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MANEUVER AND BUFFET CHARACTERISTICS OF FIGHTER AIRCRAFT

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16. Abstract

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SUMMARY

Recent research efforts in the improvement of the maneuverability of fighter aircraft in the high-subsonic and transonic speed range are reviewed in the present paper with emphasis on the factors affecting aerodynamic boundaries, such as maximum obtainable lift, buffet onset, pitchup, "wing rock," and "nose slice." The investigations were made using a general research configuration which encompassed a systematic matrix of wing-design parameters. These results illustrated the sensitivity of section and planform geometry to a selected design point. The incorporation of variable-geometry wing devices in the form of flaps or leading-edge slats was shown to provide controlled flow over a wide range of flight conditions and substantial improvements in maneuver capabilities. Additional studies indicated that the blending of a highly swept maneuver strake with an efficient, moderately swept wing offers a promising approach for improving maneuver characteristics at high angles of attack without excessive penalties in structural weight.

INTRODUCTION

The maneuver and performance capability of aircraft engaged in air-to-air combat is often limited by flow separation which can be manifested in a variety of adverse factors such as buffeting, increases in drag, and losses in lift and stability. Figure 1 illustrates the impact that these limiting factors could have on the maneuver characteristics of a fighter aircraft. This figure illustrates the sensitivity of turn rate to typical aircraft boundaries at subsonic, transonic, and supersonic speeds. The fighter configuration selected for this illustration represents a moderately swept, thin-wing aircraft with a supersonic capability of about Mach 2. The boundaries shown illustrate the relationship between the maximum lift capability of the aircraft, the structural limits, and the steady-turn boundary. The shaded area shown in the high subsonic range represents a region in

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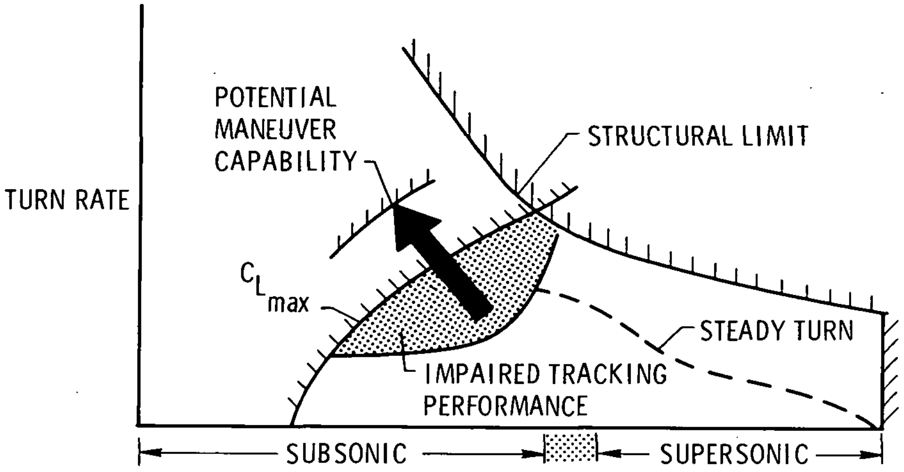


Figure 1.- Maneuver boundaries of a typical fighter aircraft.

which the maneuver capability of the aircraft is impaired as a result of buffeting and degradations in performance and stability.

The present trend toward designing one aircraft to accomplish a variety of missions over wide velocity and altitude spectra often leads to aerodynamic compromises, particularly in this high subsonic and transonic range. It will be noted here that the maximum maneuver capability of this aircraft is restricted by aerodynamic considerations before reaching the limits dictated by available thrust and structures.

There is the potential, therefore, to achieve significant increases in the maneuver characteristics of this and many other aircraft through aerodynamic improvements.

Because of continuing interest in the high-subsonic and transonic combat arena, a considerable amount of research has been directed toward improvement of fighter maneuverability in this speed range. The purpose of this paper is to review some of these research efforts, with emphasis on factors which affect the aerodynamic boundaries illustrated in figure 1 and on methods which have been found to broaden and increase the high-subsonic operating corridor.

SYMBOLS

The longitudinal characteristics shown herein are referred to the stability-axis system and the lateral-directional moments are referred to the body-axis system.

Æ	aspect ratio, b^2/S
b	wing span

c	wing chord
C_D	drag coefficient
ΔC_D	change in drag coefficient
C_L	lift coefficient
$C_{L_{BUF}}$	lift coefficient for buffet onset
$C_{L_{max}}$	maximum usable lift coefficient
ΔC_L	change in lift coefficient
$\Delta C_{L_{BUF}}$	change in buffet-onset lift coefficient
C_l	rolling-moment coefficient
C_{l_β}	rolling moment due to sideslip
C_n	yawing-moment coefficient
C_{n_β}	yawing moment due to sideslip
$C_{n_{\beta_{DYN}}}$	dynamic directional-stability parameter, $\frac{\partial C_n}{\partial \beta} - \frac{I_Z}{I_X}\frac{\partial C_l}{\partial \beta} \sin \alpha$
I_X	rolling moment of inertia
I_Z	yawing moment of inertia
M	Mach number
S	wing reference area
t/c	thickness-chord ratio
α	angle of attack

β	angle of sideslip
δ_f	trailing-edge flap deflection
δ_{le}	leading-edge flap deflection
δ_s	leading-edge slat deflection
$\Lambda_{c/4}$	wing quarter-chord sweep
Λ_{le}	wing leading-edge sweep

RESULTS AND DISCUSSION

Types of Wing Airflow

Before the dependency of the aerodynamic boundaries on specific design variables is discussed, consider the aerodynamic behavior of a fighter configuration with several different airflow conditions over the wing. Figure 2 illustrates the variation of lift with angle of attack for a variable-sweep configuration at a high subsonic Mach number with the wings in a low-sweep position and in a highly swept position. A variable-sweep configuration was selected for this discussion since it illustrates several classic types of wing-flow behavior.

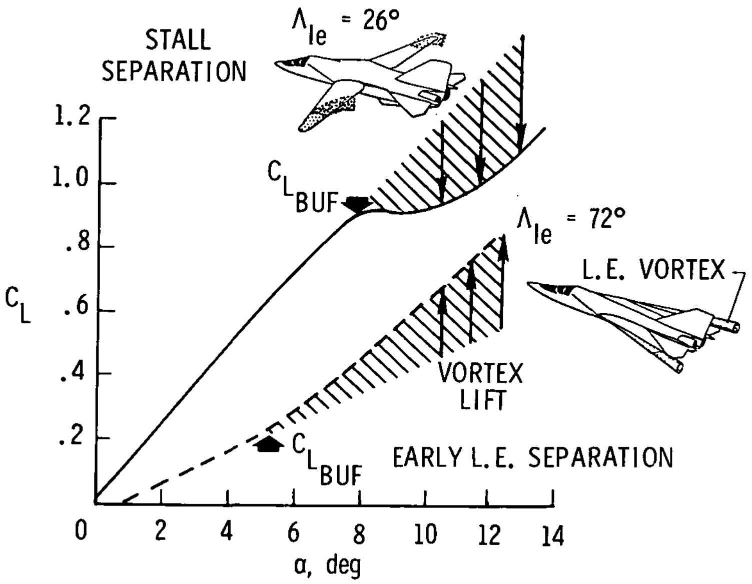


Figure 2.- Effect of aerodynamics on the maneuverability of a variable-sweep aircraft.

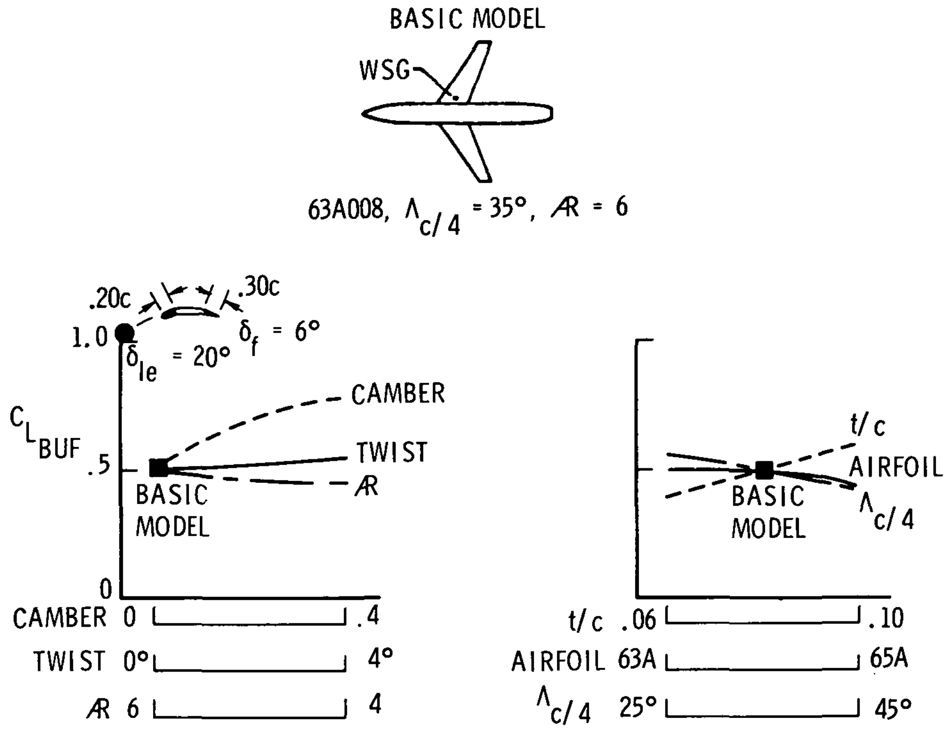
Stall separation.- The 26° sweep results (solid line) are characterized by a rather high lift-curve slope and an almost linear variation of lift in the range of low to moderate angles of attack. (See fig. 2.) In this region of attached flow, aircraft usually exhibit relatively low drag, good stability characteristics and, in general. a high degree of aerodynamic efficiency. However, for this class of conventional, moderately swept wings, the linear variation is inevitably followed by an abrupt reduction in lift which is normally accompanied by large increases in drag, rapid increases in buffet intensity, and losses in stability. Even though the lift is increasing at the higher angles of attack, this type of separation generally produces such a profound degradation in aerodynamic characteristics that the maneuver capability of the aircraft is restricted to angles of attack below the stall.

Early leading-edge separation.- Unlike the low-sweep case, the highly swept configuration exhibits a relatively low lift-curve slope at low angles of attack with gradual increases in the lift-curve slope throughout the range of angle of attack. This supersonic sweep condition is not optimum for subsonic performance, but the example illustrates that the leading-edge separation occurs early on highly swept wings and produces a very stable spiral vortex system with flow reattachment and large vortex-lift increments. This type of behavior usually produces an early onset of buffet corresponding to the occurrence of leading-edge separation, with a very gradual progression in the buffet intensity.

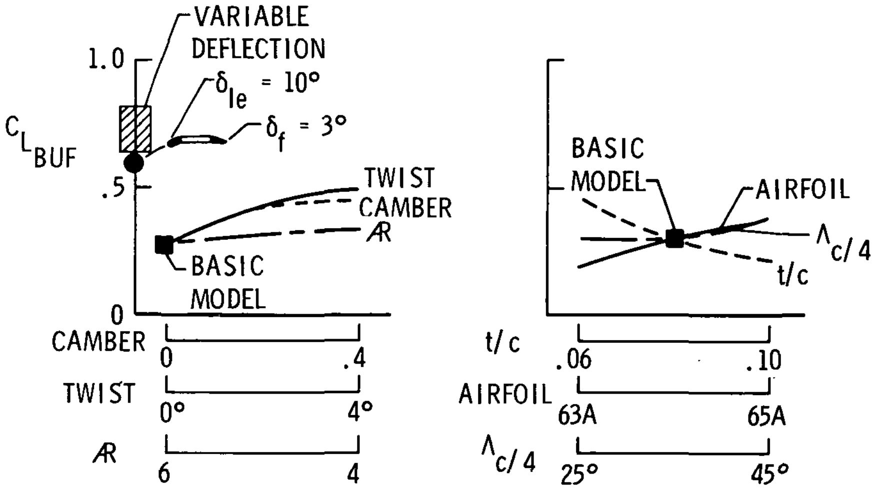
It should be emphasized here that the buffet-onset condition shown for the 72° swept-back configuration represents the onset of wing buffet and due to the very gradual rise in buffet intensity, the prediction would be expected to be conservative from a standpoint of response at the center of gravity or pilot stations. There is also an absence of other abrupt divergences such as those associated with a stall separation. It is interesting to note that for the vortex-flow case, buffet onset accompanies an increase in lift slope rather than a decrease. This phenomenon must be kept in mind when attempting to use lift inflections to predict buffet onset. The remainder of the discussion will be concerned with factors which affect the range of linear aerodynamics and, also, with techniques which might be used to achieve the beneficial effects of vortex flow with moderately swept wings.

Sensitivity of Buffet to Wing Geometry

Planform and airfoil characteristics.- An extensive wind-tunnel study to assess the sensitivity of buffet onset and other aerodynamic boundaries to wing planform and section design has recently been completed by NASA. (See ref. 1.) Figure 3 represents a brief summary of some of the results. The basic configuration, as shown at the top of figure 3, featured an untwisted 63A wing with aspect ratio of 6, thickness-chord ratio of 8 percent, and quarter-chord sweep of 35°.



(a) M = 0.50.



(b) M = 0.85.

Figure 3.- Effect of wing geometry on buffet characteristics.

The only parameter selected for this summary is the lift coefficient for buffet onset. The studies have indicated, however, that for this particular matrix the wings displaying the highest buffet-free lift coefficients generally exhibit superior aerodynamic efficiency characteristics. The onset points were determined primarily by the wing-strain-gage method (ref. 1). The results indicate the variations of buffet-onset lift coefficient with systematic wing changes in the design lift coefficient, twist, aspect ratio, thickness-chord ratio, airfoil section, and quarter-chord sweep angle.

It will be noted from the Mach 0.5 results shown in figure 3(a) that the point of initial separation, as reflected in the buffet-onset conditions, is favorably affected by increases in camber, twist, aspect ratio, and thickness. In addition, a forward movement in the position of maximum thickness and reductions in sweep angle provided beneficial increments.

The high-subsonic (Mach 0.85) results shown in figure 3(b) indicate a pronounced change in the trends discussed for the Mach 0.5 case. Although the conventional camber is still shown to be effective in postponing separation, there is a definite reduction in the influence of the higher camber. Increases in twist and sweep and a rearward movement in the position of maximum thickness provided favorable effects. There was also a definite tendency toward additional improvements as the aspect ratio and thickness-chord ratio were reduced. This systematic matrix of wing variables vividly illustrates the sensitivity of aerodynamic boundaries to section and planform geometry. In a maneuver situation a multitude of conditions might be encountered which could include both subcritical and supercritical flow over a wide range of lift coefficients.

Plain leading- and trailing-edge flaps.- One method of achieving the versatility required in a maneuver while maintaining a good level-flight capability is the use of variable-geometry wing devices. The basic wing therefore was investigated with a plain 20-percent-chord leading-edge flap and a 30-percent-chord trailing-edge flap. The Mach 0.5 results (see fig. 3(a)) indicate that with a leading-edge deflection of 20° and a trailing-edge deflection of 6°, a sizable improvement was achieved in the lift coefficient for buffet onset as compared with the basic uncambered, untwisted wing. At the higher Mach number (see fig. 3(b)) substantial benefits were again achieved with small deflections of the wing flaps. Detailed studies of various flap deflections indicated a reduction in the optimum flap deflection with increases in Mach number which is analogous to the trend toward reduced camber at the higher subsonic Mach numbers. Additional improvements could be achieved at Mach 0.85 if the flap deflections could be varied during the maneuver. The investigation of these relatively simple maneuver devices resulted in a postponement in the stall angle of attack and provided an aerodynamic flexibility not afforded by any one airfoil selection from low subsonic speeds to Mach numbers exceeding 0.9.

Maneuver Devices

Maneuver slats and flaps.- The use of wing maneuver devices has been studied on a sizable number of scaled wind-tunnel models of current fighter aircraft. Several comparisons have been made between wind-tunnel results obtained from conventional sting-mounted models and flight results, with particular emphasis placed upon the buffet and maneuver characteristics. In most cases, the interpretive and test techniques which have been developed have led to good correlations between wind-tunnel and flight characteristics (ref. 1).

One of the most extensive studies of this type was conducted jointly by the NASA Langley Research Center and the McDonnell Aircraft Company in a program directed toward improving the high-subsonic maneuverability of the F-4 aircraft (ref. 2). A brief summary of some of the findings from this study is shown in figure 4. The sketch of the aircraft indicates that the maneuver devices consisted of leading-edge slats on the mid and outboard portions of the wing and the existing inboard trailing-edge flap system. This configuration represents only one of a large number that were studied in the wind tunnel. The selection was made from wind-tunnel results which indicated that this particular arrangement would provide significant improvements in buffet onset, drag, and lift characteristics without seriously compromising the longitudinal handling qualities at high subsonic speeds.

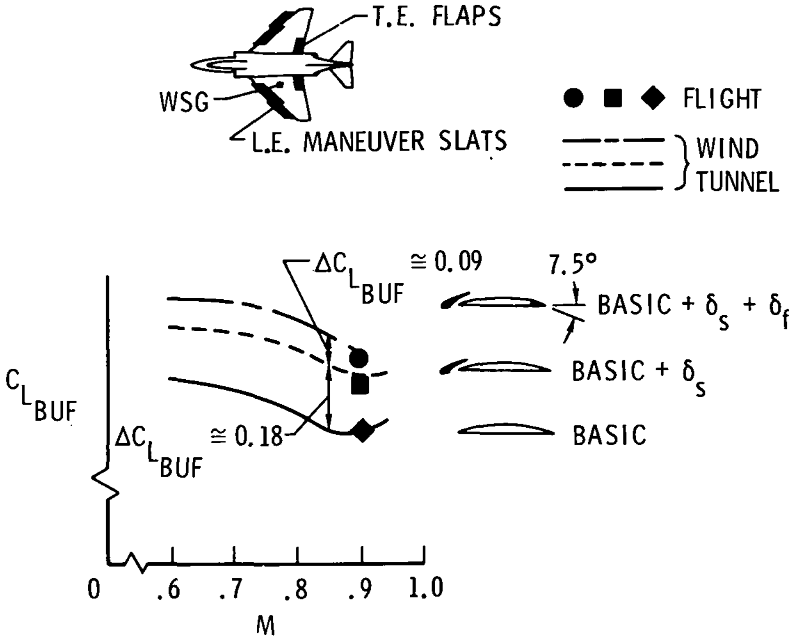


Figure 4.- Effect of maneuver slats and flaps on buffet-onset characteristics.

The results shown in figure 4 represent wind-tunnel and flight buffet-onset lift coefficients as a function of Mach number. Again the primary source of buffet information was the outputs of wing strain gages (WSG). The curves represent wind-tunnel results and the symbols represent buffet-onset points determined in flight. Flight results were obtained over a wider range of Mach numbers (ref. 3); however, the Mach 0.90 results illustrate the degree of agreement between the trends determined in the wind tunnel and in flight.

A comparison of the results for the basic configuration and the configuration with wing slats indicates that the slats provided a very substantial improvement in the buffet-onset lift coefficients throughout the Mach number range. Additional improvements were derived by deflecting the trailing-edge flap system. Only buffet characteristics are shown here; however, the flight evaluations indicated an overall improvement in the maneuver capability due to significant increases in both the lift-limited and thrust-limited turning performance. Excess-thrust characteristics were enhanced and there was an apparent reduction in the buffet intensity at high angles of attack.

Lateral-directional characteristics with maneuver slats.- The subject of lateral and directional stability has not been addressed directly in the preceding discussions. It has been found, however, that the tracking performance and overall maneuver capability of current fighter configurations is often impaired and restricted by undesirable lateral-directional characteristics such as "wing rock" and "nose slice." In many cases, divergences such as these have been shown to be associated with loss of lift on the outboard part of the wing, which results in a degradation of the effective-dihedral characteristics (ref. 4). A major portion of the F-4 studies was directed toward a determination of the effects of wing maneuver devices on the lateral and directional characteristics.

Figure 5 shows wind-tunnel results which were obtained with the F-4E model over an angle-of-attack range which extended from about 5° to 40°. The curves represent the variations of the static directional-stability parameter C_{n_β}, the effective-dihedral parameter C_{l_β}, and the dynamic directional-stability parameter $C_{n_{\beta_{DYN}}}$ with angle of attack. The parameter $C_{n_{\beta_{DYN}}}$ as used here is a function of the static derivatives C_{n_β} and C_{l_β} and the inertial characteristics of the aircraft. Experience has indicated that the parameter $C_{n_{\beta_{DYN}}}$ provides a good indication of directional divergences at high angles of attack (ref. 5).

These wind-tunnel results indicate that at the high angles of attack the slats provide an improvement in the static directional stability and a large favorable increase in the effective-dihedral characteristics. The $C_{n_{\beta_{DYN}}}$ results indicate that the basic model diverges at an angle of attack near 21°, whereas the configuration incorporating the

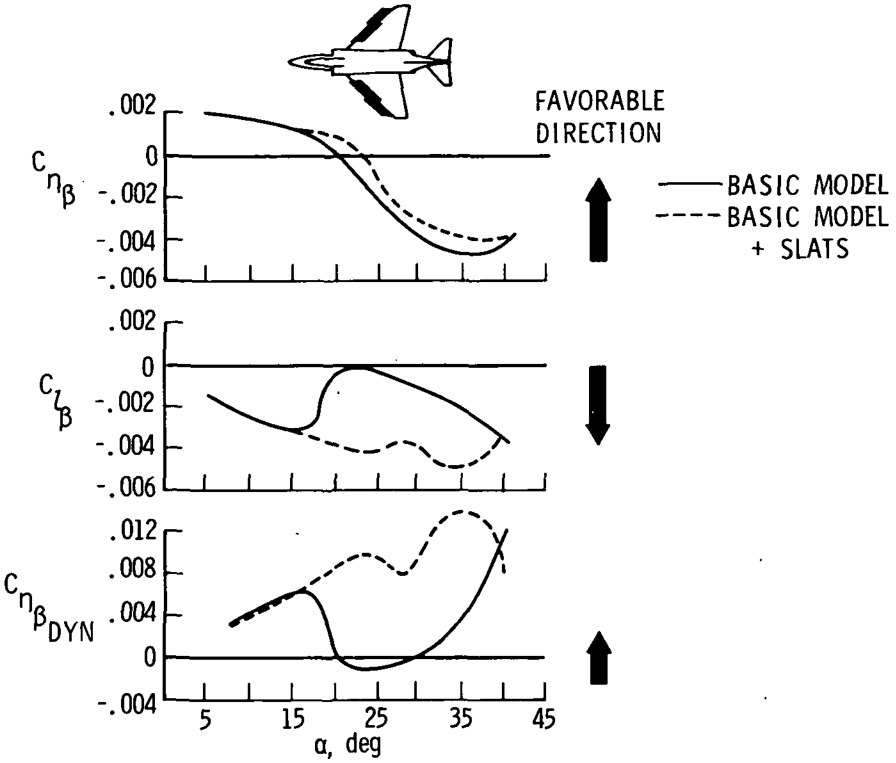


Figure 5.- Effect of maneuver slats on lateral-directional characteristics.

maneuver slats exhibits positive values of $C_{n_{\beta_{DYN}}}$ throughout the entire angle-of-attack range of the tests. The improvements suggested here were confirmed in flight by qualitative reports which indicated postponements in the onset of wing rock, reductions in wing-rock intensity, and an apparent improvement in directional stability at high angles of attack.

Krueger flaps.- It was recognized that because of structural considerations and physical size, adapting maneuver slats to many thin-wing configurations might represent an impractical solution. This particular study, therefore, included tests of the basic wing modified by the addition of simple Krueger flaps which could be readily stowed beneath the leading edge of a wing.

Figure 6 presents Mach 0.90 results which were obtained for the basic wind-tunnel model and the basic model with the addition of the maneuver slats and of Krueger flaps. The span coverage of the two types of wing devices was almost identical. Lift and drag characteristics are shown for the three different configurations. It can be seen that there is a definite improvement in lift at the high angles of attack when the Krueger flaps are employed. The buffet-onset lift coefficient for the Krueger configuration was approximately 0.15 higher than that for the basic and approached the value predicted for the configuration with maneuver slats. The incorporation of the Krueger flaps also leads to

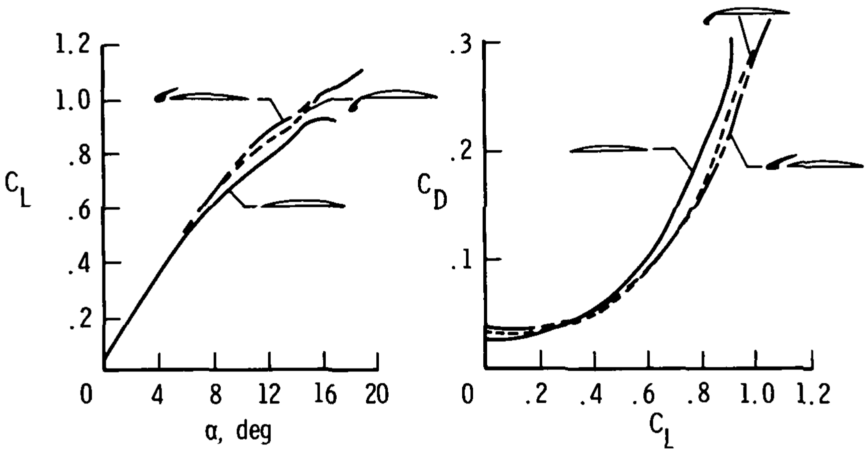


Figure 6.- Effect of maneuver slats and Krueger flaps on lift and drag characteristics. M = 0.90.

large reductions in the high-lift drag levels. Although the improvements indicated with the Krueger flaps were not as large as those with the slats, these simple devices were shown to provide very beneficial effects on the static lateral-directional trends as well as on the lift, drag, and buffet-onset characteristics. (Detailed results obtained in the F-4 Krueger-flap study are included in ref. 6.)

Vortex-Lift Maneuver Strake

Effect of strake on lift and drag characteristics.- The preceding discussions have been concerned with various methods which have been demonstrated to be effective in postponing the stall to higher angles of attack. Another promising approach which appears to be effective in allowing maneuvers well beyond the normal aerodynamic boundaries of fighter aircraft with a relatively low weight increment is the use of a highly swept maneuver strake that blends with a moderately swept wing. The strake provides vortex lift at high angles of attack and stabilizes the flow on the main wing panel.

A sketch of a general research model with a maneuver strake is shown in figure 7. Experimental and theoretical lift and drag results are presented to illustrate the aerodynamic characteristics of the model with and without the strake. The experimental lift results for the strake-off configuration (circular symbol) indicate a pronounced reduction in the lift-curve slope at the high angles of attack. The experimental lift results for the strake-on model (square symbol) indicate a nonlinear variation in lift with a gradual increase in the lift-curve slope. A comparison of the experimental results shows the large increase in lift provided by the strake at the high angles of attack. The dashed curves indicate theoretical estimates of the lift characteristics for the model with the strake on. The short-dash curve represents the potential-flow estimates (ref. 7) and the long-dash curve illustrates an estimate based on the assumption that a vortex system

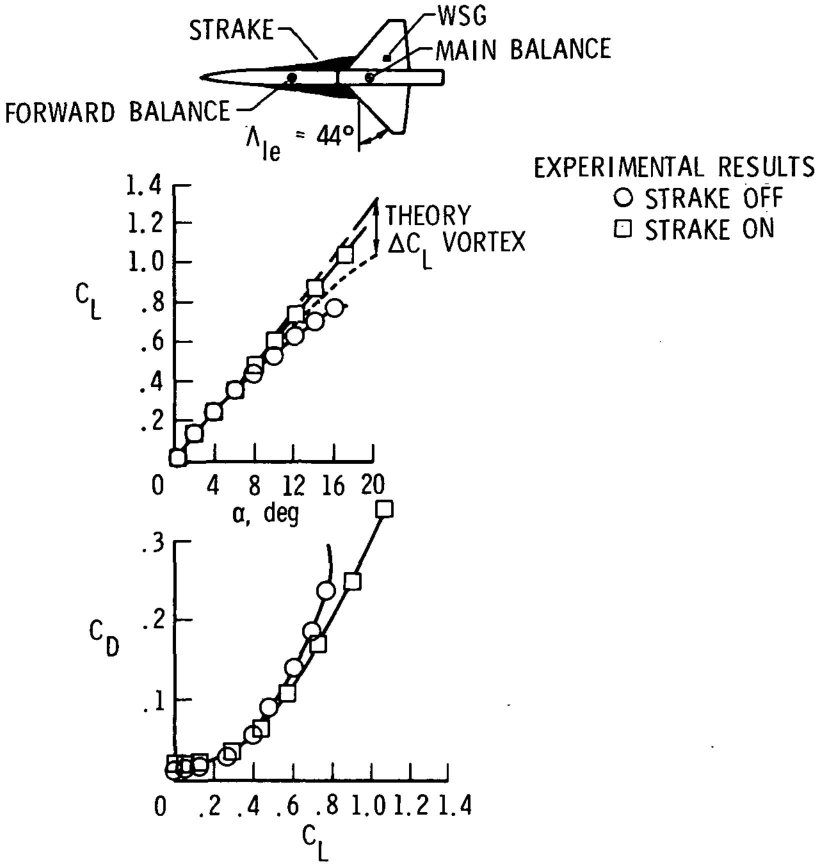


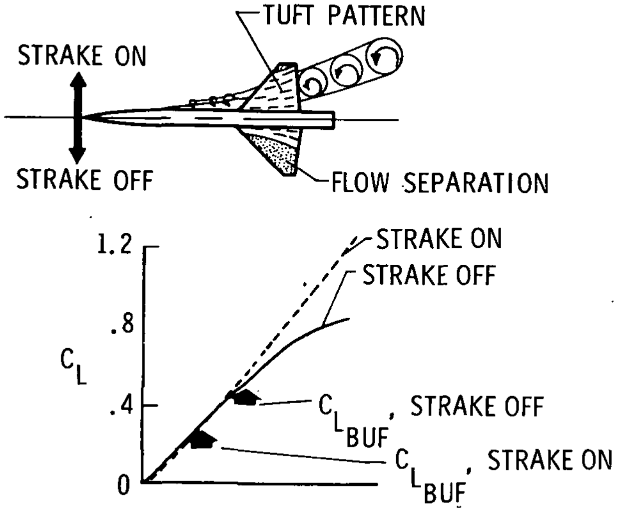
Figure 7.- Effect of maneuver strake on lift and drag characteristics. M = 0.85.

develops on the strake (ref. 8). The theory predicts a large vortex effect but the experimental results fall slightly below the vortex estimate as a result of separation on the outer wing panel.

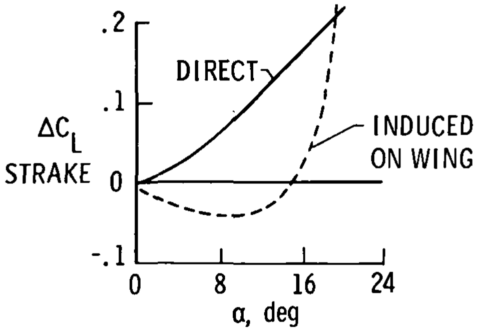
The drag results shown in figure 7 indicate that at the low lift coefficients the addition of the strake produces slightly higher drag values. At a lift coefficient of about 0.5, leading-edge thrust is completely lost on the basic wing $\left(C_D = C_L \tan \alpha\right)$, resulting in a rapid progression in the drag rise. Because of the nonlinear increase in lift produced by the highly swept strake, the addition of the strake results in large reductions in the high-lift drag coefficient. It can be seen from these results that the benefit of such a strake approach is that higher lift (or load factors) can be provided without the weight penalty which would be associated with the lower wing loadings required to accomplish the same improvement.

Airflow characteristics with vortex-lift strakes.- In order to gain some insight into the aerodynamic behavior of the straked configuration, studies were conducted with buffet gages, wing tufts, and an additional six-component balance installed in the forebody of the model. The model sketch at the top of figure 7 indicates the general locations of the balances and the WSG. It will be noted from this sketch that the internal strain-gage balances were mounted in a manner such that the main balance would measure the forces and moments of the integrated model and the forward balance would indicate the aerodynamic load on the strake-forebody combination.

Figure 8(a) shows the variations of lift with angle of attack for the strake-off configuration (solid line) and the strake-on configuration (dashed line). A composite sketch is included which illustrates the tuft behavior on the strake-on model and the strake-off configuration. The tuft displays were traced from video-tape recording. Figure 8(b) illustrates the variation of the direct lift contribution of the strake (solid line) and the lift induced on the wing by the strake (dashed line) with angle of attack.



(a) Total lift characteristics.



(b) Incremental lift characteristics.

Figure 8.- Influence of maneuver strakes on wing-airflow characteristics.

The total-lift curves indicate that at low angles of attack the strake reduces the lift only slightly and maintains a relatively high lift-curve slope. Unlike the highly swept planform discussed earlier in the paper (see fig. 2), the efficiency of the integrated strake-wing combination remains relatively high due to the moderately swept outer panel. At low angles of attack the addition of the strake results in a forward shift in the load distribution and a consequent loss in lift on the main wing panel. (See lower curve, fig. 8(b).) It will be noted, however, that at the low angles of attack the direct lift contribution of the strake (shown by the solid line) is approximately equal to adverse effects induced on the main wing panel.

At the higher angles of attack, the tuft sketch shows that the airflow over the wing panel with the strake off is almost completely separated. This is reflected in the drastic reduction in the lift-curve slope of the basic configuration. The sketch of the straked wing indicates an extensive spanwise flow system which apparently confines the separated area to small portions of the wing tip. It was observed from the visual studies that as the angle of attack is increased the spanwise flow system moves progressively outboard and reduces the area of separation. The progression of the vortex system is reflected in the constant increase in the lift of the straked-wing configuration. It can be seen from the incremental-lift curves that at the high angles of attack there is a substantial increase in the favorable lift induced on the wing. At an angle of attack of about 20°, the lift induced on the wing is equivalent to the direct lift of the strake.

With regard to the buffet characteristics at high angles of attack, there was a pronounced absence of an increase in the apparent buffet intensity of the straked configuration. The basic configuration, however, exhibited a relatively high buffet-onset lift coefficient which was followed by a progressive rise in the apparent intensity characteristics.

Effect of wing efficiency on strake contribution.- The design lift coefficient of the basic wing panel utilized in this phase of the straked-wing investigation was zero. Studies were made with cambered wings and with wings incorporating leading-edge flaps to determine the effectiveness of the strake in combination with a more efficient wing. Some of the results from these studies are presented in figure 9. The sketch at the top of the figure depicts the model with the maneuver strake and a symmetrical wing with constant-chord segmented leading-edge flaps, which when deflected, twisted and cambered the wing, thereby increasing the high-lift efficiency of the basic planform. The flap deflections used to obtain the results shown in this comparison were, from the outboard segment inward, 20°, 16°, 12°, and 8°. These deflections do not necessarily represent an optimum condition; however, this arrangement provided the most promising results of the several combinations which were studied. The data which are shown represent the increments in lift and drag due to the addition of the strake.

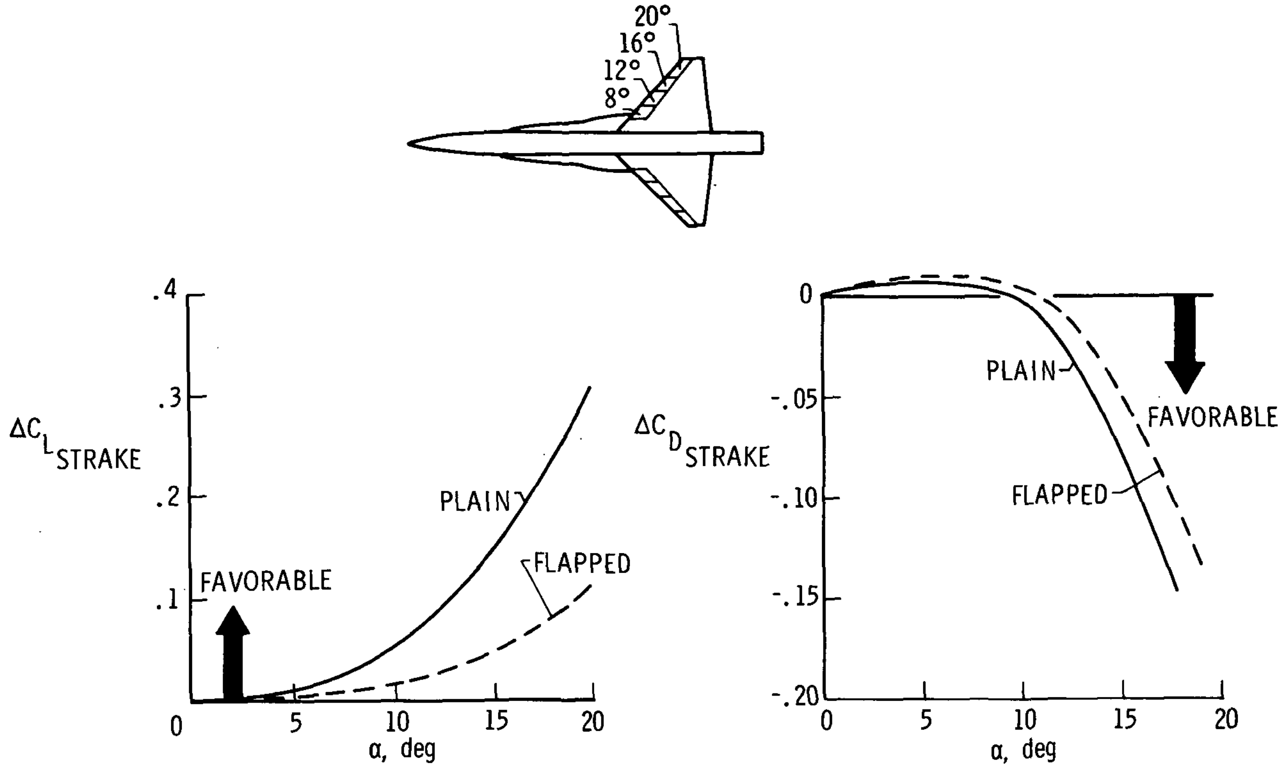


Figure 9.- Comparison of maneuver strake on plain and flapped wing. M = 0.40.

It will be noted from these results that when the flaps are deflected the favorable lift increment due to the strake is significantly reduced. This reduction in lift is directly reflected in a reduction in the favorable drag benefits due to the strake. As might be expected, the camber (ref. 9) and flap studies have indicated that as the wing design is improved to delay separation on the main wing panel, the beneficial effects of the strake are delayed to increasingly higher angles of attack. The drag results also point out that at the lower angles of attack there are small penalties associated with the addition of the strake. It is believed, however, that proper cambering and twisting of the integrated strake-wing combination can alleviate the low-lift penalties while maintaining the high-lift benefits of stabilized flow and improved buffet and maneuver characteristics at higher angles of attack.

CONCLUSION

The series of studies has illustrated the sensitivity of section and planform geometry to a selected design point. Flight and wind-tunnel studies have shown that variable-geometry wing devices in the form of flaps or leading-edge slats and flaps can provide controlled flow over a wide range of flight conditions and substantial improvements in maneuver capabilities. The incorporation of a highly swept maneuver strake with an efficient, moderately swept wing appears to offer a promising approach for improved maneuver characteristics at high angles of attack for a relatively small increase in structural weight.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., April 25, 1973.

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