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Aerodynamic Effects of Delta Planform Tip Sails on Wing Performance

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An experimental investigation was conducted to establish the effects of delta planform tip sails (DPTSs) on a planar rectangular wing. The DPTS is a small wingtip-mounted device analogous to a conventional tip sail, but with a slender planform. It is suggested that using a sharp-edged, slender tip device may alleviate some of the design complexities (e.g., twist and camber) associated with keeping attached flow on winglets and tip sails. The results indicate that performance improvements can be obtained with DPTSs. Increases in the wing lift curve slope, maximum lift coefficient and, for some configurations, the Oswald efficiency factor were obtained compared to the basic wing. Increasing the DPTS leading-edge sweep angle and taper ratio resulted in an increase in the wing's Oswald efficiency factor.

Introduction

THE significance of the wingtip in the generation of vortex drag has resulted in several tip-mounted devices aimed at reducing this drag component. Two of the more successful concepts are winglets[1–3] and tip sails.[4,5] These devices use the high-induced flow angularity of the local freestream in the vicinity of the wingtip to produce a lift component that can oppose drag.[2,4] To do this efficiently, they should be twisted and cambered[2,4] (which in turn can also cause separation[4]), to reduce flow separation along the tip device's span. Winglets[3] also improve performance by increasing the wing's effective aspect ratio. Tip sails[4] may suffer from Reynolds number effects, e.g., premature separation, as the tip device's Reynolds number is usually an order of magnitude lower than the wing's. At high incidence, tip sails tend to lose effectiveness due to flow separation, although this can be reduced to a certain extent by using a "cascade" of tip sails.[5]

In this study, a wind-tunnel investigation of a flat, slender, sharp-edged delta planform tip sail (DPTS) as shown in Fig. 1 is presented. Some of the drawbacks of conventional tip sails may be alleviated, e.g., the DPTSs would not need to be arranged in a cascade, cambered and washed-in, to function efficiently because they would not require attached flow. The sensitivity to Reynolds number would also be reduced by means of enforced flow separation. Although this would result in loss of leading-edge thrust, it should be recovered as vortex lift.[6] As a result the design of the DPTS should be simple.

Equipment and Procedure

The geometry of the wing and tip configurations tested is shown in Fig. 1. The basic wing had a NACA 64_2-015 section, an aspect ratio (AR) of 4.09, was rectangular in planform, and had end caps. The wing was planar, had a span of 69.9 cm, and a planform area of 1193.2 cm^2. To keep the wing aspect ratio similar with DPTS addition, the outboard sections of the wing were removed, giving a span of 59.1 cm, and a planform area of 1007.6 cm^2 (including the end cap area) (see Fig. 1b).

Pertinent DPTS dimensions are shown in Fig. 1c. Sail leading-edge sweep angles Λ_{LE} of 60, 65, and 70 deg were investigated, giving overall wing spans of 66.9, 66.0, and 65.3 cm, respectively. These sails were made from 1-mm-thick aluminum plate and had a planform area of 17.0 cm^2. The 70-deg DPTS was also cropped, giving overall wing spans of 64.1 cm (sail area = 16.5 cm^2) and 62.8 cm (sail area = 14.9 cm^2) for taper ratios λ of 0.2 and 0.4, respectively. The leading edges of the DPTS were sharp to enforce flow separation.

The wind-tunnel study was conducted in the University of the Witwatersrand's low-speed continuous wind tunnel. This tunnel has an elliptic cross section with a minor axis of 61.0 cm and a major axis of 91.0 cm. The repeatability of the wind-

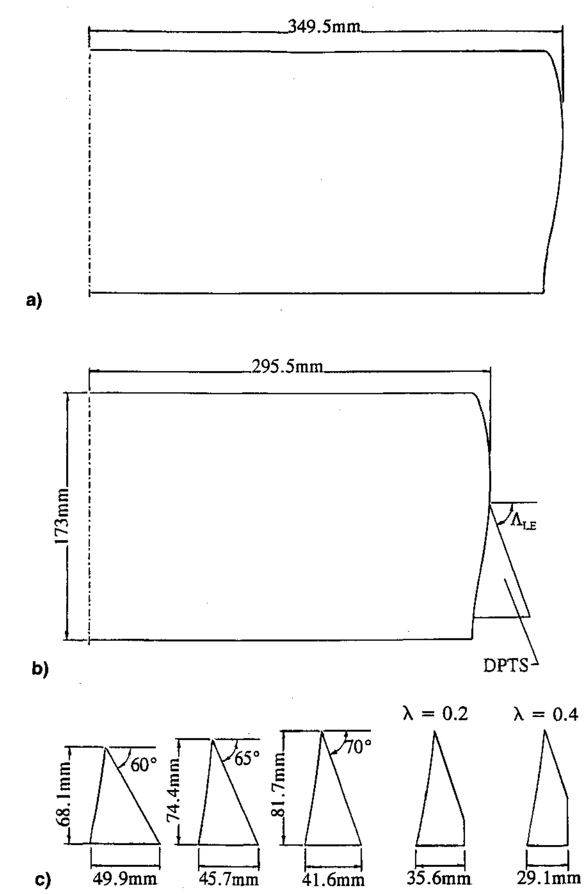

Fig. 1 a) Basic wing, b) wing showing DPTS attachment, and c) DPTS geometric details.

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Table 1 Data summary for variation of DPTS leading-edge sweep angle

Λ_{LE}	AR	$C_{L\alpha}$, deg^{-1}	$C_{L\max}$	e
60	4.30	0.068	0.793	0.59
65	4.18	0.066	0.793	0.63
70	4.09	0.068	0.808	0.67
Basic wing	4.09	0.063	0.770	0.66

Table 2 Data summary for variation of DPTS taper ratio

λ	AR	$C_{L\alpha}$, deg^{-1}	$C_{L\max}$	e
0	4.09	0.068	0.808	0.67
0.2	3.95	0.066	0.790	0.69
0.4	3.80	0.065	0.781	0.71
Basic wing	4.09	0.063	0.770	0.66

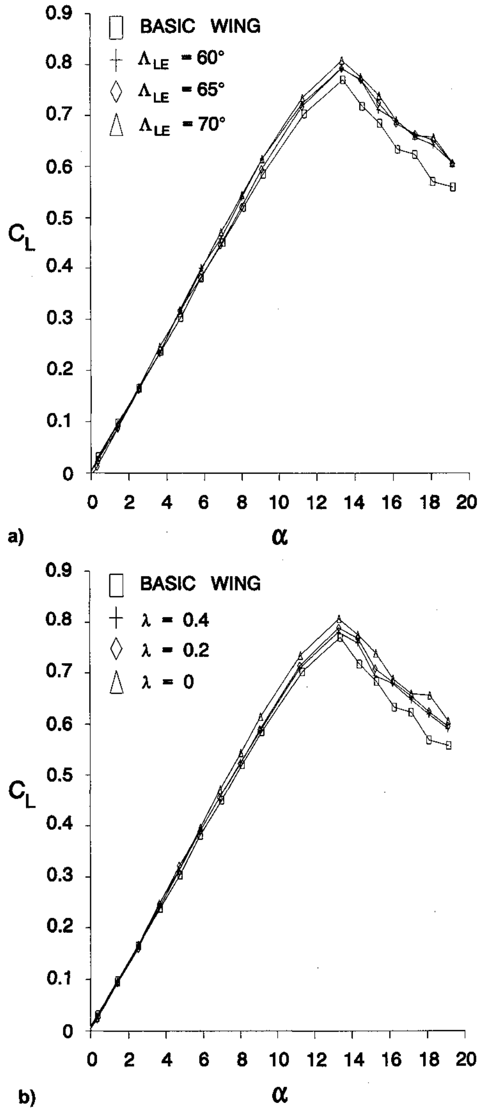

Fig. 2 Effect of DPTS on lift curve: a) variation of DPTS leading-edge sweep angle and b) variation of DPTS taper ratio.

tunnel balance for lift C_L, drag C_D, and pitching moment C_M was estimated at

$$C_L = \pm 0.0015$$

$$C_D = \pm 0.0008$$

$$C_M = \pm 0.0022$$

All the forces and moments from the tests were corrected for blockage.[7] Tare and interference effects, as well as the tunnel

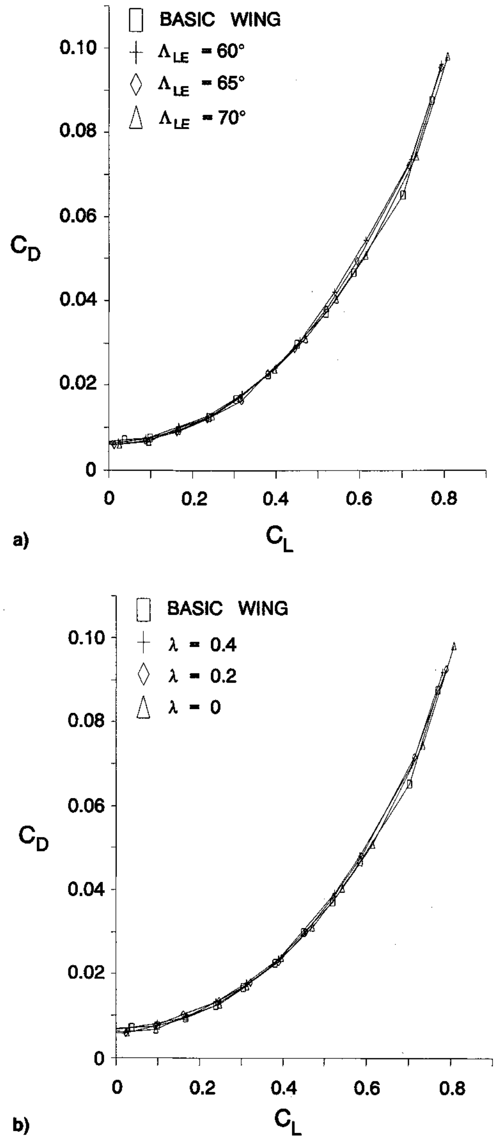

Fig. 3 Effect of DPTS on drag polar: a) variation of DPTS leading-edge sweep angle and b) variation of DPTS taper ratio.

flow angularity, were established using an image system.[7] Tests were conducted at a freestream velocity of ≈46 m/s (equivalent to a Mach number of ≈0.13), corresponding to a dynamic pressure head of approximately 1050 Pa. The set angle of attack was varied from −2 to 18 deg. The wing's Reynolds number was 4.3×10^5, based on a reference chord length of 17.3 cm.

All forces and moments were nondimensionalized using their respective planform's area. All moments were referred to the wing's quarter-chord. In the tests, the effect of DPTS leading-edge sweep angle was investigated while the tip sail's overall area remained constant (thus the sail's root chord varied). Taper ratio effects on the 70-deg DPTS were also determined. Slender wing theory[8] suggests that the aerodynamic center of a slender delta wing is located at the wing's geometric centroid, i.e., two-thirds of the root chord. The sail was attached such that its geometric centroid was positioned at a point 75% towards the rear of the wingtip. The sail's chord line corresponded to that of the wing.

Results

Tables 1 and 2 contain some geometric details and a summary of results for variation of the DPTS leading-edge sweep angle and taper ratio, respectively. Figure 2a shows an in-

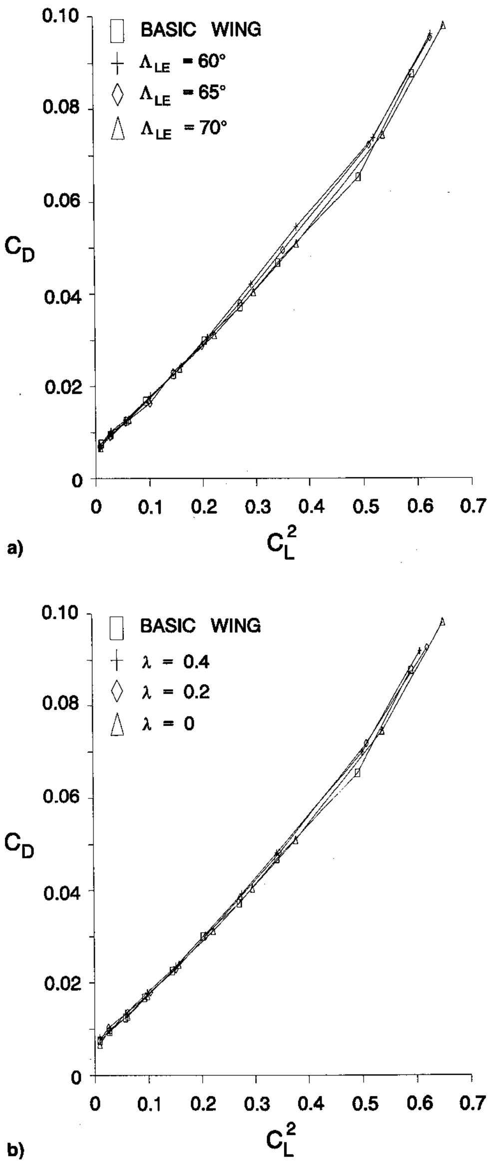

Fig. 4 Effect of DPTS on linearized drag polar: a) variation of DPTS leading-edge sweep angle and b) variation of DPTS taper ratio.

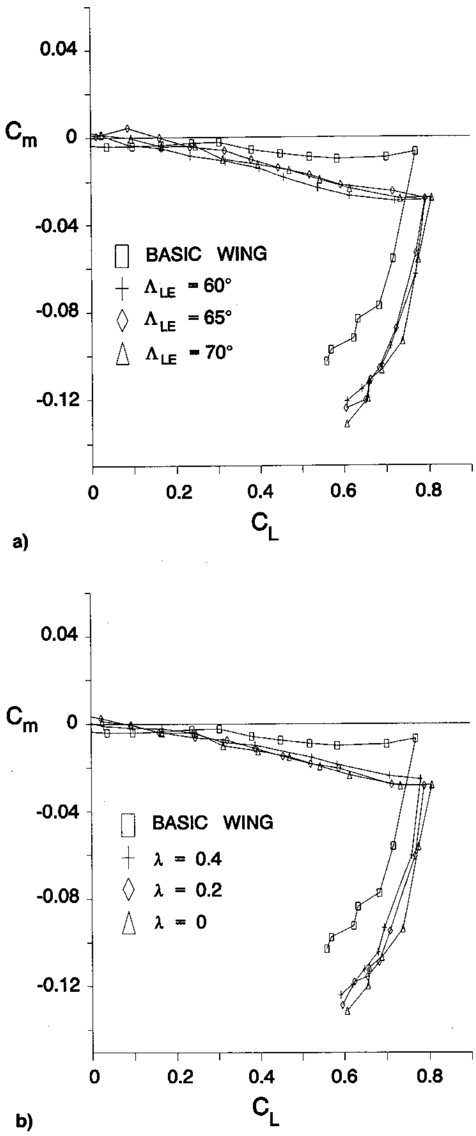

Fig. 5 Effect of DPTS on pitching moment: a) variation of DPTS leading-edge sweep angle and b) variation of DPTS taper ratio.

crease in lift coefficient for all DPTS configurations compared to the basic wing. As can be determined from Table 1, the lift curve slope $C_{L\alpha}$ increased by 7.94%, and the maximum lift coefficient $C_{L\max}$ by 4.94% over the basic wing for the DPTS with a leading-edge sweep angle of 70 deg. The lift increases are most likely associated with the high-flow angularity and induced velocities in the vicinity of the wingtip[4] in which the DPTS are situated. The variation in $C_{L\alpha}$ due to each DPTS configuration was small and suggests a weak dependence on the tip sail's leading-edge sweep angle as can be seen in Table 1. Cropping the 70-deg DPTS results in a moderate reduction in $C_{L\alpha}$ and $C_{L\max}$ as shown in Fig. 2b and Table 2. However, the wing with the cropped sail ($\lambda = 0.4$) is still able to generate a 3.2% increase in $C_{L\alpha}$ over the basic wing, despite having an aspect ratio 7.1% lower.

Figures 3a and 3b show drag polars and Figs. 4a and 4b linearized drag polars. To quantify the induced drag performance in the linear lift range, the drag polar may be approximated by

$$C_D = C_{D\min} + C_L^2/(\pi \mathrm{AR} e) \tag{1}$$

where $C_{D\min}$ is the minimum drag coefficient, and e is the Oswald efficiency factor. The efficiency factors in Tables 1 and 2 were calculated using Eq. (1). The constant e incorporates both vortex and profile drag, which are difficult to separate as both vary with C_L^2. As shown in Fig. 4b the various configurations have similar slopes, and thus effective aspect ratios. However, taking aspect ratio into account yields an improvement in the Oswald efficiency factor of 7.6% for the DPTS with $\Lambda_{LE} = 70$ deg and $\lambda = 0.4$ (compared to the basic wing), as shown in Table 2. There appears to be a gradual reduction in wing efficiency as the tip sail's leading-edge sweep angle and taper ratio reduces, and the wing's aspect ratio increases (see Tables 1 and 2). Although the performance benefits that are obtained are moderate in magnitude, it should be noted that they are achieved by smaller span wings. For example, the wing with 70-deg DPTS cropped to a taper ratio of 0.4 has a span 10.2% less than the basic wing. Figures 5a and 5b show an increase in nose-down pitching moment with the addition of the DPTS. This would be expected due to their rearward location.

Conclusions

From the experimental data the following conclusions are drawn. Improvements in wing efficiency and performance may be obtained by the application of delta planform tip sails. The largest improvement in lifting performance was obtained with a DPTS with $\Lambda_{LE} = 70$ deg, the lift curve slope increasing by 7.94% over the basic wing, and $C_{L\max}$ by 4.94%. The 70-deg

DPTS with a taper ratio of 0.4 gave an increase in e of 7.6% over the basic wing. Increasing DPTS Λ_{LE} and λ resulted in an increase in wing efficiency. Stabilizing nose-down pitching moment increased with sail addition. The validity of the results at higher Reynolds number and for other planforms requires further investigation.

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