WIND TUNNEL RESULTS OF THE LOW-SPEED NLF(1)-0414F AIRFOIL

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INTRODUCTION

Recently, increased emphasis has been placed on the development of advanced airfoils for application to high-performance general aviation and commuter aircraft. Research conducted in this area has been directed toward developing airfoils with extensive natural laminar flow (NLF) in an attempt to obtain lower cruise drag coefficients and yet maintain acceptable maximum lift and stalling characteristics. One airfoil designed with these considerations is designated as NLF(1)-0414F.

The design, theoretical calculations, and two-dimensional airfoil test results for NLF(1)-0414F have been extensively reported in references 1-4. The results presented herein highlight some of the recent wind-tunnel tests conducted with the airfoil. The most recent wind-tunnel results have been obtained in a cooperative program with Cessna by testing a full-scale modified Cessna 210 (figure 1) in the Langley 30- by 60-Foot Wind Tunnel. This aircraft features a modified wing of increased aspect ratio and incorporates the NLF(1)-0414F airfoil. In addition to documenting the characteristics of the airfoil in this application, tests were conducted to determine the effects of premature boundary-layer transition on the overall airplane performance, stability, and control. Some supporting two-dimensional airfoil results, obtained in the Langley Low Turbulence Pressure Tunnel (LTPT), are included to describe some of the basic airfoil characteristics.

Additional results are presented concerning the effects of several wing leading-edge modifications applied to the modified Cessna 210. These tests were conducted to determine whether leading-edge modifications that previously were shown to provide excellent stall/spin resistance on more conventional, wing/airfoil configurations (references 5 through 7) could be developed for application to an NLF wing design of high aspect ratio. Results are presented which show the effects of the modifications on the wing stalling characteristics and the associated effects on cruise performance.

Figure 1

NLF(1)-0414F DESIGN CHARACTERISTICS

Some of the design characteristics of the NLF(1)-0414F airfoil are indicated in figure 2. The airfoil is designed to achieve low profile drag coefficients at a cruise condition of $R = 10 \times 10^6$ by maintaining natural laminar flow (NLF) to about 70-percent chord on both upper and lower surfaces. Because of the favorable pressure gradients required for extensive NLF, the airfoil experiences a fairly rapid pressure recovery. At off-design conditions, flow separation in the pressure recovery region would be expected without implementation of some type of boundary-layer energizer.

To improve the stall and maximum lift characteristics, a thicker leading edge was utilized than is normally considered for airfoils with such extensive laminar flow operating at such high chord Reynolds numbers. It was known that this thick leading edge would limit the low drag C_l-range on the bare airfoil because of premature negative pressure peaks; however, the chance of a leading-edge type stall would be reduced. One possible means of regaining a wider low drag C_l-range is the use of a small chord trailing-edge flap to maintain favorable pressure gradients on both surfaces over a relatively wide range of lift coefficients.

More detailed discussions of the design objectives and the performance characteristics of the NLF(1)-0414F airfoil are found in references 1 through 4.

- **70% Natural laminar flow on both surfaces at $R=10 \times 10^6$**
  - **Rapid pressure recovery**
- **Thicker leading edge than normal NLF airfoils**
  - **Enhances maximum lift and stall characteristics**

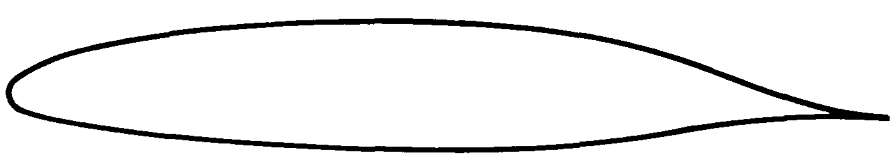


Figure 2

EFFECT OF ROUGHNESS ON SECTION CHARACTERISTICS

The effects of roughness applied near the airfoil leading edge on the two-dimensional airfoil section characteristics are shown in figure 3. These data were measured in the Langley Low Turbulence Pressure Tunnel (LTPT) at a chord Reynolds number of 6.0×10^6 which corresponds approximately to the cruise conditions of the modified Cessna 210. The data show that when transitioning from a primarily laminar to a primarily turbulent boundary layer, large increases in drag are caused by the loss of extensive laminar flow. Also, the lift and pitching moment characteristics are essentially unchanged, which is very desirable in terms of safety of flight and aircraft certification.

Another airfoil characteristic, which is independent of roughness effects, is the reduction in slope of the lift curve near 4° angle of attack. This reduction in lift-curve slope is caused by an upper-surface trailing-edge separation that occurs in the pressure recovery region. It will be shown in the next figure that the separation can be minimized by using boundary layer re-energizers (vortex generators) placed in the appropriate location.

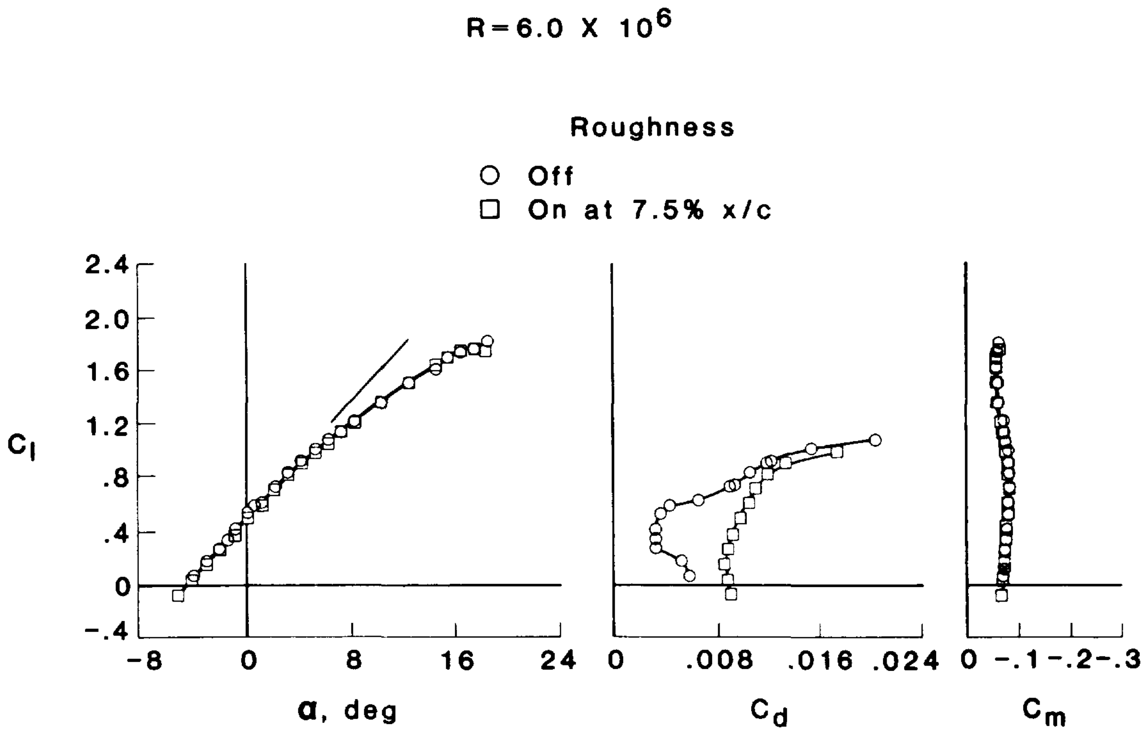


Figure 3

EFFECT OF VORTEX GENERATORS ON SECTION CHARACTERISTICS

Vortex generators are small low-aspect-ratio wings which are positioned on the airfoil surface at a high angle of incidence with respect to the local flow direction. The purpose of the vortex generator is to energize the turbulent boundary layer and thus reduce turbulent separation at off-design conditions. Figure 4 illustrates the effects of vortex generators on airfoil section characteristics for the NLF(1)-0414F airfoil at a Reynolds number of 3.0×10^6. Trailing-edge separation is indicated by the decrease in lift-curve slope for angles of attack greater than about 4 degrees for the vortex generators removed. Installation of a spanwise row of vortex generators, 0.2 inches high, spaced 1.6 inches apart, and located at 0.60 chord, results in an improvement in lift and drag performance for angles of attack greater than about 4 degrees. However, in the low lift-coefficient range a drag penalty is shown for the results with the vortex generators installed.

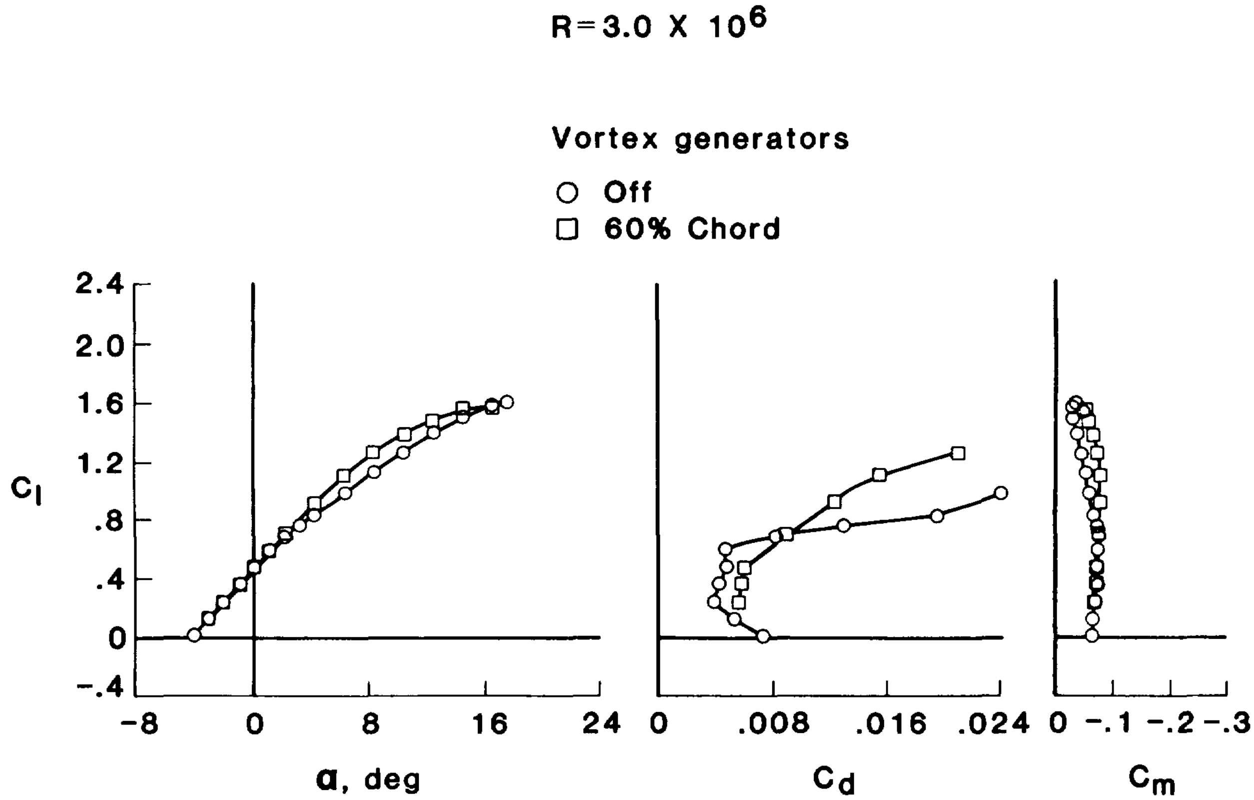


Figure 4

EFFECT OF REYNOLDS NUMBER ON SECTION CHARACTERISTICS

The effect of Reynolds number on the two-dimensional airfoil section characteristics are shown in figure 5 for Reynolds numbers of 2.0 x 10^6 and 6.0 x 10^6. A Reynolds number of 2.0 x 10^6 corresponds approximately to the high-lift (landing) condition of the modified Cessna 210 and was the Reynolds number used for the majority of the tests in the 30- by 60-Foot Wind Tunnel. As mentioned previously, a Reynolds number of 6.0 x 10^6 corresponds approximately to the cruise condition of the modified Cessna 210.

The differences in lift and drag shown in figure 5 illustrate the importance of accounting for the Reynolds number effects on airfoils such as NLF(1)-0414F. The data measured at R = 6.0 × 10^6 could be used to predict the cruise performance of the aircraft but would indicate unrealistically high levels of lift available for landing. The data measured at R = 2.0 x 10^6 (including the data from the 30- by 60-Foot Wind Tunnel) would accurately represent the landing condition but would indicate higher values of drag at cruise conditions. However, it was found that the incremental changes in total airplane drag due to roughness at R = 2.0 x 10^6 (shown in later figures) were very similar to the increments obtained in flight at higher Reynolds numbers.

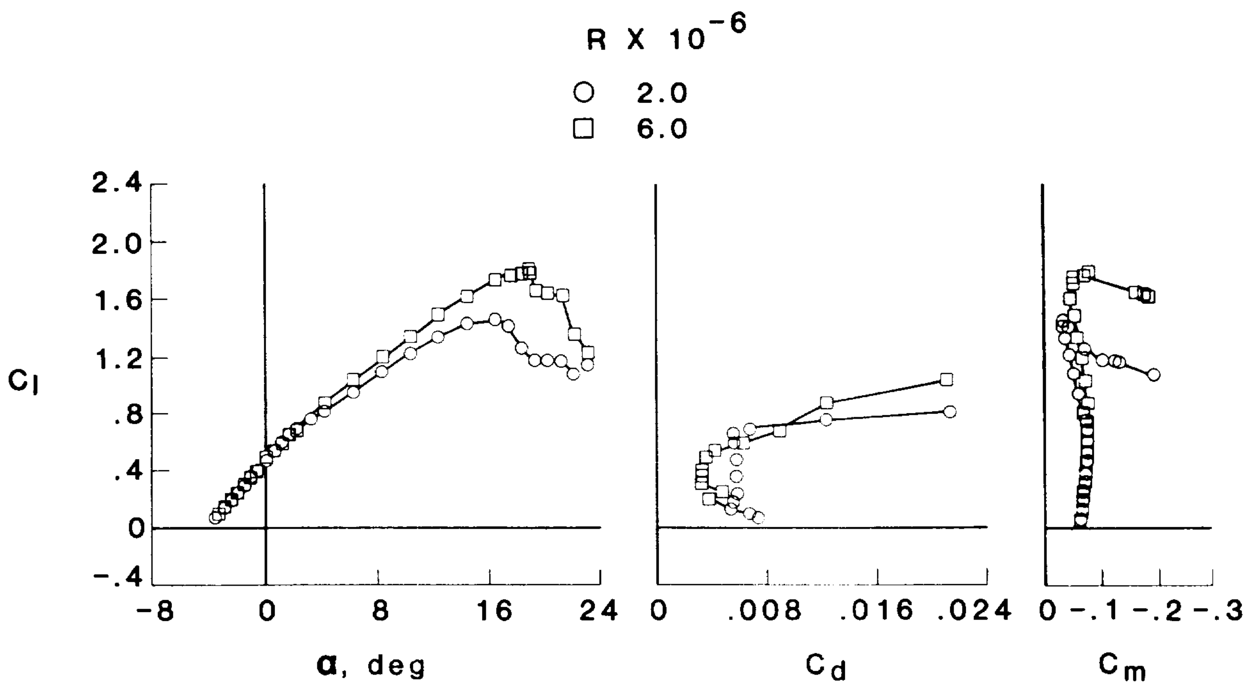


Figure 5

EFFECT OF TAPE TURBULATORS ON SECTION CHARACTERISTICS

At the lower Reynolds numbers, increases in drag can be partly due to areas of laminar separation. As the Reynolds number is decreased, the boundary layer becomes increasingly stable at the laminar separation point in the beginning of the steep pressure rises on both surfaces. When the highly stable boundary layer reaches the laminar separation point, it separates and takes a considerable distance before transitioning and reattaching back to the airfoil surface. Large drag penalties are associated with this separated region. One method of eliminating this separated region is utilizing turbulators to trip the flow before the laminar separation point is reached. Figure 6 illustrates the drag reduction realized by suppressing these laminar separation regions on the NLF(1)-0414F airfoil for a Reynolds number of 3.0×10^6. The type of turbulator used in this case was tape of 0.012 inches thick and 0.25 inches wide placed at 68-percent chord on the upper surface and 66-percent chord on the lower surface.

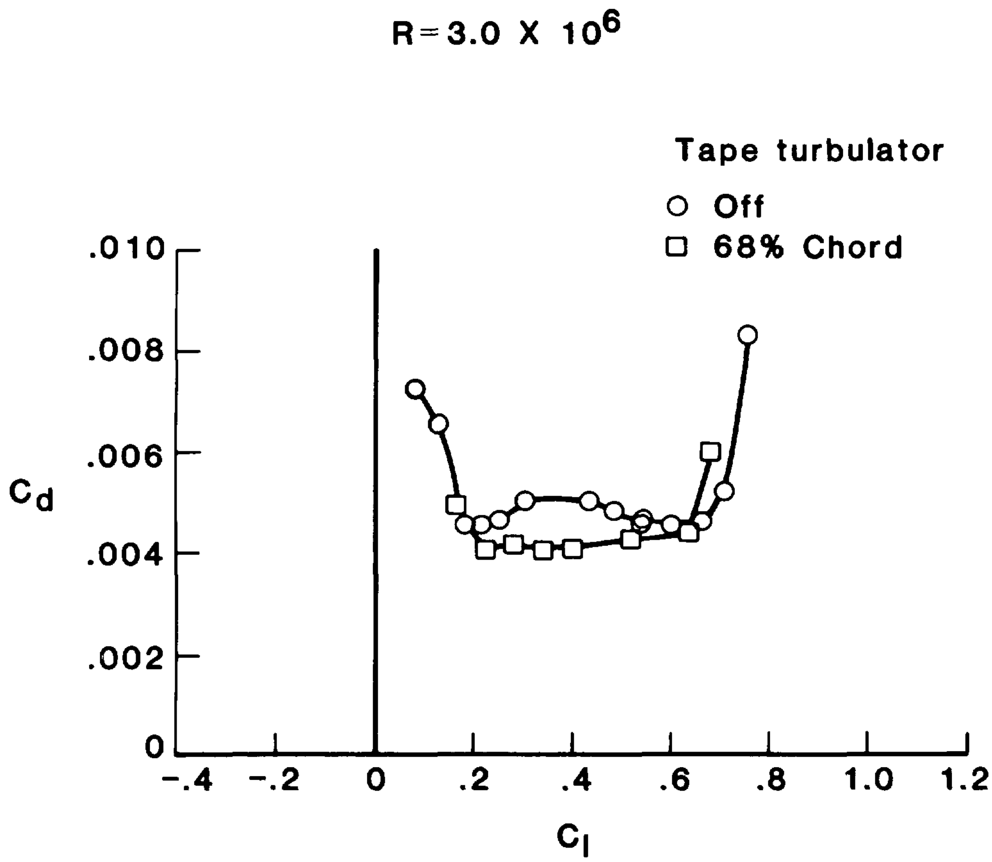
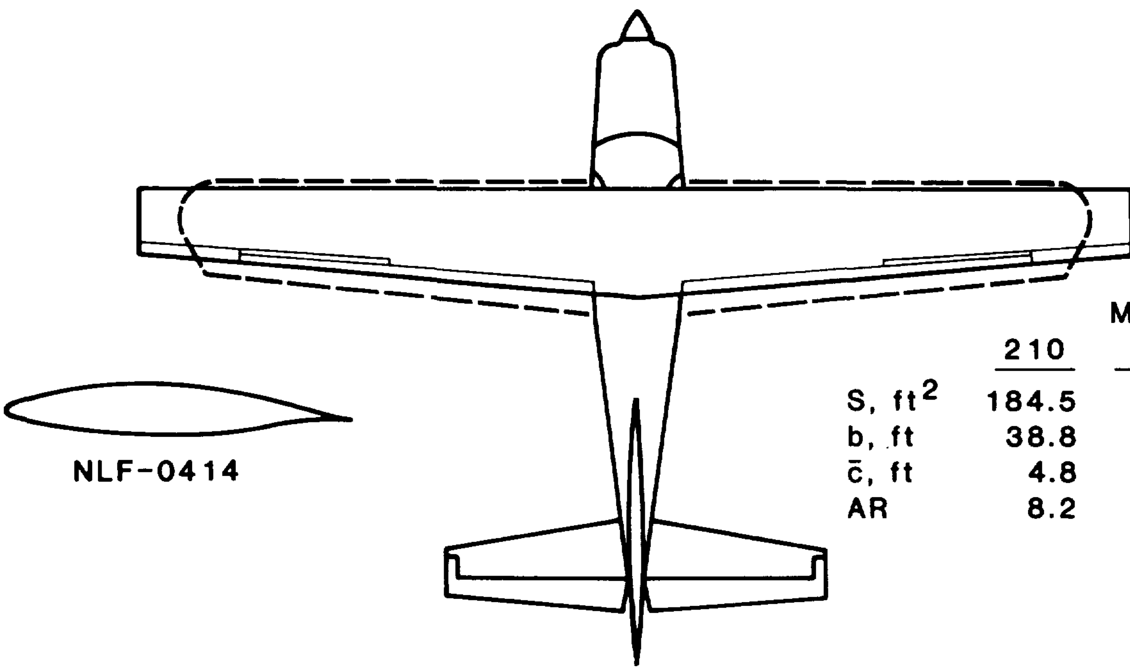


Figure 6

MODIFIED CESSNA 210 DESIGN CHARACTERISTICS

The design characteristics of the modified Cessna 210 are shown in figure 7. The modified wing is of higher aspect ratio, higher wing loading, and incorporates the NLF(1)-0414F airfoil. All of these changes are designed to improve cruise performance. A small 12.5-percent chord trailing-edge "cruise" flap is designed to vary the low-drag C_l-range with small flap deflections. This "cruise" flap could also be set to large trailing-edge-down deflections to enhance the maximum lift characteristics. Roll control is provided by a combination of ailerons and spoilers.



	210	Modified 210
S, ft^2	184.5	160.0
b, ft	38.8	42.0
$\bar{c}$, ft	4.8	3.9
AR	8.2	11.0

Figure 7

30- by 60-FOOT WIND-TUNNEL TESTS

The modified Cessna 210 airplane (figure 8) was mounted in the 30- by 60-Foot Wind Tunnel using the landing-gear attachment points. The tunnel conditions varied from a free-stream velocity of 40 mph to 72 mph which corresponds to Reynolds numbers based on $\bar{c}$ of 1.4×10^6 to 2.4×10^6. Overall aerodynamic forces and moments were measured over ranges of angle of attack and sideslip of -6° to 40° and -6° to 20° respectively. Additional tests were conducted to measure boundary-layer transition using both the hot-film and sublimating chemical techniques, and the wing stall pattern was documented through flow visualization studies using tufts.

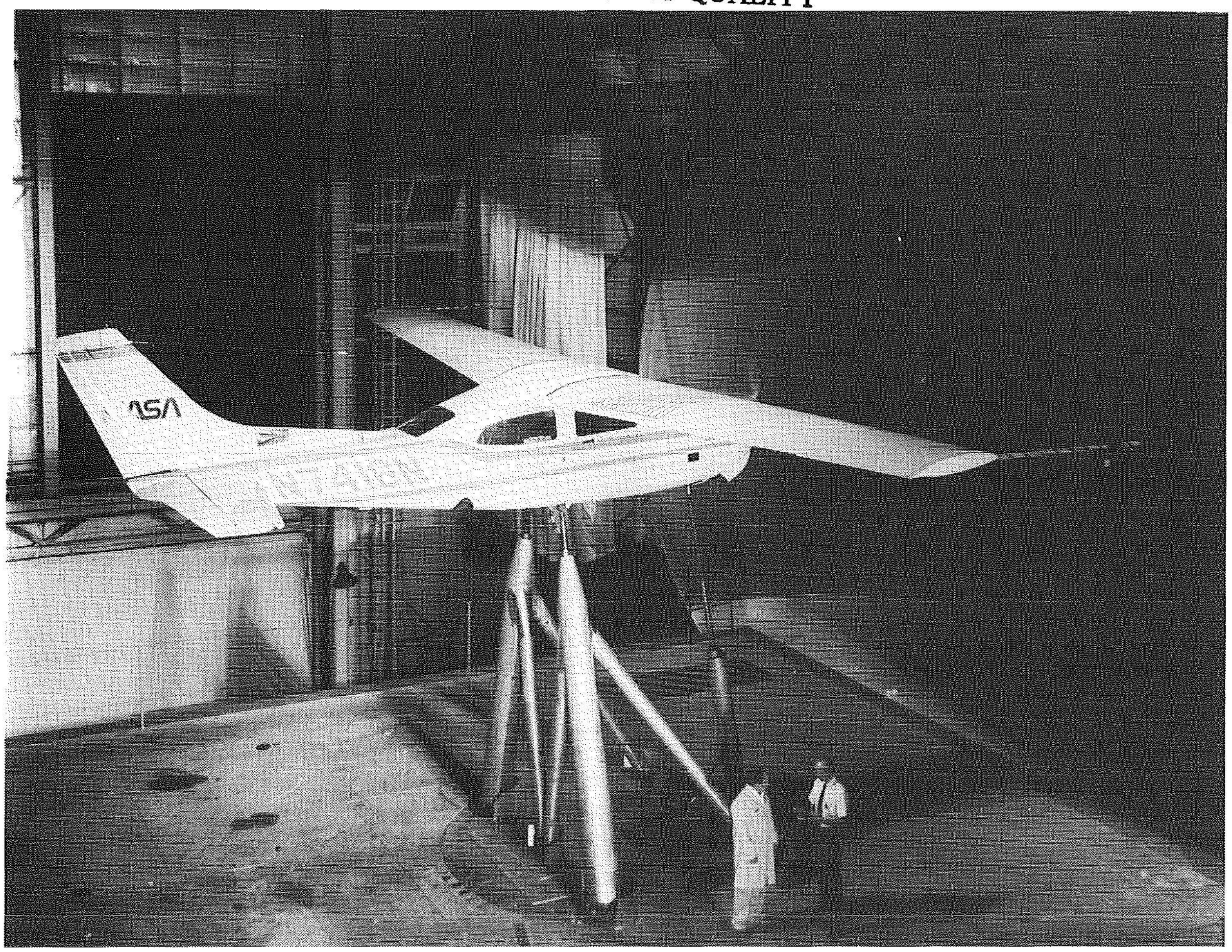


Figure 8

EFFECT OF ROUGHNESS ON AIRPLANE CHARACTERISTICS

The effects of fixing boundary-layer transition near the wing leading-edge on the lift, pitching moment, and drag characteristics are shown in figures 9 and 10. The data show that the lift and pitching moment characteristics are essentially unchanged when transition is fixed near the leading edge. Additional data (not shown) indicate that fixing transition also had essentially no effect on the lateral-directional stability and control. These characteristics are obviously very desirable from a safety and certification standpoint where premature boundary-layer transition (due to insect contamination, etc.) must be considered.

The effects of fixing transition on the drag characteristics (figure 10) illustrate the large drag reduction due to the extensive areas of laminar flow maintained on both the upper and lower wing surfaces at cruise lift coefficients (approximately C_L = .3).

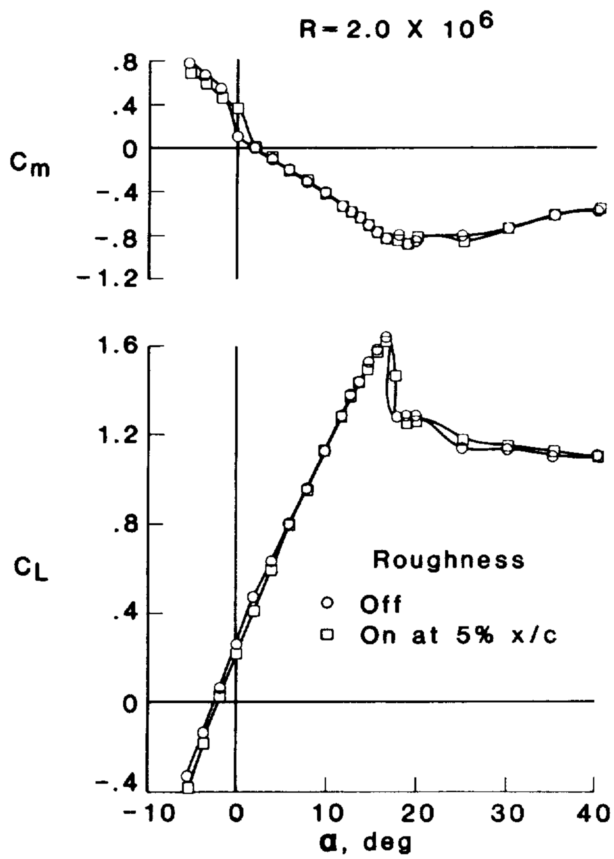


Figure 9

EFFECT OF ROUGHNESS ON AIRPLANE CHARACTERISTICS

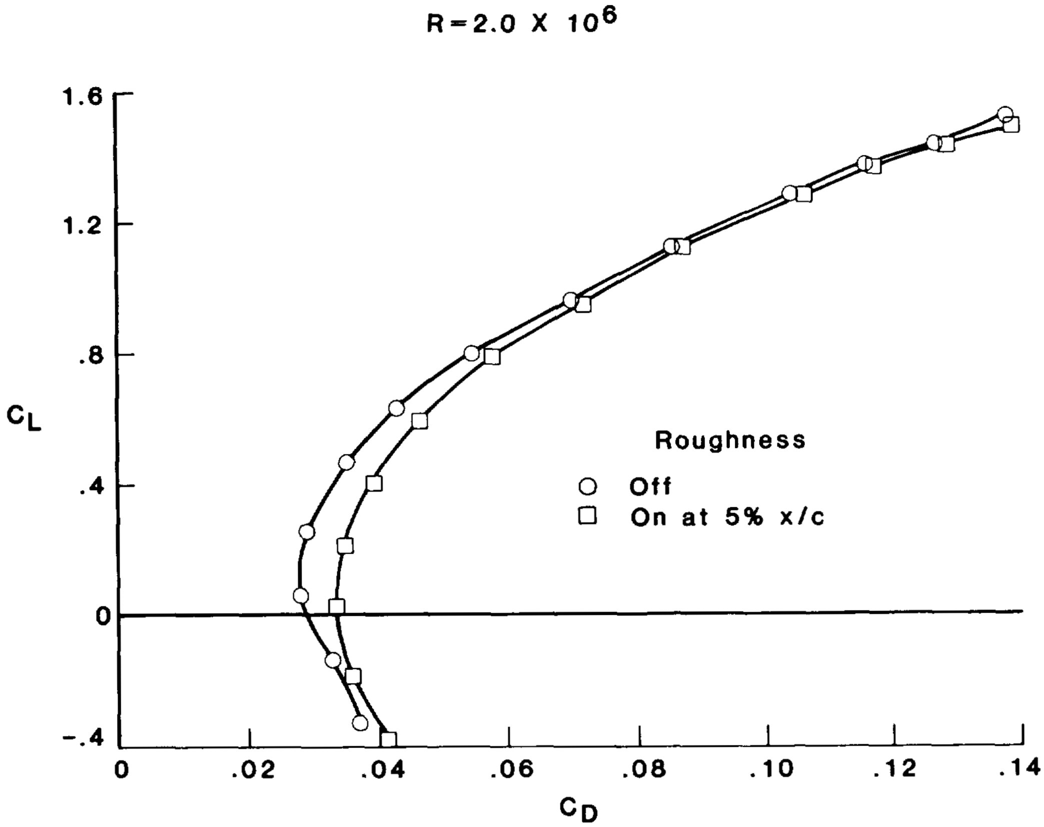


Figure 10

WIND-TUNNEL TRANSITION RESULTS

The extent of laminar flow was measured in the 30- by 60-Foot Wind Tunnel using both the hot-film and sublimating chemical techniques. An example of one of the sublimating chemical tests is shown in figure 11 for alpha = 1° and $R = 2.4 \times 10^6$. The test results showed that laminar flow was maintained to about 70-percent chord on both upper and lower surfaces at the cruise angle of attack. These results agree well with the theoretical predictions and the transition measurements made at higher Reynolds numbers in the Low Turbulence Pressure Tunnel (LTPT) with the two-dimensional airfoil model (figure 12). All of these data also agree very well with the transition measurements made by Cessna during flight tests of the modified Cessna 210 (reference 8).

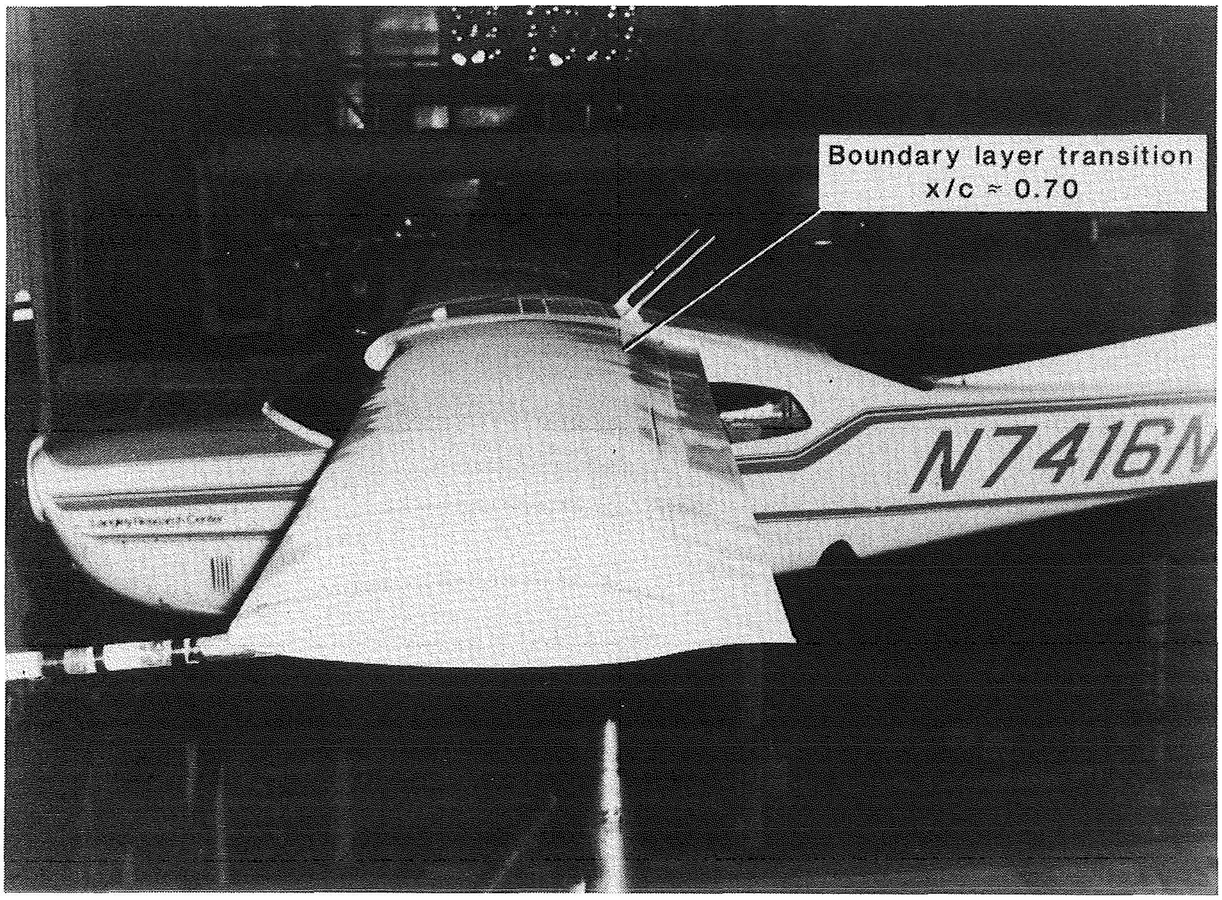


Figure 11

WIND-TUNNEL TRANSITION RESULTS

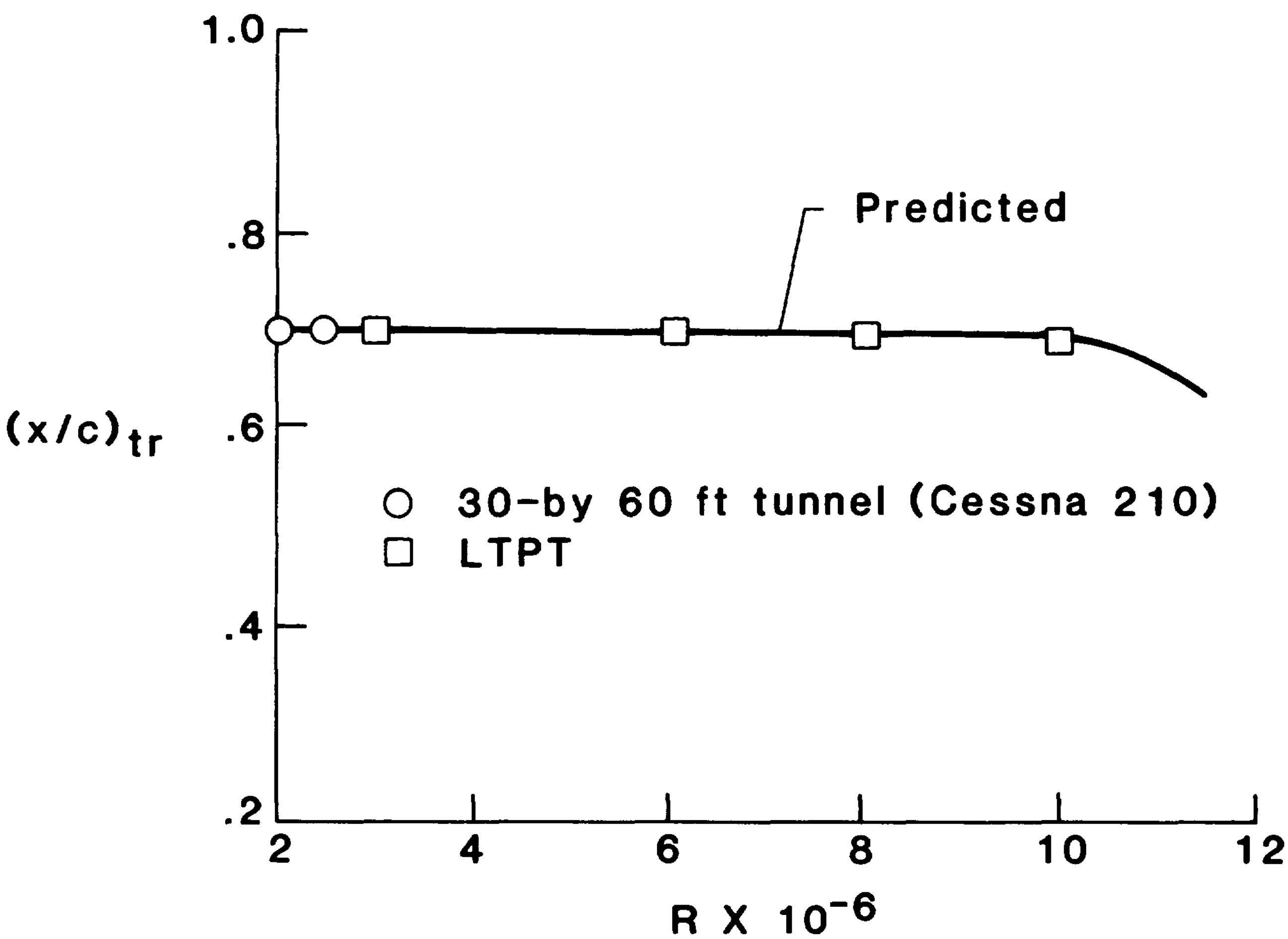


Figure 12

EFFECT OF TRANSITION ON CALCULATED CRUISE PERFORMANCE

The calculated performance increases on the modified Cessna 210 due to the large extent of laminar flow are illustrated in figure 13. These performance calculations are made for an altitude of 10,000 ft, a weight of 3,500 lbs, and 75-percent power. It is noted that these calculations are derived from the wind-tunnel data measured at $R = 2.0 \times 10^6$, where the airfoil is not performing as well (in terms of drag) as at the true cruise Reynolds number (approximately $R = 6.0 \times 10^6$). As a result, the calculated performance would be expected to be less than what could be obtained in flight; however, the calculations were found to give a reasonable estimate of the incremental effects of fixing transition.

The calculations presented in figure 13 indicate that the large extent of laminar flow would be responsible for about a 10-percent increase in speed and range for the same power setting. These incremental effects are similar to the performance measurements made by Cessna during flight tests of the modified Cessna 210 (reference 8). The calculations also show that if power were reduced to fly at the same cruise speed, then the large extent of laminar flow would be responsible for about a 29-percent increase in range.

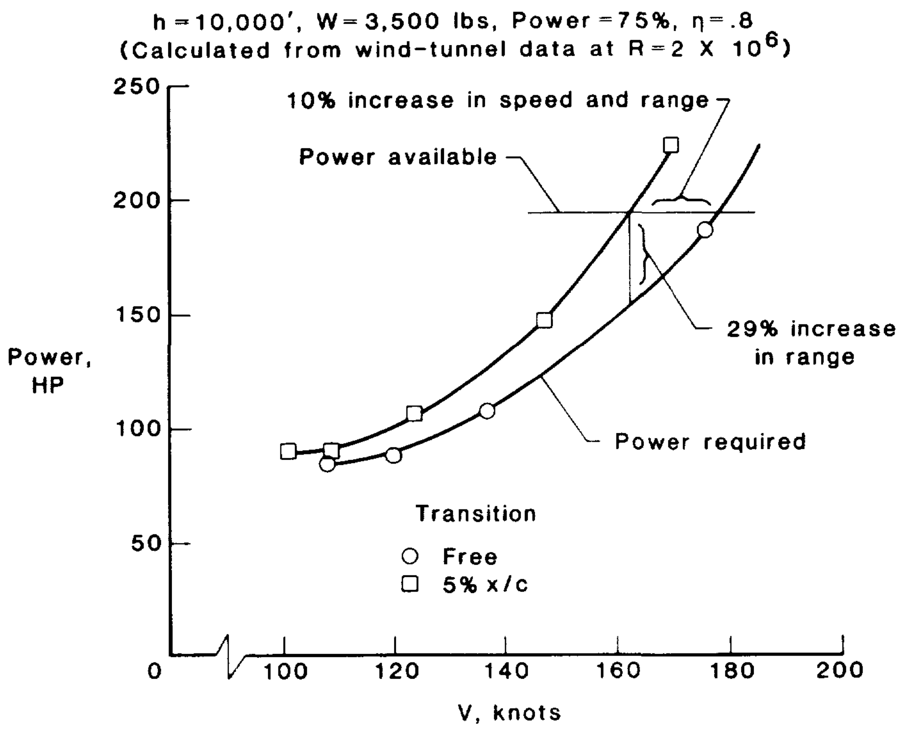


Figure 13

PRELIMINARY HIGH-LIFT RESULTS

Some preliminary high-lift results obtained with the NLF(1)-0414F airfoil are shown in figure 14. The two-dimensional airfoil data on the left show the effect of deflecting a 20-percent-chord split flap to an angle of 60°. The data on the right show the effect of deflecting the 12.5-percent-chord "cruise" flap to 40° on the modified Cessna 210. Although neither of these flap configurations was optimized to develop high lift on this airfoil, the data indicate the potential to develop effective high-lift systems. A discussion on the development of high-lift systems for this airfoil is presented in reference 4.

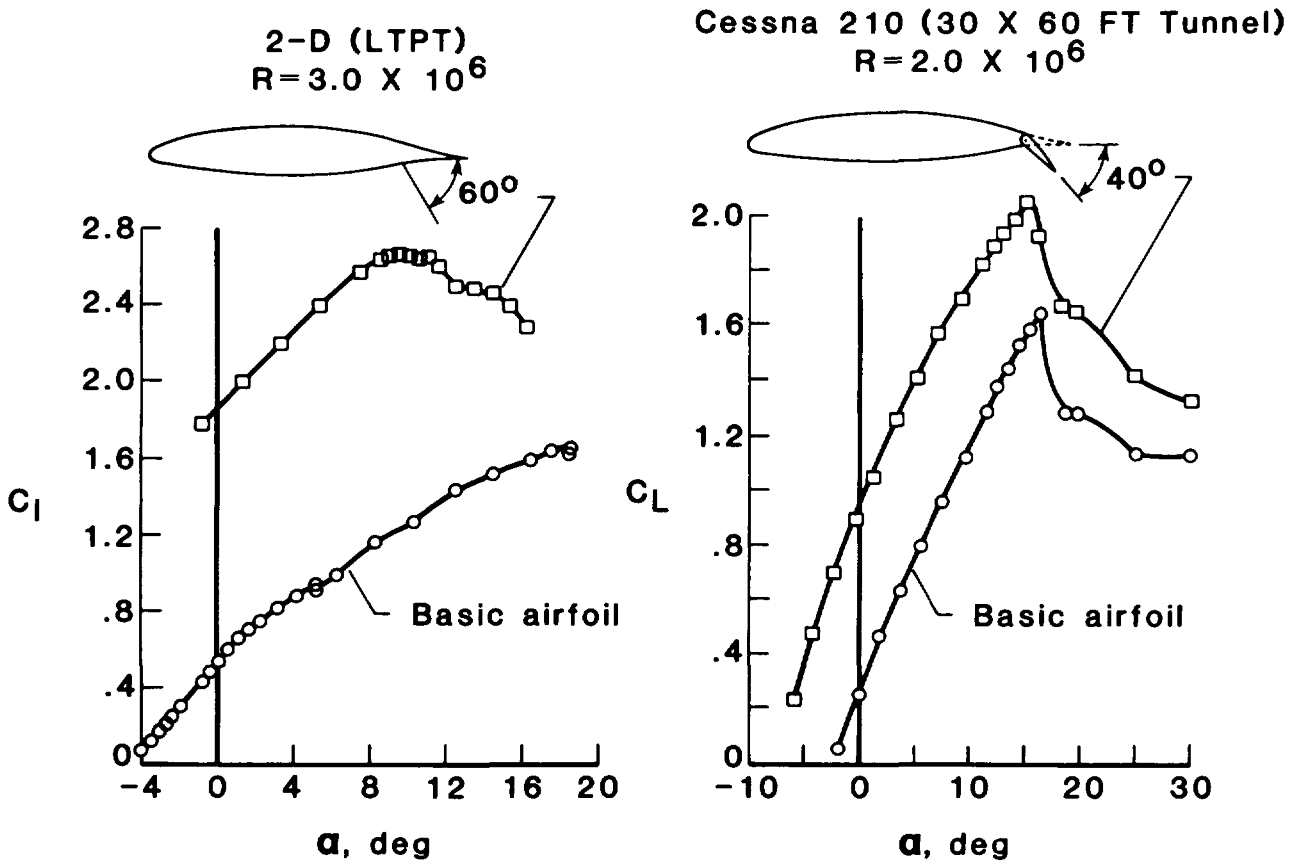


Figure 14

LEADING-EDGE DROOP DESIGN

The primary leading-edge modifications tested on the modified Cessna 210 are shown in figure 15. Research conducted on more conventional wing/airfoil configurations has shown that the application of an outboard wing leading-edge droop can significantly enhance stall/spin resistance by maintaining attached flow at the wing tips at angles of attack well above the normal wing stall (references 5 through 7). During development of an outboard droop for the modified Cessna 210, preliminary sub-scale tests showed that adding a small inboard droop segment in conjunction with the outboard droop could further enhance the stall characteristics.

In an attempt to minimize any increase in the drag characteristics of the basic wing, the droop airfoil section was derived from another NLF airfoil.

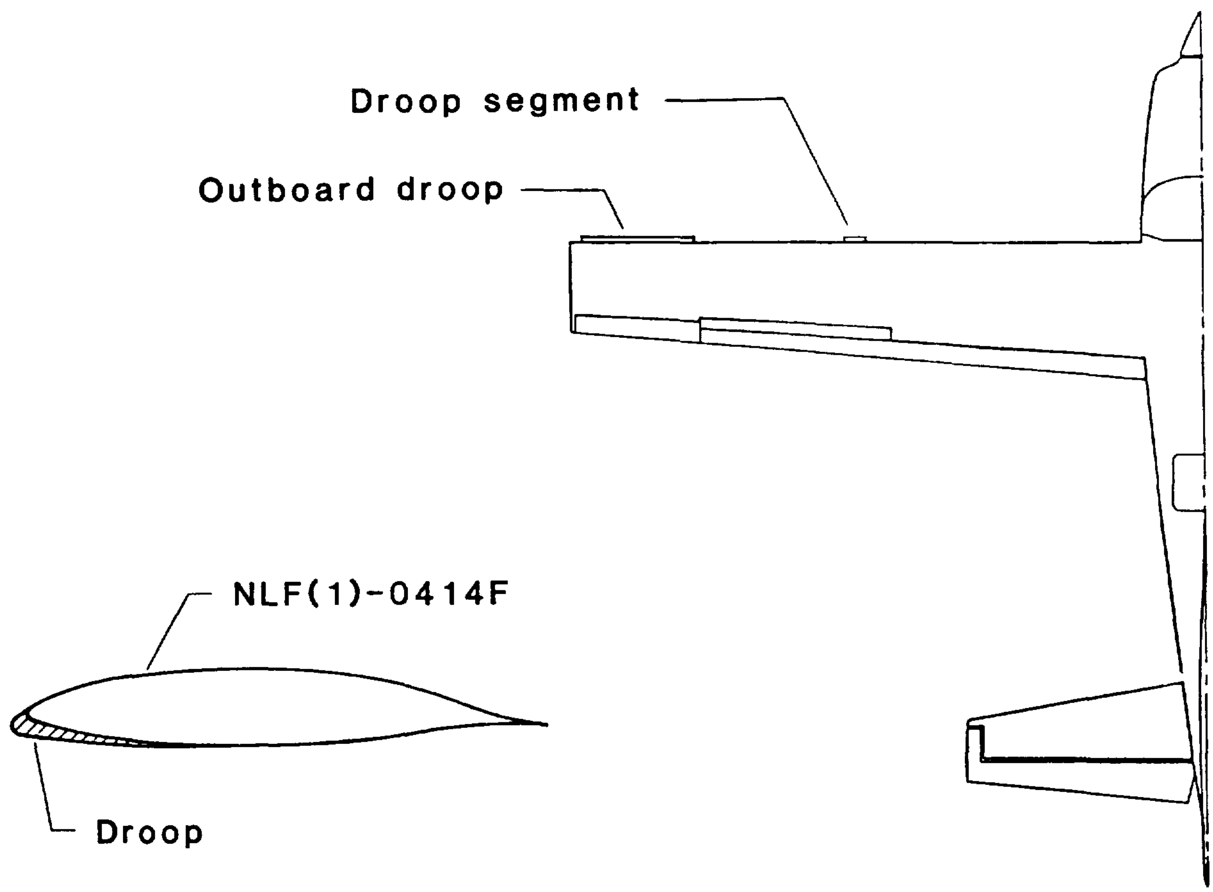


Figure 15

EFFECT OF OUTBOARD DROOP ON WING STALL CHARACTERISTICS

The effect of the outboard droop modification on the wing stall pattern is illustrated in figure 16. These sketches are based on flow visualization tests of the modified Cessna 210 in the 30- by 60-Foot Wind Tunnel. The sketches show that by 18° angle of attack the basic wing is almost completely stalled. With the outboard droop modification, however, attached flow was maintained at the wing tips up to about 28° angle of attack.

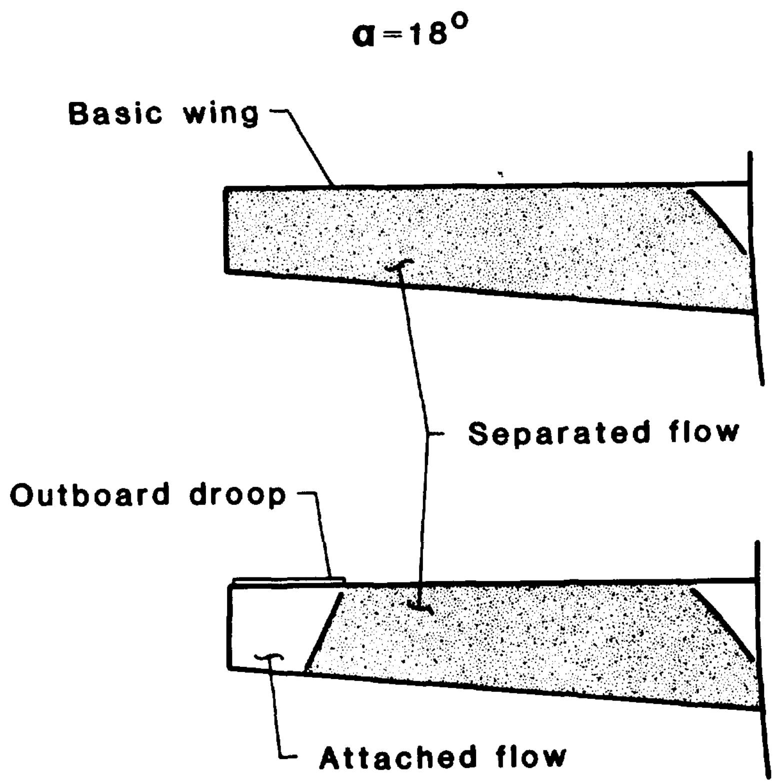


Figure 16

EFFECT OF OUTBOARD DROOP ON DAMPING IN ROLL

One criteria for assessing stall/departure resistance is the level of aerodynamic damping in roll. The effect of the outboard droop on the roll damping of the modified Cessna 210 was measured during sub-scale forced-oscillation tests and is presented in figure 17. It is noted that wing stall occurred at a lower angle of attack in these tests because of the lower test Reynolds number ($R = .65 \times 10^6$). The data show that the basic configuration exhibits highly unstable roll damping at the stall because of the negative lift-curve slope of the wing. The addition of the outboard droop is shown to significantly enhance these characteristics; however, unstable roll damping is still produced because of the rapid stall of the large inboard area of the wing.

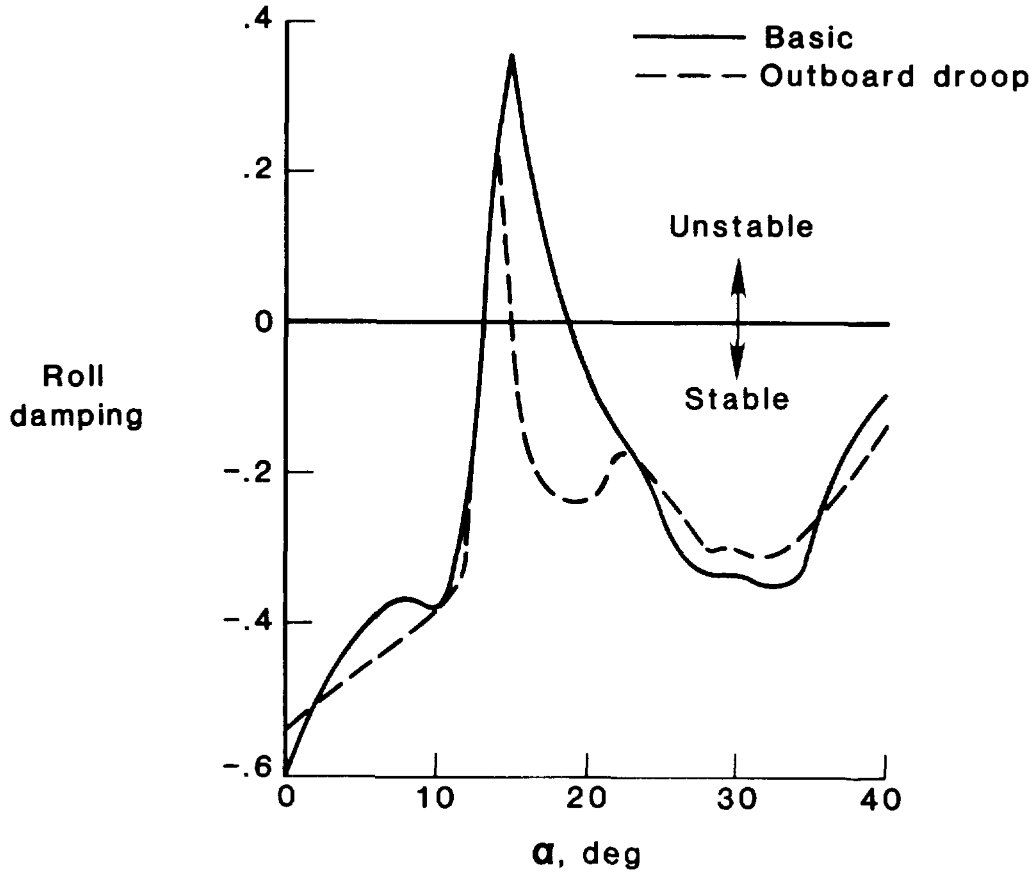


Figure 17

EFFECT OF DUAL SEGMENT DROOP ON WING STALL CHARACTERISTICS

The combined effect of the outboard droop and the inboard droop segment (called a dual segment droop or segmented droop) on the wing stall pattern is shown in figure 18 at 18° angle of attack. In this case, the inboard droop segment was found to act as a vortex generator and was effective in delaying the rapid stall of the inboard area of the wing.

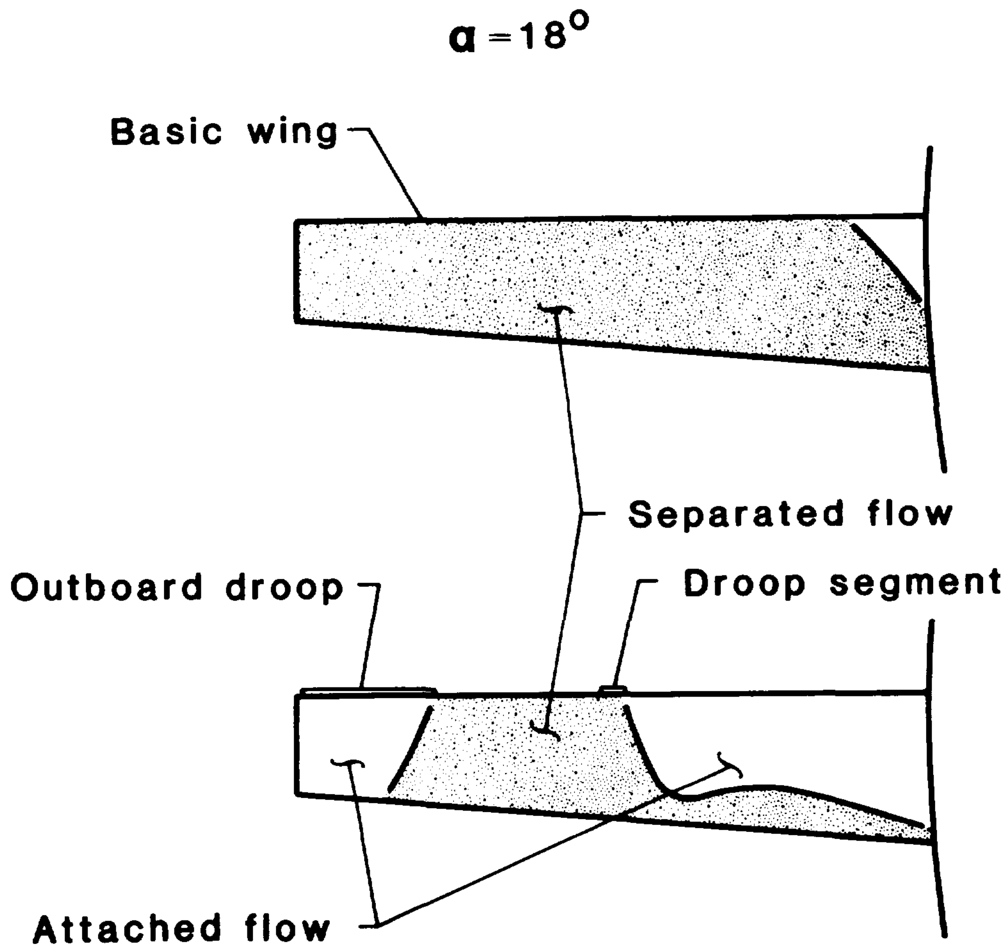


Figure 18

EFFECT OF DUAL SEGMENT DROOP ON DAMPING IN ROLL

The effect of the dual segment droop (segmented droop) on the roll damping characteristics are shown in figure 19. By delaying the rapid stall of the inboard area of the wing, the addition of the inboard droop segment was found to eliminate the unstable roll damping at the stall that was encountered with the outboard droop modification. Therefore, a combination of the outboard droop and the inboard droop segment was found to provide stable roll damping characteristics across the entire angle-of-attack range.

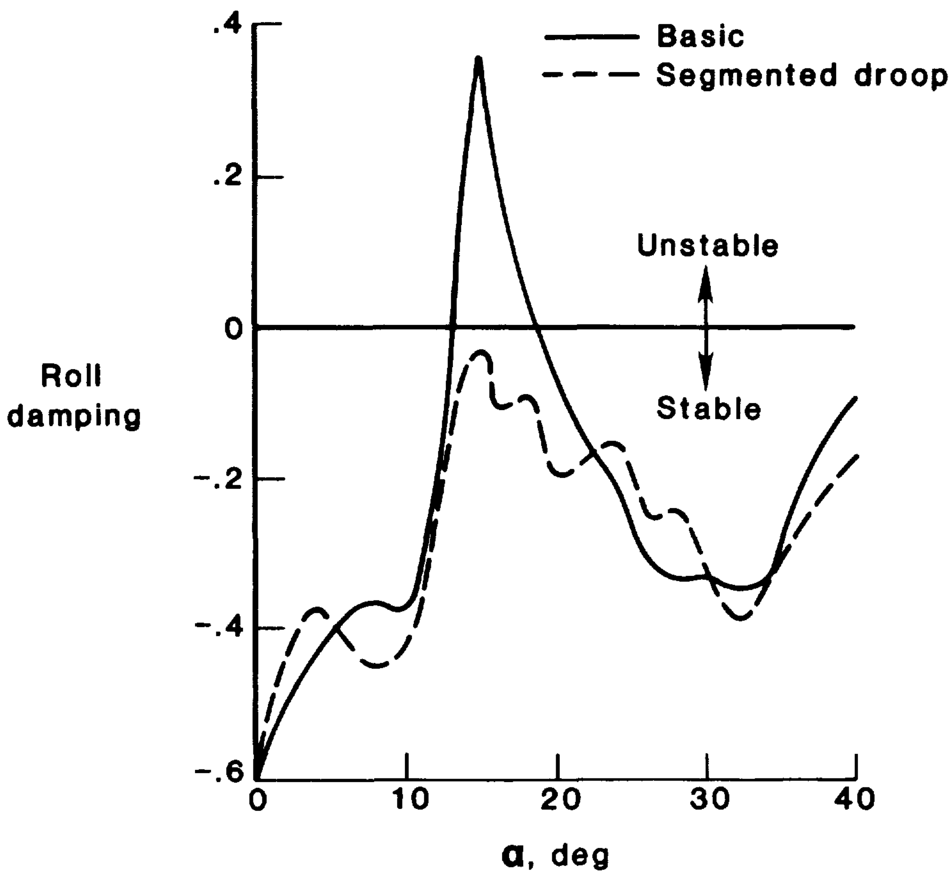


Figure 19

BOUNDARY LAYER TRANSITION WITH LEADING-EDGE MODIFICATIONS

A photograph of a sublimating chemical test with the leading-edge modifications in place is shown in figure 20. The photograph shows turbulent wedges emanating from the droop discontinuities and boundary layer transition occurring on the upper surface of the droop airfoil section at about 70-percent chord. Boundary layer transition was found to occur near the leading edge on the lower surface of the droop airfoil section; however, it is felt that more extensive laminar flow could be maintained on the lower surface by redesigning the droop airfoil section. In any case, the good laminar flow characteristics observed on the upper surface of the droop airfoil section would be expected to help minimize the drag penalty of the modifications.

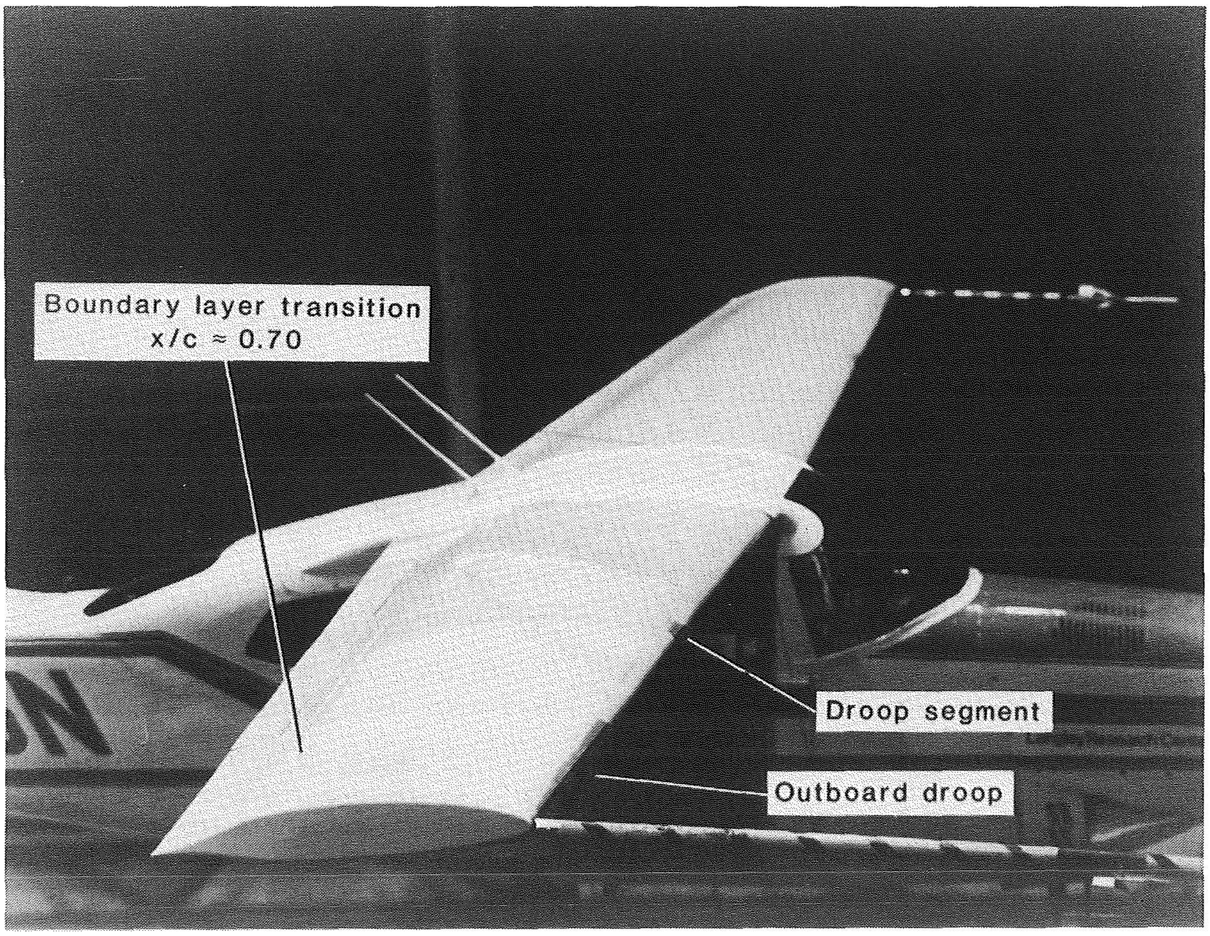


Figure 20

EFFECT OF LEADING-EDGE MODIFICATIONS ON CALCULATED CRUISE PERFORMANCE

The calculated effects of the leading-edge modifications on the cruise performance characteristics are presented in figure 21 using the same cruise conditions explained previously. The data show that the outboard droop modification would be responsible for about a 1.1-percent decrease in cruise speed whereas the segmented droop would be responsible for about a 2.8-percent decrease. The reason for the proportionately larger speed reduction with the addition of the small inboard droop segment is probably due to the addition of two discontinuities to each wing leading edge. However, additional tests have suggested the possibility of using a large vortex generator that only affects the wing upper surface, in place of the inboard droop segment. These tests, with the combination of the outboard droop and a large inboard vortex generator, predicted a cruise speed reduction only slightly more than with the outboard droop alone. This leading-edge configuration also produced wing stall patterns similar to the segmented droop configuration; however, roll damping data are not presently available for comparison. In any case, these cruise speed reductions are considered small compared to the potential stall/departure enhancement provided by the leading-edge modifications.

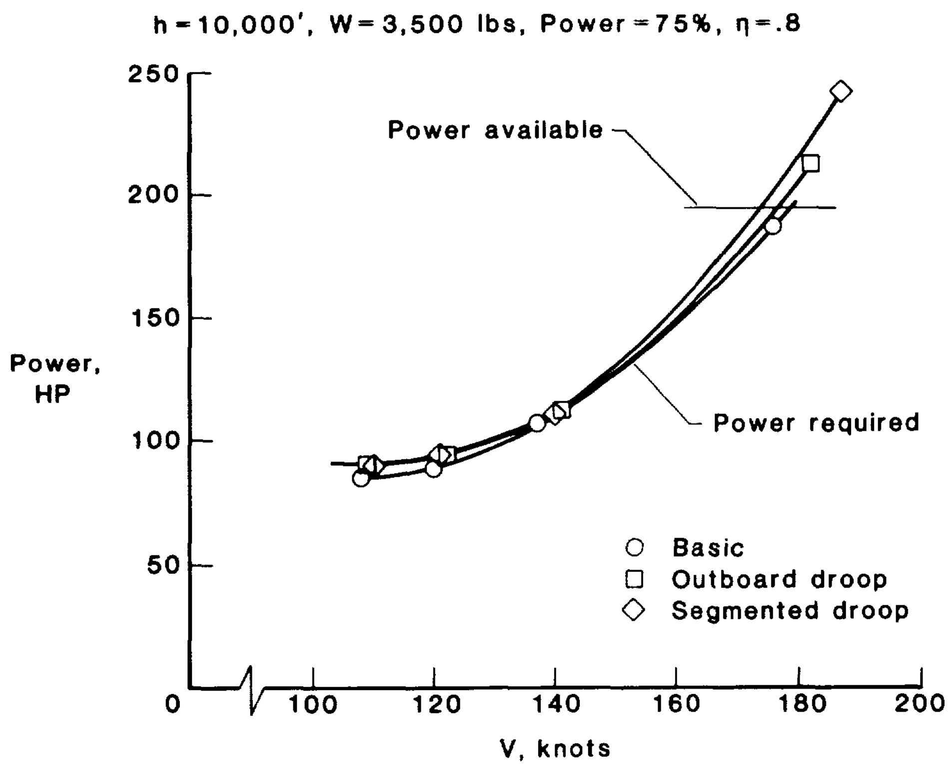


Figure 21

SUMMARY

The large performance gains predicted for the NLF(1)-0414F airfoil have been demonstrated in two-dimensional airfoil tests and in wind-tunnel tests conducted with a full-scale modified Cessna 210. The performance gains result from maintaining extensive areas of natural laminar flow, and have been verified by flight tests conducted with the modified Cessna 210 (see reference 8).

The lift, stability, and control characteristics of the modified Cessna 210 were found to be essentially unchanged when boundary layer transition was fixed near the wing leading edge. These characteristics are very desirable from a safety and certification standpoint where premature boundary layer transition (due to insect contamination, etc.) must be considered.

The leading-edge modifications were found to significantly enhance the roll damping characteristics of the modified Cessna 210 at the stall, and were therefore considered effective in improving the stall/departure resistance. Also, the modifications were found to be responsible for only minor performance penalties. A cooperative NASA/Cessna flight test program is planned to further investigate the effects of the leading-edge modifications on the modified Cessna 210.

- **Performance gains of NLF(1)-0414F airfoil demonstrated in wind-tunnel tests and verified in flight**
- **Lift, stability, and control characteristics not affected by transition from laminar to turbulent flow**
- **Leading-edge modifications improve the stall/departure resistance with only minor performance penalties**

Figure 22

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