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A METHOD FOR LOCALIZING WING FLOW SEPARATION AT STALL TO ALLEVIATE SPIN ENTRY TENDENCIES

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ABSTRACT

A wing leading-edge modification has been developed, applicable at present to single-engine light aircraft, which produces stabilizing vortices at stall and beyond. These vortices have the effect of fixing the stall pattern of the wing such that the various portions of the wing upper surface stall nearly symmetrically. The lift coefficient produced is essentially constant to very high angles of attack above the stall angle of the unmodified wing. It is hypothesized that these characteristics will help prevent inadvertent spin entry after a stall. Results are presented from recent large-scale wind-tunnel tests of a complete light aircraft, both with and without the modification.

INTRODUCTION

Stalls and spins have continued to be a major cause of fatal and nonfatal accidents involving general aviation aircraft. As discussed in a historical review of stall/spin characteristics,[1] the aerodynamic factors that affect stall/spin behavior have been studied for many years and are well known; however, the incorporation of the proper combination of these factors to provide stall/spin avoidance in current general aviation aircraft has proved to be a difficult design challenge.

A key part of providing acceptable stall/spin behavior involves the wing aerodynamics. Lateral instabilities and the loss of lateral control, common to most aircraft when in a stall, are due to a rapid spread of flow separation on the outer portion of the wing. Many methods to control wing-flow separation have been examined, including aerodynamic twist or geometric washout, wing slots or slats, change in airfoil section, variable thickness ratio, and the use of leading-edge stall strips. Although some of these methods have been somewhat successful in improving stall/spin behavior, the increased complexity of the wing design and loss of performance have acted as deterrents to widespread acceptance by the general aviation industry.

Recently an improvement in post-stall aerodynamic flow control has been made in a research program conducted jointly at Ames Research Center and at the University of Michigan. Basically, the concept involves the shedding of vortices at stall at the mid-semispan leading edge, which serves to preserve the lift, both inboard and outboard, to very large angles of attack.

Theoretical models of three-dimensional wings, using a nonlinear-lifting-line approach with a simulated stalled wing section, had suggested that strong vorticity would be shed at the edges of the unattached section. A wind-tunnel model was fabricated with partial span slats added along the entire leading-edge except for a small length near the mid-semispan. These differences in leading-edge configuration were intended to produce a strong streamwise vorticity around the stalled section and thus, due to a decrease in the local induced angle of attack, keep the other areas attached to high angles of attack. By varying the spanwise position and width of the unslatted section, a post-stall lift curve shape could be produced, which varied from practically flat on top to double-peaked, depending on the spanwise position of the gap in the leading-edge slats.

This mid-semispan flow-control technique was first developed in experiments in the University of Michigan 5- by 7-Foot Wind Tunnel and in the NASA-Ames 7- by 10-Foot Wind Tunnel.

A second series of tests was performed in the NASA-Ames 7- by 10-Foot Wind Tunnel; the results are reported in Ref. 2. In these studies, using a half-span model, the slats were replaced by leading-edge gloves which added camber and a larger radius to the leading edge, similar to a GAW-1 airfoil section. The results showed similar flow control capabilities but the effect was not quite as dramatic on the post-stall lift curve as the slats. However, the gloves were capable of producing a flat-top lift curve without showing a perceptible drag penalty with respect to the clean wing. In addition, they were simple enough to constitute an acceptable type of add-on to a general aviation production aircraft. Subsequent wind-tunnel studies of a full-span wing in the NASA-Ames 7- by 10-Foot Wind Tunnel showed that sideslip did not significantly alter the effectiveness of this flow-control concept.

As a next step, the decision was made to test the flow-control method on a typical light airplane in the NASA-Ames 40- by 80-Foot Wind Tunnel, both with and without engine power and with various control surface deflections. This paper presents and discusses some results of these recent studies. The aircraft chosen was a Beechcraft Musketeer, Model 23A. A photograph of the aircraft/wind-tunnel model mounted in the tunnel is shown in Fig. 1.

FULL-SCALE WIND-TUNNEL TESTS

The aircraft was modified by attaching a removable fiberglass leading-edge glove which was installed in segments. The design of the glove was similar to that used in the earlier 7- by 10-foot wind tunnel tests, i.e., by matching the nose of a GAW-1 airfoil to the leading edge of the wing such

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that the upper surfaces of the two airfoils approximately coincide over 20-30% of the chord (a sketch is shown in the lower part of Fig. 2). This results in a larger leading-edge radius as well as greater camber at the nose; the lower surface is faired flat so that it blends with the bottom of the wing at about 30% chord. This simple modification is by no means optimum, but it has been shown to delay leading-edge separation to significantly higher angles of attack.

The leading-edge glove segments were designed so they could be removed and rearranged to produce an unprotected gap, varying from 1/16 to 1/4 of the semispan in width, at various spanwise positions on each of the wings. A sketch of the layout and nomenclature is shown in Fig. 2. Figure 3 is a close-up photograph of a typical modification. The location and width of the unprotected gap were varied systematically during the exploratory part of the tests. These tests were run with the horizontal tail removed, in order to focus on the wing characteristics, at an airspeed of about 77 mph (124 kph).

Results with Modified Leading-Edge and for Basic Aircraft

The most desirable leading-edge modification configuration tested in this phase, based on the shape of the lift curve and the rolling moments produced at stall, was approximately the same as that used in the earlier 7- by 10-foot wind tunnel tests with a semispan wing,[2] i.e., a 1/8 semispan gap located just inboard of the mid-semispan (position 4 in Fig. 2).

Longitudinal Characteristics

The tail-off lift curve for this configuration is shown in Fig. 4a, along with the basic tail-off aircraft characteristics for comparison in Fig. 4b. (Note that these data are for the configuration with tail off, power off, and flaps up so that wing-body effects only are being shown.) It can be seen that both the modified and unmodified configurations have approximately the same $C_{L_{max}}$. The shape of the top of the lift curve, however, is quite different. The lift of the modified configuration, instead of steadily decreasing, remains essentially constant to an angle of attack of about 32°. It is hypothesized that this characteristic implies improved roll damping past stall; i.e., from the tuft photos, the flow on the outer portion of the wings stays attached, with separation occurring in the vicinity of the mid-semispan and inboard. The tips then, which are the largest contributors to roll, presumably have a positive C_{L_α} resulting in an improved roll damping for the wing. The lift of the basic configuration, on the other hand, falls off steadily after the maximum. This negative slope and the observed tip-flow separation imply negative roll damping as is known to occur in the classic post-stall case.

Flow Visualization

The tuft photos in Fig. 5 correspond to the lift curves shown in Fig. 4. They illustrate the flow structure over the wing for a range of angles of attack from immediately pre-stall to deep post-stall. The photos of the unmodified version are on the left and those of the modified are on the right. Starting with the bottom pair of photos, the angle of attack is 12°. As expected for this pre-stall angle, the flow is about the same on both wings, with a small amount of separation occurring at the trailing edge in the wing root region. The tuft patterns at $\alpha = 16°$ and $\alpha = 20°$ (not shown) reveal little to distinguish between the two configurations. At $\alpha = 24°$, in the next pair of photos shown, the favorable effect of the leading-edge modification is especially well illustrated, with the flow ahead of the aileron breaking down on the unmodified wing while it is still well attached on the modified version; it remains so through $\alpha = 28°$. In the final set of pictures, at $\alpha = 36°$, the flow separation at the tip of the modified wing, which was partial at 32° (not shown), is complete (it is interesting to note that the tuft pattern here is similar to that for the unmodified wing at $\alpha = 24°$).

Lateral Characteristics

The rolling-moment data for these two configurations with neutral controls, and with some maximum roll control limits for full aileron deflection (represented by the open points at selected angles of attack), are shown in Fig. 6. As would be expected from the tuft photos, the rolling moments for the modified wing (in Fig. 6a) are fairly well-behaved to an angle of attack of about 32°, above which they start to depart. The excursion at 20°-21° (Point "A") is thought to be due to the leading-edge stall in the unprotected gap occurring on one wing first. Subsequent tests with a sharper leading-edge radius in the gap have reduced this excursion. For the unmodified wing (in Fig. 6b) the divergence in roll is much more extreme, with large uncontrollable excursions occurring at 22°-26°; these excursions are due to asymmetric wing flow separation which was observed in the tufts. As can be seen, the aileron effectiveness was significantly higher for the modified wing at the higher angles of attack, with that of the unmodified wing dropping to very low values at $\alpha = 28°$ to 36°. The yawing moments for both versions (not shown) were relatively small. A cursory look at the contribution of the modification to dihedral effect C_{ℓ_β} and, to a lesser extent, directional stability C_{n_β} (for the configurations with tail on), indicates that they are enhanced somewhat at the higher angles of attack. The sensitivity of the post-stall lateral characteristics of the modified aircraft to small yaw angles is still being investigated.

Results with Two Other Types of Leading-Edge Modifications

In order to investigate other means of obtaining the same results, two other leading-edge modification schemes were tested, both with a discontinuity at position 4 (Fig. 2)—that position found optimum for the gap in the leading-edge glove.

The first of these consisted of the same leading-edge glove full-span in combination with a large, 1.5 in. (3.8 cm) wide, horizontally disposed leading-edge spoiler 1/8 semispan long. The data for this variation, along with a sketch, are shown in Figs. 7a and 7b. A somewhat larger drop in C_L resulted after $C_{L_{max}}$, but recovery was good, with a reasonably flat top on the lift curve. The rolling moments, as shown, look better than for the modification presented earlier—probably because of stronger vortices being shed by the large leading-edge spoiler. The yawing moment (not shown) was small. Further investigations are being made to determine whether similar results can be obtained with a smaller spoiler.

The next variation in the leading-edge modification schemes investigated resembled the conventional stall pattern control treatment used on current light aircraft. It employed the basic wing, with no leading-edge glove, but with a 3/8 in. (0.95 cm) square "stall strip" at the same position 4 (Fig. 2). This resulted in the lift curve shown in Fig. 8a; $C_{L_{max}}$ is lower and occurs at a lower angle of attack. However, the level of C_L is maintained for a few degrees farther than for the basic wing, but beyond $\alpha = 22°$ it declined steadily as before, indicating a probable negative roll damping. Rolling moment (Fig. 8b) and yawing moment (not shown) stayed within reasonable bounds.

Characteristics of the Complete Aircraft, with Modified Leading Edge in the Landing Approach Configuration

Data are shown in Fig. 9 to substantiate the effectiveness of the modification for a landing approach condition—that in which it is most likely to be needed. These data are for the modified aircraft with the gap in the leading-edge glove at position 4, tail on, with trailing-edge flaps down to 15°, and engine power on at 1800 rpm. The effect of the flaps on the shape of the wing lift curve is to produce a greater decrease in lift, after the maximum, before a plateau is reached. This effect is nullified somewhat, however, by the addition of the lift of the horizontal tail which is set at constant incidence in these data. It can be seen from Fig. 9a, that the maximum lift plateau is high and extends to an angle of attack of 36°. The rolling moment data (Fig. 9b) show greater excursions than in the previous figures, partly due to the presence of the propeller slipstream; the maximum excursions, however, stay within the $C_\ell = 0.03$ limit (defined as satisfactory in Ref. 3 and shown earlier to be within aileron control capability in most cases) at angles below $\alpha = 32°$. The pitching moment, shown untrimmed about the wing quarter-chord in Fig. 9b, is well-behaved to $\alpha = 40°$, showing no adverse effect of the leading-edge modification on the contribution of the horizontal tail.

CONCLUDING REMARKS

A wing leading-edge modification has been developed that changes the stall pattern so that the onset of separation is localized at the semi-span leading edge. Vortices shed at this point are thought to help relieve the flow on the inboard and outboard portions of the wing, so that the flow separation pattern is stabilized and stays fixed to large angles of attack. The resulting aerodynamic characteristics of the airplane are improved in most of the important aspects affecting spin departure. For example, while $C_{L_{max}}$ is about the same as for the unmodified wing, the shape of the top of the lift curve for the modified wing is improved so that it is essentially flat to approximately 32° angle of attack. In addition, flow visualization studies showed that the flow over the outboard portion of the wing stays attached to much higher angles, indicating that favorable effects on post-stall roll damping would be expected. The post-stall excursions of the rolling moment are decreased, so that they stay within acceptable levels to an angle of attack of 28° to 32°. Yawing moments, likewise, are within satisfactory limits. Finally, the effectiveness of the ailerons is maintained to higher angles of attack with the modified configuration.

Flight tests proposed for the near future will help to determine if these characteristics are a substantial aid in preventing spin entry after a stall. Recent radio-controlled model tests at Langley Research Center (unpublished) have yielded supporting results. Further theoretical work will continue with the goal of developing a method of analytically designing a wing with the desired characteristics for a particular aircraft. Further work is required to apply a similar flow-control technique to other types of aircraft; an application to light twins, in particular, should have a high priority.

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[3] Anderson, Seth B., "Correlation of Flight and Wind-Tunnel Measurements of Roll-Off in Low-Speed Stalls on a 35° Swept-Wing Aircraft," NACA RM A53G22, 1953.

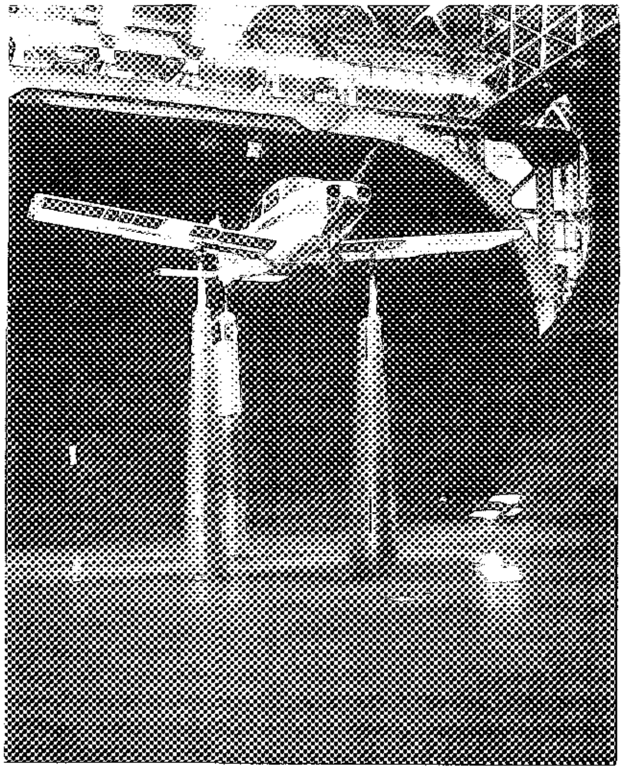


Fig. 1 Photograph of modified aircraft in NASA-Ames 40- by 80-Foot Wind Tunnel.

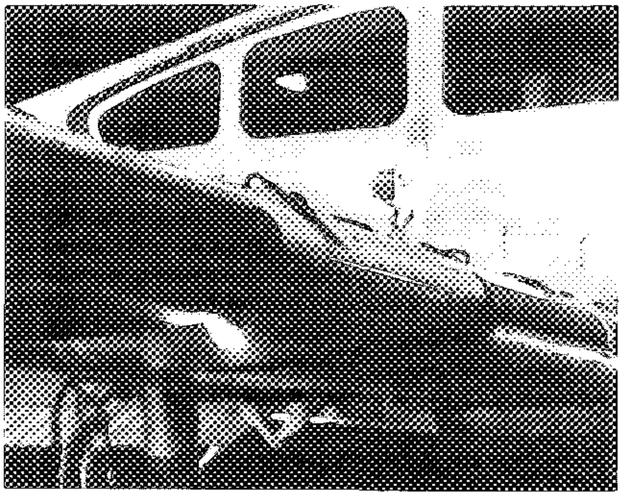
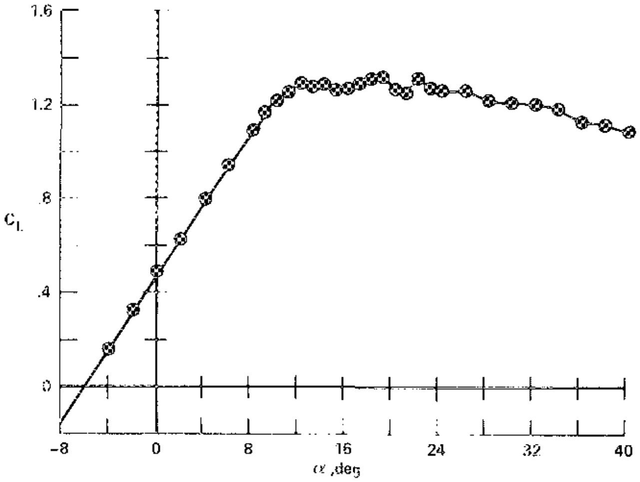


Fig. 3 Close-up of leading-edge modification.



(a) Aircraft with modified leading edge.

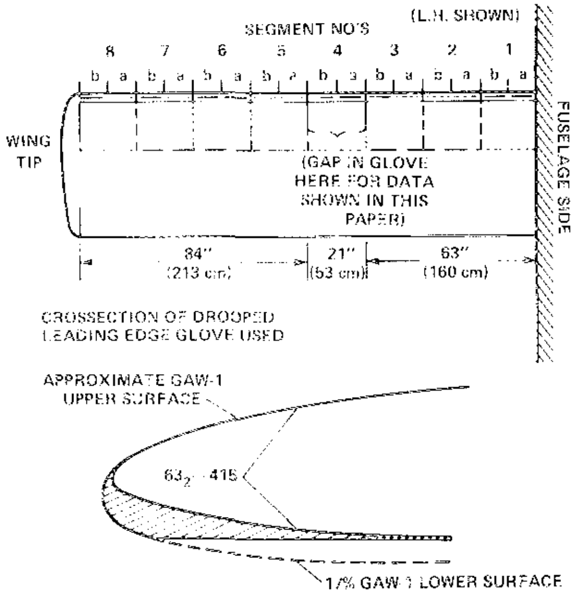
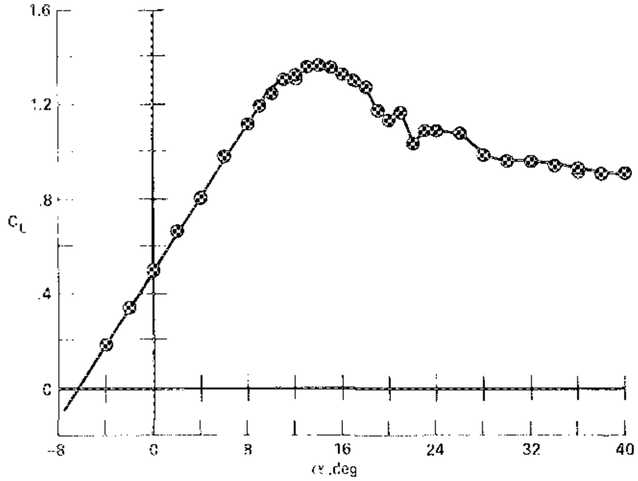


Fig. 2 Removable leading-edge glove configuration and nomenclature.



(b) Basic aircraft.

Fig. 4 Tail-off lift curves.

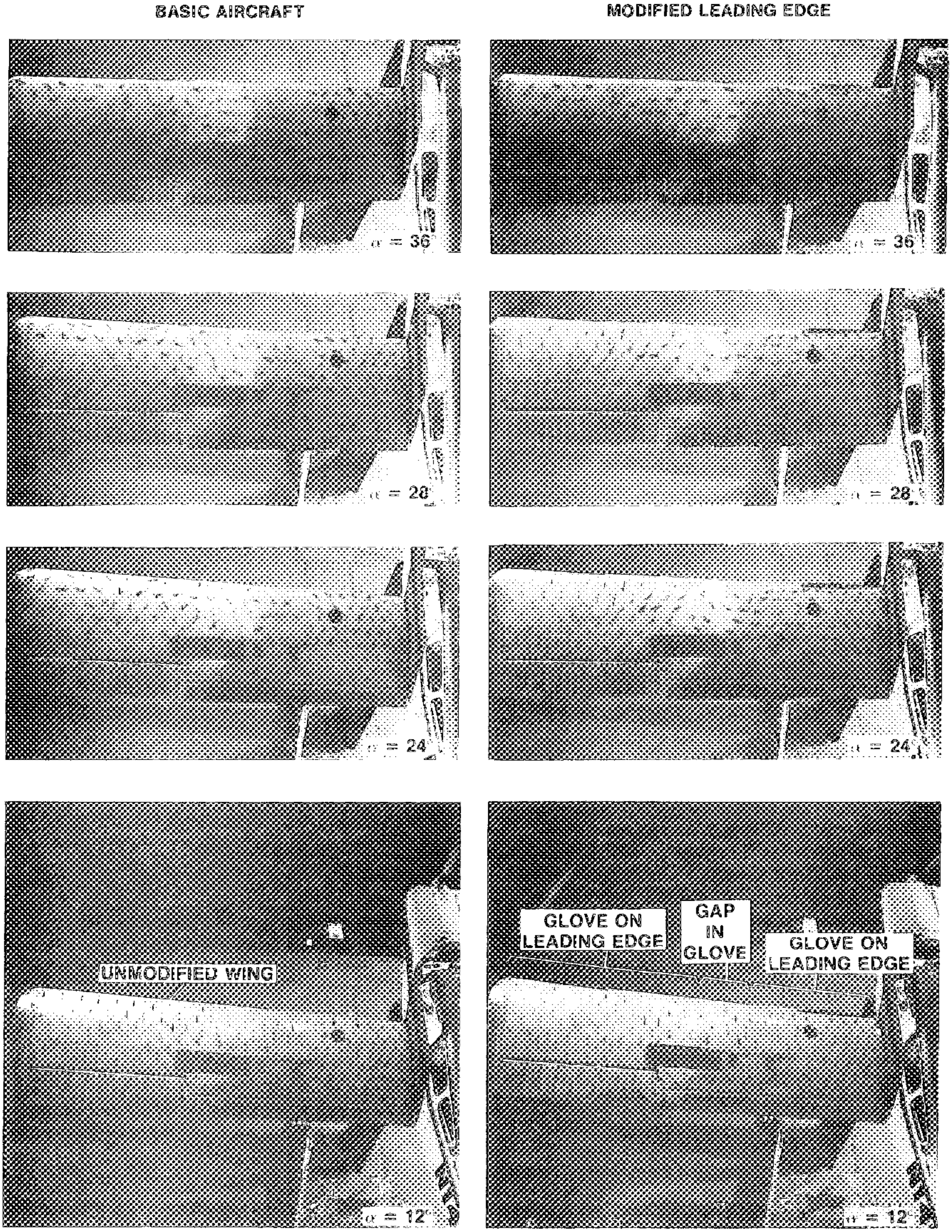
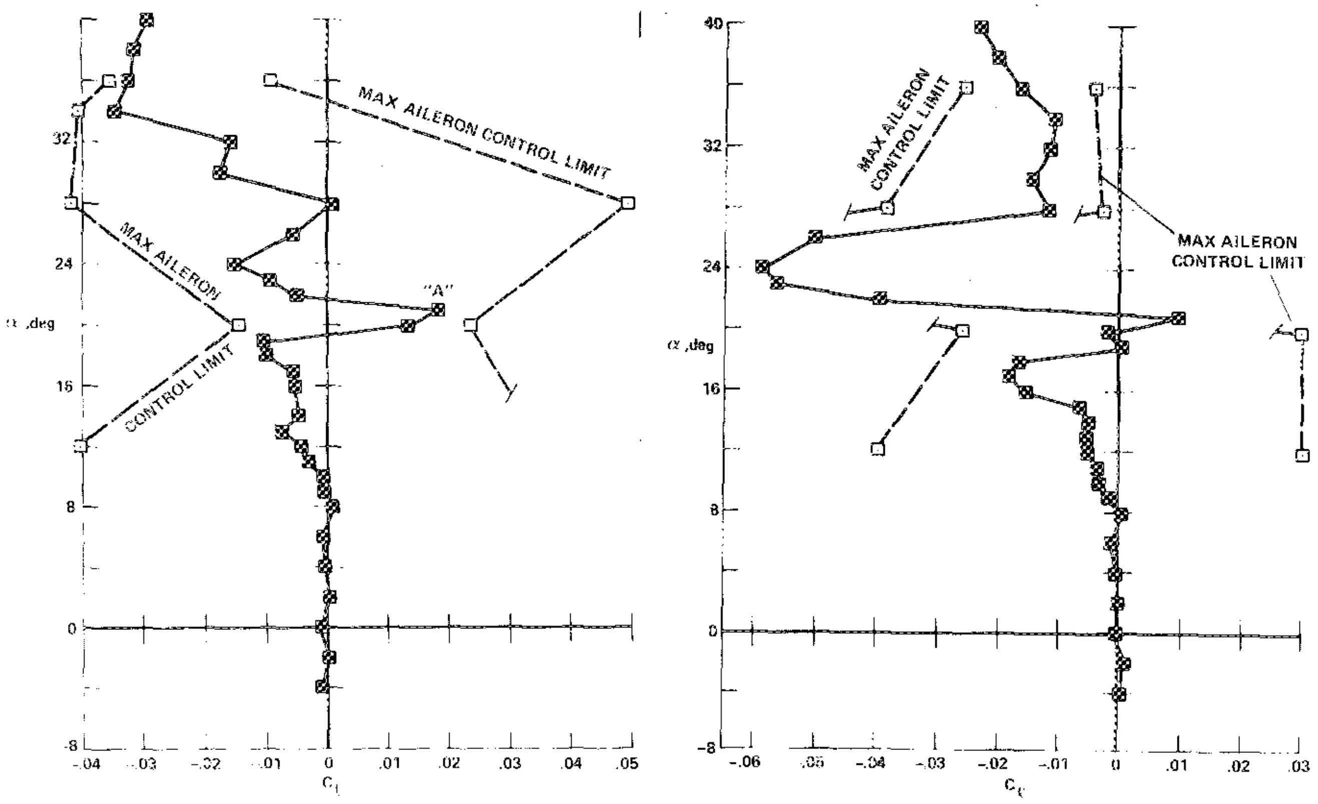


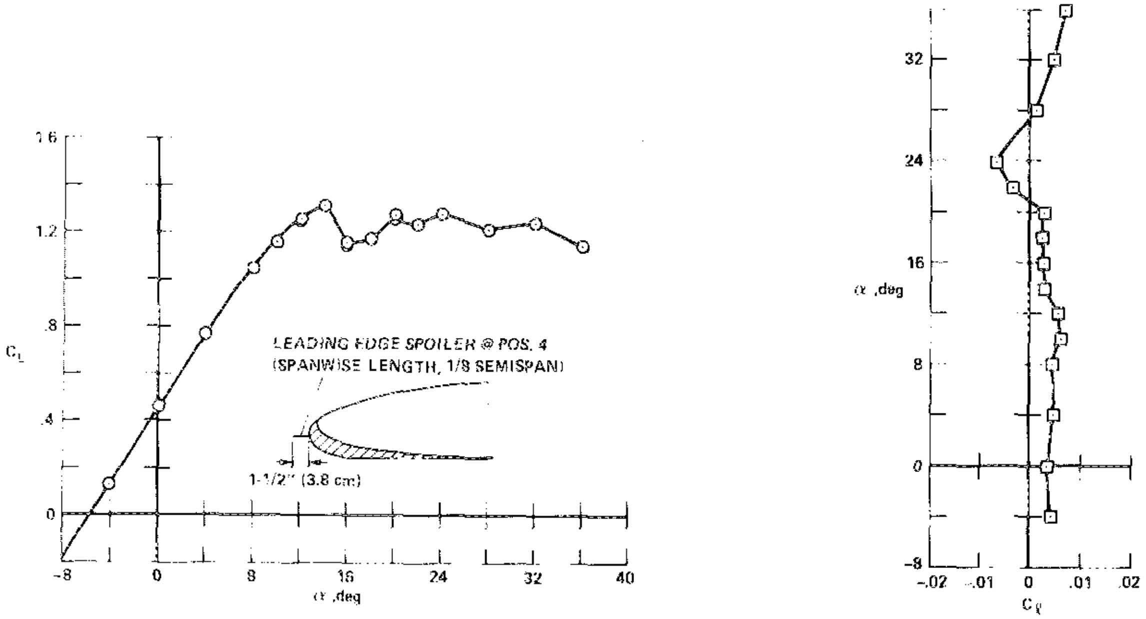
Fig. 5 Comparative tuft photos for modified and unmodified wings, α = 12° - 36°.



(a) Aircraft with modified leading edge.

(b) Basic aircraft.

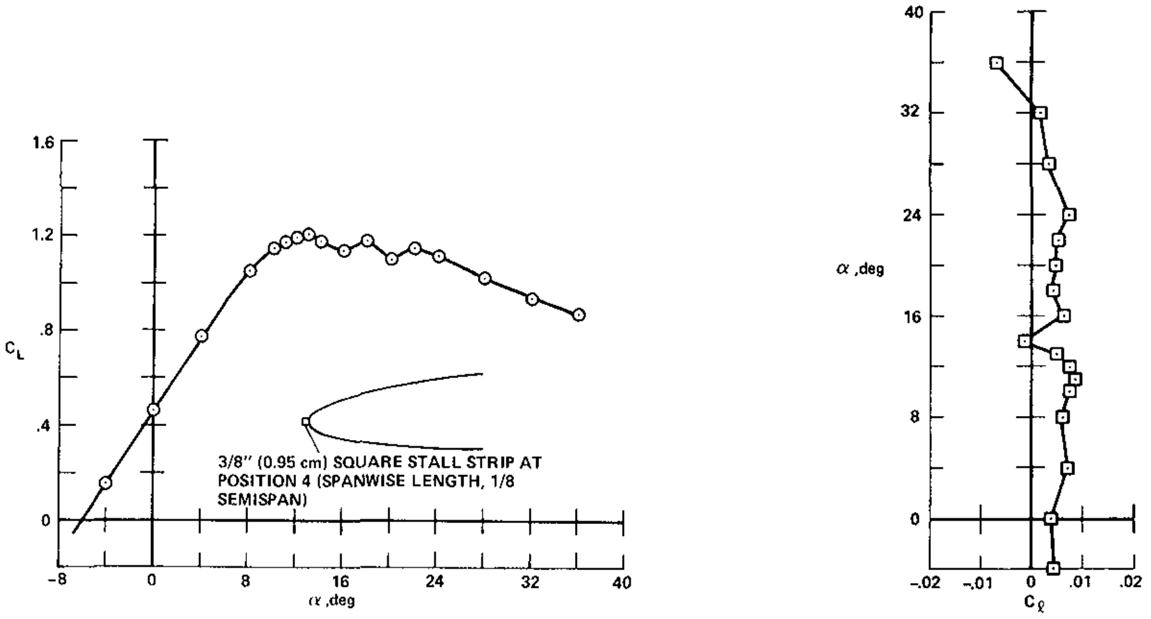
Fig. 6 Tail-off rolling moment characteristics.



(a) Lift characteristics.

(b) Rolling moments.

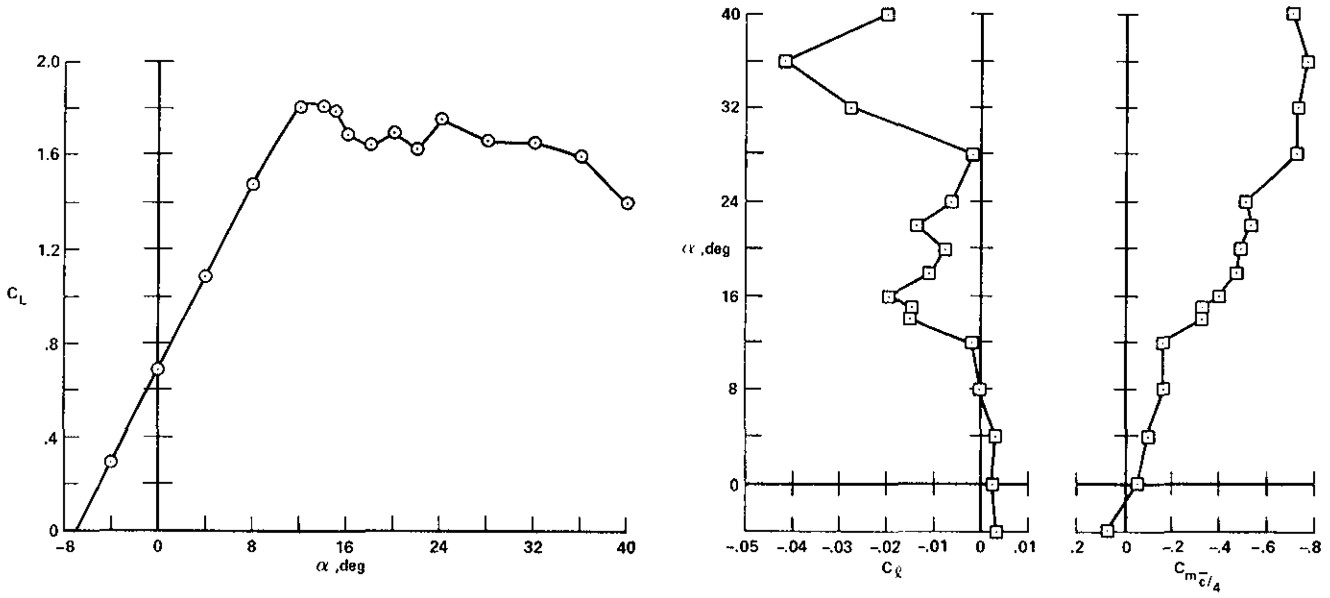
Fig. 7 Aircraft with full leading-edge glove, tail-off — spoiler at position 4.



(a) Lift characteristics.

(b) Rolling moments.

Fig. 8 Basic aircraft with stall strip at position 4, tail-off.



(a) Lift characteristics.

(b) Rolling and pitching moments.

Fig. 9 Complete aircraft with modified leading edge — landing approach condition.