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Engineering Notes

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Examining Effects of Increased Effective Area on Performance of Movable Tip Strakes

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Nomenclature

Æ	=	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
Re	=	$\rho_\infty V_\infty c/\mu_\infty$, 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

MOVABLE wing tip strake represents a new idea proposed by the author [1]. It embodies a novel use of a time-proven concept: the one of traditional, fixed-wing strakes located at the wing–fuselage juncture. Wing–fuselage strakes have been known since the 1970s to significantly improve airplane aerodynamics over a range of α by creating controlled flow separation along the strakes' leading edges, thus producing powerful vortices and contributing a large amount of lift to the lift generated by the main wing. This idea has been implemented into the designs of many fighter airplanes to improve their maneuverability. Some particularly successful examples are given by aircraft such as the F-5, F-16, F/A-18, and MiG-29. Wide research efforts have been undertaken to better understand the effects of strakes on the main wing aerodynamics; for example, see [2–12] for a good sample of these research endeavors. The reader is referred to [1] for a very extensive review of this research.

The author's recent interest in strakes was aroused by the article by Staufenbiel and Vitting [13], in which they report the use of fixed, delta-type wing tip extensions to generate additional, short-lived vortices in the wing tip region, thus attempting to destabilize the main wing vortices by introducing breakdown of the vortex cores and spreading the vorticity of the trailing vortices. This led the present author to the following reasoning: If the fixed delta extensions were capable of generating additional vortices of significant strengths, which interfere with the wing trailing vortices, then, if these sharp-edged delta extensions are made movable relative to the main wing, the desired strength of the delta-extensions-generated vortices may be attained without having to bring the main wing to a relatively high α, therefore avoiding the increased drag price present in the case of fixed delta extensions. The author termed these devices movable tip strakes (MTSs) and initiated an exploratory study in which a single pair of MTSs, having $\Lambda = 67.5$ deg was investigated [1]. The study revealed clear advantages of this configuration; its L/D ratio exceeded that of the baseline wing by as much as 23%. This configuration outperformed by a factor of 2.24 on a per-percent-increase-in-area basis the one having the same Æ as the strake–wing combination and having a constant airfoil and chord length as the baseline wing. Furthermore, 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 $(L/D)_{\max}$. Thus, the MTS deflection appeared to be a useful new control variable of interest to airplane designers. Even with the expected increased wing root bending moments, which will necessarily accompany this modification, it still seemed to hold promise for improving the overall airplane specific excess power, thus its performance, due to the very low structural weight of the movable strakes themselves.

Next, three additional MTS configurations, all having high Λ between 67.5 and 80 deg, were investigated [14]. These results showed that a double-delta planform strake with Λ of 80 and 45 deg for the inboard and outboard sections, respectively, and the sweep transition point at 57.5% of the strake root chord achieved the best results. It increased the L/D of the wing by as much as 26%.

A more extensive study of the leading-edge-form effects on the aerodynamic performance of wing–MTS configurations was conducted next [15]. Five additional strake configurations, all having high Λ and either pure delta or double-delta planforms, were investigated experimentally. Although all of the tested configurations outperformed the baseline wing, the best results were again achieved with the best strake of [14]. The excellent performance of this strake has been attributed to several factors, and they are discussed in [15]. One among them is what appears to be an optimal combination, or a balance, of the inboard strake section, having high Λ and capable of generating very strong leading-edge (LE) vortices, with the moderately-swept outboard portion that provides ample surface area over which the effects of these strong vortices are exhibited. Apparently, an interesting direction in which this study may continue is to attempt to optimize the location of the LE breakpoint and thus the ratio of the inboard and outboard areas. Also, looking into the LE bevel amount and orientation seems worthwhile.

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Alternatively, attempts to optimize the movable strake performance may also be directed toward lowering Λ, thus increasing the effective strake area. In this case, a somewhat less strong strake vortex would act over a considerably larger area, thus the overall effect may turn out to be more advantageous. This is precisely the direction taken in the present study. Five new strakes, all having lower Λ and much larger areas than the ones previously studied, have been designed and investigated. Three among the strakes had straight LEs, and the remaining two featured composite planforms involving lower sweeps inboard and a higher sweep outboard: opposite from the previously studied double-delta forms of [14,15]. The strake geometries and their effects on the wing performance are discussed next.

Models and Testing Procedure

The tests for this study have been completed in a low-speed wind tunnel at Minnesota State University, having a test section of 305 mm square. The maximum airflow speed in the tunnel is 45.7 m/s. A two-component, linear variable differential-transformer-based balance is used to measure lift and drag. The experiments have been run at $Re = 0.225 \times 10^6$ based on the wing model chord. A detailed description of the tunnel and its instrumentation can be found in [16]. The standard wind-tunnel corrections [17] have been applied to all data presented.

The baseline wing (BLW) model was a rectangular wing having a NACA 4412 airfoil, a chord of 99 mm, a span of 161 mm, and thus $AR = 1.63$. The five MTS models all had an identical root chord of 94 mm, a semispan of 37 mm, and a thickness of 2.54 mm, and the same attachment brackets located at $0.485c$. The LEs have been made sharp by applying a symmetrical 45 deg bevel on both sides. The strakes' geometries are presented in Table 1.

Figure 1 shows the starboard halves of the five MTSs, M65 through M4580, along with a short section of the wing model, for comparison purposes. The actual geometries were very close to the theoretical values. Figure 2 shows the wing with the M4580 movable tip strakes installed in the test section. The conditions are $\alpha = 17$ deg and $d_s = -10$ deg.

The six configurations (the BLW and the wing plus each among the five strake pairs) have been tested at $q = 0.625$ kPa, whereas α was changed from −5 to 20 deg with 1 deg increments. For the first series of tests, $d_s = 0$ deg. The second series of tests involved four additional settings of the M4580 strake, that is, $d_s = +5, +10, -5$, and −10 deg.

Experimental Uncertainties

The following are estimates of the uncertainties associated with the experimental variables involved in the 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.

Discussion of Results

First the six configurations consisting of the BLW and the wing combined with each of the five MTSs at $d_s = 0$ deg have been tested at a constant $q = 0.625$ kPa and α from −5 to 20 deg. The effects of the MTSs on the aerodynamic characteristics of the wing are given in Figs. 3–5. The presence of the strakes led to the creation of controlled flow separation along the sharp strake LEs. This fixed type of

Table 1 Geometric characteristics of movable wing tip strakes

Strake	Λ, deg	Λ_i, deg	Λ_o, deg	Δ*S*, %	Δ*AR*, %
M65	65	——	——	25.94	70.62
M625	62.5	——	——	27.68	66.89
M60	60	——	——	30.04	66.64
M6080	——	60	80	27.71	68.49
M4580	——	45	80	30.78	62.96

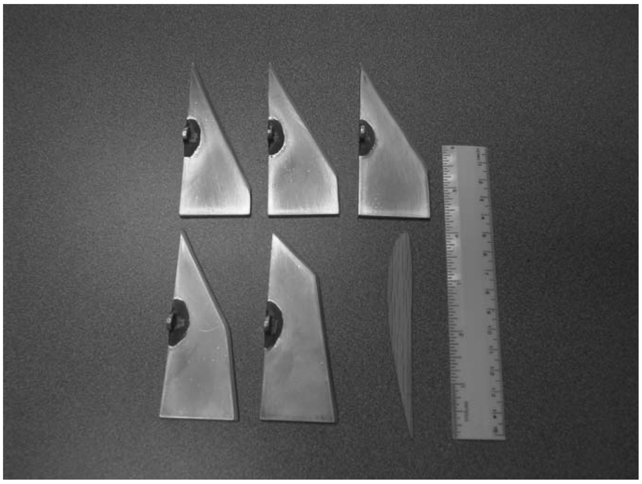

Fig. 1 Starboard (right) halves of five movable tip strakes studied, from left to right, from top to bottom: M65, M625, M60, M6080, and M4580, along with a short wing section.

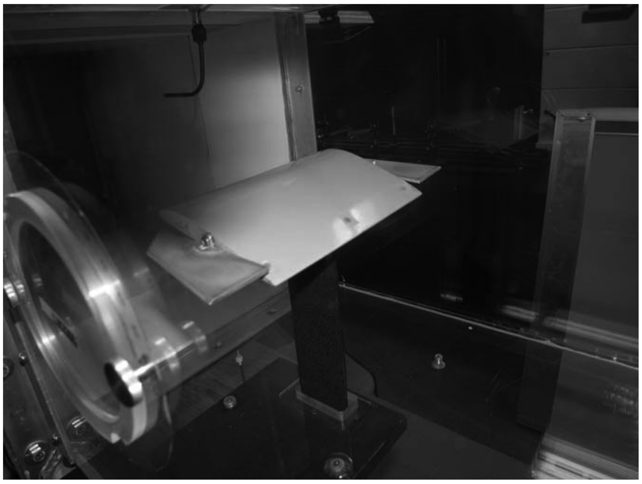

Fig. 2 Wing with M4580 strakes installed in test section, $\alpha = 17$ deg, $d_s = -10$ deg.

boundary-layer transition is *Re* independent. The strong LE vortices, as they progress downstream, subject significant portions of the strake surface to high velocities, thus increased lift. It was shown in [1] that the LE vortices also postpone the flow separation on the main wing at high α.

Figure 3 shows the C_L increases due to the addition of the five strakes. It can be seen that all strakes significantly increase C_L at moderate and high α. The strake areas have been included in the reference areas for the force calculations. Although all among the strakes improve C_L, it appears that the composite-planform strake, having the inboard and outboard sweep angles of 60 and 80 deg, respectively, (the M6080 model) produced the highest values of the C_L increase. For example, at α between approximately 17 and 19 deg corrected, C_L increased by about 16% relative to the BLW. It can also be seen from this figure that, at negative values of α, the presence of the strakes causes lower C_L as would be expected because, at those conditions, the strake-created vortices pass under the strakes and thus generate lift forces which are in the negative direction, and also S is larger.

As a general conclusion, the five strakes all performed within a couple percent from one another. This should not be surprising because all the strakes had their LEs swept at around between 60 and 65 deg, as an average. Another general conclusion regarding this figure is related to the character of the curves. Whereas the BLW curve exhibits the typical linear behavior, the configurations with strakes are characterized by nonlinear C_L vs α curves, as it should be

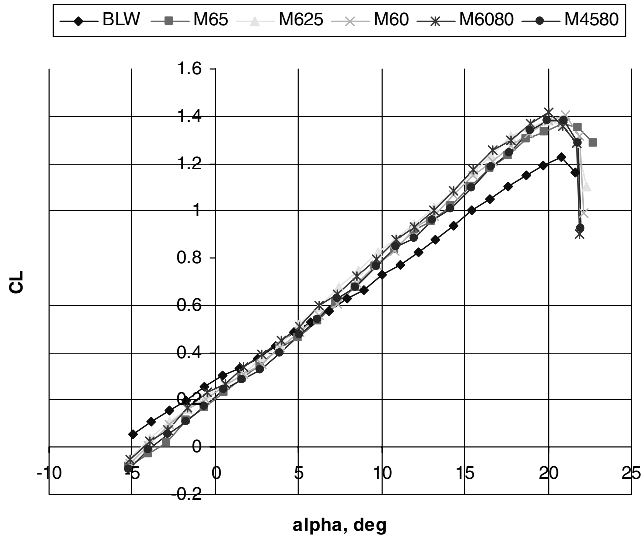

Fig. 3 Effect of movable tip strakes on lift coefficient.

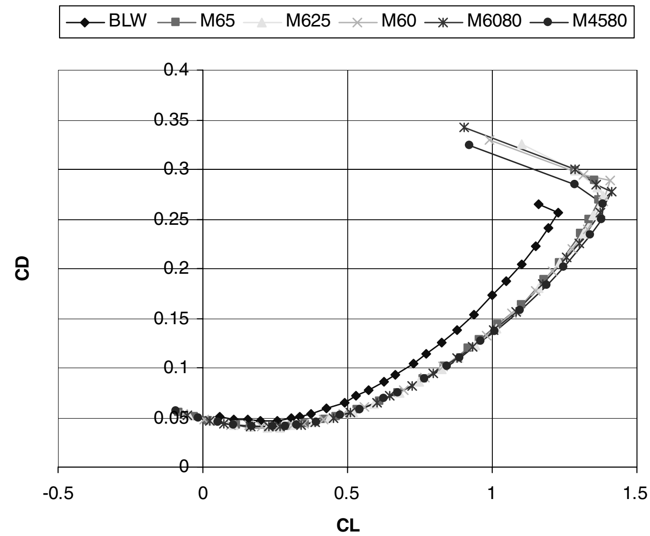

Fig. 4 Effect of movable tip strakes on drag coefficient.

expected due to the nonlinear nature of the vortex lift generated by the strakes' LE vortices. It should be kept in mind that the increased slopes of the curves for the configurations with strakes are due to the added nonlinear vortex lift and, to an extent, to the increased AR of the wing–strake combinations. These two effects have been separated, analyzed, and discussed in [1].

Figure 4 shows the effects of the strakes on C_D. The presence of the strakes leads to increased C_D at the same α, again, as expected. These changes are due to the increases in both the minimum drag and the induced drag. However, it can be seen from Fig. 4 that any among the five configurations with the MTSs generates lower C_D at a constant C_L than the BLW throughout most of the range of α. Also, the range of available C_L increases by, for example, about 13% when the M4580 strake is added.

The overall effect of the strakes on the wing performance is shown in Fig. 5 which gives the L/D ratios, or the aerodynamic efficiencies, as a function of C_L for the six configurations tested. It can be seen that the strakes outperform the BLW by a wide margin. Once again, the curves for the configurations with strakes are within a fairly narrow band for the aforementioned reasons. It is noted, however, that at moderate to high α, the M4580 MTS slightly outperformed the other strakes. At a $C_L = 0.5$, this strake improved L/D of the BLW by approximately 22%. This improvement is maintained at higher lift coefficients. Also, the range of useful C_L has increased. At lower C_L, this strake performed comparably with the other strakes.

Because the M4580 movable tip strake somewhat outperformed the other strakes investigated in this study, an additional series of tests has been conducted with this strake. In these tests, the setting of the M4580 strakes relative to the main wing chord plane has been varied within the set (5, 10, −5, and −10 deg). It is noted that the flow conditions on an MTS are determined by both the main wing α *and* the setting of the strake relative to the main wing d_s. Thus, for example, an MTS deflected to a positive setting, that is, $d_s > 0$, will develop its maximum lift at a lower α of the wing than when the strake is at its neutral setting, that is, $d_s = 0$ deg. A summary of these results is given in Fig. 6. It can be seen that deflection of the strake in the positive sense, that is, LE up, expands the operational envelope of the wing–strake configuration to much higher lift coefficients. It is also seen from this figure that an optimal schedule for this MTS would involve flying at a positive d_s at low lift coefficients then, returning the strake to $d_s = 0$ deg as the C_L approaches 0.5 and maintaining this setting over a large portion of the moderate range of α and, finally, deflecting the strake downward (negative setting) as $C_{L,\max}$ is approached. This deflection schedule could be very efficiently controlled by an onboard computer.

Although the study has revealed that these low-sweep and composite-planform MTSs are capable of improving the wing's performance at levels of up to 22%, it should be kept in mind that they

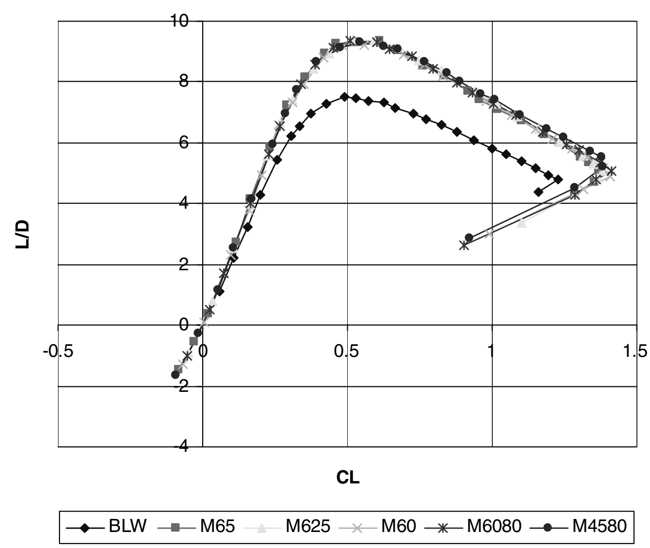

Fig. 5 Effect of movable tip strakes on lift-to-drag.

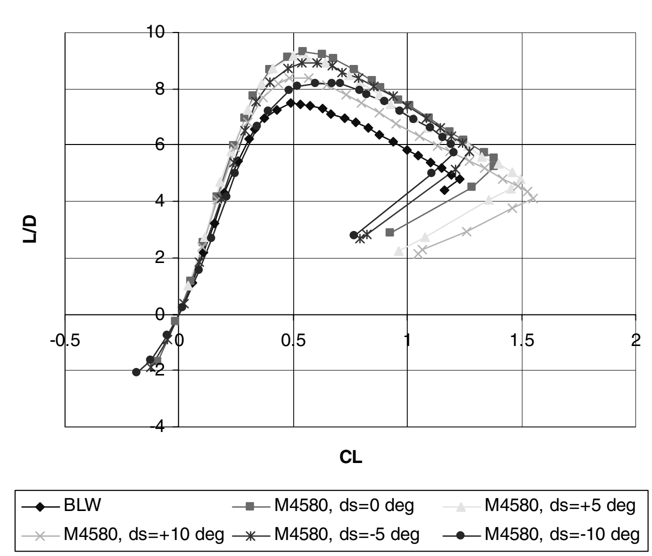

Fig. 6 Effect of deflection of M4580 on wing–strake aerodynamic efficiency.

are less effective than the double-delta strake having the inboard and outboard sweep angles of 80 and 45 deg, respectively, which, at $d_s = 0$ deg, improves the L/D by 26% [14,15]. At $d_s \neq 0$ deg, this benefit is shifted toward lower α for positive d_s, and toward higher α for negative d_s. In other words, it appears that the LE vortex strength is more significant than the effective strake area over which the LE vortices act. Therefore, the optimal strake configuration should be sought among the high-sweep, low-area movable wing tip strakes.

Conclusions

Five low-sweep and composite-planform movable wing tip strakes have been investigated in combination with a rectangular wing in a low-speed wind tunnel. The study has been conducted with the objective to examine the presumption that the diminished strength of the LE vortex may be compensated for, or possibly surpassed by, the increased strake area. The configurations tested included three strakes having straight LEs swept at 65, 62.5, and 60 deg, respectively, as well as two strakes featuring composite planforms with an LE sweep angle changing from 60 to 80 deg, and from 45 to 80 deg, respectively. All five strakes produced significantly higher lift coefficients, as well as drag coefficients at the same α (but lower C_D at the same C_L) than the baseline wing. The overall effect of the strakes, as measured by the L/D ratio, has been found to be favorable for all configurations with strakes. The best performance has been achieved with the composite-planform MTS having Λ of 45 and 80 deg for the inboard and outboard section LE, respectively. With the neutral setting of the strake, the L/D improved by about 22% relative to the baseline wing. When the strakes are deflected, the operational envelope of the wing–strake configuration expands significantly. These findings are in agreement with those of three previous studies of MTSs. They all showed consistently that the vortex strength increases with the increased LE sweep toward 80 deg. Therefore, the vortex strength, rather than the strake area, appears to be the primary element determining the effectiveness of an MTS. Further studies, with the objective of determining the optimal strake configuration, appear warranted. The optimum configuration should be sought among the high-sweep, low-area strake configurations. Off-surface flow visualization techniques, employing helium bubbles and tufts, are planned to aid in better understanding the complex nature of the wing–MTS flow.

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