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Aerodynamic Characteristics of Strake Vortex Flaps on a Strake-Wing Configuration

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The effects of strake vortex flaps (SVFs), determined experimentally, on the aerodynamic characteristics of a strake-wing configuration are presented. SVFs may improve cruise performance over that of a planar strake by partially unloading the strake and generating a thrust component. The magnitude of the nose-up pitching moment may also be reduced by unloading the strakes. The use of SVFs as lateral control devices is also investigated. The results indicate that cruise performance is improved for all vortex flap deflection angles compared to planar strakes, with minimal or no concomitant penalty at high lift coefficients. Positive pitching moment is also substantially reduced. Differentially deflected strakes appear to be capable of generating significant rolling moments at high angles of attack.

Nomenclature

AR = aspect ratio, b^2/S
b = wing span
C_C = chordwise force coefficient, chordwise force/$q_\infty S$
C_D = drag coefficient, drag/$q_\infty S$
C_L = lift coefficient, lift/$q_\infty S$
C_l = rolling moment coefficient, rolling moment/$q_\infty Sb$
C_m = pitching moment coefficient, taken about the quarterchord of the wing centerline root, pitching moment/$q_\infty Sc$
C_n = yawing moment coefficient, yawing moment/$q_\infty Sb$
C_Y = sideforce coefficient, sideforce/$q_\infty S$
c = wing mean aerodynamic chord
q_∞ = freestream dynamic pressure
S = wing area (wing leading and trailing edges extended to wing centerline) plus projected strake area
α = angle of attack
δ_{SVF} = strake vortex flap deflection angle measured normal to hinge line

Subscripts
ell = elliptic spanwise loading
max = maximum
min = minimum

Introduction

THE benefits of strake-wing configurations are well documented.[1–4] They include the ability to generate large lift increments with minimal structural weight penalty, and reduce buffet intensity and the suddenness of stall. The additional lift results from vortex lift developed on the strake and on the inner wing under the suction of the strake vortices, as well as the favorable synergistic effects of the strake vortex on the outer wing panel[1,2] and the wing on the strake vortex. However, as shown in Ref. 3 and the current investigation, there is a reduction in the maximum lift-to-drag ratio (L/D) compared to the wing without strakes. This results from an increase in wetted area and the loss of leading-edge thrust over the spanwise extent of the sharp-edged strake. Variable geometry and incidence strakes have been shown to be aerodynamically effective, but present application problems and complexities.[4]

A destabilizing nose-up pitching moment may also occur due to a forward shift of the wing's aerodynamic center with strake addition. At high angles of attack, vortex breakdown may occur, causing an increase in pitch-up as the center of pressure moves towards the strakes.[1]

Slender delta wings are poor lift generators.[5] Lift augmentation may be accomplished by employing sharp leading edges so that the flow is forced to separate, which Polhamus[6] has shown, effectively results in a rotation of the leading-edge suction force so as to supplement the normal force coefficient. This loss of leading-edge thrust results in a large drag penalty. The leading-edge vortex flap (LEVF) concept has been successfully employed as a means to reduce drag on these configurations,[7–9] as well as on a moderate aspect ratio rectangular wing.[10] The LEVFs work by concentrating the suction of the leading edge or wingtip vortex on the flap,[7–10] which with suitable orientation may result in a thrust force. However, investigation has shown that maximum performance improvement coincides with smooth flow onto the vortex flap, with no vortex formation being present.[8,9]

The aerodynamic effects of strake vortex flaps (SVFs) on a strake-wing configuration as shown in Fig. 1 are detailed in this article. It is suggested that SVFs may improve cruise performance as well as reduce the magnitude of the nose-up pitching moment. To verify these effects, a low-speed wind-tunnel investigation was conducted.

Equipment and Procedure

The model configuration and dimensions are shown in Fig. 1a. The wing consisted of a flat aluminum plate 4.5 mm thick, had a planform area of 120,401 mm^2, and an AR of 2.99. The leading edge of the wing was rounded, and the trailing edge bevelled. The SVF was formed by rotating a 1.1-mm-thick, suitably profiled aluminum extension, attached to the strake, through an angle δ_{SVF}, a downward flap deflection being defined as positive. The strake flap's hinge line sweep angle was 78.7 deg. A constant chord (giving a delta planform strake) and gothic vortex flap, as shown in Fig. 1b, were tested. The area of each strake was 11,711 mm^2, of which the flap occupied 5543 mm^2, representing 9.7 and 4.6% of the wing area, respectively. The gothic and constant chord flaps had equal area. The University of the Witwatersrand's low-speed continuous wind tunnel was used, with the tests being run at a freestream velocity of 47 m/s. The corresponding Reynolds number based on the wing's mean aerodynamic chord was 551,000. The wind-tunnel balance repeatability was estimated

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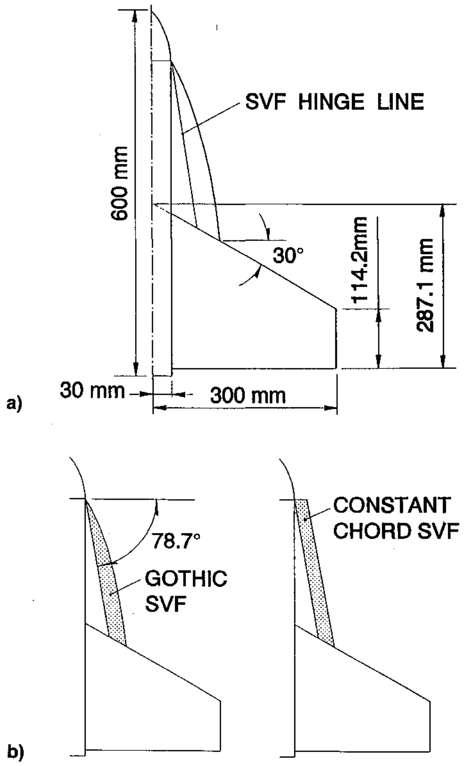

Fig. 1 a) Model configuration and geometric details and b) SVF details.

at $C_D = \pm 0.0008$, $C_L = \pm 0.0015$, $C_m = \pm 0.0022$. Figs. 2a–2c show repeated data runs for the gothic strake with $\delta_{SVF} = 45$ deg.

All forces and moments were nondimensionalized by the area of the wing plus the projected strake area, unless stated otherwise. All the coefficients were corrected for blockage and interference effects using the procedure detailed in Ref. 11. The model set angle of attack was varied in 2-deg increments; in the vicinity of $(L/D)_{max}$, 1-deg increments were used.

Results and Discussion

Tests were undertaken with the strake vortex flaps positioned at $\delta_{SVF} = 0$, 15, 30, and 45 deg. Figs. 3a and 3b show lift curves for the gothic and constant chord flap configurations, respectively. For α less than approximately 12 deg, there is minimal loss of lift with SVF deflection. LEVF deflection generally reduces lift for a given angle of attack.[9] This effect may be attributed primarily to[12] "partial suppression of the leading-edge vortex system." However, as reported in Ref. 1, the strake may induce a lift decrement on the main wing panel at low to moderate angles of attack. Thus, a partial suppression of the strake vortex formation by deflecting the SVF could result in a reduced induced lift decrement on the main wing. For both flap configurations, $\delta_{SVF} = 45$ deg does show a reduction in C_L beyond $\alpha \approx 13$ deg. For this deflection angle the gothic strake shows a pronounced "kink" point from which lift increases noticeably ($\alpha \approx 18$ deg). As shown in Fig. 2a this characteristic is repeatable and will be discussed later in this article.

The drag polars (see Figs. 4a and 4b) show that a flap deflection angle of 30 deg gives the best overall performance. This is also shown in Figs. 5a and 5b where L/D is presented as a function of lift coefficient. The results for $(L/D)_{max}$ are summarized and presented in Fig. 5c. To determine the reduction in $(L/D)_{max}$ associated with strake addition and how this reduction may be affected by SVF deflection, data for the wing without strakes is also included in Fig. 5c. The results indicate that for the gothic strake $(L/D)_{max}$ is relatively insensitive to flap deflection angle in the vicinity of $\delta_{SVF} \approx 30$ deg. There is a reduction in $(L/D)_{max}$ of 13.8 and 12.8% compared to the wing without strakes for the planar gothic and delta strakes, respectively. Deflecting the constant chord SVF to 30 deg increases $(L/D)_{max}$ from 12.8 to 3.5% less than that of the wing without strakes, an increase of 10.7% over $\delta_{SVF} = 0$ deg. Although 1-deg increments were used to define the lift-to-drag ratio in the vicinity of $(L/D)_{max}$, the form of the plots in this region suggest that the actual maximums may not have been determined, thus the percentage increases calculated should be treated with caution. Figs. 5a and 5b also indicate that with the exception of $\delta_{SVF} = 45$ deg, all the flap deflection angles have superior performance to the planar flap throughout most of the tested incidence range. The results suggest that overall, there is minimal performance variation between the gothic and constant chord flaps. Lamar[13] has shown that strake shape typically becomes important near the maximum lift coefficient, a region which due to equipment limitations, was not fully explored. The constant chord configuration does, however, show an increase in $(L/D)_{max}$ compared to the gothic flaps as seen in Fig. 5c.

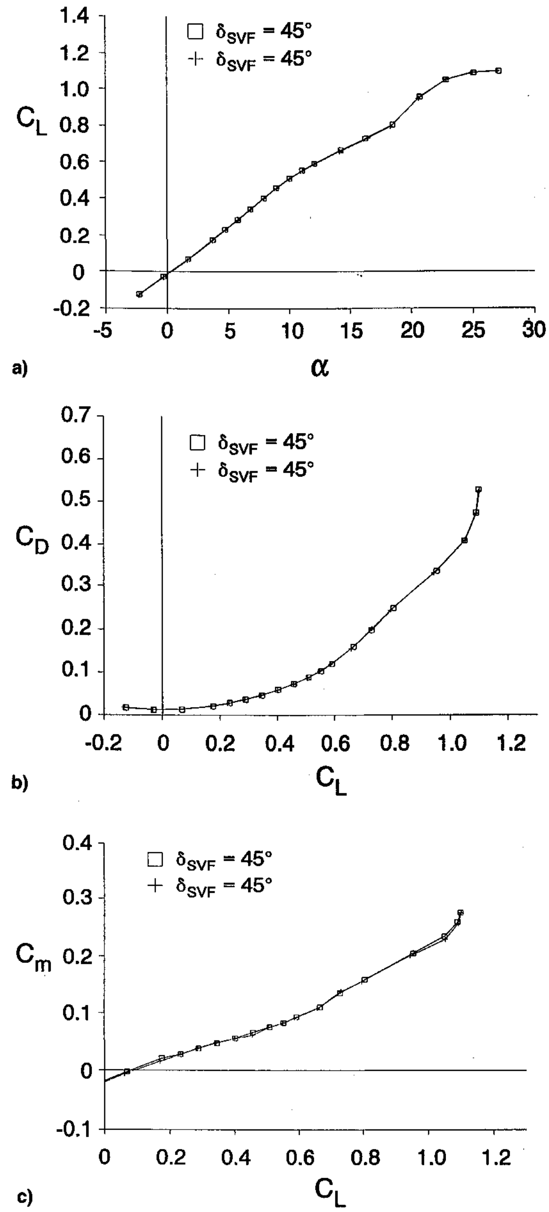

Fig. 2 Repeated data run for gothic SVF: a) lift curve, b) drag polar, and c) pitching moment coefficient.

Increasing flap deflection angle results in a decrease in nose-up pitching moment (Figs. 6a and 6b) as a consequence of

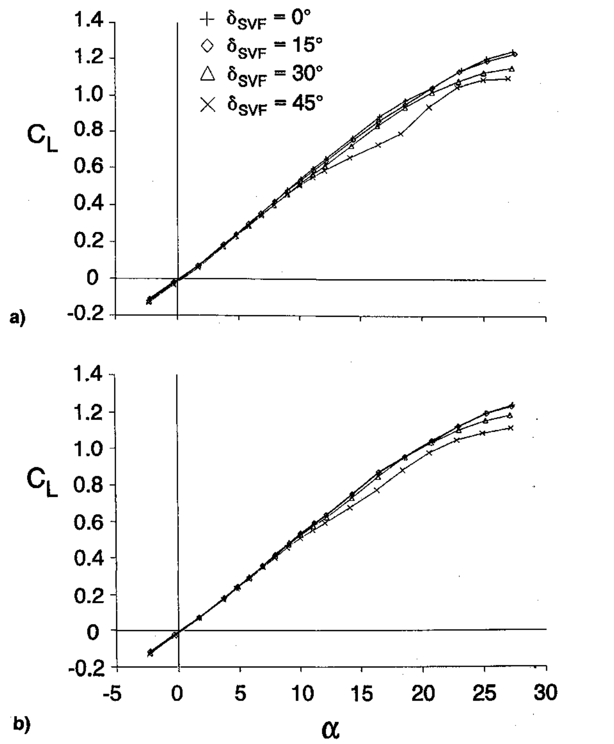

Fig. 3 Effect of SVF deflection angle on lift coefficient: a) gothic flap and b) constant chord flap.

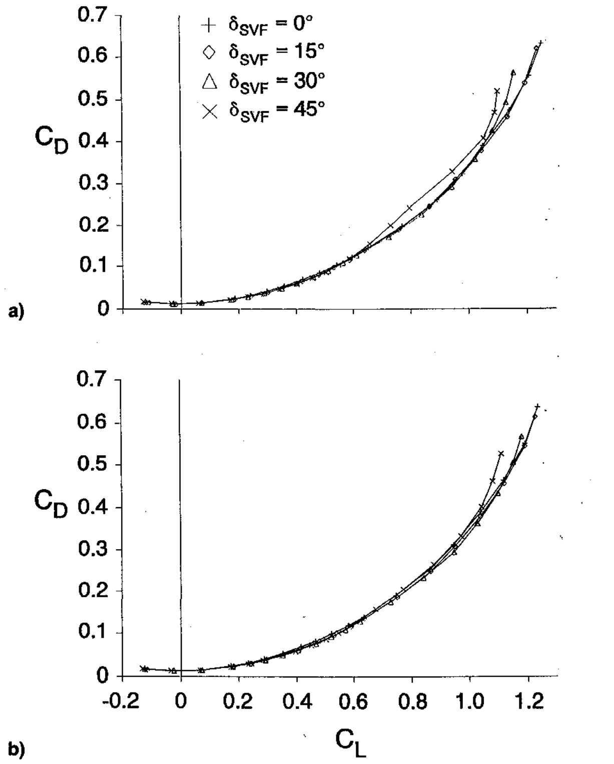

Fig. 4 Effect of SVF deflection angle on drag polar: a) gothic flap and b) constant chord flap.

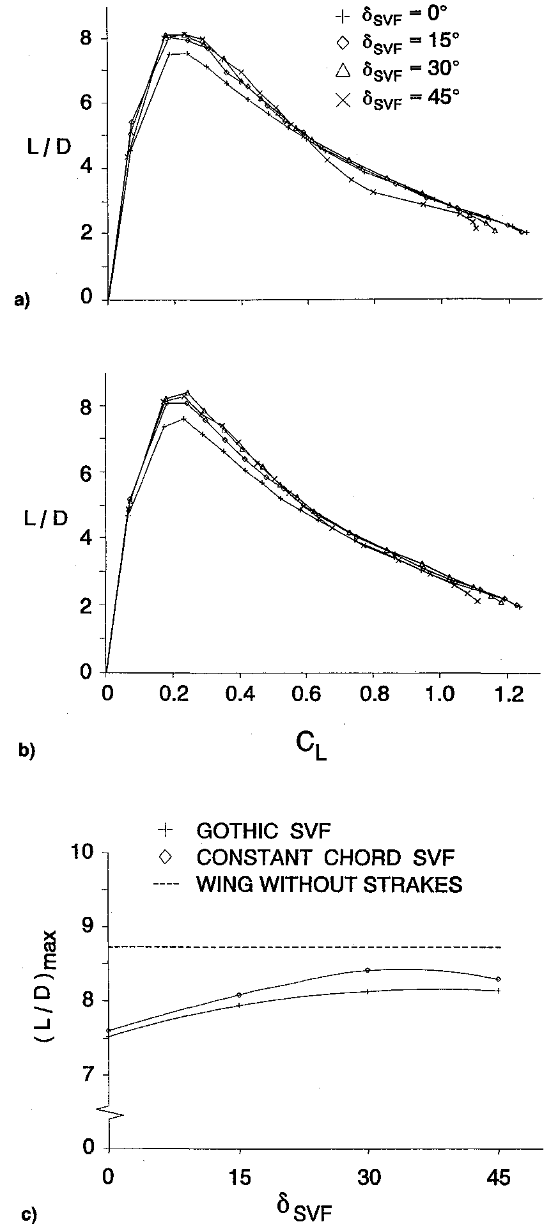

Fig. 5 Effect of SVF deflection angle on *L/D* ratio: a) gothic flap, b) constant chord flap, and c) effect of SVF deflection angle on maximum *L/D*.

the load on the strake being reduced. At a C_L of 1, the reduction in pitching moment compared to the planar strakes is 15 and 17% for the gothic and constant chord SVFs (δ_{SVF} = 30 deg), respectively.

The extent to which thrust is generated by the SVFs may be examined by determining the chordwise thrust force coefficient. As the wing was planar, the inviscid chordwise force would be equal to the wing leading-edge thrust plus the thrust force from the flaps. A useful parameter to investigate the thrust characteristics of the flaps is that of the attainable thrust ratio,[14,15] which may be defined as the actual chordwise thrust divided by the theoretical thrust:

$$\frac{C_C}{C_{C\text{ell}}} = \left[\frac{C_L \sin\alpha - (C_D - C_{D_{\min}})\cos\alpha}{C_L \sin\alpha - (C_L^2/\pi \mathrm{AR})\cos\alpha}\right] \times 100\% \tag{1}$$

The denominator of Eq. (1) represents the maximum thrust attainable with 100% leading-edge suction (i.e., assuming elliptic loading). Equation (1) was evaluated to determine Figs. 7a and 7b. It can be seen that increasing flap deflection results in an increase in the percentage of thrust developed. There is also a moderate reduction in the thrust obtainable with increasing C_L (not in the actual magnitude of the thrust force), as would be expected.[14]

As mentioned earlier, the gothic strake showed a pronounced kink in its lift curve at δ_{SVF} = 45 deg (Fig. 3a). It is suggested that this may occur due to the vortex flap partially "losing" the vortex or vortices located on it (i.e., the vortex

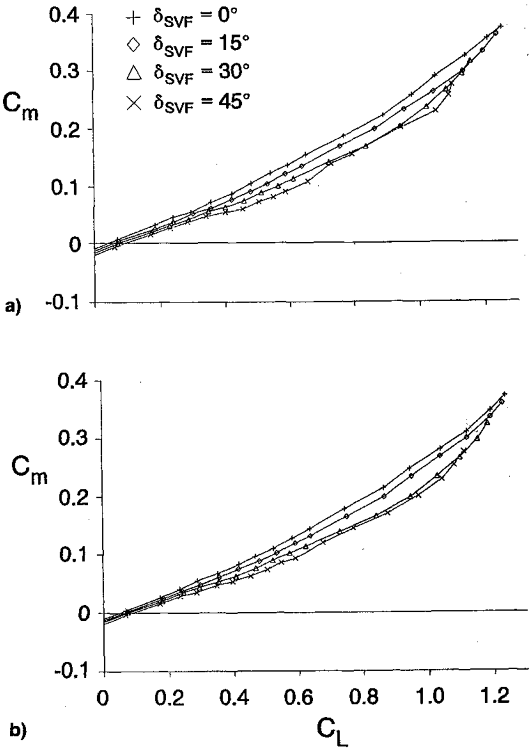

Fig. 6 Effect of SVF deflection angle on pitching moment coefficient: a) gothic flap and b) constant chord flap.

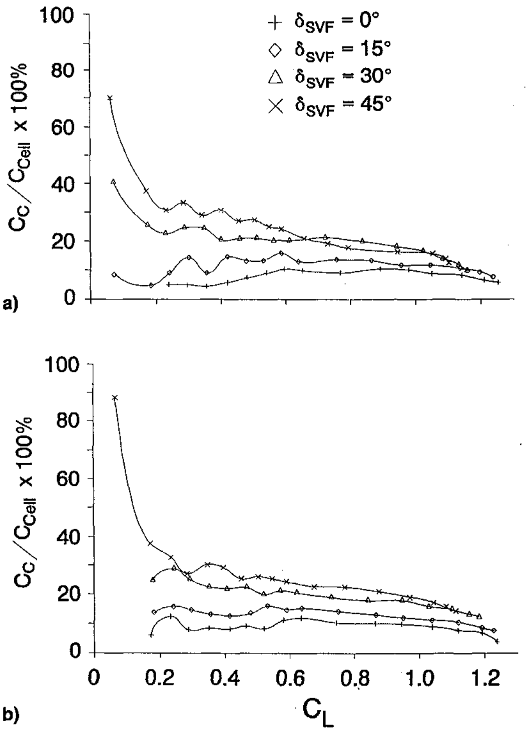

Fig. 7 Effect of SVF deflection angle on attainable thrust coefficient: a) gothic flap and b) constant chord flap.

moves inboard, off the flap), resulting in the vortex suction acting on a larger projected planform area. This is supported by Fig. 6a, which shows an increase in nose-up pitching moment at the related lift coefficient. As lift increases substantially beyond this kink point, vortex breakdown is unlikely to be responsible for this increased positive pitching moment. Figure 7a reveals a noticeable reduction in attainable thrust in the vicinity of the lift coefficient corresponding to the kink point, which may indicate that the flap has partially "lost" the vortex.

Lateral and directional characteristics are presented in Figs. 8a and 8b for the gothic strake; the delta planform strake displayed similar trends. The data proposes that for the incidence range tested, SVF deflection has a marginal effect on rolling and yawing moment at zero side slip compared to the planar strake.

To determine the feasibility of the SVF as a control device, the left-hand SVF was deflected to 45 deg, and the right-hand one was left planar. Figure 8c shows yawing and rolling moment coefficients as well as sideforce. To facilitate comparison with the data in Ref. 16 the coefficients in Fig. 8c were similarly nondimensionalized, i.e., by the area of the wing without strakes. The deflection of the left-hand flap and the resulting reduction in lift on the left-hand panel results in a negative rolling moment. The characteristics and magnitude of C_l are comparable with those detailed in Ref. 16, which were deemed as exhibiting superior roll control to conventional ailerons at high angles of attack. Strake induced rolling moments should also remain effective to higher incidence than those generated by ailerons.[16] The associated yawing moment is also equivalent to that in Ref. 16, which was cited as being less detrimental than that due to ailerons.

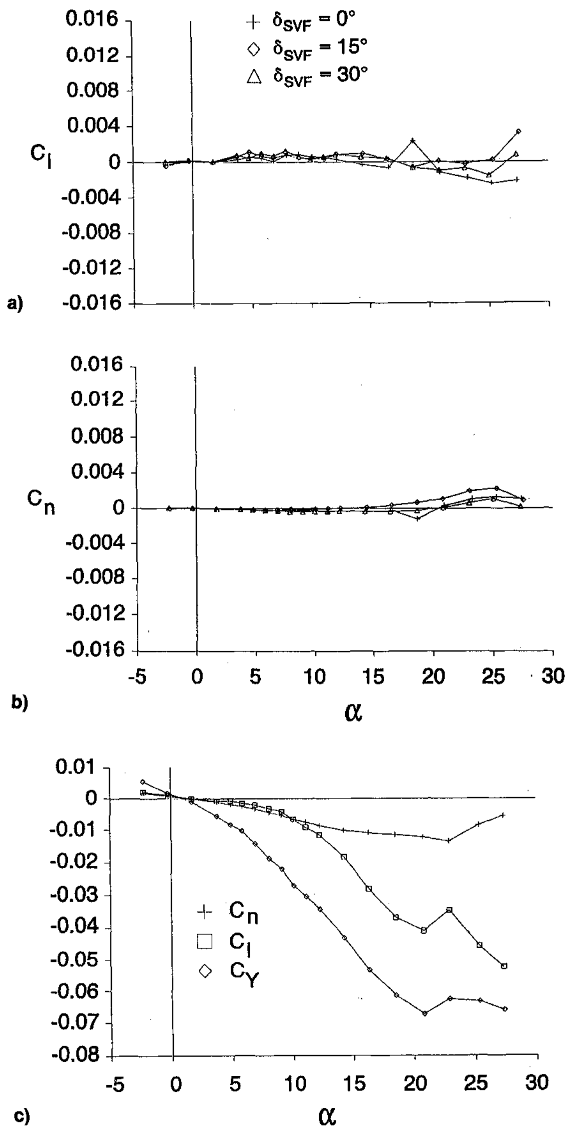

Fig. 8 Effect of SVF deflection angle on lateral and directional characteristics: a) rolling moment (symmetric SVFs), b) yawing moment (symmetric SVFs), and c) effect of asymmetrically deflected gothic SVFs. Left-hand δ_{SVF} = 45 deg, right-hand δ_{SVF} = 0 deg.

As may be seen in Fig. 8c, asymmetrically deflected flaps are capable of generating substantial sideforce. From approximately 6–21 deg, the sideforce is seen to vary roughly linearly with angle of attack.

Summary and Conclusions

An experimental investigation to determine the effects of SVFs on the aerodynamic characteristics of a strake-wing is presented. It is proposed that an improvement in cruise performance, and a reduction in nose-up pitching moment may result. The flaps may also prove beneficial as lateral control devices. From the experimental data the following conclusions may be drawn:

The L/D increased for all SVF deflection angles for $C_L < 0.6$ compared to the planar strake, e.g., $(L/D)_{\max}$ of the constant chord SVF increased by 10.7% for $\delta_{SVF} = 30$ deg. In deflecting the flaps from 0 to 30 deg, $(L/D)_{\max}$ of the constant chord SVF increased from 12.8 to 3.5% less than that of the wing without strakes. Positive pitching moment reduced as the flap deflection angle increased, e.g., at a C_L of 1, positive C_m reduced by 15 and 17% for the gothic and constant chord SVFs ($\delta_{SVF} = 30$ deg), respectively, compared to $\delta_{SVF} = 0$ deg.

Although a variable incidence SVF would be optimal, the investigation has shown that performance benefits may be realized even if a fixed deflection angle of either 15 or 30 deg is used with little or no performance penalties compared to a planar strake throughout the incidence range tested.

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