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Engineering Notes

Optimal Movable Wing Tip Strake

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Nomenclature

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

Introduction

STRAKES are small aerodynamic surfaces placed at the wing-fuselage junction of certain airplanes to improve their aerodynamic performance. They feature very low aspect ratios and sharp, highly swept leading edges. Strakes create controlled flow separation along their leading edges, producing vortices that cause high rotational velocities above the main wing's and the strake's top surfaces and thus generate vortex lift, of significant amounts and non-linear in nature. Strakes have been known to considerably improve high-angle-of-attack characteristics of many combat airplanes. Movable wing tip strake represents an extension of the classical strake concept proposed by the author [1]. In this application, the strakes have been placed at the main wing's tips and also made movable, or articulated, about an axis perpendicular to the main wing chord plane. With this arrangement, the beneficial effects of strakes may be obtained without having to bring the main wing to a high angle of attack, accompanied by a high drag penalty and possible other complications. When used in this manner, it seemed that the angle of deflection of the strakes relative to the main wing would provide an additional variable for controlling the wing performance.

In the past, numerous studies have been undertaken to improve the understanding of the wing-strake aerodynamics. Consequently, a vast body of literature on strakes exists (see, for example, [2–12]). Although other researchers have studied fixed wing tip strakes (notably, Ma [13], Traub et al. [14], and Staufenbiel and Vitting [15]), the author first proposed to make them movable in flight [1]. An extensive review of the wing-fuselage strake research is given in [1].

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To validate the movable tip strake concept, first a single-strake configuration was tested [1]. The strakes were installed on a rectangular baseline wing. The results showed that the wing equipped with the strakes outperformed by a factor of 2.24, on a per unit area basis, a modified rectangular wing, obtained by extending the span of the baseline wing and maintaining the same airfoil and having the same AR as the wing with movable, tip-mounted strakes. The strake-equipped wing achieved a lift-to-drag ratio that was approximately 23% better than that of the baseline wing. This improvement was found at the optimal lift coefficient: i.e., at the lift coefficient corresponding to $(L/D)_{\max}$. In the case of the MTS1 strake, set at d$s = 0°$, that C_L was approximately 0.55. By deflecting the strakes up or down, these benefits shifted to lower, or higher, respectively, angles of attack of the main wing, as would be expected, since the flow conditions on the strake depend on the setting of the strake relative to the main wing *and* on the main wing angle of attack.

In subsequent studies, nine planform shapes of movable tip strakes (MTSs) were investigated in order to maximize their positive effect on the wing-strake performance, as measured by the aerodynamic efficiency, L/D, of the configurations for a given lift coefficient C_L. These results were reported in [16–21]. It was found that among the nine planforms tested the best performance was achieved with a cropped double-delta strake planform, the MTS4, featuring an inboard portion swept at 80° and an outboard portion swept at 45°, with the transition, or the leading-edge sweep break point, located at 57.5% of the strake root chord. When used at moderate to high angles of attack of the main wing and set to the neutral setting with respect to the main wing chord plane, i.e., at d$s = 0°$, this strake improved the L/D of the baseline wing by as much as approximately 26%. This beneficial effect of the strake persisted at both d$s > 0$ and d$s < 0$, and the optimal point moved to lower, or higher, angles of attack of the main wing, respectively, as would be expected. The optimal angle of attack of the main wing depended on the strake setting angle, again as would be expected. This confirmed the supposition that ds would represents a new and useful variable for controlling wing geometry.

To further improve the movable strake design it appeared of interest to examine the effect of the leading-edge break-point position while maintaining the inboard and outboard sweep angles of the MTS4. Apparently, by moving the break point forward (and, consequently, slightly inboard) the relative size of the inboard, highly swept portion of the strake decreases and that of the outboard, moderately swept portion increases. Moving the break point backward (and somewhat outboard) produces exactly the opposite effects. It was presumed that the relative sizes of the inboard and outboard segments of the strake must have an effect on both the initial formation and the final disposition of the generated vortices and the resulting wing-strake aerodynamics. An experimental study with the objective to investigate these effects has been conducted. It was found that moving the sweep break point forward benefits the lift-to-drag ratio of the configuration using the same maximum L/D criterion, while moving the sweep break point backward was detrimental [22,23]. Of the seven strake configurations tested in the study the best L/D was obtained with the strake having the break point farthest forward of any strake in the study (at 40% of the strake root chord) the MTS4A-2 strake [22,23]. Thus, the study clearly established the direction in which the optimal strake configuration should be sought.

The objective of the present study has been to attempt to pinpoint the optimal location of the leading-edge sweep break point and to attempt to answer the following question: Does the continued movement of the leading-edge sweep break point forward from 40% consistently produce higher L/D values?

Table 1 Movable tip strakes used in the study

Strake	$x_{\mathrm{BP},\%}$	ΔS, %	AR
MTS4A-3	35.0	23.5	2.79
MTS4A-2b	37.5	22.5	2.81

Experimental Setup and Procedure

The tests of this study have been done in the open-circuit, low-speed wind tunnel at Minnesota State University. The tunnel has a test section of 305 × 305 mm and it can produce airspeeds of up to 46 m/s. The lift and drag are measured using a dynamometer-type balance having two linear variable differential transformers. A detailed description of the tunnel and its instrumentation can be found in [24]. All of the data points have been taken at a dynamic pressure of 0.625 kPa, so that the measured lift force would remain within the range recommended by the balance manufacturer. The resulting Reynolds number, based on the main wing chord, has been kept constant at approximately 0.225×10^6.

The main wing model used in this study represented a rectangular wing having a NACA 4412 airfoil, a span of 161 mm, a chord of 99 mm, and thus an AR = 1.63. This configuration is referred to as the baseline wing (BLW). First, a pair of movable tip strakes MTS4A-3, having the sweep break point at 35% of the strake root chord, has been constructed and tested. The strake still had the same sweep angles of the inboard and outboard segments of 80 and 45°, respectively, a characteristic common to all of the MTS4 strakes. Next, based on the findings from the first phase of the study, an additional pair of strakes, the MTS4A-2b, having the sweep break point located at 37.5% of the strake root chord, was designed and tested. All the other geometric characteristics of the strakes remained the same. Table 1 gives the major geometric characteristics of these strakes, based on the manufactured dimensions. Figure 1 shows the

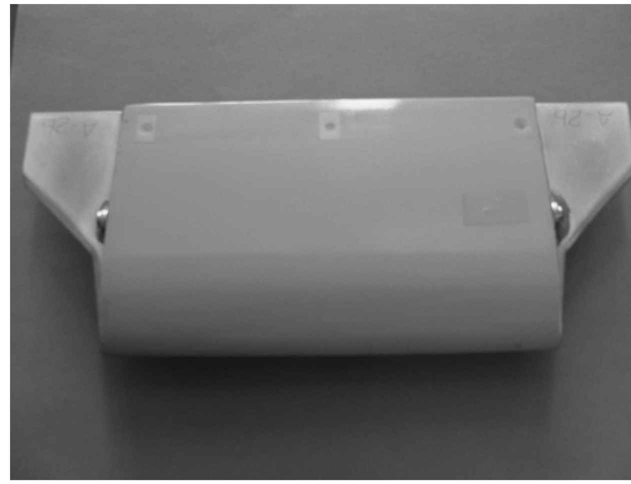

Fig. 3 Strakes MTS4A-2b attached to main wing.

Fig. 1 Movable wing tip strakes MTS4A-2b.

Fig. 4 View from starboard tip of MTS4A-2b set at ds = 0°.

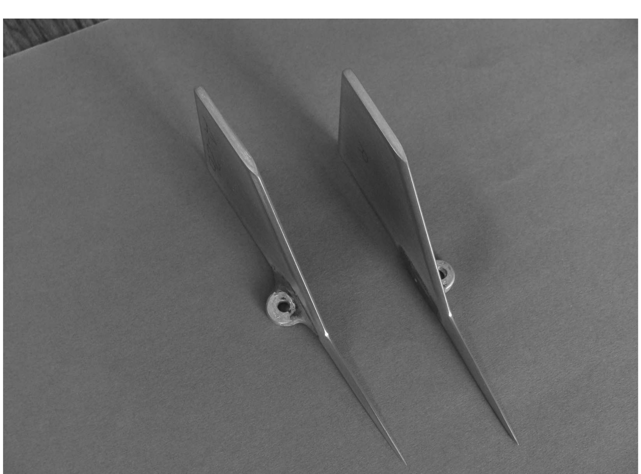

Fig. 2 Another view of strakes MTS4A-2b.

Fig. 5 View from starboard tip of MTS4A-2b set at ds = −5°.

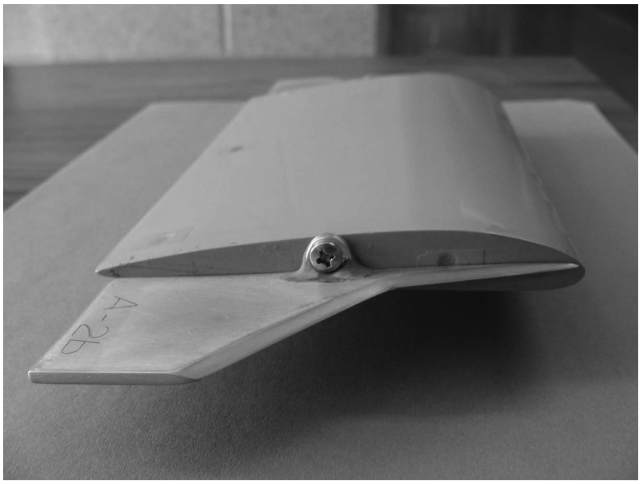

Fig. 6 View from starboard tip of MTS4A-2b set at d$s = +5°$.

MTS4A-2b strakes, side by side, so that the underside of the starboard strake is also visible. Figure 2 gives another view at the same pair of strakes, viewed at a different angle, such that the strakes' sharp leading edges (the key feature of their design) are clearly visible. Figure 3 depicts the MTS4A-2b strakes attached to the wing model, and Fig. 4 gives a view of the starboard tip of the BLW with the MTS4A-2b strake installed at d$s = 0°$.

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 $\pm 0.25°$. The same estimate is made for the strake setting angle relative to the main wing, ds. 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.

In this study the strakes have been tested first at the neutral setting relative to the main wing chord plane: i.e., at d$s = 0°$. Finally, the MTS4A-2b strakes have also been tested with the strakes set at $-5°$ (see Fig. 5) and at $+5°$ (see Fig. 6), relative to the main wing chord plane. All the presented results have been corrected by applying the

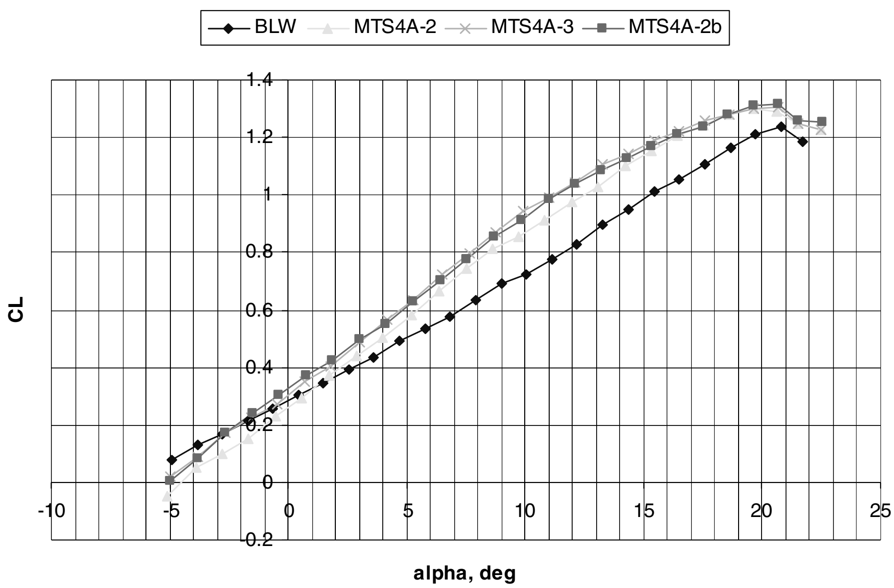

Fig. 7 Lift coefficients of four configurations.

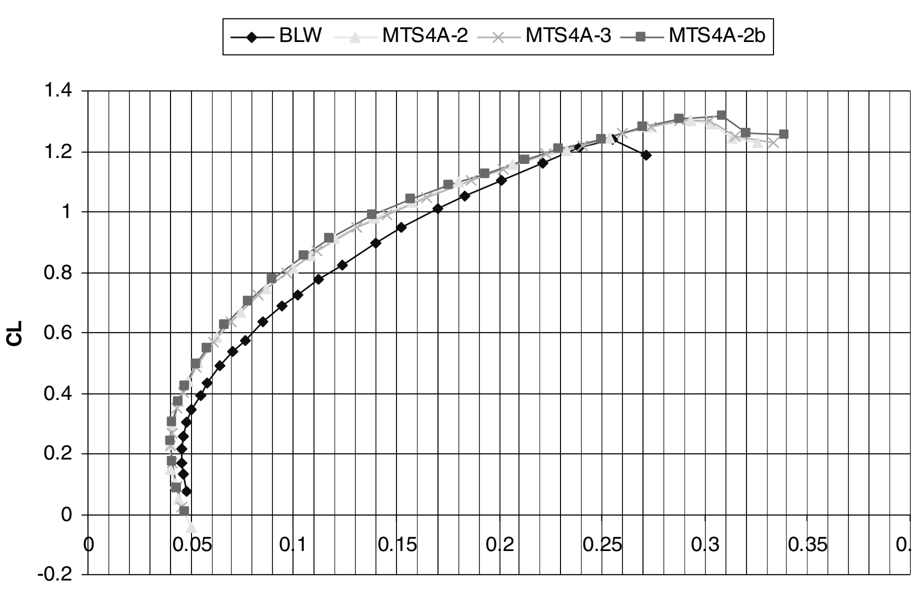

Fig. 8 Drag polars of four configurations.

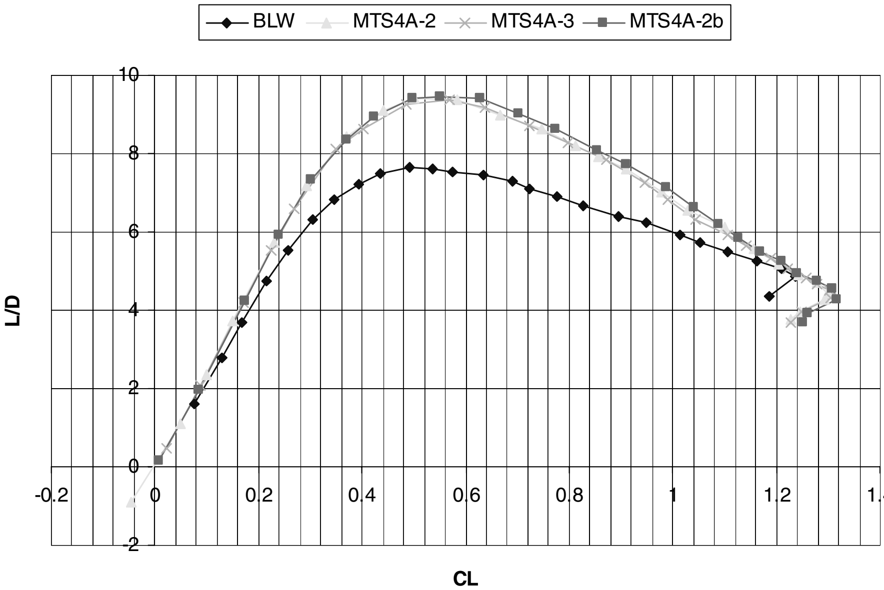

Fig. 9 Lift-to-drag ratios of four configurations.

standard wind-tunnel corrections following the methodology described in [25].

Discussion of Results

All the configurations have been tested over the same range of angles of attack, from $-5°$ to $+20°$, uncorrected. The areas of the strakes have been included in the reference area. The change in this area due to the strake deflections to $-5°$ or to $+5°$ has been neglected as very small: on the order of 0.4% of the strake area, or approximately 0.08% of the total reference area for the baseline wing with the MTS4A-2b installed.

First, the MTS4A-3 strake was tested. It attained values of L/D rather close to those obtained with MTS4A-2 throughout the range of angles of attack tested, or lift coefficients obtained, with a slight decrease in the $(L/D)_{\max}$ of 0.4% relative to the MTS4A-2 best L/D. Based on this finding, it was concluded that moving the sweep break point too far forward from the 40% location would be detrimental from the aerodynamic performance standpoint. It was presumed that there might be a point of optimal leading-edge kink location somewhere between 40 and 35%. Therefore, an additional pair of strakes, the MTS4A-2b, having the sweep break point at 37.5% of the strake root chord, was designed, constructed and tested. The results confirmed the starting supposition, as discussed below.

Figure 7 shows the lift coefficient vs angle of attack for the three strake configurations. Note that the MTS4A-2 had also been tested as part of the previous study [23,24]. The curve for the BLW has also been added for reference. It can be seen from this figure that the MTS4A-3 strakes produced somewhat higher lift coefficient over most of the range of angles of attack than the other configurations. Figure 8 shows the standard drag polars for these four configurations. From Fig. 8, it can be seen that the MTS4A-3 also generated higher drag coefficients at the same lift coefficients. The overall effects on the aerodynamic performance are best seen in Fig. 9, which shows L/D vs C_L. It indicates that the MTS4A-2 and MTS4A-3 strakes are rather comparable, with the note from above on the slight drop in

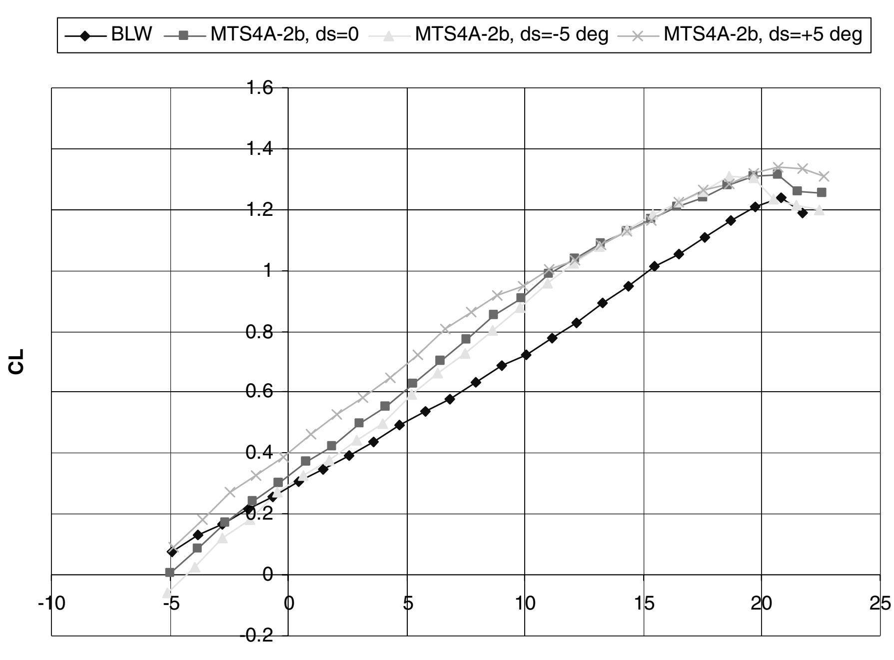

Fig. 10 Lift coefficients of optimal strake for three strake settings.

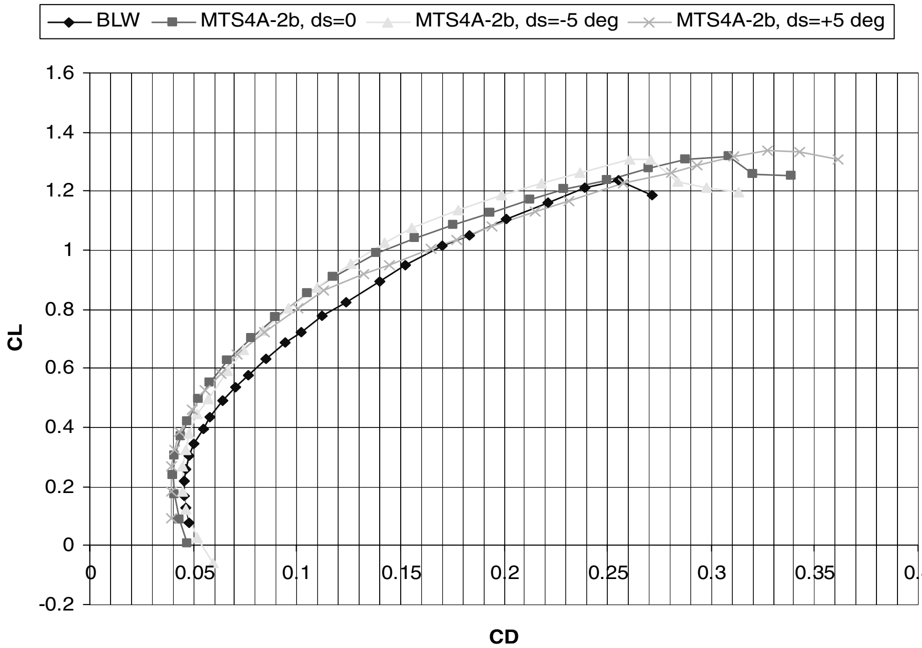

Fig. 11 Drag polars of optimal strake for three strake settings.

$(L/D)_{max}$ for the latter strake. From this figure, the MTS4A-2b emerges as the best configuration, which supports the supposition above that somewhere between 40 and 35% of the strake root chord (the location of the leading-edge sweep break point) there might be an optimum.

It has improved the configuration L/D by as much as 24.1% relative to the BLW. The largest improvements obtained in this study with the MTS4A-2 and MTS4A-3 strakes have been 23.1 and 22.5%, respectively. Note that the improvement for the MTS4A-2 strake is somewhat smaller than that previously found. It is believed that the small difference may be attributed to the difficulty in exactly duplicating the strake-to-wing setting and to the combined effects of the other experimental uncertainties as described above.

The lift coefficient for the configurations with strakes clearly shows a nonlinear behavior typical of vortex lift generated by strakes (see Fig. 7). Whereas the baseline-wing curve exhibits the classical linear range, characteristic of attached flow, the curves corresponding to the three configurations with strakes are clearly nonlinear. Also, the curves for the three configurations with strakes show higher C_{L_α} gradients. This is due to the combined effects of the strake action and of the increased AR, as discussed in detail in [1].

It should be noted that the flowfield around a wing-movable tip strake configuration is rather complex. It involves elements of both classical, attached flow as well as those of controlled flow separation from the strakes' sharp leading edges, highly swept. This part of the flow pattern should not be significantly Reynolds number dependent. The presence of the strakes not only injects powerful leading-edge vortices, which affect to a great degree the flow in the main wing tip region, but it also moderates the tendency of the main wing's flow to separate at higher angles of attack. The many facets of this combined flow deserve further studies in order to acquire a more thorough understanding.

Next, found the optimal strake, the MTS4A-2b was tested at two additional strake settings, one negative and one positive, relative to

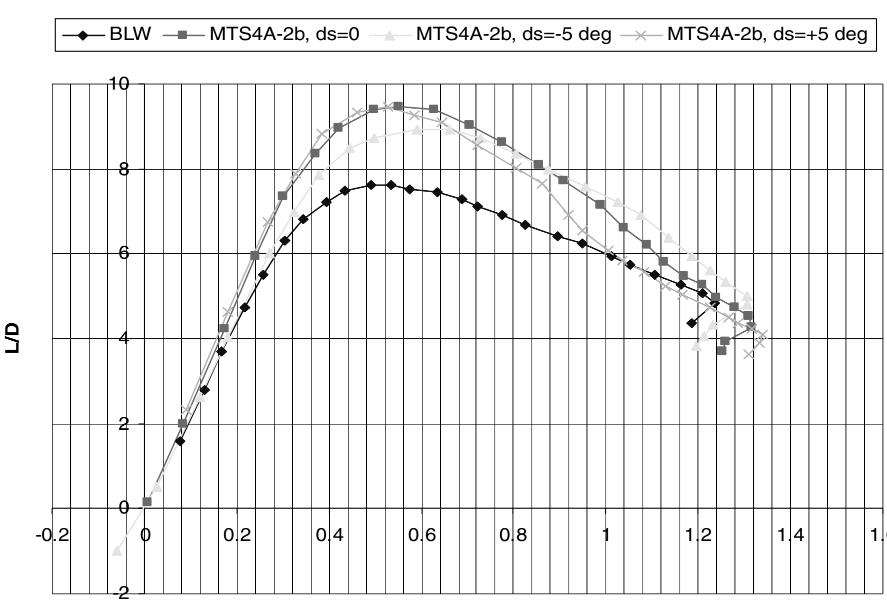

Fig. 12 Lift-to-drag ratios of optimal strake for three strake settings.

the main wing chord plane. These results are shown in Figs. 10–12. Figure 10 shows C_L vs α. It can be seen that when the strakes are deflected leading edge down, the configuration reaches its full lifting potential at a higher angle of attack of the main wing, as would be expected. The opposite is true for the positive deflection of the strakes. It is also noted that the positive strake deflection improves the stall characteristics of the configuration. The differences between these two cases are not due merely to the two different setting angles. With this negative setting, gaps were present between the main wing and the strake in the regions near the leading and trailing edges. These gaps were not present in the case of the $+5°$ strake setting; the reader is referred to Figs. 5 and 6. With the gaps present, the flow pattern in the wing tip region, as well as the interaction between the main wing trailing vortex and the strake leading-edge vortices, changes.

The results for the configurations with the strakes deflected agreed very well with those from the previous studies that have consistently shown that the achieved benefits of the strakes shift toward lower, or higher, angles of attack or, equivalently, to higher or lower lift coefficients, when the strakes are deflected upward or downward, respectively, relative to the main wing [1,16,17,19,20].

Figure 12 has a pragmatic significance. It indicates that this wing-strake configuration would need to be controlled (most probably by an onboard computer) so that, at lower lift coefficients, the strakes are deflected up. Then, as the lift coefficient increases, this positive deflection is gradually decreased to zero, and then the strakes need to be deflected in the negative direction. In this manner, the configuration appears to be capable of always flying at an optimal setting, which would enable the pilot to use the points on the envelope enclosing the many possible L/D vs C_L curves, thus continuously flying at $(L/D)_{\max}$.

Conclusions

A wind-tunnel study with the objective to pinpoint the optimal shape of a double-delta movable wing tip strake by varying its streamwise location of the leading-edge sweep break point has been conducted. Starting with the findings of previous studies that it is beneficial to move the leading-edge break point forward toward 40% of the strake root chord, a relatively short range of 5% of the strake root chord, between 40 and 35%, has been identified as the zone within which the optimum may be located. Once the range of the potential optimum has been bracketed, an additional point (the midpoint of the range) has been examined. These experiments indeed confirmed that the strake having the leading-edge break point located at 37.5% of the strake root chord achieved the best performance. It improved the $(L/D)_{\max}$ of the baseline wing by as much as 24.1% at the optimal lift coefficient of about 0.6. This is 1.0 and 1.6% better than the improvements obtained with the strakes featuring the leading-edge sweep break point at 40 and 35%, respectively. Finally, additional experiments have been conducted, which demonstrated that the advantages of applying movable wing tip strakes are shifted to lower and to higher angles of attack for positive and for negative, respectively, strake deflections relative to the main wing. It has been pointed out that the configuration with movable tip strakes appears to be capable of constantly operating at an optimal setting throughout the whole range of lift coefficients attainable. To better understand the intricacies of the interactions between the classical attached and the controlled separated flows involved, use of flow visualization in future studies appears to be highly beneficial. Further studies at higher Reynolds numbers also appear to be warranted.

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