tested flap angle of 30 deg recording the best overall performance.

References

[1]Marchman, J. F., "Effectiveness of Leading Edge Vortex Flaps on 60° and 75° Delta Wings," *Journal of Aircraft*, Vol. 18, No. 4, 1981, pp. 280–286.

[2]Rinoie, K., "Experiments on a 60° Delta Wing with Vortex Flaps and Vortex Plates," *Aeronautical Journal*, Vol. 97, Jan. 1993, pp. 33–38.

[3]Grantz, A. C., and Marchman, J. F., "Trailing Edge Flap Influence on Leading Edge Vortex Flap Aerodynamics," *Journal of Aircraft*, Vol. 20, No. 2, 1983, pp. 165–169.

[4]Rao, D. M., "An Exploratory Study of Area-Efficient Vortex Flap Concepts," *Journal of Aircraft*, Vol. 20, No. 12, 1983, pp. 1062–1067.

[5]Hoffler, K. D., and Rao, D. M., "An Investigation of the Tabbed Vortex Flap," *Journal of Aircraft*, Vol. 22, No. 6, 1985, pp. 490–497.

[6]Campbell, J. F., and Osborn, R. F., "Leading Edge Vortex Research: Some Nonplanar Concepts and Current Challenges," NASA CP-2416, Oct. 1986, pp. 31–63.

[7]Polhamus, E. C., "Applying Slender Wing Benefits to Military Aircraft," *Journal of Aircraft*, Vol. 21, No. 8, 1984, pp. 545–559.

[8]Smith, C. W., Campbell, J. F., and Huffman, J. K., "Experimental Results of a Leading Edge Vortex Flap on a Highly Swept Cranked Wing," NASA CP-2162, Oct. 1980, pp. 563–580.

[9]Pope, A., and Rae, W. H., "Low-Speed Wind Tunnel Testing," Wiley, New York, 1984, pp. 199–208, 362–424.

[10]Oh, S., and Tavella, D., "Analysis of a Delta Wing with Leading-Edge Flaps," *Journal of Aircraft*, Vol. 24, No. 6, 1987, pp. 353, 354.

[11]Carlson, H. W., and Mack, R. J., "Studies of Leading-Edge Thrust Phenomena," *Journal of Aircraft*, Vol. 17, No. 12, 1980, pp. 890–897.

[12]Traub, L. W., "Analytic Prediction of Lift for Delta Wings with Partial Leading-Edge Thrust," *Journal of Aircraft* (to be published).