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ADVANCED NATURAL LAMINAR FLOW AIRFOIL WITH HIGH LIFT TO DRAG RATIO

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ABSTRACT

An experimental verification of a high performance natural laminar flow (NLF) airfoil for low speed and high Reynolds number applications has been completed in the Langley Low Turbulence Pressure Tunnel (LTPT). The airfoil was designed for a c_ℓ = 0.4-0.45 at a Reynolds number of 10 million and $M_\infty < 0.4$ with a thickness of 0.14 chord. Theoretical development allowed for the achievement of 0.70 chord laminar flow on both surfaces by the use of accelerated flow as long as tunnel turbulence did not cause upstream movement of transition with increasing chord Reynolds number. With such a rearward pressure recovery, a concave type deceleration was implemented. This type of recovery efficiently recovers pressure by decelerating most when the boundary layer has the most energy, then continuously decreasing the gradient toward the trailing edge. The airfoil's leading edge is moderately sharp representing a compromise between a sharp nose needed for a wide low drag c_ℓ range and a blunt nose for better $c_{\ell max}$ performance. A 0.125 chord simple flap is incorporated to substantially increase the low drag c_ℓ range by keeping the stagnation point at the leading edge at different c_ℓ's.

Two-dimensional theoretical analysis indicated that a minimum profile drag coefficient (c_{d_∞}) of 0.0026 was possible with the desired laminar flow at the design condition. With the three-foot chord two-dimensional model constructed for the LTPT experiment, a minimum profile drag coefficient of 0.0027 was measured at a c_ℓ = 0.41 and $Re_c = 10 \times 10^6$. The low drag bucket was shifted over a considerably large c_ℓ range by the use of the 12.5% chrod trailing edge flap. At a Reynolds number of 10 million and $\delta_f = -10°$, the lower end was shifted to $c_\ell \approx 0$. With a positive flap deflection of 12.5°, the upper end was shifted to c_ℓ = 0.81. This yielded a two-dimensional lift to drag ratio (L/D) of 245.

Suprisingly high $c_{\ell max}$ values were obtained for an airfoil of this type. A $c_{\ell max}$ of 1.83 was obtained for $\delta_f = 0°$ at $Re_c = 10 \times 10^6$ and $M_\infty = 0.12$. The $c_{\ell max}$ decreases slowly with decreasing Reynolds number. A 0.20 chord split flap with 60° deflection was also implemented to verify the airfoil's high lift capabilities. A maximum lift coefficient of 2.70 was attained at Reynolds numbers of 3 and 6 million.

NLF(1)-0414F DESIGN OBJECTIVES

The first and primary objective of the design was to design a natural laminar flow (NLF) airfoil, for low speed applications, that achieved significantly lower profile drag coefficients at cruise than existing NLF airfoils but was still practical to use. This resulted in an exercise to design an airfoil with as extensive favorable gradients ($dp/dx < 0$) as seemed practical without making the far aft pressure recoveries too severe. The airfoil was also designed for reasonably high chord Reynolds numbers, approximately 10 million (fig. 1).

To help lessen the severity of the far aft pressure recoveries with respect to separation, concave type pressure recoveries were utilized. A concave pressure recovery decelerates the flow when the boundary layer has the most energy, tapering the gradient of the deceleration downstream on the airfoil as the boundary layer loses energy. For off-design conditions, the possibility of utilizing boundary layer re-energizers or momentum redistributors was also examined as a means of alleviating the problem of turbulent separation in the pressure recovery.

To improve $c_{\ell max}$ performance, 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 with premature negative pressure peaks, however, the chance of a leading edge type stall would be reduced. Also, Pfenninger's earlier work (ref.1) showed that the use of a small chord simple trailing edge flap could be used to regain a respectable low drag c_ℓ range. Deflection of this small chord flap, both positively and negatively, allows the conversion of lift due to angel of attack into lift due to flap deflection. By changing the lift at the design angle of attack, favorable gradients can be maintained on both surfaces simultaneously for a relatively wide range of lift coefficients.

With the steep pressure recoveries that result on an airfoil of this kind, it was known that there would be problems with laminar separation at lower chord Reynolds numbers. In the far aft pressure rises this results in profile drag penalties due to the formation of separation bubbles. In the leading-edge region this could result in poor high lift performance. The use of boundary layer trips was explored as a means of causing transition before the laminar separation point was reached, thereby eliminating the problem.

Finally, when designing configurations for maximum cruise performance, one is inevitably led to flying as close to $(L/D)_{max}$ as possible. This means increasing the wing loading, and results in the need for greater maximum lift coefficients. NLF(1)-0414F was designed with the intent of integrating it with a slotted Fowler flap arrangement and possibly even a Kruger flap to achieve high maximum lift coefficients.

NLF(1)-0414F DESIGN OBJECTIVES

- 70% CHORD NATURAL LAMINAR FLOW (NLF) ON BOTH SURFACES AT R_{E_C} = 10 MILLION
- COMPROMISE SOME LOW DRAG C_l RANGE (AT $\delta_F = 0°$) TO IMPROVE $C_{l_{MAX}}$ PERFORMANCE BY THICKENING THE LEADING EDGE
- INCREASE LOW DRAG C_l RANGE WITH A SMALL CHORD TRAILING-EDGE FLAP
- IMPLEMENT CONCAVE PRESSURE RECOVERY TO REDUCE THE TURBULENT SEPARATION PROBLEM WHEN TRANSITION OCCURS FAR FORWARD ON THE AIRFOIL. ALSO, POSSIBLY USE SOME FORM OF BOUNDARY LAYER RE-ENERGIZATION OR MOMENTUM REDISTRIBUTION
- USE OF BOUNDARY LAYER TRIPS (TAPE, GRIT, BLEED AIR, ETC.) TO ELIMINATE LAMINAR SEPARATION AT LOWER REYNOLDS NUMBERS, BOTH IN THE REAR PRESSURE RECOVERY AND AT THE LEADING EDGE AT HIGH ANGLES OF ATTACK
- IMPLEMENTATION OF AN EFFICIENT HIGH LIFT SYSTEM: SLOTTED FOWLER FLAPS AND POSSIBLY A KRUGER FLAP

Figure 1

NLF(1)-0414F PROFILE WITH FLAP DEFLECTION

Shown in figure 2 is the profile of NLF(1)-0414F. It is characterized by a moderately sharp leading edge. This leading edge is thicker than a normal high Reynolds number NLF airfoil but sharper than a conventional turbulent flow airfoil. Maximum thickness is 14.3% of the chord, being relatively far aft on the airfoil at the 45% chord location. The trailing-edge region is sharp for low pressure drag penalties. The 12.5% chord trailing-edge flap is illustrated at two deflection angles: -10° and 12.5°.

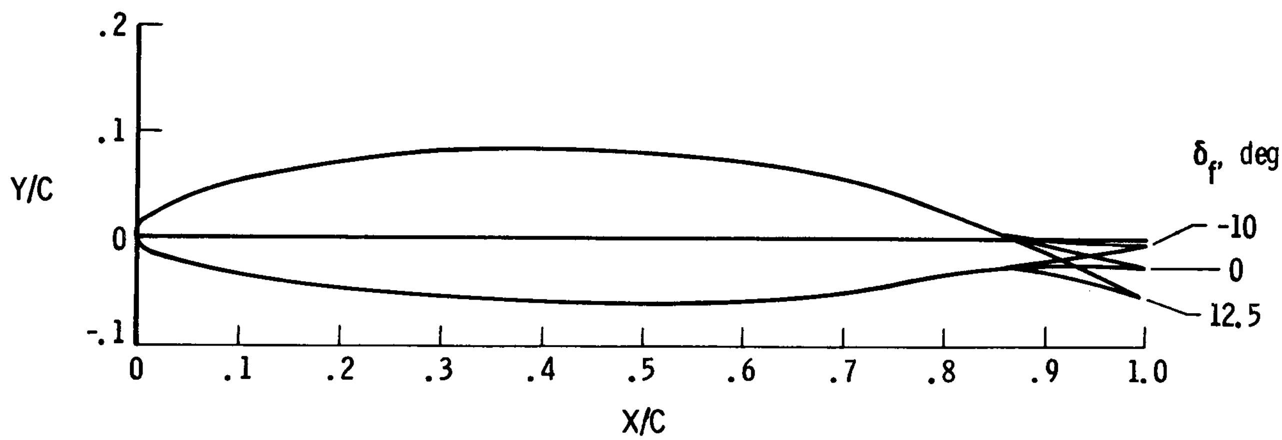


Figure 2

EXPERIMENTAL/THEORETICAL PRESSURE DATA AT DESIGN CONDITIONS

A comparison of the experimental pressure distribution of NLF(1)-0414F at $M_\infty = 0.40$, $Re_c = 10 \times 10^6$, and $\alpha = -1^\circ$ is compared with theoretical pressure distribution calculated by the Korn-Garabedian (ref. 2) potential flow analysis (fig. 3). There are favorable gradients on both surfaces up to the 70% chord location. The steep concave pressure recoveries of NLF(1)-0414F are also illustrated. There is a flat spot in the upper surface pressure distribution at $x/c = 0.15$. This resulted from the addition of thickness in the leading-edge region to improve $c_{\ell max}$ performance. Results form the Tollmien-Schlichting boundary layer stability analysis showed that this flat spot in the pressure distribution yielded a smaller disturbance growth than with a continuous acceleration in this region.

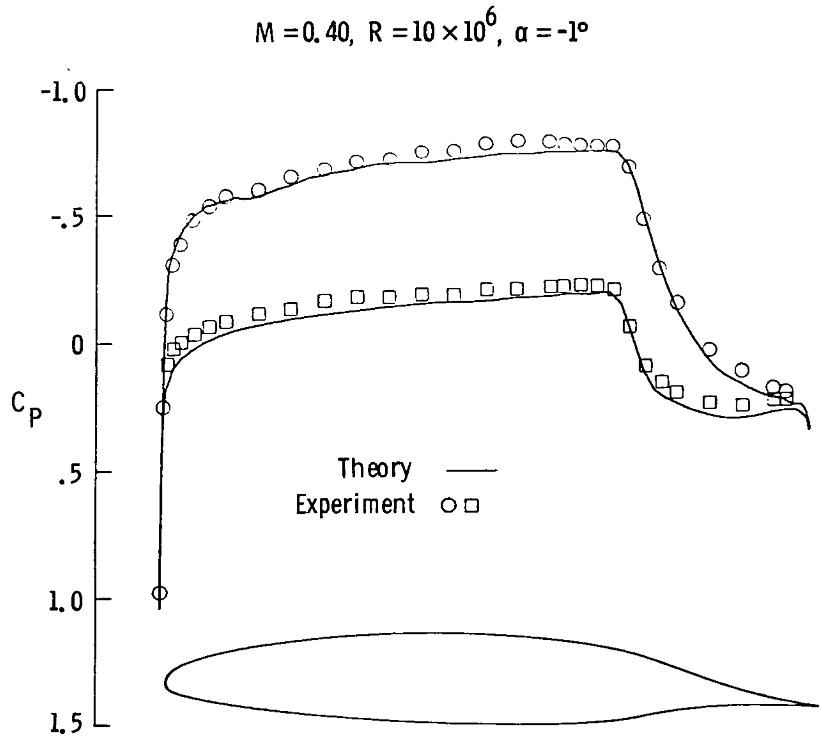


Figure 3

STALL CHARACTERISTICS AND REYNOLDS NUMBER EFFECTS

The section characteristics of NLF(1)-0414F are shown in figures 4 and 5 at chord Reynolds numbers ranging from 2 to 10 million with no flap deflection. For a chord Reynold number of 10 million (the design case) the minimum profile drag coefficient, at $\alpha = -1°$, is 0.0027 with 70% chord laminar flow on both surfaces. This represents a profile drag coefficient that is only 38% that of an unseparated fully furbulent airfoil. The low drag bucket is very narrow at this high Reynolds number in the wind tunnel experiment. The pitching moment coefficient about the quarter chord point is -.079, at $\alpha = -1°$. At the design chord Reynolds number of 10 million $c_{\ell max}$ was 1.83, at $a = 18.0°$, with a gentle stall behavior. If the chord Reynolds number is reduced to 6 million, the $c_{\ell max}$ is still 1.82. However, below $Re_c = 6 \times 10^6$, the $c_{\ell max}$ decreased. This is because of the increased energy losses in the boundary layer due to the increase effects of viscosity. Note that even $Re_c = 2 \times 10^6$, where $c_{\ell max} = 1.45$, the stall is still very gently and there is no indication of a leading edge type stall. As Reynolds number is decreased, the minimum profile drag coefficient increases in a manner greater than unseparated airfoils. Significant laminar separation bubbles start to occur at the beginning of the pressure rise on each surface, resulting in profile drag penalties. Note the character of the low drag bucket at chord Reynolds numbers of 2 and 3 million. at both ends, when the leading edge negative pressure peak eliminates the laminar separation bubble on one surface or the other, the profile drag coefficient is lower than in the middle of the low drag bucket. In the middle of the low drag bucket, there are laminar separation bubbles on both surfaces.

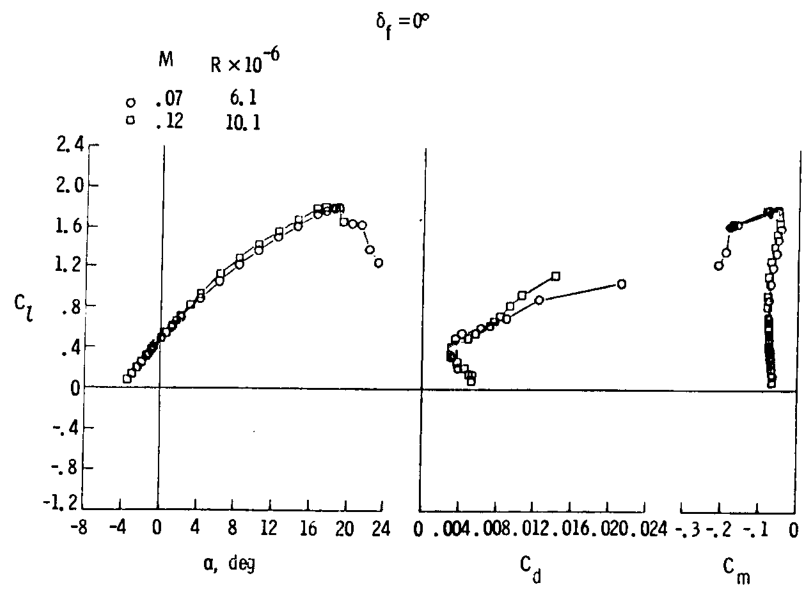
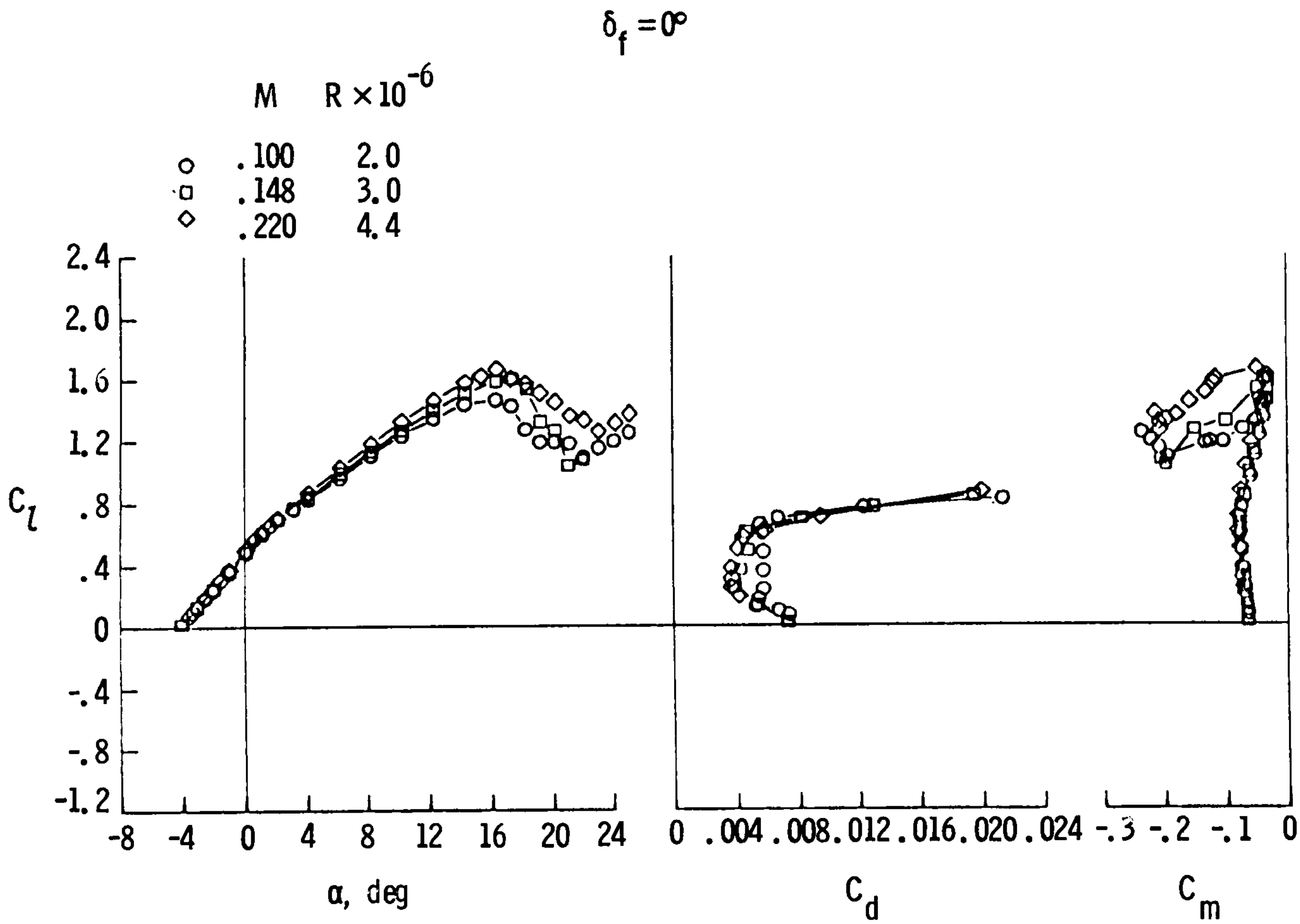


Figure 4



$\delta_f = 0°$
M
$R \times 10^{-6}$
.100 2.0
.148 3.0
.220 4.4
2.4
2.0
1.6
1.2
c_l
.8
.4
0
-.4
-.8
-1.2
-8
-4
0
4
8
12
16
20
24
α, deg
0
.004
.008
.012
.016
.020
.024
c_d
-.3
-.2
-.1
0
c_m

Figure 5

FLAP DEFLECTION EFFECTS

The drag polar at $Re_c = 6.1 \times 10^6$ for various flap deflections ranging from -10° to 20° is shown in figure 6. Deflecton of this 12.5% chord simple trailing-edge flap gave a c_ℓ rang with a low drag from c_ℓ = -.007 to nearly c_ℓ = 1.06. The minimum profile drag coefficient with 0° flap deflection at $Re_c = 6 \times 10^6$ is 0.0032 for a c_ℓ range from 0.273 to 0.417. At the lower end of the drag bucket, with a flap deflection of -10°, the minimum profile drag coeffficient is 0.0036 at c_ℓ = .-007. At the upper end of the low drag c_ℓ range, with a flap deflection of 20°, the minimum profile drag coefficient is 0.0043 at c_ℓ = 1.06. This yields a L/D of 247; however, this is only at one c_ℓ and it would be hard to fly at one design point. Examining the 17.5° flap deflection, this same minimum profile drag coefficient, 0.0043, is realized at a section lift coefficient as high as 0.905, yielding a L/D of 210. For this flap deflection, there is a reasonable c_ℓ range to fly in. At the design chord Reynolds number of 10 million, at the upper end of the low drag range (12.5° flap deflection), there was minimum profile drag coefficient of only 0.0033 with c_ℓ = 0.81. This gives a L/D of 245.

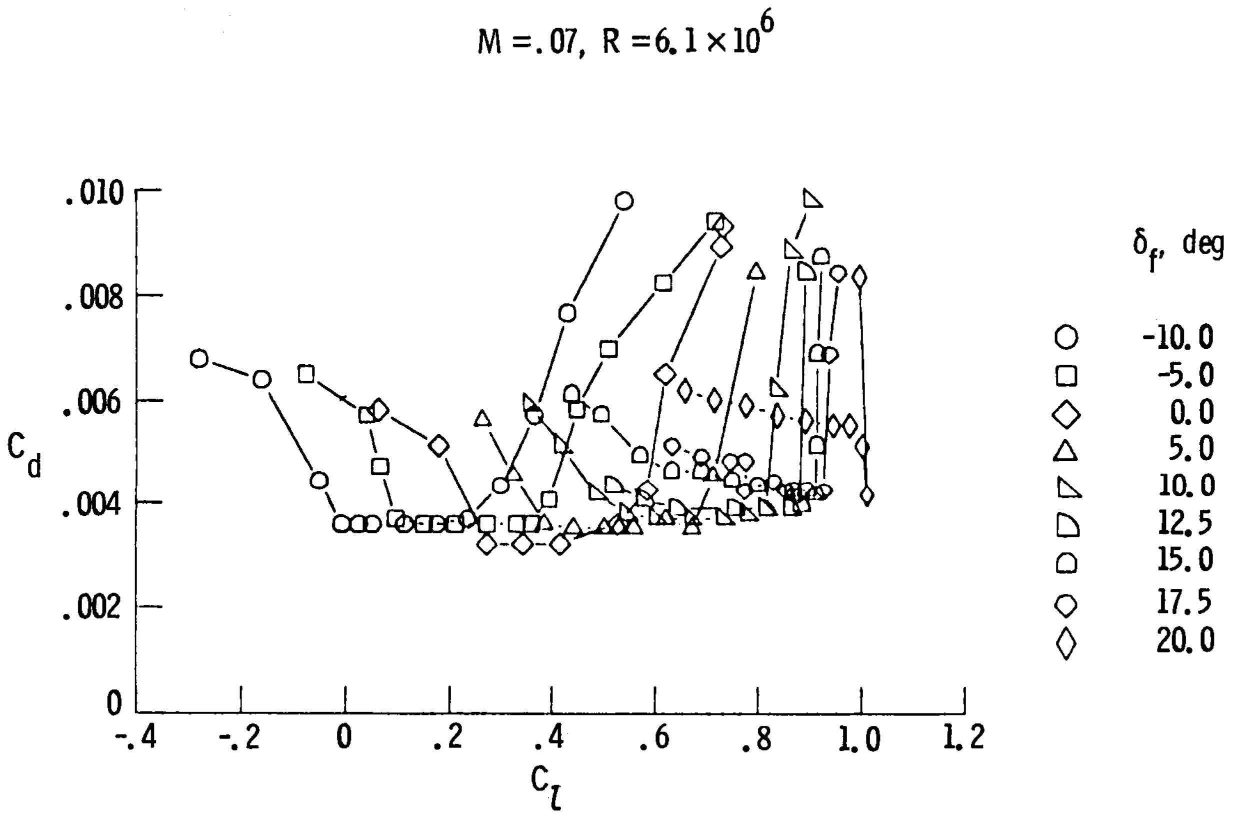


Figure 6

ROUGHNESS EFFECTS

A NLF airfoil has to not only be designed to achieve low profile drag coefficients with extensive laminar flow but must also be able to perform well when the flow is fully turbulent. This can happen when insects or rain cause transition far forward on the airfoil. First, the $c_{\ell max}$ performance should not be degraded. Second, the airfoil should be designed so that the profile drag at cruise is not usually high, resulting from separation in the far aft pressure recovery. Figure 7 shows that section characteristics of NLF(1)-0414F with transition free and transition fixed near the leading edge at $Re_c = 10 \times 10^6$. The $c_{\ell max}$ with the flow fully turbulent is 1.81 as compared to 1.83 with free transition. With the flow fully turbulent, the minimum profile drag coefficient is 0.0080, nearly three times that of the extensively laminar value. However, this profile drag coefficient is comparable to that of normal unseparated fully turbulent airfoils.

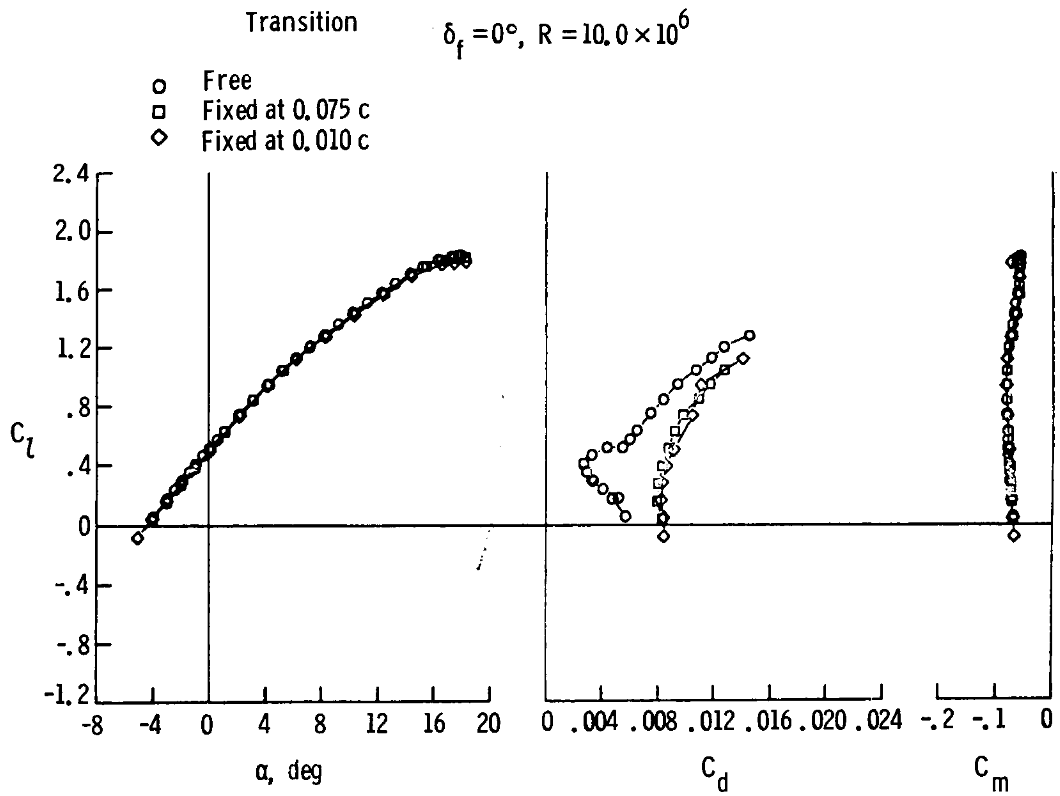


Figure 7

SPLIT FLAP PERFORMANCE

To show the performance of NLF(1)-0414F under the conditions of a high lift system, a split flap was tested in the wind tunnel experiment. A high lift system causes very large negative pressure peaks and will aggravate the leading-edge stall problem if their is one. This split flap was similar to those tested on the NACA 4 and 5 digit and the 6 series airfoils, a 20% chord plate deflected 60° from the lower surface of the model. The section characteristics of NLF(1)-0414F with and without the split flap are shown in figure 8. Drag values were not measured because of the large unsteady wake behind the model. With the split flap installed, $c_{\ell max}$ NLF(1)-0414F was increased to 2.73 at $\alpha = 9.36°$ and $Re_c = 6.1 \times 10^6$. As seen in the plot, the stall is very gently, showing no signs of a leading-edge type stall. At $Re_c = 3 \times 10^6$ with the split flap, $c_{\ell max}$ was 2.66 with the same kind of stall performance.

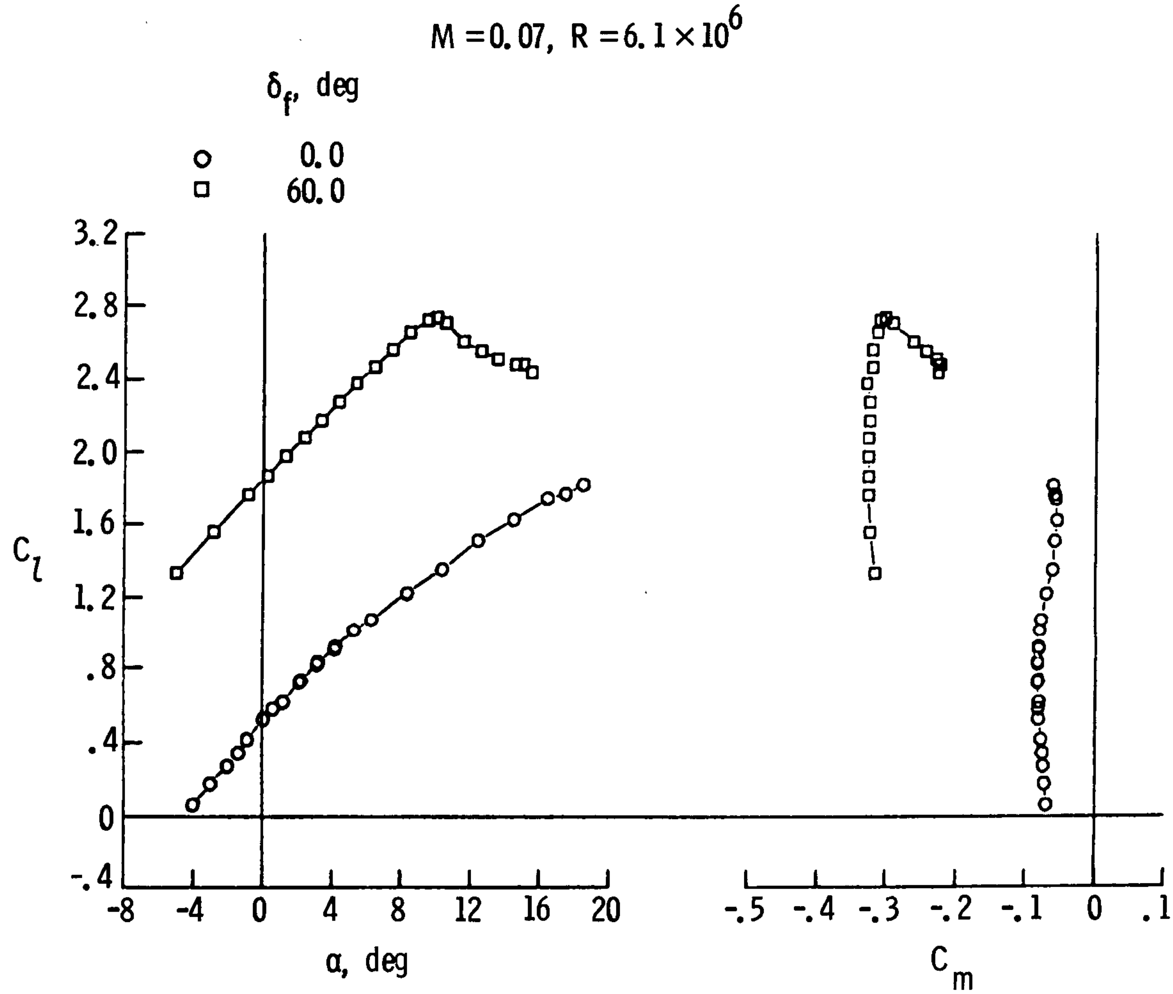


Figure 8

TAPE TURBULATOR EFFECTS

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. Associated with this separated region are large pressure drag penalties. One method of eliminating this separated region is utilizing turbulators to trip the flow before the laminar separation point is reached. Figure 9 illustrates the drag reduction realized by suppressing these laminar separation regions on NLF(1)-0414F for a range of chord Reynolds numbers from 3 to 10 million. The type of tubulator used in this case was tape of 0.012" thick and 1/4" wide placed at 68% chord on the upper surface and 66% chord on the lower surface. At $c_\ell = 0.4$ and $Re_c = 3 \times 10^6$, with the turbulator tape installed, the profile drag coefficient is 0.0041. This is 20% less than the profile drag coefficient of 0.0051 measured on the clean airfoil. This benefit is reduced as the Reynolds number increases and the boundary layer becomes naturally more unstable. Once the separated region is eliminated naturally, then there is a drag penalty from the tape on the airfoil surface. At $Re_c = 10 \times 10^6$, with turbulator tape installed, the profile drag coefficient is 0.0031, instead of the 0.0027 measured on the clean airfoil.

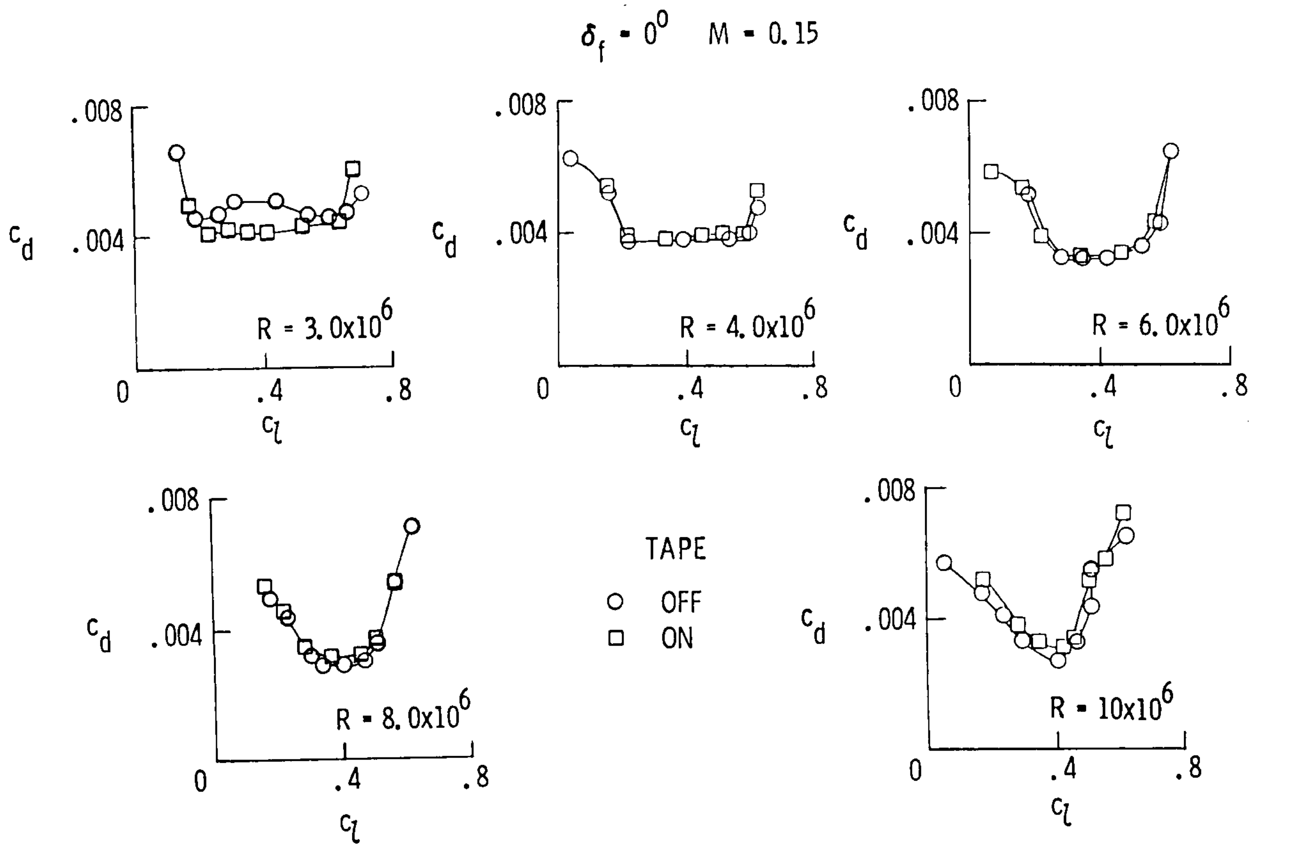


Figure 9

COMPARISON OF AIRFOIL PERFORMANCE

The section characteristics of NLF(1)-0414F are compared with Somers' NASA airfoil section NLF(1)-0215F (ref. 3) figure 10 at $Re_c = 6 \times 10^6$. The NLF(1)-0215F was designed for 40% chord laminar flow on the upper surface and 60% on the lower. With the increased extent of laminar flow for NLF(1)-0414F, 70% of the chord on both surfaces, the minimum profile drag coefficient is 0.0032, where that of NLF(1)-0215F is 0.0045. Even though NLF(1)-0414F has less overall camber, at a chord Reynolds number of 6 million NLF(1)-0414F has a $c_{\ell max}$ of 1.82 at $\alpha = 18.5°$ and NLF(1)-0215F has a $c_{\ell max}$ of 1.74 at $\alpha = 13.2°$.

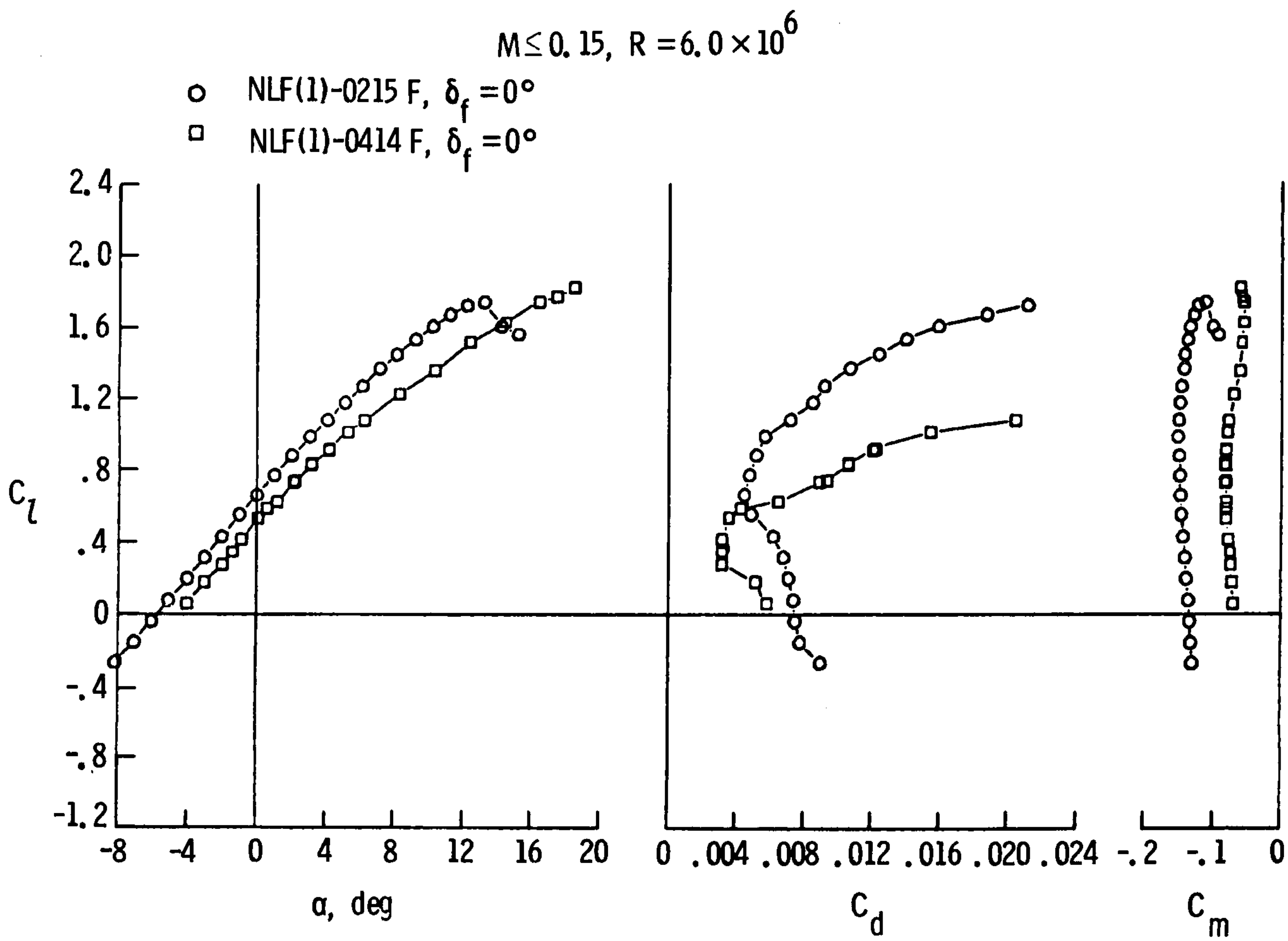


Figure 10

CONCLUSIONS

- 70% CHORD NLF ACHIEVED ON BOTH SURFACES AT $R_{E_C} = 10\text{x}10^6$ IN LTPT ($\tilde{u}/u$ = 0.04%), C_D = 0.0027

- WIDE LOW DRAG C_l RANGE (C_l = 0.0 TO 0.81) ACHIEVED AT HIGH REYNOLDS NUMBERS BY DEFLECTING A 0.125 CHORD TRAILING-EDGE FLAP, L/D = 245 AT C_l = 0.81

- $C_{l_{MAX}}$ PERFORMANCE CONSIDERABLY HIGHER THAN EXPECTED, 1.83 WITH $\delta_F = 0°$ AND 2.70 WITH 0.20 CHORD SPLIT FLAP ($\delta_F = 60°$), WITH CORRECT DESIGN OF THE LEADING EDGE AND STEEP PRESSURE RECOVERY

- LOW DRAG PERFORMANCE AT $R_{E_C} = 3\text{x}10^6$ IMPROVED ABOUT 20% BY ELIMINATING LAMINAR SEPARATION BUBBLES ON BOTH SURFACES WITH TAPE TURBULATORS

- ADDITION OF ROUGHNESS NEAR THE LEADING EDGE REDUCED $C_{l_{MAX}}$ BY ONLY 1% AT $R_{E_C} = 10\text{x}10^6$ AND 3% AT $R_{E_C} = 6\text{x}10^6$

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