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Engineering Notes

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Effect of Leading-Edge Form on Performance of Wing-Movable Tip Strake Configurations

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Nomenclature

$AR = b^2/S$	=	aspect ratio
b	=	span, mm
C_D	=	wing drag coefficient
C_L	=	wing lift coefficient
c	=	chord, mm
d	=	angle relative to wing chord plane, deg
$q = (1/2)\rho_\infty V_\infty^2$	=	freestream dynamic pressure, kPa
$R_e = \rho_\infty V_\infty c/\mu_\infty$	=	Reynolds number based on wing model chord
S	=	reference area, mm^2
V_∞	=	freestream velocity, m/s
x, y, z	=	aerodynamic axes
α	=	angle of attack, deg
Λ	=	strake leading edge sweep angle, deg
μ	=	absolute viscosity, N · s/m^2
ρ	=	air density, kg/m^3

Subscripts

i	=	inboard
o	=	outboard
s	=	strake
∞	=	freestream conditions

Introduction

IT IS known that wing-fuselage strakes improve a wing's aerodynamic performance over a wide range of angles of attack and, particularly, at moderate-to-high values of α. Extensive efforts have been devoted to studying strakes, thus a voluminous body of literature has been generated; see, for example, [1–11]. Nikolic in [12] provides quite an extensive review of this research.

By creating controlled flow separation and powerful vortices springing from strakes' sharp leading edges, and traveling over the suction side of the wing, strakes contribute a great deal of lift, the so-called vortex lift, nonlinear in nature. As a result, numerous military aircraft designs since the 1970s have used the advantageous features of strakes to improve their maneuverability. Aircraft such as the F-5 Freedom Fighter, the F-16 Fighting Falcon, the F/A-18 Hornet/Super Hornet, the MiG-29 Fulcrum, and the Su-30 Flanker represent but a few remarkable examples.

The author's interest in tip strakes is due to a large extent to the paper by Staufenbiel and Vitting [13] who used sharp-edged, half-delta extensions rigidly attached at the tips of a wing in an attempt to hasten the breakdown of the wing's trailing vortices. This idea led the present author to the following reasoning: Because fixed half-delta fins are capable of generating powerful vortices then, if these fins are made movable, the desired fin vortex strength may be achieved by deflecting the fins in flight without having to bring the whole airplane to a relatively high α. Furthermore, this deflection of the tip half-delta extensions appeared to hold promise as a useful additional control variable available for controlling the lift and drag of the airplane.

An extensive review [12] of the available literature showed that, although there has been work in the past directed at studying tip strakes [14,15], tip sails [16–19], hinged strakes [20], strake flaps [21], and half-delta-tip control in conjunction with a delta wing [22], no reference to a sizable movable tip strake, involving a sharp-edged, low aspect delta configuration, employed on a nondelta main wing, has been found. The movable tip devices (sails) used in [16,17] were very small, on the order of $0.015S$, and they use the existing flow conditions near the wing tips. This led the author to conduct an exploratory study [12] in which a pair of half-delta fins was tested in combination with a rectangular wing. The motivation for the study was in the expectation that, unlike sails, these tip strakes would produce significant flow patterns—primarily strong leading-edge vortices—of their own, which affect both the strakes and the main wing. To address the effect of increased AR, a longer rectangular wing, having the same AR as the wing with tip strakes, the same airfoil and the same c as the baseline wing, was also tested. Five settings of the strakes relative to the main wing were tested over a range of α.

The exploratory study showed a definite advantage of this configuration—the movable half-delta type extensions, which were named "movable tip strakes" or MTS. They improved the wing's L/D over a range of α by as much as 23% [12]. The movable strakes were found superior to increasing the wing span while keeping the airfoil constant; the strakes did approximately 2.2 times better on a per-percent-increase-in-area basis than increasing the wing AR by extending its span. It was concluded that, by deflecting the tip strakes, it appeared possible to always fly at the optimum setting, the "optimum" being defined in this context as the one yielding $(L/D)_{\max}$.

Furthermore, based on limited near-field flow visualization results, the concept seemed to alter the trailing vortex roll-up pattern, at lest in the $1.5b$ region behind the wing trailing edge studied [12]. The attractiveness of the concept is further accentuated by the relatively small increase in structural weight which would accompany the modification in a full-scale implementation. It appeared that, even with the necessary strengthening of the wing structure to compensate for the increased root bending moment, the concept still held promise to improve the airplane specific excess power, particularly for airplanes with shorter wing spans.

Prompted by these findings, the author then studied three additional movable tip strake configurations, along with the MTS1 of [12], and the results were reported in [23]. A tip strake involving a cropped semidouble-delta planform was found to outperform the other three models yielding increases in the wing's L/D of up to 26%

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depending on α. These results are discussed in detail in [23] and are only summarized below for completeness.

Further investigations deemed warranted. An additional series of five movable tip strakes, along with the four from [23] have been tested. Except for the MTS1, which has been tested at 10 values of d_s, and the MTS4, which will eventually have been tested at five d_s, see later, the rest of the strakes have been tested only at the neutral setting relative to the main wing chord plane. The objective of the present study has been to attempt to discover the direction in which the optimal configuration should be sought.

Experimental Setup

The tests of this study have been completed in the low-speed, open-circuit wind tunnel at Minnesota State University. The tunnel has a test section of 305 mm square and is capable of producing wind speeds of up to 45.7 m/s. The lift and drag forces are measured using a dynamometer-type balance. A detailed description of the tunnel and its instrumentation can be found in [24]. All of the data points have been taken at $q = 0.625$ kPa and $R_e = 0.225 \times 10^6$ based on c.

The wing model used in this study consisted of a rectangular wing having a NACA 4412 airfoil, $b = 161$ mm, $c = 99$ mm, thus $AR = 1.63$. This configuration is referred to as the "baseline wing" (BLW).

Nine configurations of movable tip strakes have been tested. All nine strakes had identical root chords of 94 mm, the same thickness of 2.54 mm, and the same attachment brackets located at $0.485c$. The strake leading edges were made sharp by applying a symmetrical 45 deg bevel on both sides. Figure 1 shows the port (left) halves of the nine strakes, MTS1 through MTS9, from left to right, from top to bottom, along with a short section of the wing, the actual size "airfoil" included here for size comparison. The first strake, the MTS1, included a half-delta type having $\Lambda = 67.5$ deg. It was used in the exploratory study of [12]. The MTS2 also had $\Lambda = 67.5$ deg between 0 and 47.9% of the strake root chord, at which point the straight leading edge transitioned into a parabolic curve yielding $b_s = 56.4$ mm, resembling the planform of the F/A-18 Super Hornet strake. Table 1 gives the geometries of the strakes. The measured values of the sweep angles were very close to the design values.

The strakes MTS1–MTS4 were tested during the second phase and the results were reported in [23].

These particular strake planforms were chosen in some cases based on several successful examples of strake design in combat aircraft applications. For example, the F-16, F-16XL, MiG-29, and Su-30 all employ strakes having sweep angles in the range used in this study. Also, to enhance the effect of the strake vortices on the strake suction surface, the double-delta and cropped double-delta planforms were selected with the results of [10,25,26] in mind, which show the upper surface pressure contours [25], and numerically generated vortex trajectories over double-delta wings [10,26]. Finally, the results of the studies reported in [12,23] influenced the design of the strakes for the present study, that is, the planforms of MTS5–MTS9.

Table 1 Movable tip strakes used

Strake	Λ_i	Λ_o	b_s	ΔS, %	AR
1	67.5	——	74	21.8	2.84
2	67.5	——	56.4	19.7	2.48
3	80	——	34	10.0	2.17
4	80	45	74	17.5	2.95
5	74	——	27	15.7	2.48
6	77.5	——	20.8	12.3	2.29
7	75	45	74	18.4	2.93
8	77.5	45	72	16.3	2.93
9	80	60	74	16.6	2.97

The areas of the strakes were included in the reference areas. Figure 2 shows the wing model with the MTS4 installed in the wind-tunnel test section; the strakes are set to $d_s = -10$ deg and the wing is at $\alpha = 19$ deg.

The following are estimates of the uncertainties associated with all the experimental variables involved in this study. The angle of attack of the wing model could be determined to within ± 0.25 deg. All lengths could be considered reliable to within 0.5 mm. The dynamic pressure uncertainty is estimated at ± 0.005 kPa. Finally, the lift and drag force readouts are estimated to be reliable to within ± 0.05 N. All results have been corrected by applying the standard wind-tunnel corrections [27].

Discussion of Results

The strakes significantly changed the wing performance. They create strong vortices which form over the strakes' sharp leading edges and then subject significant portions of the strakes and the main wing suction surfaces to high rotational velocities, thus increasing lift. As expected, this additional lift—the vortex lift—is nonlinear, which is readily observed by inspecting any of the presented C_L vs α curves for the configurations with strakes.

The effect on the wing drag is twofold: by changing the zero-lift drag and through the increased lift thus induced drag. However, the induced drag portion is also affected by the increased wing AR. The pronounced overall favorable effect of the MTS1 strake at five settings has been reported earlier [12,23]. The next phase of this work involved strakes MTS2–MTS4 and the results were reported in [23].

The present study has dealt with the MTS5–MTS9. First, they all have been tested at $d_s = 0$ deg. These results, along with those for the BLW and MTS1–4, are shown in Figs. 3–5. Several conclusions

Fig. 1 Port (left) halves of nine models of movable tip strakes: MTS1–MTS9 (from left to right and top to bottom).

Fig. 2 Model of wing at $\alpha = 19$ deg with MTS4 at $d_s = -10$ deg in test section.

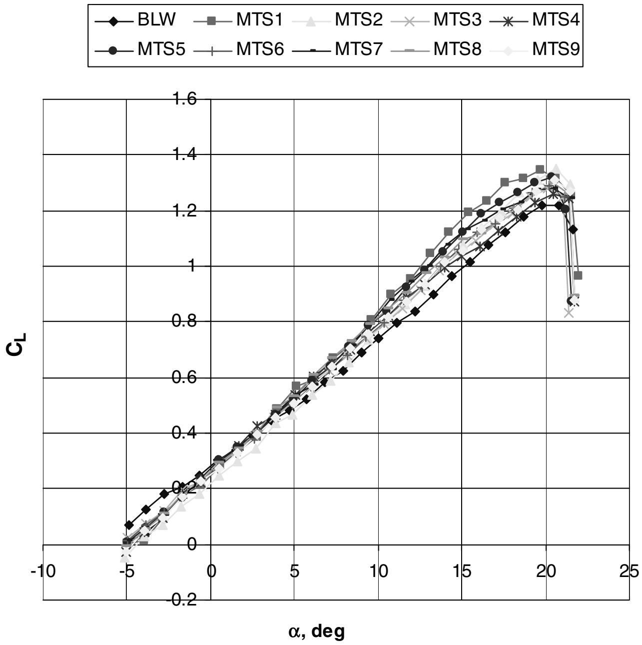

Fig. 3 Lift coefficients for 10 configurations tested with strakes at $d_s = 0$ deg.

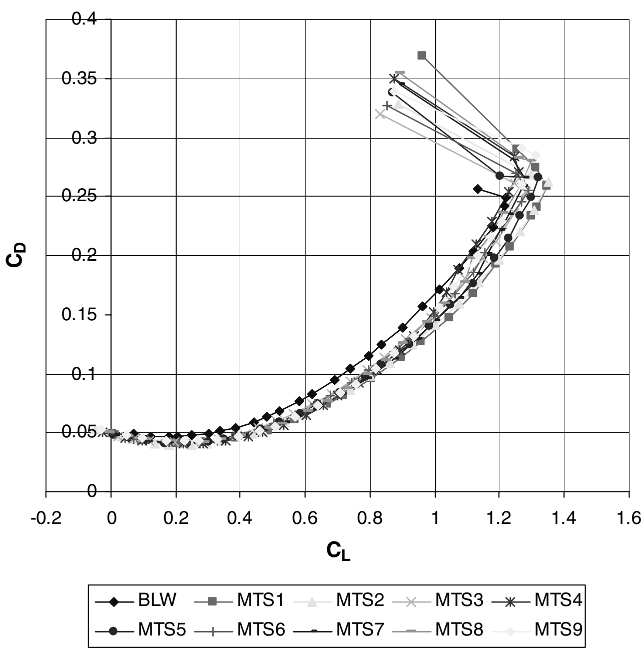

Fig. 4 Drag polars for 10 configurations tested with strakes at $d_s = 0$ deg.

can be drawn based on these figures. First, the effect of the increased AR is evident through the increased slope of the $C_L - \alpha$ curves. However, unlike with a simple increase of AR, these curves exhibit nonlinear character. These two effects were addressed in detail in [12]. It is seen that MTS1 is the most potent generator of vortex lift among the configurations tested at $\alpha > +10$ deg. This may be attributed to the stronger vortex springing from this leading edge swept at 67.5 deg than in the case of the configurations employing higher sweep angles. At α above approximately 15 deg, the remaining strakes create C_L levels between those of the BLW and MTS1. It appears that at low αs, between 2 and 3 deg, the MTS4 yields a higher C_L than MTS1. Figure 4 shows the drag coefficients for the 10 configurations. Once again, the configurations employing strakes yield drag coefficients which fall between those for the BLW and the MTS1. It is noted again that at values of C_L below approximately 0.75 the MTS4 yields the best performance.

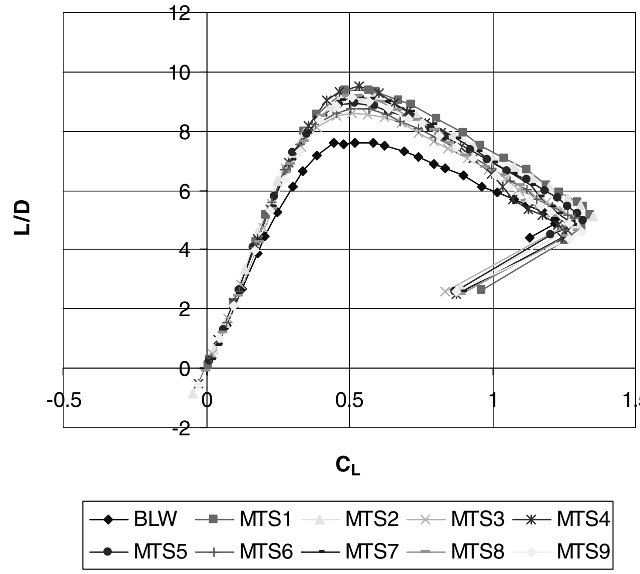

Fig. 5 Lift-to-drag for 10 configurations tested with strakes at $d_s = 0$ deg.

The effect on the configuration L/D, or aerodynamic efficiency, is shown in Fig. 5. It is seen that, while basically all configurations involving strakes are superior to the BLW, the largest improvement in L/D of approximately 26% is attained with the MTS4. This may be attributed to several effects. First, this result is observed at moderate angles of attack of the wing. At these values of α, the highly swept strakes are operating at or close to their full potential for creating vortex lift. Second, the relatively large outboard portions of this strake provide additional suction surfaces over which the effect of the leading edge vortices is exhibited. Third, this configuration had the second highest AR among the 10 tested. Fourth, the transition point, or the leading edge kink, may create an additional vortex, which interacts favorably with the inboard and outboard vortices. It is noted that MTS4, having an area equal to $0.175S$, improved the L/D by approximately 3% more than the MTS1 strake, having an area equal to $0.218S$.

Based on these results for $d_s = 0$ deg, it would be expected that the beneficial effects of MTS4, when deflected, would shift to other, higher or lower values of C_L depending on d_s. Thus, four additional settings of MTS4, including values for d_s of $+5$, $+10$, -5, and -10 deg, were tested. These results are shown in Figs. 6–8. It can be seen from Fig. 6 that, by deflecting the strake in the positive, that is, leading-edge up sense, the configuration generates higher lift coefficients at lower values of α, as would be expected. On the other hand, by deflecting the strake in the nose-down sense, the beneficial effect is shifted toward higher α. These results are consistent with those previously found for MTS1 and reported in [12]. Inspection of Fig. 7 indicates that the strake setting at -5 deg yields the lowest drag over a wide range of C_L. Figure 8 shows the total effects, as measured by L/D. It can be seen from this figure that the optimal d_s setting, among the five values tested, for flight at low-to-moderate lift coefficients, would be either -5 or 0 deg. At higher values of C_L above approximately 0.7, the optimal configuration would require setting the strakes to, first, -5 deg and then, as C_L increases, to -10 deg. By doing this, noticeable savings would be achieved: an increase of 18.3% in L/D at a C_L of approximately 0.92 for $d_s = -5$ deg versus an increase of 14.1% with $d_s = 0$ deg. At a C_L of approximately 1.1, this difference becomes even more significant: the $d_s = -10$ deg setting produces an 11% improvement in L/D while $d_s = 0$ deg yields a loss of about 3% relative to the BLW.

Further testing will include several strakes featuring lower Λ, as well as varying the sweep angle break point and the leading-edge bevel. Flow visualization techniques, such as helium bubbles and a tuft grid, will be used to help better understand the complexities of

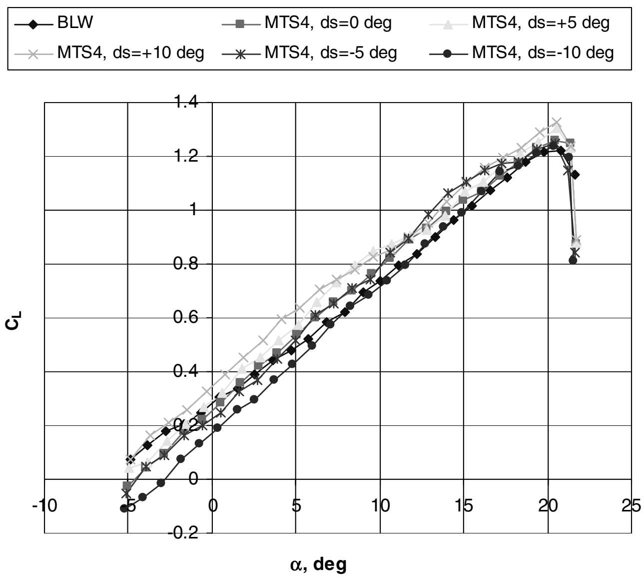

Fig. 6 Effect of MTS4 deflection on wing lift coefficient.

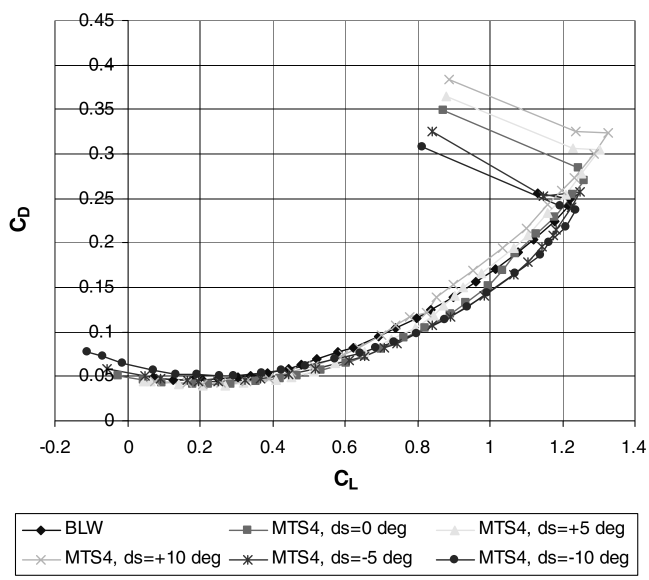

Fig. 7 Effect of MTS4 deflection on wing drag polar.

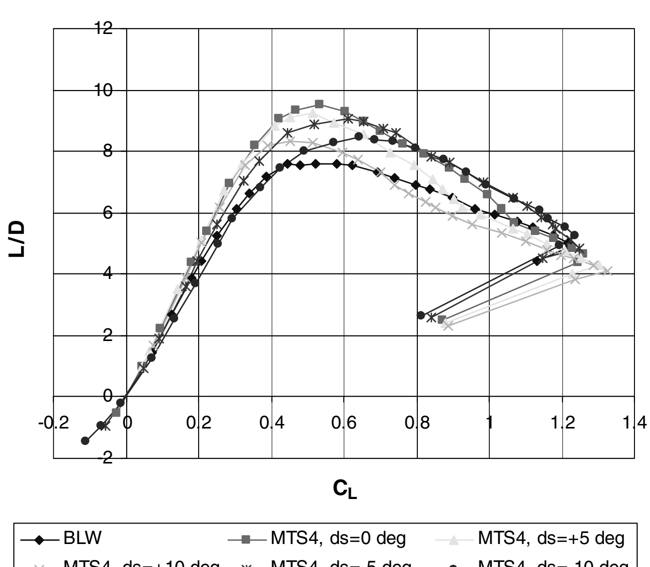

Fig. 8 Effect of MTS4 deflection on wing lift to drag.

this type of flow, particularly the vortex trajectories and their interactions in the wing tip region.

Conclusions

Movable tip strake is an innovative use of the time-tested strake concept which is, based on the results gathered so far, believed to be important to the design of future airplanes. An experimental study has been conducted to explore the effects of the leading-edge form on the performance of a family of movable tip strakes in combination with a rectangular wing. Nine strake configurations, including four half-delta types, one modified half-delta having a portion of the leading edge curved, and four either cropped double delta or full double delta, have been tested in a low-speed wing tunnel. The results showed noticeable advantages of the configurations employing strakes over the baseline wing. All strakes produced higher lift and drag coefficients than the clean wing. The highest lift-to-drag ratio was obtained when an $80/45$ deg cropped double-delta strake was used at moderate angles of attack, yielding improvements of up to 26% over the clean wing. When this strake was deflected to positive or negative angles relative to the wing, this beneficial effect shifted to lower or higher lift coefficients, as expected. Further studies, involving lower-sweep strakes and varying locations of the leading-edge sweep break point, appear warranted. Future plans also include use of off-surface flow visualization to aid in better understanding the flow phenomena associated with these types of flows. Effects of movable tip strakes on wake vortex attenuation and their possible use in roll control also appear to warrant examination.

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