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Engineering Notes

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Planform Variations and Aerodynamic Efficiency of Movable Tip Strakes

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Nomenclature

b	=	span, mm
c	=	chord, mm
D	=	wing drag, lb
C_L	=	wing lift coefficient
C_D	=	wing drag coefficient
d	=	angle relative to wing chord plane, deg
L	=	wing lift, lb
q	=	$\frac{1}{2}\rho_\infty V_\infty^2$ freestream dynamic pressure, kPa
Re	=	$\rho_\infty V_\infty c/\mu_\infty$ Reynolds number based on chord
S	=	reference area, mm^2
V_∞	=	freestream velocity, m/s
x, y, z	=	aerodynamic axes
α	=	angle of attack, deg
Λ	=	leading-edge sweep, deg
μ	=	absolute viscosity, $N \cdot s/m^2$
ρ	=	air density, kg/m^3

Subscripts

s	=	strake
∞	=	freestream conditions

Introduction

WING–FUSELAGE strakes have been known for a long time to improve a wing's aerodynamic performance over a wide range of angles of attack and, particularly, at moderate-to-high values of α. A great deal of research has been devoted to studying strakes, thus a large body of literature has been generated. The reader is referred to [1] for a quite extensive review of strake research. By creating controlled flow separation and powerful vortices springing from a strake's sharp leading edges and traveling over the suction side of the wing, strakes contribute a great deal of lift, the so-called vortex lift, that is nonlinear in nature. Thus, numerous combat aircraft designs since the 1970s have used the advantageous features of strakes to improve their maneuverability. Some notable examples of their use are provided by aircraft such as the F-5, F-16, F/A-18, and MiG-29.

The author's interest in tip strakes was initially aroused by the paper by Staufenbiel and Vitting [2], who used sharp-edged half-delta extensions rigidly attached at the wing tips in an attempt to hasten the breakdown of the wing 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 this half-delta fin is made articulated, the desired vortex strength may be achieved without having to bring the main wing (and thus the whole aircraft) to a relatively high angle of attack. Furthermore, this deflection of the tip half-delta appeared to hold promise as a useful additional control variable, available for controlling the lift and drag of the airplane. An extensive review [1] of the available literature showed that although there have been efforts in the past that were directed at studying tip strakes [3], tip sails [4–7], hinged strakes [8,9], strake flaps [10], and half-delta-tip control in conjunction with a delta wing [11], no reference has been found to a movable tip strake (MTS) employing a sharp-edged, low-aspect half-delta configuration, employed on a nondelta main wing.

This led the author to conduct an exploratory study [1] in which a movable half-delta strake was tested in combination with a rectangular wing. To address the effect of increased aspect ratio, a longer rectangular wing, having the same airfoil section and the same chord length as the main wing, was also tested. Five different settings of the strakes relative to the main wing chord plane d_s were tested throughout a large range of angles of attack of the main wing. It is noted that the flow conditions over the movable strake are determined by the main wing α *and* by d_s. The exploratory study clearly revealed a definite advantage of this configuration; the movable delta-type extensions, which were named movable tip strakes, dramatically boosted the wing's aerodynamic efficiency over a range of angles of attack, resulting in an improvement of the wing L/D by as much as 23% (see [1]). The movable strakes were found superior to increasing the wing span while keeping the airfoil constant. It was concluded that, by deflecting the tip strakes, it appeared possible to always fly at the optimum setting, the optimum being defined here based on the wing's L/D, which would yield a maximum range of the airplane. Furthermore, based on limited near-field flow visualization results, the concept seemed to alter the wake vortex rollup pattern, at least in the $1.5b$ region behind the wing trailing edge studied.

The attractiveness of the concept seemed further accentuated by the expected relatively small increases in structural weight that would accompany the modification in full-scale implementation. It appeared that even with the necessary strengthening of the wing root structure for the increased root-bending moment, the concept would still hold significant promise to improve the specific excess power of the airplane, particularly, for airplanes with shorter wing spans.

Based on the results of [1], further investigations deemed warranted. Therefore, a series of movable tip strakes have been tested at $d_s = 0$ deg. The objective of the study has been to attempt to discover the direction in which the optimal configuration design space for the strakes should be sought.

Models and Test Procedure

All tests of this study have been completed in the low-speed tunnel at Minnesota State University. The tunnel has a test section of 305×305 mm 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, comprising two linear variable differential transformers. A detailed description of the tunnel and its

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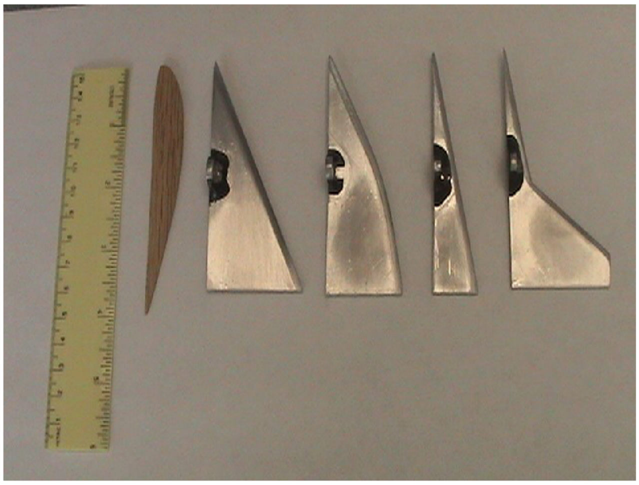
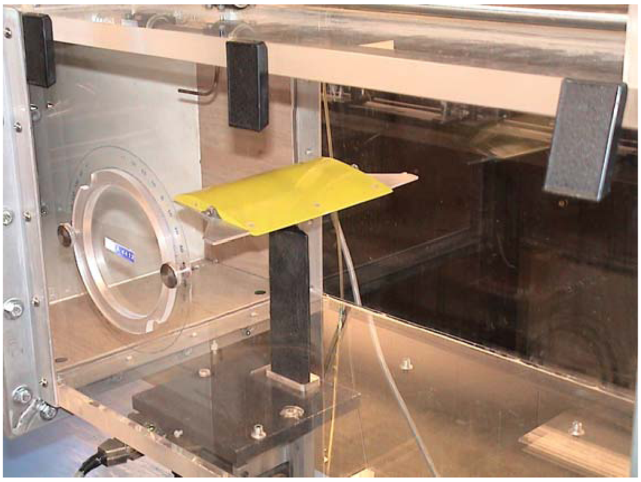
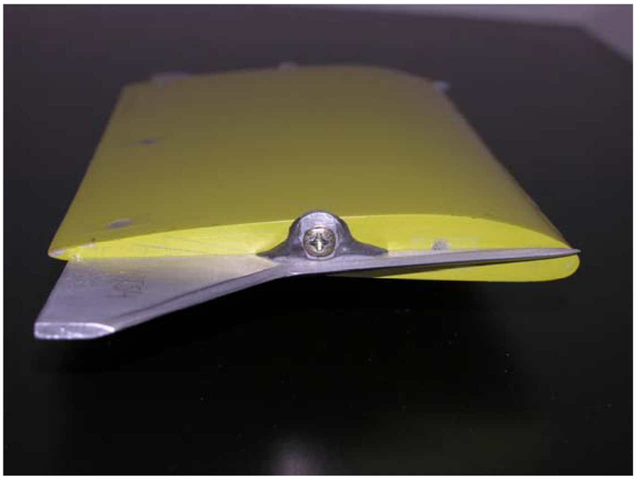


Fig. 1 Right halves of four models of movable wingtip strakes (from left to right) MTS1, MTS2, MTS3, and MTS4.

instrumentation can be found in [12]. All of the data points have been taken at a dynamic pressure of 0.625 kPa so that the measured lift forces would remain within the range recommended by the balance manufacturer. The resulting Reynolds number has been kept constant at approximately 0.225×10^6. The angle of attack of the wing is set using a simple method of visually matching the wing side



a)



b)

Fig. 2 Movable tip strake installed: a) model of a wing with MTS4 in the test section and b) close-up view of a wing with strake.

Table 1 Effects of strakes on model geometry

Strake	Increase in S, %	Aspect ratio
MTS1	21.8	2.84
MTS2	19.7	2.48
MTS3	10.0	2.17
MTS4	17.5	2.95

view (when looking from the port wingtip toward the centerline along the y axis) with a NACA 4412 contour scribed on the 101.6-mm-diam plug fitting into an access aperture on the right test-section wall.

The wing model used in this study consisted of a rectangular wing having a NACA 4412 airfoil, a span of 161 mm, and a chord of 99 mm, thus, $\mathrm{AR} = 1.62$. This configuration is referred to as the baseline wing (BLW). Four different configurations of MTS have been tested, counting MTS1 of [1], the results for which have been included here for comparison. All four strakes had an identical root chord of 94 mm, the same thickness of 2.54 mm, and the same attachment brackets located at 48.5% of the wing chord. The leading edges were made sharp by applying a symmetrical 45-deg bevel on both sides. Figure 1 shows the right halves of the four strakes, MTS1 through MTS4, from left to right, along with a short section of the wing: the actual size of the airfoil included here for size comparison purposes. The MTS1 is a half-delta, $\Lambda = 67.5$ deg. The MTS2 had the same Λ between 0 and 47.9% of the strake root chord, at which point the straight leading edge transitioned into a curve yielding a 28.2-mm semispan of the strake resembling the planform of the F/A-18 Super Hornet strake. The MTS3 involved a straight half-delta planform with $\Lambda = 80$ deg. The MTS4 is a cropped double-delta 80/45-deg configuration with the transition point located at 57.5% of the strake root chord and the same semispan as MTS1. Table 1 gives the increases in S and resulting aspect ratios. Figure 2a shows the wing model with the MTS4 installed in the test section. Figure 2b shows a close-up of the wing–strake juncture.

In this study, α of the wing could be determined to within ± 0.25 deg, all lengths are reliable to within 0.5 mm, q is accurate to within ± 0.005 kPa, and L and D are considered reliable to within ± 0.05 N.

Effects of Movable Tip Strakes on Aerodynamic Efficiency

The addition of the strakes prominently affects the wing aerodynamic performance. The strakes create strong leading-edge vortices that form over the strakes' sharp leading edges and then progress downstream subjecting significant portions of the wing suction surface to high rotational velocities, thus increasing its lift. As expected, this additional lift, the vortex lift, has been found to be nonlinear. The effect on the wing drag is twofold, by changing the wing minimum drag and through the increased lift, thus, inducing drag. However, the induced drag portion is also favorably affected by the increased wing aspect ratio. The pronounced overall favorable effects of the MTS1 for five values of d_s have been reported earlier [1].

Next, the three new strakes, MTS2, MTS3, and MTS4, were tested at $d_s = 0$ deg. These results, along with those for the BLW and MTS1, are shown in Figs. 3–5. All the results have been corrected by applying the standard wind-tunnel corrections [13]. Also, the contribution to the model drag by the attachment brackets and the associated screw heads have been estimated and subtracted.

Several conclusions can be drawn based on these figures. It appears that the MTS1 is the most potent generator of additional vortex lift among the configuration tested at $\alpha \geq 10$ 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 configuration with $\Lambda = 80$ deg. It is noted that there is little difference between the MTS1 and MTS2 lift curves up to $\alpha \approx +10$ deg. This would suggest that the curved leading edge of the MTS2 is not as efficient a vortex generator at higher angles of attack as the straight leading edge of the

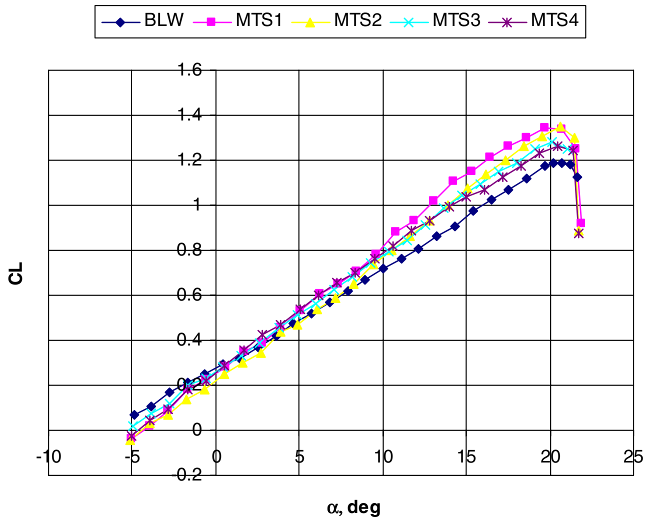


Fig. 3 Wing lift coefficient for five configurations tested; strakes at $d_s = 0$ deg.

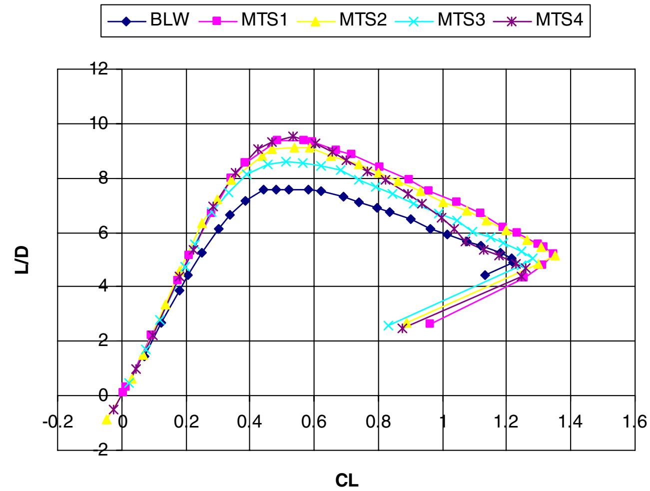


Fig. 5 Wing lift-to-drag ratio for five configurations tested; strakes at $d_s = 0$ deg.

MTS1. Both MTS3 and MTS4 also create higher lift coefficients than the BLW. Figure 4 shows the drag coefficients for the five configurations. Although the differences between them are hardly noticeable at lower C_L, they become more pronounced at higher C_L, due to the predominant effect of the induced drag at these conditions.

Figure 5 shows the effect on the wing L/D, or aerodynamic efficiency. Although basically all configurations involving strakes are superior to the baseline wing, the highest improvement in L/D of approximately 26% is achieved with the cropped double-delta configuration, the MTS4. This may be attributed to several effects. First, this result is observed at moderate α 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 highest aspect ratio among the five tested. Fourth, it is believed that the transition point, or the leading-edge kink, creates an additional vortex that interacts favorably with the inboard and outboard vortices. It is noted that MTS4, having an area equal to 17.5% of the wing reference area, improved the wing L/D by 26% or approximately by 3% more than the MTS1 strake, having an area equal to 21.8% of the wing reference area.

It should be noted that only the neutral settings were tested for this preliminary comparison of the three new strakes, MTS2 though MTS4. It would be expected that the beneficial effects of MTS4,

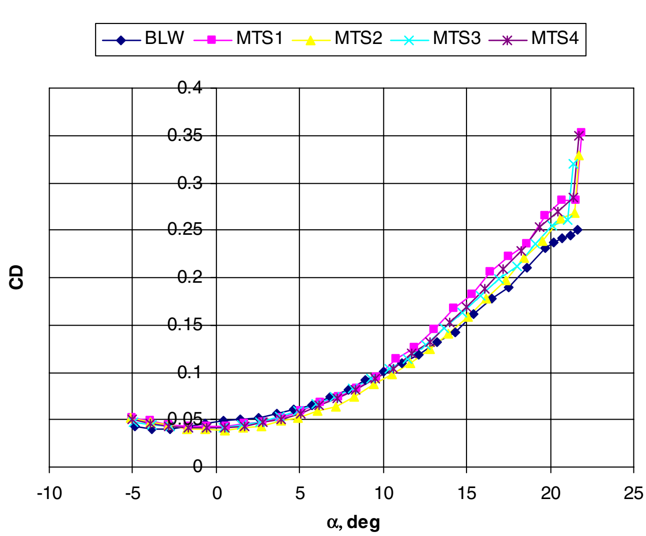


Fig. 4 Wing drag coefficient for five configurations tested; strakes at $d_s = 0$ deg.

when deflected, would shift to other, higher or lower values of C_L, depending on d_s. To arrive at an optimal configuration, one needs to examine both the planform and setting effects. As it was hinted in [1], higher values of L/D should be attainable by judiciously determining the optimal ratio of the two kinds of lift generated by a wing–MTS combination: the classical, attached flow lift and the controlled-separation leading-edge-vortex lift. On- and off-surface flow visualization can be used to greatly enhance the understanding of the flow phenomena involved.

Conclusions

The movable tip strake represents a novel use of the renowned concept believed to be important to the design of future airplanes. An experimental study has been conducted to explore the effects of varying strake planform on the performance of a rectangular wing. Four strake configurations, including two delta types, then one modified delta having a portion of the leading edge curved, and one cropped double delta, have been tested in a low-speed wind tunnel. The strakes were held at a constant setting relative to the main wing. 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 the cropped double-delta strake was used at moderate angles of attack, yielding improvements of up to 26%. It is believed that the minimal weight penalty associated with the actual implementation of the strake would further accentuate the attractiveness of this concept, which represents an innovative use of a traditionally very successful model. Further studies of additional planforms and settings appear warranted. Future plans include extensive use of flow visualization to aid in better understanding the flow phenomena associated with these types of configurations. Effects on wake vortex attenuation and possible use in roll control should also be addressed.

References

[1] Nikolic, V. R., "Movable Tip Strakes and Wing Aerodynamics," *Journal of Aircraft*, Vol. 42, No. 6, 2005, pp. 1418–1426.

[2] Staufenbiel, R., and Vitting, T., "On Aircraft Wake Properties and Some Methods for Stimulating Decay and Breakdown of Tip Vortices," *Vortex Flow Aerodynamics*, CP 494, AGARD, Neuilly sur Seine, France, July 1991, pp. 1, 6, 13; also AGARD Paper No. 26.

[3] Traub, L. W., Galls, S. F., and Rediniotis, O., "Effects of Wing-Tip Strakes on Sheared-Tip Wing," *Journal of Aircraft*, Vol. 36, No. 6, Nov.–Dec. 1999, pp. 1055–1062.

[4] Ma, E. C., "Effect of Wing Tip Strakes on Wing Lift-Drag Ratio," *Journal of Aircraft*, Vol. 26, No. 5, May 1989, pp. 410–416.

[5] Traub, L. W., "Aerodynamic Effects of Delta Planform Tip Sails on Wing Performance," *Journal of Aircraft*, Vol. 31, No. 5, Sept.–Oct. 1994, pp. 1156–1159.

[6] Traub, L. W., "Effects of Delta Planform Tip Sail Incidence and Arrangement on Wing Performance," *Journal of Aircraft*, Vol. 32, No. 5, 1995, pp. 1160–1162.
[7] Spillman, J. J., "The Use of Wing Tip Sails to Reduce Vortex Drag," *The Aeronautical Journal*, Vol. 82, Sep. 1978, pp. 387–395.
[8] Spillman, J. J., "Wing Tip Sails; Progress to Date and Future Developments," *The Aeronautical Journal*, Vol. 91, Dec. 1987, pp. 445–453.
[9] Rao, D. M., and Huffman, J. K., "Hinged Strakes for Enhanced Maneuverability at High Angles of Attack," *Journal of Aircraft*, Vol. 19, No. 4, Apr. 1982, pp. 278–282.
[10] Traub, L. W., and Merwe, J. V. D., "Aerodynamic Characteristics of Strake Vortex Flaps on a Strake-Wing Configuration," *Journal of Aircraft*, Vol. 31, No. 5, Sept.–Oct. 1994, pp. 1116–1120.
[11] Brewer, J. D., "Description and Bibliography of NACA Research on Wing Controls January 1946-February 1955," NACA RM 54K24, Mar. 1954.
[12] Nikolic, V. R., and Jumper, E. J., "First Look into Effects of Discrete Midspan Vortex Injection on Wing Performance," *Journal of Aircraft*, Vol. 41, No. 5, Sept.–Oct. 2004, pp. 1177–1182.
[13] Barlow, J. B., Rae, W. H., Jr., and Pope, A., "Low-Speed Wind Tunnel Testing," 3rd ed., Wiley, New York, 1999, pp. 367–390.