AIAA 81-0357R

Hinged Strakes for Enhanced Maneuverability at High Angles of Attack

Dhanvada M. Rao*
Vigyan Research Associates, Inc., Hampton, Va.
and
Jarrett K. Huffman†
NASA Langley Research Center, Hampton, Va.

A controllable strake concept for alleviating the adverse effects of vortex breakdown on the longitudinal and lateral aerodynamics of strake-wing configurations at high angles of attack is presented. The concept aims to control the strake load independently of angle of attack and sideslip by varying the anhedral angle of strakes hinged along the root chord. The strakes may be deflected symmetrically or nonsymmetrically for longitudinal or lateral control functions. This paper presents the results of an exploratory wind-tunnel investigation to evaluate the potential of the hinged-strake concept for enhanced three-axis controllability in post-stall flight.

Nomenclature

b = wing reference span = 50.80 cm
C_L = total lift coefficient = lift/qS
$C_{L,2}$ = forebody lift coefficient (based on reference area S)
$C'_{L,2}$ = forebody lift coefficient (based on exposed strake projected planform area)
$C_{L,w}$ = wing lift coefficient = $C_L - C_{L,2}$
C_l = total rolling moment coefficient = rolling moment/qSb
C_m = total pitching moment coefficient = pitching moment/$qS\bar{c}$
$C_{m,2}$ = forebody pitching moment coefficient
C_n = total yawing moment coefficient = yawing moment/qSb
$\Delta C_{n\beta,2}$ = forebody yawing moment derivative increment = [$\partial C_{n,2}/\partial\beta$ deflected strakes $- \partial C_{n,2}/\partial\beta$ undeflected strakes]
$\bar{c}$ = reference chord = 23.33 cm
q = freestream dynamic pressure
S = wing reference area = 1032 cm^2
α = angle of attack
β = angle of sideslip

Introduction

HIGHLY swept strakes (or leading-edge extensions) applied to trapezoidal wings have dramatically improved the subsonic maneuverability of contemporary fighters exemplified by F-16 and F-18. The aerodynamic basis of strakes is generally well understood.[1,2] The strake vortices generated at high angles of attack greatly improve the maximum lift capability of the basic wing by way of induced suction over the inboard surfaces directly under the vortices and additionally through beneficial interaction with the separating flow outboard on the wing. As a result, the abruptness of stall and severity of buffet are also alleviated. When the overall airframe including empennage is configured to properly take into consideration the strake vortices, lateral and directional stability may also be improved at elevated angles of attack.

These beneficial effects, however, are degraded or may even be reversed at higher angles of attack as the upstream-moving breakdown of the strake vortices begins to influence first the tail surfaces and then the wing itself. The main effects are nonlinearities in the pitching moment and a rapid decline of the lift-curve slope, accompanied by pitch-up as the center of pressure moves forward to the strakes.[2] Seemingly minor asymmetries of the airframe or in the flight attitude cause unequal progression of breakdown in the vortex pair and generate sudden and unpredictable rolling and yawing moments. Sideslip guarantees asymmetrical vortex breakdown, leading to lateral/directional instabilities (see, for example, Ref. 3). When such adverse tendencies coincide with degraded control effectiveness commonly occurring at high angles of attack, serious handling difficulties and reduced resistance to departure may result.

Attempts at refining the strake shape have enabled the angle of attack for vortex breakdown to be raised by a few degrees[4]; however, the potential for further gains by planform shaping alone appears limited. For a breakthrough towards "unlimited alpha" maneuver capability, strake technology must logically develop in the direction of variable geometry. Variable strakes should provide a mechanism for controlled deviations from the otherwise fixed relationship between vortex strength and angles of attack and sideslip, thereby allowing a more precise control of the post-stall flight characteristics while still providing the aerodynamic benefits of the strake at intermediate angles of attack. While the advantages of variable geometry strakes have previously been discussed,[5] a satisfactory and practical device has yet to emerge. For example, the variable incidence or camber approaches studied in Ref. 5, although aerodynamically effective, will pose structural design, flutter, sealing, and actuation problems. This paper describes a "hinged-strake" concept which appears to avoid the above-mentioned practical difficulties, and presents selected results of a wind-tunnel investigation conducted to explore its aerodynamic aspects.

The "Hinged-Strake" Concept

The proposed concept aims to control the strake aerodynamic characteristics independently of angle of attack by varying the strake anhedral. Not only is this a simple means of varying the projected strake planform area, but the anhedral configuration is also known to reduce the normal force coefficient at a given angle of attack, both the potential and vortex contributions being affected.[1] Although direct

Presented as Paper 81-0357 at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Mo., Jan. 12-15, 1981; submitted March 4, 1981; revision received July 30, 1981.

*Vice President. Member AIAA.
†Aerospace Technologist.

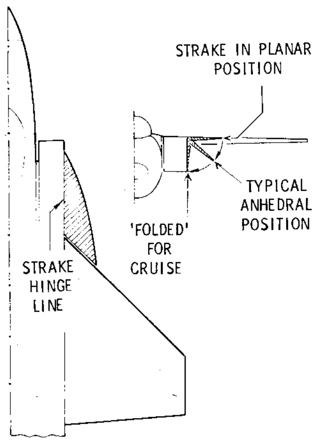

Fig. 1 Hinged-strake concept illustrated on a hypothetical aircraft configuration.

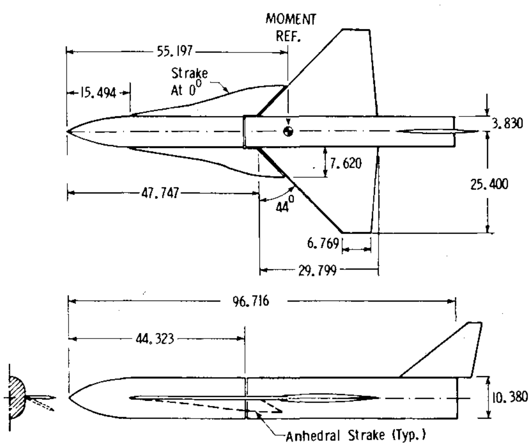

Fig. 2 Model geometry and major dimensions, in centimeters.

evidence is lacking, it is surmised that anhedral reduces the vortex strength and by implication postpones its breakdown to a higher angle of attack.

As shown in Fig. 1, the strakes are hinged along a longitudinal axis close to the root chord and rotated downwards to an anhedral configuration when a specified angle of attack is exceeded. By controlling the anhedral angle, the load on the strake as well as its induced effect on the wing flow are modulated. This mechanism may be utilized to control the aircraft in a variety of ways, particularly at post-stall angles of attack when the conventional control surfaces have been degraded by separation and wake effects, whereas the strakes continue to be effective. Thus both strakes may be actuated in unison to dump the strake load and thus alleviate the pitch-up tendency when exceeding a critical angle of attack. By deflecting the strakes in a differential mode, a unique roll control system is obtained. Asymmetric anhedral may also be utilized to generate a controlled side force on the forebody and therefore a yawing moment to counter nose-slice and directional divergence. The hinged strake may conceivably be folded against the fuselage in order to eliminate its skin friction penalty in supersonic cruise.

Model and Test Details

The model was a wing-body-strake-vertical tail configuration employed in a previous investigation.[2] A trapezoidal wing of aspect ratio 2.5 and 44-deg leading-edge sweep was combined with the largest strakes of Ref. 2 (exposed area equals 26.6% of wing reference area) as a test configuration judged to be well-suited for the purpose of the present study, viz., to clearly bring out the effects of strake anhedral. The model geometry and leading dimensions are presented in Fig. 2. A dual balance arrangement was housed in the two-part fuselage, the forebody supporting the strakes being independent of the aft fuselage on which the wings were mounted. The strakes in the conventional (i.e., coplanar) configuration were physically separated from the wing leading edges by a small (approximately 1 mm) gap. Thus the strake loads could be monitored separately from the total loads. Three sets of strakes identical in planform were fabricated to simulate 0-, 30-, and 45-deg anhedral when attached to the forebody.

The tests were conducted in the NASA Langley 7×10-ft high-speed tunnel at a nominal Mach number of 0.3 and a 1.3×10^6 Reynolds number based on a 23.3-cm mean geometrical chord. The angle of attack ranged from -4 to 40 deg, at sideslip angles of 0 and ± 5 deg. Corrections were applied to angles of attack and sideslip to account for balance and sting deflections.

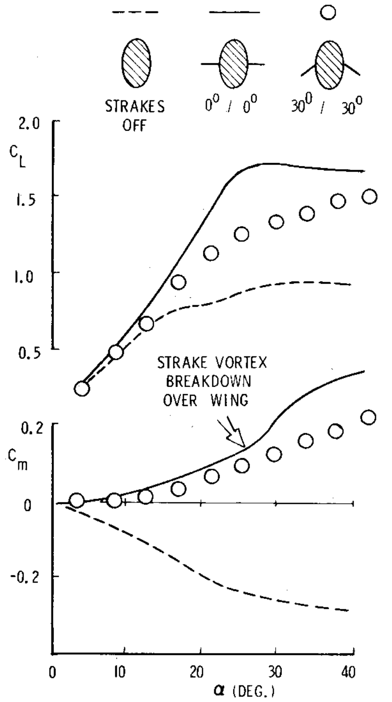

Fig. 3 Longitudinal characteristics with symmetric strakes.

Results and Discussion

The longitudinal and lateral/directional characteristics of the model with strakes deflected will be assessed in comparison with data for undeflected strakes, emphasizing the high angle-of-attack regime. The overall characteristics as measured by the main balance, as well as those measured separately by the forebody balance and representing the strake loading, will be discussed as appropriate. The results have been grouped in the following subsections according to whether the strakes were deflected symmetrically or nonsymmetrically and for conditions with or without sideslip. Note that the lateral and directional aerodynamic moments shown are with respect to the body axis.

Symmetrical Strakes at Zero Sideslip

The total lift coefficient with undeflected (0 deg/0 deg) strakes, shown as the solid curve in Fig. 3, indicates the typical improvement provided by the strakes at high angles of attack in comparison with the basic wing represented by the dashed curve. The incremental lift reaches a maximum at approximately 26-deg angle of attack, which corresponds reasonably well with the arrival of vortex breakdown over the wing as observed during the subsequent smoke visualization tests conducted at very low speeds. [The identification of vortex breakdown from the balance data lacks precision because of the relatively coarse (i.e., 4 deg) increments of angle of attack; its correspondence with visual results is equally uncertain owing to the nonstationary breakdown position in the smoke test. However, this is not regarded as a deficiency in the present investigation, which primarily was concerned with the modification of overall force and moment characteristics produced by strake anhedral.] The leveling off in total lift coincides with a pronounced nose-up trend in the pitching moment, indicating a rapid forward movement of the center of pressure as the wing flow begins to separate, while vortex-induced lift continues to build on the planar strakes themselves. This feature is notably absent in the data for strakes set at 30-deg anhedral (circle symbols), which yield smoother lift and pitching moment characteristics through the angle-of-attack range.

Further insight into the effect of strake anhedral is offered by simultaneous measurements of body-axis rolling and yawing moments, as shown in Fig. 4. A minor asymmetry either of the model or in the relative wind causes unequal loading of the 0 deg/0 deg strakes and a consequent rolling moment, both increasing with angle of attack. Approaching the incipient breakdown condition, the stronger vortex, related to the more heavily loaded strake, collapses earlier, leading to a sudden rolling-moment reversal. Asymmetric vortex breakdown also generates a yawing moment. The angle of attack for the onset of the above lateral/directional behavior is consistent with the breaks in the longitudinal data of Fig. 3 and with the observed vortex breakdown. By contrast, the results for anhedral strakes are free of pronounced roll and yaw disturbances. These results suggest that the anhedral strake vortices either remain stable well past the breakdown angle of attack of planar strakes, or are too weak to produce significant effects of breakdown on the forces and moments.

It was observed (Fig. 3) that strake deflection caused a loss of total lift compared to the planar strakes. However, this apparent lift loss has less operational significance, since it occurs mainly at angles of attack when the planar strake vortices are close to breakdown with the consequent onset of pitch-up and lateral/directional difficulties.

The dual-balance system utilized in this investigation allowed the strake and wing loads to be monitored separately. The forebody balance data were changed to

$$C'_{L,2} = C_{L,2} \times \frac{\text{Reference area}}{\text{Strake exposed area}}$$

to obtain the strake lift coefficient based on its own projected area, while the difference of the outputs of the two balances gave $C_{L,w} = C_L - C_{L,2}$, representing the wing lift coefficient. These are plotted vs angle of attack in Fig. 5 for two strake deflections (indicated by symbols) and compared with strake-off (dashed curve) and undeflected strake (solid curve). The relatively high strake lift coefficients result from the large upwash induced at the strakes by the forebody and the wing, and additionally because the lift carried by forebody is assigned to the strakes. The aerodynamic effect of anhedral is to progressively linearize the strake lift curve and to smooth the "stall" of the planar strakes associated with vortex breakdown. These data lend credence to the supposition that anhedral weakens the strake vortex and that the hinged strake modulates the strake lift through planview projected area variation coupled with vortex strength control. Further, the diminished vortex intensity with anhedral delays the strake vortex breakdown to a higher angle of attack or alleviates its adverse consequences.

The pitching-moment data measured by the forebody balance are presented in Fig. 6. Not only are the results for deflected strakes more linear with angle of attack, they also indicate that significant pitch control can be obtained at high

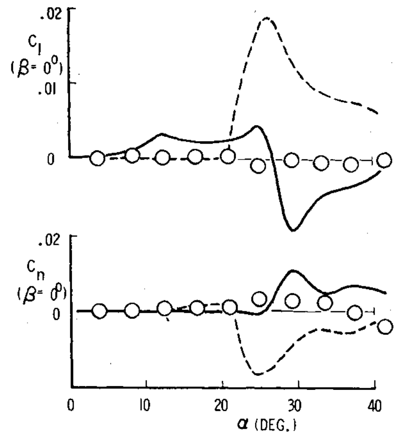

Fig. 4 Lateral and directional characteristics with symmetric strakes at zero sideslip (legend as in Fig. 3).

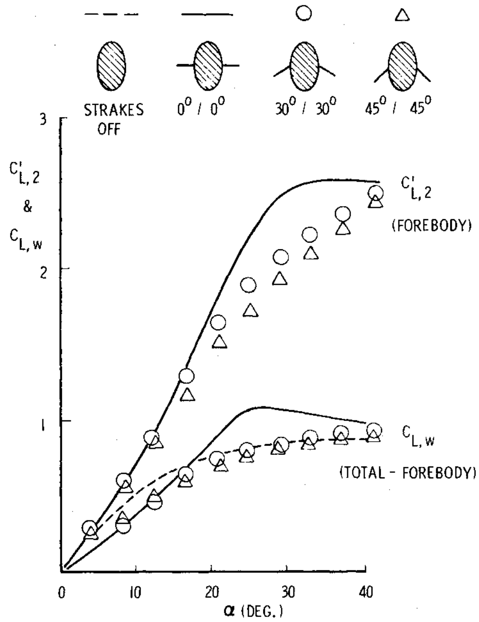

Fig. 5 Component lift coefficients with symmetric strakes.

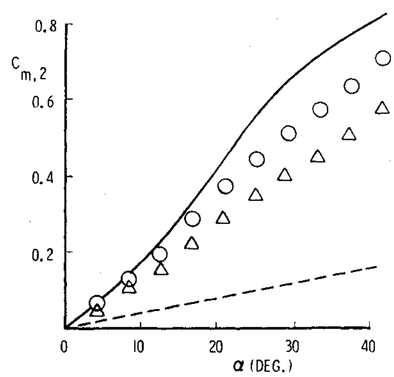

Fig. 6 Forebody component of pitching moment with symmetric strakes (legend as in Fig. 5).

alpha by varying the anhedral angle. In particular, the use of hinged strakes offers an effective pitch-down control capability, which is known to contribute significantly to post-stall maneuverability.[6,7]

To summarize the results presented in this section, strakes with anhedral are found to produce more linear longitudinal characteristics and also to alleviate the zero sideslip

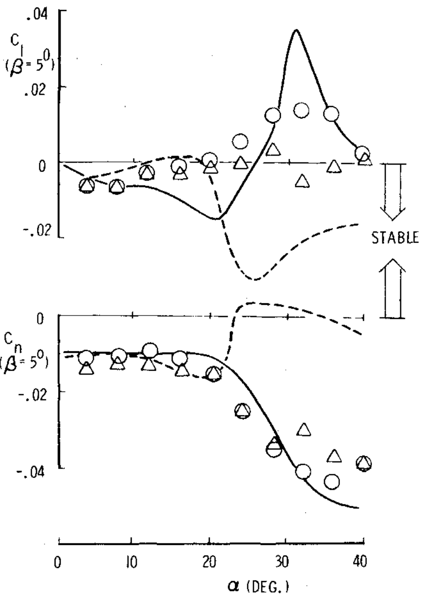

Fig. 7 Lateral and directional characteristics with symmetric strakes in sideslip (legend as in Fig. 5).

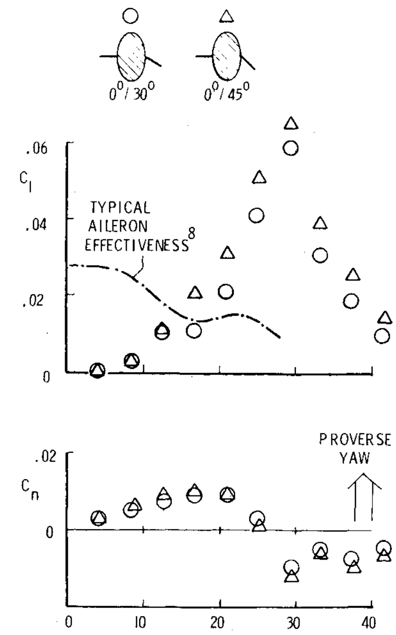

Fig. 8 Rolling moment and associated yaw with asymmetric strakes at zero sideslip.

lateral/directional disturbances associated with vortex breakdown at high angles of attack. In combination with basic trapezoidal wings, therefore, strakes with anhedral appear to represent a more favorable aerodynamic configuration than conventional planar strakes with respect to high alpha maneuverability. In addition, articulated strakes with variable anhedral angle offer an effective pitch-down control capability for use in the post-stall regime when conventional (aft-tail) pitch controls may be inadequate.

Symmetrical Strakes at Sideslip

The advantage of strakes with anhedral over planar strakes evident in symmetric high-angle-of-attack flight invites a consideration of their characteristics in sideslip. Body-axis rolling and yawing moment data measured at 5-deg sideslip are shown in Fig. 7. Whereas the strakes-off configuration (shown with dashed curve) becomes strongly stable both laterally and directionally at angles of attack exceeding about 20 deg, the addition of planar strakes (solid curves) has just the opposite, i.e., destabilizing, effect. This well-known behavior of planar strake configurations in sideslip is a result of accelerated breakdown of the windward strake vortex (see, for example, Ref. 3). The vortex-alleviating characteristic of anhedral strakes would therefore be expected to show a corresponding improvement, as is strikingly evident in the rolling-moment due to sideslip particularly for 45 deg/45 deg strakes in Fig. 7. The corresponding improvement in directional stability is not quite so impressive. Note, however, that these are vertical-tail-off data; it is generally known that the high-alpha directional stability of strake-wing configurations is controlled primarily by the vertical-tail design.

Asymmetric Strakes at Zero Sideslip

Hinged strakes allow the possibility of asymmetric deflection in order to command lateral and directional control forces and moments. This capability is particularly attractive at high angles of attack when the conventional aft controls are starting to lose effectiveness, whereas the strakes continue to be aerodynamically active. This section examines the feasibility of roll control in symmetric flight by deflecting one strake down while the other remains in the 0-deg position. This special type of asymmetry was expedient in the present wind-tunnel program; in general, both strakes may be deflected to unequal anhedral angles to achieve the same purpose.

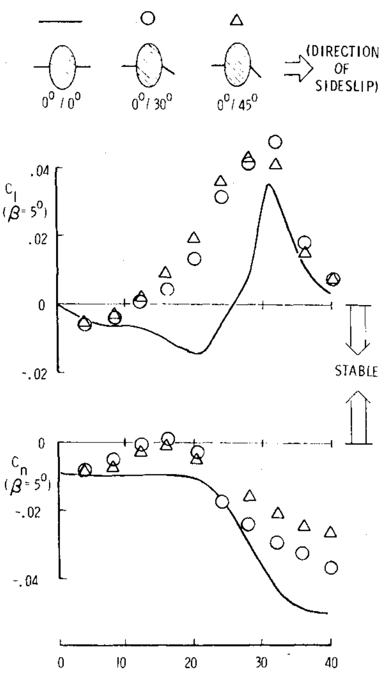

Fig. 9 Lateral and directional characteristics with asymmetric strakes in sideslip.

With only the right-hand strake deflected, the reduced strake projected area together with a weaker strake vortex reduces the lift on the right-hand panel, thus generating a positive rolling moment. The differential lift and the associated rolling moment increase with angle of attack until the vortex from the left-hand (i.e., undeflected) strake breaks down. This behavior is well indicated in the body-axis rolling moment data presented in the upper part of Fig. 8. Also shown for comparison is the result with 30-deg aileron deflection obtained on a comparable rigid model configuration.[8] The asymmetric strakes generate substantially greater roll power than conventional ailerons at the higher angles of attack, even after vortex breakdown. When the anticipated adverse effect of aileron-induced twist of an

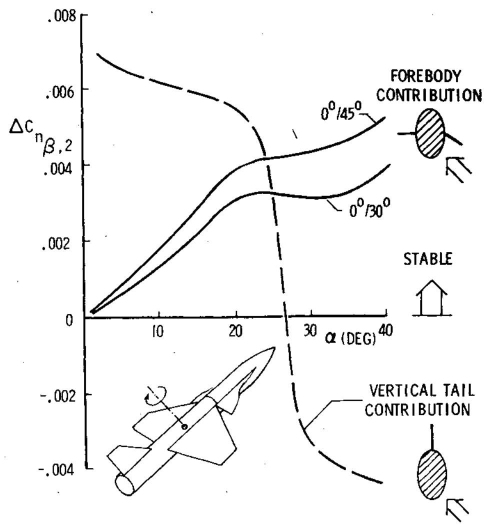

Fig. 10 Forebody yawing moment increment due to sideslip with asymmetric strakes; vertical tail contribution.

elastic wing is taken into consideration, this roll-effectiveness comparison will favor the asymmetric strakes even more.

The asymmetric strake arrangement also produces a yawing moment mainly due to a side force generated on the forebody (as evidenced by the nose-balance measurements, not shown). The body-axis yawing moment data shown in the lower part of Fig. 8 indicate a proverse yaw up to 25-deg angle of attack, changing at higher alpha to adverse yaw, which, however, remains small relative to the rolling moment levels. This is yet another aspect favoring the hinged strake as a roll device when compared with conventional ailerons whose adverse yaw characteristics can contribute to departure tendencies.

Asymmetric Strakes at Sideslip

Asymmetric deflection of hinged strakes may also be utilized to control the high alpha behavior in sideslip; e.g., to counter nose-slice and for recovery from sideslip. The effect of deflecting the windward strake (i.e., the one in the direction of sideslip, the opposite strake remaining at 0 deg) on the lateral-directional characteristics is shown in Fig. 9. This asymmetrical strake configuration at angles of attack above 30 deg is found to generate stabilizing yawing moment increments (relative to the planar strake characteristics shown by solid curve) in association with minor incremental rolling moment. The limited data show the favorable yawing moment increment to increase with strake angle. This is further illustrated by the forebody balance measurements presented in the form of incremental yawing moment derivative $\Delta C_{n\beta,2}$ (relative to planar strakes) plotted vs angle of attack in Fig. 10. The vertical tail contribution to weather-cock stability measured by the main balance is also indicated by dashed curve for comparison. From these data, differentially deflected hinged strakes show promise as effective sideslip controllers at high angles of attack when rudder effectiveness is degraded by immersion of the aft-tail in low-dynamic-pressure flow.

Concluding Remarks

A hinged-strake concept has been proposed as an approach to variable geometry strakes for improved controllability in the post-stall regime. An exploratory wind-tunnel investigation of the concept on a fighter research configuration up to 40-deg angle of attack has shown that 1) strakes with anhedral generate more linear longitudinal characteristics at angles of attack approaching and exceeding the vortex breakdown onset on planar strakes; 2) symmetrically controlled anhedral of the strakes can provide an effective pitch control at high angles of attack; and 3) differential strake anhedral appears as a powerful motivator for roll and yaw at high angles of attack when conventional aileron and rudder controls are degraded.

From the results of this preliminary study, hinged strakes appear to be a promising and practical means for combining the maneuver benefits of conventional strakes in the well-behaved vortex regime, with enhanced controllability at higher angles of attack when vortex breakdown effects lead to stability problems and the conventional controls lose effectiveness. Further research is needed to clarify the flowfields associated with these strakes, and also tests on a more realistic fighter model in order to answer questions concerning the configuration design aspects.

Acknowledgment

Research supported by NASA.

References

[1] Kuchemann, D., *The Aerodynamic Design of Aircraft,* Pergamon Press, N.Y., 1978, p. 381.

[2] Luckring, J. M., "Aerodynamics of Strake-Wing Interactions," *Journal of Aircraft,* Vol. 16, Nov. 1979, pp. 756-762.

[3] Johnson, J. L. Jr., Grafton, S. B., and Yip, L. P., "Exploratory Investigation of Vortex Bursting on the High Angles of Attack Lateral-Directional Stability Characteristics of Highly Swept Wings," *Proceedings of the AIAA 11th Aerodynamic Testing Conference,* 1980, pp. 282-297.

[4] Frink, N. T. and Lamar, J. E., "An Analysis of Strake Vortex Breakdown Characteristics in Relation to Design Features," AIAA Paper 80-0326, Jan. 1980.

[5] Moss, G. F., "Some UK Research Studies of the Use of Wing-Body Strakes on Combat Aircraft Configurations at High Angles of Attack," AGARD-CP-247, Paper 4, 1978.

[6] Herbst, W. B., "Future Fighter Technologies," *Journal of Aircraft,* Vol. 17, Aug. 1980, pp. 561-566.

[7] Nguyen, L. T., Gilbert, W. P., and Grafton, S. B., "Control Considerations for CCV Fighters at High Angles of Attack," AGARD-CP-262, Paper 11, May 1979.

[8] Staudacher, W. et al., "Aerodynamic Characteristics of a Fighter-Type Configuration During and Beyond Stall," AGARD-CP-247, Paper 8, Oct. 1978.