JOURNAL OF AIRCRAFT
Vol. 47, No. 2, March–April 2010

Engineering Notes

Determining Direction for Optimization of Movable Wing Tip Strake

Vojin R. Nikolic*
Minnesota State University, Mankato, Minnesota 56001

DOI: 10.2514/1.45830

Nomenclature

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	=	freestream dynamic pressure, kPa, $\frac{1}{2}\rho_\infty V_\infty^2$
R_e	=	Reynolds number based on 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, $N \cdot s/m^2$
ρ	=	air density, kg/m^3

Subscripts

BP	=	break point
s	=	strake
∞	=	freestream conditions

Introduction

STRAKES are lifting surfaces featuring low aspect ratios and highly swept sharp leading edges conventionally located at the fuselage–wing junction. The benefits of using strakes on various airplane configurations have been known since the early 1970s. By imposing controlled flow separation and creating powerful leading-edge vortices that then subject both the strake and the main wing to high rotational velocities, strakes generate significant amounts of additional lift. Movable tip strake is an extension of the strake concept first proposed by the author [1]. Wing-fuselage strakes have been the subject of numerous studies; see, for example, [2–12]. The reader is referred to [1] for an extensive review of strake research.

Movable wing tip strake is a novel design idea. Other researchers have studied fixed wing tip strakes in the past, notably Ma [13], Traub et al. [14], and Staufenbiel and Vitting [15]. The author proposed making them movable in flight. Then the advantageous effect of the strakes on the aircraft performance is achieved *without* having to set the aircraft to a high α, accompanied by a high C_D. Instead, the optimal angle of operation of the strakes is attained by simply setting independently the strakes relative to the wing. This setting angle then represents an additional variable for controlling the airplane configuration.

Received 4 June 2009; revision received 20 December 2009; accepted for publication 21 December 2009.

*Professor. Associate Fellow AIAA.

First, a simple semidelta movable tip strake (MTS) shown in Fig. 1 was tested in combination with a rectangular baseline wing [1]. The results showed that this configuration outperformed by a factor of 2.24 a modified wing obtained by extending the span of the baseline wing and maintaining the same airfoil and having the same aspect ratio ($\frac{b^2}{S}$) as the wing with movable tip-mounted strakes. By deflecting the strakes up or down, the L/D benefit shifted to a lower, or higher, respectively, α of the main wing, as it would be expected, because the flow conditions on the strake depend on both the α of the wing and d_s.

In subsequent studies, the author studied various planform shapes of MTSs with the objective of maximizing their positive effect as measured by the L/D of the wing-strake configuration for a given C_L [16–21]. Nine various strake planforms, MTS1–9, were tested. These included strakes with straight leading edges swept at angles from 60 to 80 deg, a strake for which the leading edge was a parabolic arc, and a series of strakes featuring two straight-line portions of the leading edge swept at different angles, thus resulting in a leading-edge break point. It has been found that the best performance is achieved with the MTS4, which had a cropped double-delta strake planform featuring an inboard portion swept at 80 deg and an outboard portion swept at 45 deg with the transition, or the leading-edge break point, located at 57.5% of the strake root chord. This strake is shown in Fig. 2. When used at moderate-to-high α of the wing and set to the neutral setting with respect to the wing chord plane, that is, at $d_s = 0$ deg, this strake improved the L/D by approximately 26%. This beneficial effect of the strake persisted at both positive and negative settings of the strake ($d_s > 0$ deg, the strake leading edge up, and $d_s < 0$ deg, the strake leading edge down) and the optimal point corresponding to the $(L/D)_{max}$ shifted to a lower or higher α of the main wing, respectively, as it would be expected. This confirmed the supposition that d_s would represent a new and useful variable for wing configuration control.

To continue to optimize the movable strake design, it appeared of interest to examine the effect of the leading-edge break point position, x_{BP}, while maintaining the inboard and outboard sweep angles of MTS4. Apparently, by moving the break point forward (and, consequently, slightly inboard), the area 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) accomplishes the opposite effect. The relative sizes of the inboard and outboard segments of the strake presumably have an effect on the formation and disposition of the generated leading-edge vortices and the resulting wing-strake aerodynamics. This study has been commenced with the goal to investigate those effects.

Experimental Setup and Procedure

All tests of this study have been done in the low-speed wind tunnel at Minnesota State University. The tunnel has a test section of 305×305 mm and can produce speeds of up to 46 m/s. The lift and drag are measured using a dynamometer-type balance with two linear variable differential transformers. Detailed descriptions of the tunnel and its instrumentation can be found in [22]. All of the data points have been taken at a freestream dynamic pressure of 0.625 kPa so that the maximum lift forces would remain within the range recommended by the balance manufacturer. The Re of the tests, based on the wing chord, has been kept constant at approximately 0.225×10^6.

The wing model used in this study consisted of a rectangular wing with a NACA 4412 airfoil, a span of 161 mm, and a chord of 99 mm. This configuration is referred to as the "baseline wing" (BLW). In the first phase of the study, five MTSs, including the MTS4, were tested. Because of the manner in which the new strakes, all with the same

Fig. 1 Movable wing tip strake used to validate the concept.

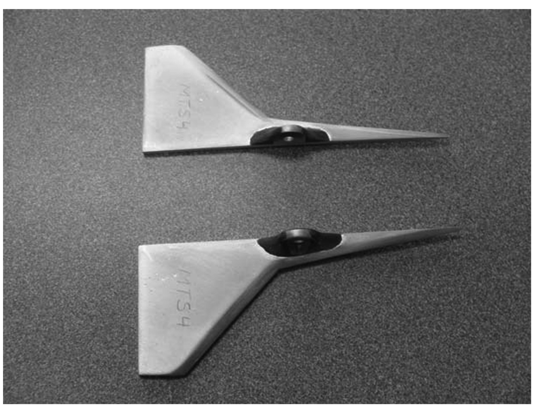

Fig. 2 Best-performing movable tip strake from previous studies.

sweep angles of the inboard and outboard segments of 80 and 45 deg, respectively, were constructed, the MTS4 has been referred to as the MTS4C in this study. The four new strakes are the MTS4A, B, D, and E. The A and B models have the leading-edge break point moved forward from the initial MTS4 (i.e., the MTS4C) strake location, while models D and E have this point moved backward; see Table 1. Figure 3 shows the port (left) halves (semispans) of these five strakes, MTS4A–E, from left to right. Also, a short segment of the baseline wing, the "airfoil," is included for comparison purposes.

In the second phase of the study, based on the results of the first phase (see the Discussion of Results section), two additional strakes were designed, the MTS4A-1 and -2, featuring leading-edge break points farther ahead than those of the MTS4A. Table 1 gives the geometric characteristics of the seven strakes tested in this study calculated from the manufactured dimensions. It is noted that they have been ordered from the one with the forwardmost (the MTS4A-2) to the one with the backwardmost position of the leading-edge sweep break point (the MTS4E), that is, from the smallest to the largest x_{BP} given as a percentage of the strake root chord. Figure 4 shows the MTS4A, A-1, and A-2 versions. All of the strakes had the same design span of 74 mm and the identical root chord of 94 mm, the same thickness of 2.54 mm, and the same attachment brackets

Table 1 Movable tip strakes

Strake	x_{BP}, %	ΔS, %	Aspect ratio
MTS4A-2	40.0	22.9	2.84
MTS4A-1	45.0	21.9	2.88
MTS4A	50.0	20.4	2.92
MTS4B	53.2	19.0	2.91
MTS4C	57.5	17.5	2.95
MTS4C	61.7	16.8	2.96
MTS4E	66.5	15.8	2.99

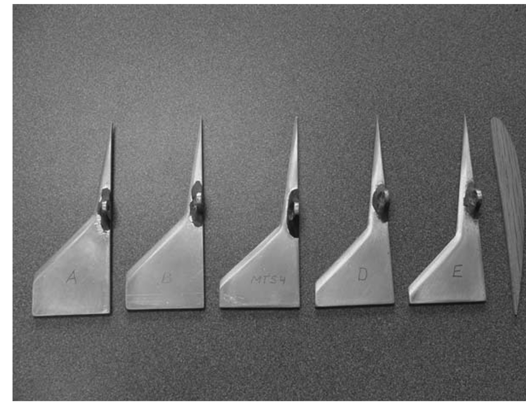

Fig. 3 Five movable wing tip strakes tested in the first phase of this study.

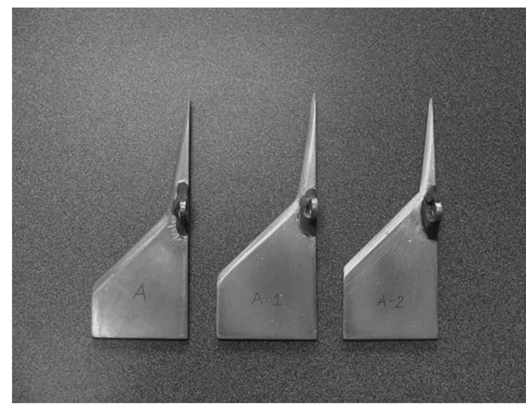

Fig. 4 Movable tip strakes MTS4A, A-1, and A-2, from left to right.

located at 0.485c. The strakes' leading edges were made sharp by applying a symmetrical 45 deg bevel on both sides. The areas of the strakes were included in the reference areas. The drag contribution of the two attachment brackets and the two attachment screw heads have been estimated and subtracted. Figure 5 shows the wing model with the MTS4A-1 installed at $d_s = 0$ deg in the tunnel test section.

The following are estimates of the uncertainties associated with the experimental variables involved in this study. The angle of attack of the wing model could be determined to within ± 0.25 deg. The same estimate is made for the strake setting angle relative to the wing, d_s. 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 all the strakes have been tested at $d_s = 0$ deg. The previous studies have shown that the benefits of adding the strakes, achieved with this setting, shift toward lower, or higher, α or, equivalently, to higher or lower C_L, when the strakes are deflected upward or downward, respectively, relative to the wing [1,16,17,19–21]. Finally, all the results presented have been corrected by applying the standard wind-tunnel corrections [23].

Discussion of Results

Eight different configurations, including the BLW and the combinations of the BLW with the seven different MTSs as described earlier, have been tested over a range of α corresponding to the range from -5 to $+20$ deg, uncorrected. First, a series of five MTSs were tested. They included, in addition to the MTS4 from the previous studies, two strakes for which the break point was moved forward, the MTS4A and B, and two strakes for which the break point was moved backward, the MTSD and E, as described earlier. In this context, the "old" MTS4 was termed the MTS4C, to keep the logical naming sequence. These tests have consistently showed that moving

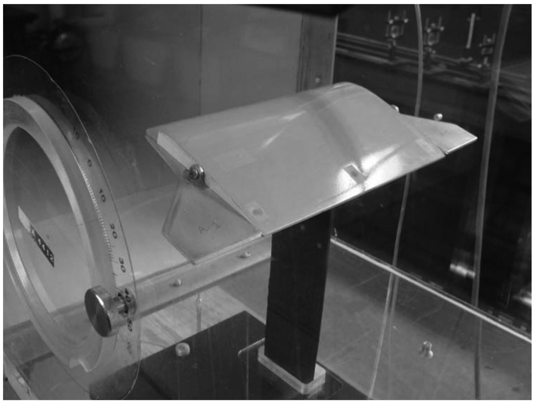

Fig. 5 Movable tip strakes MTS4A-1 installed on baseline wing in wind-tunnel test section.

the sweep break point forward is beneficial, that is, the MTS4A and B strake configurations outperformed the MTS4C, whereas the two configurations with the leading-edge break point located backward, the MTS4D and E, attained L/D consistently lower than that of the MTS4C. Therefore, it was decided to design two additional MTSs whose break points would be located even farther forward than that of the A model, the A-1 and A-2 strakes. The test results for all eight configurations are summarized in Fig. 6.

All the configurations employing MTSs exhibited both higher C_L and higher C_D over the complete range of α. Clearly the measured lift and drag forces were larger than those of the baseline wing. It is noted that the reference areas included the strake areas. The additional lift is primarily due to the vortex lift produced by the strakes' leading-edge vortices. These vortices appear to be rather powerful. After springing from the sharp leading edges of the strakes, they progress downstream, exposing the upper surfaces of the strakes and of the wing to high rotational velocities, thus generating additional lift. It is also possible that some additional lift in the high α range could be attributed to a potentially favorable interaction of the strake flow, the vortices, and the main wing flow in the tip region, thus postponing, or reducing, the flow separation from the main wing. The additional drag is due to both higher zero lift drag and higher induced drag. The overall effect, as measured by the lift-to-drag ratio, has been found to be beneficial; see Fig. 6. It indicates that, in addition to all the strakes improving the L/D, they also extend the range of available C_L. It is seen from this figure that the strakes with the leading-edge sweep break point ahead of that of the MTS4C outperformed the MTS4C, that is, it is advantageous from the L/D standpoint to have this point forward. It is pointed out that these differences are much more pronounced if the uncorrected values of C_D are used. The configurations employing strakes create much higher lift values; thus, the drag coefficient correction terms [23], which vary as C_L^2, are much higher than the values for the BLW. However, as stated earlier, all the results included in the paper present corrected values.

These results clearly point to the direction in which the optimal configuration should be sought, by moving the leading-edge break point forward. Apparently, the leading-edge vortex system from the strake is affected by these changes to the leading-edge geometry. By moving the sweep break point forward and leaving everything else the same, the highly swept inboard portion of the strake becomes shorter and the area of the moderately swept outboard portion increases. It could be that, in that case, some of the possibly reduced strength of the vortex separating from the shorter inboard leading edge is compensated for by the increased area over which this vortex, as well as the vortices generated by the outboard portion and the leading edge kink, act. It is also possible that there exists a minimum length of the highly swept sharp leading edge, which is necessary for the formation of the bulk of a leading-edge vortex structure, and that even in the case of the MTS4A-2 the length of the available leading edge satisfies that requirement. Further studies are necessary to explain this behavior. Finally, a comparison of the numerical values of the maximum L/D for the BLW, the MTS4C, and the MTS4A-2 yields an L/D increase of approximately 23 and 25% for the MTS4C and the MTS4A-2, respectively, over the BLW. It is noted that the improvement for the MTS4C is somewhat smaller than that previously found. It is believed that the small difference may be attributed to the difficulty in duplicating exactly the α and d_s settings and to the possible combined effects of other experimental uncertainties. It is noted that the strakes could have been at effective angles 1 deg apart.

The additional C_L for the configurations with strakes clearly shows a nonlinear character typical of vortex lift generated by strakes. Figure 7 shows C_L versus α for the three most significant configurations of the study, the BLW, the MTS4C, and the MTS4A-2. The remaining MTS configurations have been omitted in this figure to avoid unnecessary clutter. Whereas the BLW exhibits the classical linear range characteristic of attached wing flow, the curves

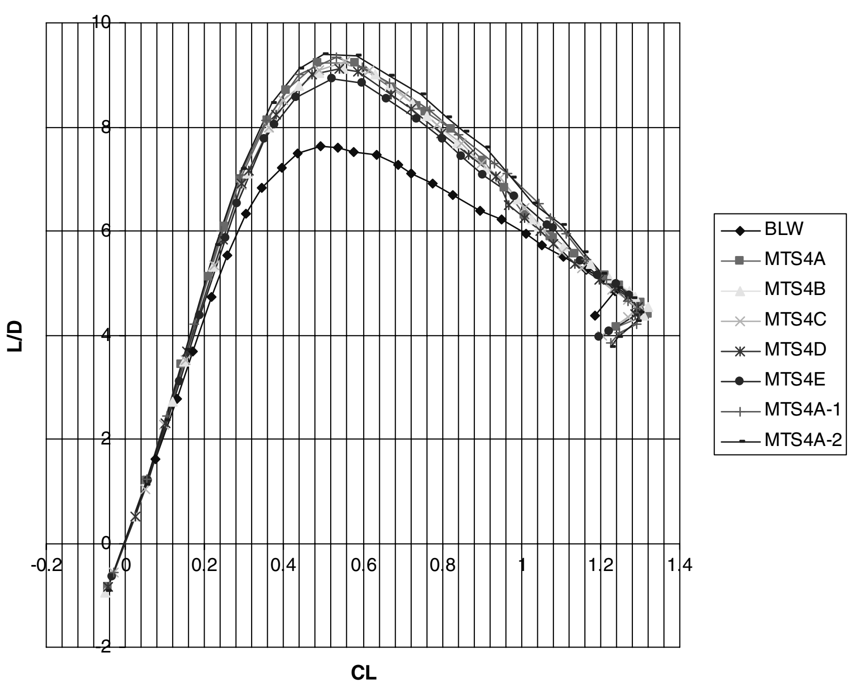

Fig. 6 Effect of movable tip strakes on lift-to-drag ratio.

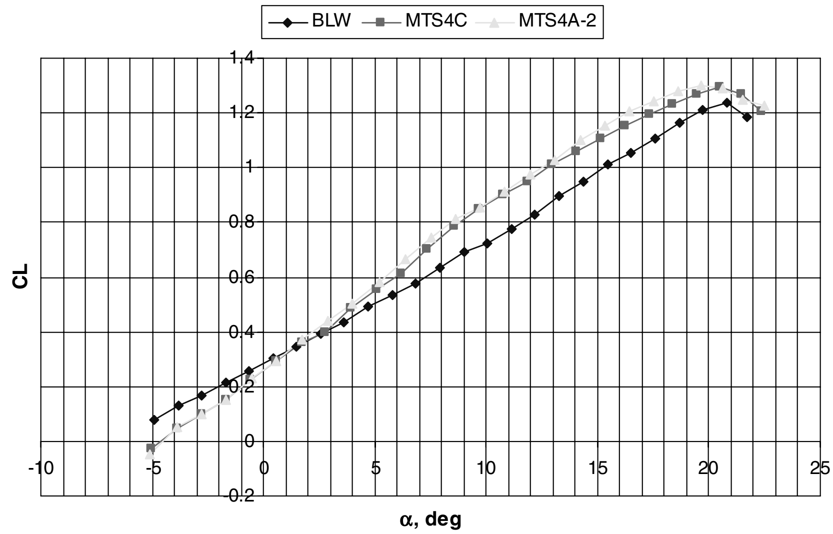

Fig. 7 Effect of movable tip strakes on lift coefficient.

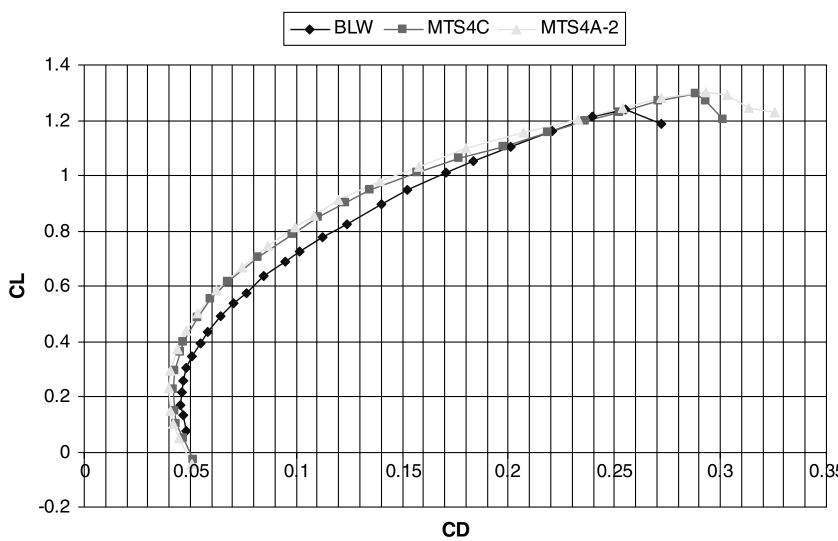

Fig. 8 Effect of movable tip strakes on drag polars.

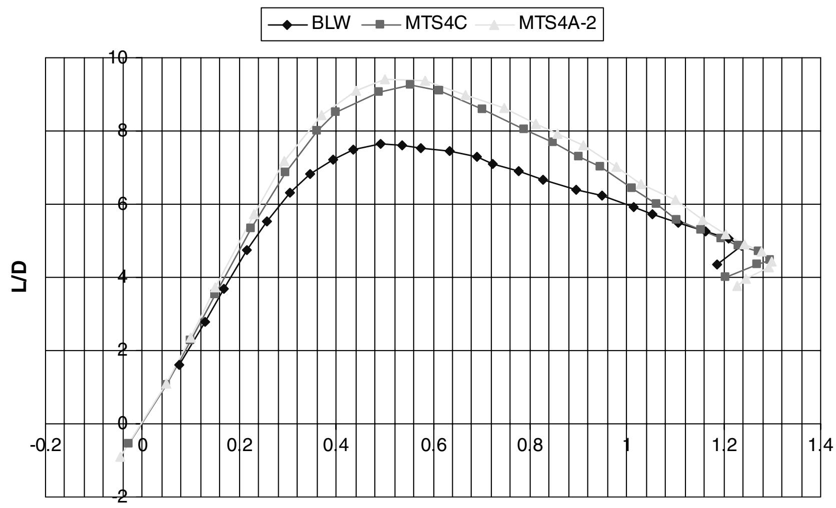

Fig. 9 Effect of movable tip strakes on lift-to-drag ratio for the three most significant configurations of the study.

corresponding to the two configurations with strakes are clearly nonlinear, as they should be. Also, the curves for the two configurations with strakes show higher lift gradients, $dC_L/d\alpha$. This is believed to be due to a combined effect of the strake action and the increased aspect ratio. These combined effects were addressed in [1] using a rectangular wing with the same aspect ratio as the wing with the MTS. Figure 8 shows the drag polars for the same three configurations. It can be seen from this figure that, over most of the range of α, the configurations with strakes exhibit lower C_D than the BLW at the same C_L. On the other hand, the drag forces generated by the configurations with strakes were found to be larger. It should be kept in mind that the configurations equipped with strakes are capable of producing higher lift coefficients. Figure 9, a subset of Fig. 6, shows the L/D ratio as a function of C_L for the three most significant configurations. It is seen that the MTS4A-2 outperforms the MTS4C over a wide range of C_L. It is clearly of interest to continue this study by investigating those configurations of this strake that will have the leading-edge break point still farther forward. Because the structural weight of these movable wing tip strakes is relatively small, it is believed that the overall effect on the airplane's specific excess power will be highly beneficial.

Conclusions

An experimental study with the objective of determining the effect of moving the leading-edge sweep break point of a cropped double-delta movable wing tip strake on its aerodynamic performance has been conducted. A series of four strake configurations, along with an initial planform, which had been found in previous studies to be highly efficient, have been tested over a wide range of angles of attack. It has been found that moving the sweep break point forward increases the L/D of the configuration. Also, it has been shown that moving the break point backward is detrimental, using the maximum L/D criterion. To further explore this trend, two additional strakes with the break point farther forward have been designed and tested; the results confirmed the previously identified trend. Of the seven strake configurations tested, the best L/D has been obtained with the strake with the break point farthest forward of any strake in the study, at 40% of the strake root chord. The addition of this strake improved the L/D of the baseline wing by approximately 25%. The study has clearly determined the direction in which the optimal strake configuration should be sought. Further studies, with the goal of optimizing the wing-movable tip strake configuration, appear to be warranted.

References

[1] Nikolic, V. R., "Movable Tip Strakes and Wing Aerodynamics," *Journal of Aircraft*, Vol. 42, No. 6, 2005, pp. 1418–1426. doi:10.2514/1.4615

[2] Sohn, M. H., Lee, K. Y., and Chang, J. W., "Vortex Flow Visualization of a Yawed Delta Wing with Leading-Edge Extension," *Journal of Aircraft*, Vol. 41, No. 2, March–April 2004, pp. 231–237. doi:10.2514/1.9281

[3] Schultz, M. P., and Flack, K. A., "Effect of Strake Geometry and Centerbody on the Lift of Swept Wings," *Journal of Aircraft*, Vol. 39, No. 2, March–April 2002, pp. 377–379. doi:10.2514/2.2938

[4] Moss, G. F., "Some UK Research Studies of the Use of Wing-Body Strakes on Combat Aircraft Configurations at High Angles of Attack," CP-247, AGARD Paper 4, 1979.

[5] Luckring, J. M., "Aerodynamics of Strake-Wing Interactions," *Journal of Aircraft*, Vol. 16, No. 11, Nov. 1979, pp. 756–762. doi:10.2514/3.58600

[6] Lamar, J. E., "Analysis and Design of Strake-Wing Configurations," *Journal of Aircraft*, Vol. 17, No. 1, Jan. 1980, pp. 20–27. doi:10.2514/3.57870

[7] Lamar, J. E., and Frink, N. T., "Aerodynamic Features of Designed Strake-Wing Configurations," *Journal of Aircraft*, Vol. 19, No. 8, Aug. 1982, pp. 639–646. doi:10.2514/3.57444

[8] Rao, D. M., and Campbell, J. F., "Vortical Flow Management Techniques," *Progress in Aerospace Sciences*, Vol. 24, No. 3, 1987, pp. 173–224. doi:10.1016/0376-0421(87)90007-8

[9] Polhamus, E. C., "Applying Slender Wing Benefits to Military Aircraft," *Journal of Aircraft*, Vol. 21, No. 8, Aug. 1984, pp. 545–559. doi:10.2514/3.45023

[10] Beyers, M. E., "From Water Tunnel to Poststall Flight Simulation: The F/A-18 Investigation," *Journal of Aircraft*, Vol. 39, No. 6, Nov.–Dec. 2002, pp. 913–926. doi:10.2514/2.3026

[11] Fujii, K., and Schiff, L. B., "Numerical Simulation of Vortical Flows Over a Strake-Delta Wing," *Journal of Aircraft*, Vol. 27, No. 9, Sept. 1989, pp. 1153–1162. doi:10.2514/3.10239

[12] Nelson, R. C., and Pelletier, A., "The Unsteady Aerodynamics of Slender Wings and Aircraft Undergoing Large Amplitude Maneuvers," *Progress in Aerospace Sciences*, Vol. 39, Nos. 2–3, Feb.–April 2003, pp. 185–248. doi:10.1016/S0376-0421(02)00088-X

[13] 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. doi:10.2514/3.45778

[14] Traub, L. W., Galls, S. F., and Redniotis, O., "Effects of Wing-Tip Strakes on Sheared-Tip Wing," *Journal of Aircraft*, Vol. 36, Nov.–Dec. 1999, pp. 1055–1062. doi:10.2514/2.2549

[15] 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, 1991, pp. 1, 6, 13.

[16] Nikolic. V. R., "Planform Effects on Wing-Movable Tip Strake Aerodynamic Performance," AIAA Paper 2006-7705, Sept. 2006.

[17] Nikolic, V. R., "Examining a Family of Movable Wing Tip Strakes Involving Varying Leading Edge Forms and Sweep Angles," AIAA Paper 2007-1270, Jan. 2007.

[18] Nikolic, V. R., "Planform Variations and Aerodynamics Efficiency of Movable Tip Strakes," *Journal of Aircraft*, Vol. 44, No. 1, Jan.–Feb. 2007, pp. 340–343. doi:10.2514/1.23490

[19] Nikolic, V. R., "Effect of Leading-Edge Form on Performance of Wing-Movable Tip Strake Configurations," *Journal of Aircraft*, Vol. 44, No. 5, Sept.–Oct. 2007, pp. 1749–1753. doi:10.2514/1.30322

[20] Nikolic, V. R., "Low-Sweep and Composite Planform Movable Wing Tip Strakes," AIAA Paper 2008-0290, Jan. 2008.

[21] Nikolic, V. R., "Examining Effects of Increased Effective Area on Performance of Movable Tip Strakes," *Journal of Aircraft*, Vol. 45, No. 4, July–Aug. 2008, pp. 1460–1463. doi:10.2514/1.32929

[22] 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. doi:10.2514/1.3888

[23] Barlow, J. B., Rae, W. H., Jr., and Pope, A., *Low-Speed Wind Tunnel Testing*, 3rd ed., Wiley, New York, 1999, pp. 367–390.