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Natural Laminar Flow Airfoil Design Considerations for Winglets on Low-Speed Airplanes

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Symbols

c	airfoil chord length, ft
C_D	total airplane drag coefficient
c_d	section profile-drag coefficient
c_ℓ	section lift coefficient
c_m	section pitching-moment coefficient about quarter-chord point
R	Reynolds number based on free-stream conditions and airfoil chord length
U_∞	free-stream velocity, ft/sec
v	local velocity, ft/sec
W	airplane weight, lb
x	airfoil abcissa, ft
α	angle of attack relative to chord line, deg
β	angle of sideslip, deg

Introduction

Wind-tunnel and flight tests have demonstrated that the use of winglets can provide increased aerodynamic efficiency by reducing lift-induced drag without overly penalizing wing structural weight (ref. 1). The design of winglet airfoil sections, however, has not received much specific attention. In general, most winglets are currently designed using an airfoil section similar to the NASA low-speed family of airfoils (formerly GA(W) airfoil family) (ref. 2). The most important factors favoring these airfoils for winglet usage are their high maximum lift coefficient and docile stall behavior. Originally, this family of airfoils was developed for applications on low-speed airplanes with the assumption that the flow over the entire airfoil would be turbulent, primarily as a result of roughness of construction. Currently, however, modern construction materials and fabrication methods provide significantly improved capabilities for the production of airframe surfaces without significant roughness and waviness. These modern production techniques include composite materials, milled aluminum skins, and bonded aluminum skins, among others. Flight tests have demonstrated that extensive runs of laminar flow can be obtained over the region of favorable pressure gradient on these smooth airplane surfaces and provide a significant reduction in profile drag (ref. 3). As a result, a resurgence is occurring in developing new low-drag airfoils and wings designed to obtain significant amounts of natural laminar flow (NLF) (refs. 4, 5, and 6). Two recent NLF research results should be considered in developing new lifting surface designs: (1) the feasibility of maintaining NLF at large values of transition Reynolds number, and (2) the ability to design low-drag NLF airfoils while retaining the desirable high-lift characteristics of low-speed airfoils with largely turbulent boundary layers.

Typically, existing winglet designs provide net drag reductions only over the part of the airplane flight envelope that involves higher lift coefficients and, hence, higher lift-induced drag. The potential benefit of obtaining NLF on the winglet results from the smaller profile drag losses which the wing-tip-mounted lifting surfaces must overcome (through reduced aircraft lift-induced drag) to produce a net drag reduction. By significantly reducing winglet profile drag, the opportunity exists for a properly designed NLF winglet to provide net performance gains throughout the airplane flight envelope.

The purpose of this paper is to indicate the benefits of using a NLF airfoil section for winglet applications. In order to be effective, such an airfoil should have a low cruise drag coefficient while retaining a high maximum lift coefficient. Other airfoil design requirements, including a wide laminar drag bucket and a gradual and steady movement of transition and separation locations with angle of attack, will also be discussed.

Influence of Winglet NLF on Airplane Performance

The winglet concept was originally developed for large, high-speed transport aircraft which operate at transonic flight conditions. Hence, the design guidelines for these surfaces focused not only on reducing lift-induced drag but also on minimizing adverse interference due to shock waves in the wing-winglet juncture. The minimization of adverse Mach number effects has a strong influence on the airfoil section shape of the winglet for those applications. The problem of shock waves in the wing-winglet juncture becomes negligible, however, when developing winglets for low-speed airplanes. As a result, more design freedom is available to minimize viscous drag losses associated with these surfaces through maximization of natural laminar flow.

An example of the effect that winglet profile drag can have on airplane performance is shown in figure 1. In this figure, the total airplane drag reduction due to winglets is plotted as function of true airspeed for a six-passenger, single-engine airplane cruising at 5,000 ft altitude. For this aircraft configuration the area of one winglet is 11.6 percent of the wing semispan area. With increasing airspeed, the total drag reduction due to the wing-tip-mounted surfaces becomes smaller, as expected because of the lower required lift coefficient and, hence, lower induced drag. The benefit of the winglet disappears at a crossover velocity when the profile drag increase due to the winglets is as large as the reduction in lift-induced drag. With turbulent boundary layer flow on the entire winglet surface, the airplane crossover velocity is 146 knots. With approximately 50 percent laminar flow on the winglet surfaces (transition at the 50 percent chord location on both the suction side and the pressure side of the winglet) the crossover velocity is increased to 160 knots. The maximum airspeed of the unmodified airplane in level flight is about 170 knots at this altitude. Hence, figure 1 indicates the significant effect of winglet laminar flow on the crossover velocity of an airplane.

Analysis of Turbulent Low-Speed Airfoils

Initial airfoil sections recommended for winglet applications (ref. 1) were developed to operate at supercritical, high Mach number design conditions and were highly cambered to obtain satisfactory high-lift characteristics. In order to avoid producing shock waves on the upper winglet surface and to minimize the added induced velocities on the wing tip upper surface associated with the winglet, the thickness ratio of the winglet airfoil was held to 8 percent. In a number of cases, subsequent winglet designs for low-speed airplanes have also used this airfoil section. However, this airfoil was not specificially designed for low Reynolds number, low-speed applications, and the airfoil performance under these conditions can be improved. Airfoil section characteristics were examined using the low-speed airfoil design and analysis method developed by Epper and Somers (refs. 8 and 9). In figure 2, the airfoil section shape and two inviscid velocity distributions for the original supercritical winglet airfoil are shown. At a cruise lift coefficient $c_\ell = 0.4$, the velocity gradient on the upper surface is favorable up to about 65 percent of the chord. On the lower surface, however, a sharp suction peak occurs near the leading edge. This suction peak grows with decreasing angle of attack and the integral boundary layer method predicts leading edge separation on the lower surface below c_ℓ = 0.3 - 0.4. As shown in figure 3, a high maximum lift coefficient is achieved, but the laminar flow drag bucket is narrow and starts and ends very abruptly. The results also indicate that minimum drag coefficient is obtained at a lift coefficient $c_\ell = 0.6$. The combination of a high design lift coefficient and a narrow drag bucket makes this airfoil less desirable for winglet applications on low-speed airplanes.

In addition, the narrow drag bucket which produces abrupt changes in section drag with angle of attack is a concern when the winglets also provide directional stability. For example several current canard airplane configurations utilize winglets as vertical stabilizers. The sketch in figure 4 shows the drag polar of the winglet airfoil section and illustrates the potential problem. This problem was brought to the author's attention by Dr. Eppler of the University of Stuttgart, Stuttgart, West Germany. Point A indicates the cruise condition at a sideslip angle, β, of zero degrees. A small positive sideslip excursion causes increased c_ℓ (point B) for the upwind winglet and reduced c_ℓ (point C) for the downwind winglet. For this airfoil, the drag at the onset of the drag bucket changes rapidly and abruptly, causing a significant profile drag differential between the two winglets. This force differential produces a destabilizing yawing moment and can produce undesirable airplane handling qualities. This problem has been encountered by some winglet configured canard airplanes in their early development stage. These results demonstrate a lateral-directional stability problem which might occur when selecting a winglet airfoil section incorrectly.

More recently, the LS(1)-0413 airfoil section (ref. 7) has been commonly used for applications on low-speed airplanes. This 13-percent airfoil section was obtained by linearly scaling the mean thickness distribution of the 17-percent LS(1)-0417 airfoil and combining this thickness distribution with the mean camber line of the LS(1)-0417 airfoil. Wind-tunnel and flight tests have demonstrated that this type of section provides substantial regions of laminar flow for chord Reynolds numbers less than approximately 5 million (refs. 3 and 7). The geometry of the LS(1)-0413 airfoil and two inviscid velocity distributions are shown in figure 5. Although the LS(1)-0413 airfoil section designers did not intentionally develop this airfoil for extensive laminar flow, the pressure gradients at design lift condition are favorable to NLF. At the design lift coefficient $c_\ell = 0.4$, the velocity on the upper surface is constant up to 55 percent chord, while the velocity on the lower surface is approximately constant up to 50 percent chord. For Reynolds numbers less than 6 million, the stability of the boundary layer is sufficient to retain NLF up to 50-60 percent of the chord on both the pressure and the suction sides of the airfoil. With increasing angle of attack, a suction peak starts to develop on the upper surface near the leading edge. At a lift coefficient $c_\ell = 1.0$, the suction peak is quite sharp and will cause boundary layer transition to occur near the leading edge due to laminar separation short bubble. The theoretical and experimental section characteristics are shown in figure 6 for natural and artificial transition at a chord Reynolds number of

2.1 million. The theoretical results (using the method of reference 8) show that the airfoil has a low minimum drag coefficient and a high maximum lift coefficient. The theoretical and experimental lift characteristics indicate good agreement. Pitching moment and angle of attack for zero lift coefficient were both overpredicted because a boundary-layer displacement thickness iteration was not included in the analysis. Comparison of theoretical and experimental drag coefficient shows some disagreement inside the laminar bucket. Similar discrepancies between results obtained with the method of reference 8 and wind-tunnel data have been explained by R. Eppler in reference 10, as caused by premature transition due to wind-tunnel turbulence. In the very low turbulence of the flight environment, increased width of the drag bucket can be expected compared to wind-tunnel data. Results presented in references 4, 5, and 10, however, demonstrate that the method is quite suitable to compare the section characteristics of a newly developed airfoil and existing airfoils.

An Improved Winglet Airfoil Design

Several design objectives and constraints have been identified for a NLF airfoil section designed specifically for winglet applications. These objectives are dependent on the winglet operating conditions in terms of lift coefficient range and Reynolds numbers. For the commonly used ratio of winglet-root chord to wing-tip chord of about 65 percent, cruise and climb lift coefficients of the tip-mounted surface are similar to the cruise and climb lift coefficients of the wing (refs. 1 and 11). For a low-speed aircraft, the winglet chord Reynolds number is generally low. The mean winglet chord is approximately 30 percent of the mean chord of the wing. As a result, winglet chord Reynolds numbers range from 1-4 million, similar to the Reynolds numbers encountered by sailplanes. As indicated in reference 13, NLF has been a practical reality for sailplanes for many years because of the relatively low chord Reynolds numbers and the use of construction methods and materials which produce accurate and smooth airfoil surfaces. Three objectives were identified for the present winglet airfoil design. The first objective was that the airfoil should produce a high maximum lift coefficient to maximize the crosswind component allowable during approach for landing. To prevent nonlinearities in airplane lateral-directional stability and control characteristics during final approach for landing in crosswinds, the upwind winglet should not be stalled. As mentioned previously, the LS(1)-0413 airfoil is commonly used for this reason for winglet applications on low-speed airplanes. Therefore, the first objective was that the maximum lift coefficient of the present airfoil design should be at least as high as that of the LS(1)-0413 at a Reynolds number of about one million.

The second objective was to obtain profile drag coefficients for cruising flight as low as those produced by comparable, smooth 6-series airfoils at $R \cong 3 \times 10^6$. This performance goal was established in order to obtain sufficiently low winglet profile drag losses that the crossover of airplane drag polars with winglets off and on would occur at a very low airplane lift coefficient, outside the normal flight envelope.

The third objective was to obtain a wide laminar bucket in order to reduce the sensitivity of winglet profile drag to twist (geometric and aerodynamic) misalignment. Also, the low drag region should not start and end very abruptly. Such changes in winglet section drag with angle of attack can produce destabilizing airplane yawing moments, as discussed previously. To obtain this characteristic, the transition location on the lower and upper surfaces should show a gradual chordwise movement due to changes in angle of attack. A gradual chordwise movement of the suction peak on the lower and upper surfaces with angle of attack will round off the edges of the drag bucket and prevent abrupt changes in section drag. This behavior of the suction peak also slows down the chordwise movement of the separation location of the turbulent boundary layer, which results in a docile stall behavior at maximum and minimum angle of attack (ref. 14).

The design constraints which were placed on this airfoil were: (1) thickness ratio should be close to 13 percent to achieve a similar critical Mach number and structural weight as for the LS(1)-0413 airfoil section; and (2) the airfoil should be a single element design. In addition, if leading-edge separation occurs on the lower surface of the airfoil, it should not occur at lift coefficients greater than about -0.5. This requirement is established for safety considerations relative to the probable changes in airplane stability and controllability induced by flow separation during sideslip conditions in crosswind landings.

A constraint often placed on a wing airfoil design is the level of negative pitching moment allowed. The purpose of this limitation is to prevent a large amount of airplane trim drag that may result from balancing this moment. The maximum allowable pitching moment that can be tolerated for a winglet airfoil section is much greater than for a wing airfoil section. Because of the approximately vertical position of a winglet, the airplane longitudinal trim requirements are not significantly affected by the level of winglet pitching moments. Also, the wing structure is loaded in its plane by the pitching-moment loads on the tip device. This results in a minimal wing-weight penalty for any large pitching moment which may result from optimization of a winglet airfoil section. For these reasons, pitching moment is not constrained for this winglet airfoil design.

The winglet airfoil design objectives and constraints previously discussed were considered in the application of the airfoil design and analysis code of reference 8. The result, after a number of iterations, is the airfoil section shown in figure 7. The airfoil shape is presented in addition to the inviscid velocity distribution for two angles of attack. The resulting airfoil has a thickness ratio of 13.4 percent and a relatively blunt leading edge. The nondimensional airfoil coordinates are presented in table I.

At a cruising lift coefficient of $c_\ell = 0.4$, the upper surface velocity gradient is favorable for NLF up to 55 to 60 percent of the chord. This region of favorable velocity gradient is followed by a short boundary-layer transition ramp immediately downstream of the maximum velocity on the upper surface. The pressure recovery region, which follows the transition ramp, displays a concave velocity gradient. A concave velocity distribution results in a thinner turbulent boundary layer at the trailing edge and shows less tendency to separate than a linear or convex distribution (ref. 12). On the lower surface, the velocity gradient is only slightly adverse up to 48 percent chord, where a transition ramp is located. To verify the stability of the laminar boundary layer in the slightly adverse velocity gradient on the lower surface, a linear incompressible boundary-layer stability analysis (ref. 15) was conducted for $c_\ell = 0.4$ and $R = 5 \times 10^6$. The analysis shows a maximum Tollmien-Schlichting amplification ratio of $e^{16.7}$ (maximum amplification wave frequency is 5000 Hz, no sweep). This amplification ratio is reached at 48 percent chord at which location the finite difference method of reference 16 predicts laminar separation to occur. Past analyses of flight data using the method of reference 15 indicate that boundary-layer flow can maintain a laminar state when encountering Tollmien-Schlichting disturbance amplification ratios in excess of e^{17} (refs. 17 and 18). Therefore, at $c_\ell = 0.4$ and for Reynolds numbers less than and equal to 5 million and small sweep angles the boundary-layer stability on the airfoil lower surface appears to be sufficient to guarantee a laminar state up to 48 percent of the chord. The short transition ramp is followed by a concave velocity distribution in the pressure recovery region. The magnitude of pressure recovery on the upper surface is much less than on the lower surface, resulting from a large amount of aft camber. At a lift coefficient $c_\ell = 1.0$ a suction peak starts to develop on the upper surface near the leading edge. However, this peak is not as sharp as is the case for the LS(1)-0413 airfoil (fig. 5), indicating a wider drag bucket and a more docile stall for the present airfoil section.

The predicted section characteristics for the newly designed airfoil are presented in figure 8. The theoretical results indicate that a high maximum lift coefficient and a low cruise drag coefficient are achieved. Also, the low drag region is wide and does not start or end very abruptly. With increasing Reynolds number, minimum drag coefficient decreases as shown, although the width of the low drag region with respect to lift coefficient becomes smaller as well. The reduction in width is caused by the forward motion of upper surface and lower surface transition location with increasing Reynolds number, These changes are due to the influence of unit Reynolds number on the stability of the laminar boundary layer.

With transition near the leading edge due to surface roughness sectional drag coefficient increases; however, the lift characteristics of the airfoil section are not affected. This desirable behavior minimizes potential changes in airplane handling qualities that can be caused by flow separation induced by premature boundary-layer transition.

In figure 9, section characteristics of the newly-designed airfoil are compared with those of the LS(1)-0413 airfoil at a Reynolds number of 3 million. The lift characteristics for both airfoil sections are similar with the new airfoil indicating a more gradual stall behavoir. The results indicate that the improved airfoil has a wider drag bucket and that the section drag coefficient does not change as abruptly at the edges of the drag bucket. However, the newly-designed airfoil has a slightly higher minimum drag coefficient compared to the LS(1)-0413 section.

Conclusions

As discussed, winglet airfoil section characteristics can significantly influence cruise performance and handling qualities of an airplane. A good winglet design requires an airfoil section with (1) a low cruise drag coefficient, (2) a high maximum lift coefficient and (3) gradual and steady movement of the boundary-layer transition location with angle of attack. The first design requirement provides a low crossover lift coefficient of airplane drag polars with winglets off and on. The other two requirements prevent nonlinear changes in airplane lateral-directional stability and control characteristics. Although not intentionally designed for extensive natural laminar flow, the LS(1)-0413 airfoil has good laminar flow behavior; the resulting low drag combined with good high lift characteristics make it a good winglet airfoil. However, abrupt changes in airfoil section drag with angle of attack can have undesirable effects on certain airplane handling qualities. The new, natural laminar flow airfoil section presented in this paper was specifically designed for winglet applications on low-speed airplanes and provides modest improvements over the LS(1)-0413 because of its wider drag bucket, more gradual drag changes at the edges of the drag bucket, and more gentle stall. The new airfoil will provide improved airplane lateral-directional handling qualities when used on winglets designed for directional stability.

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TABLE I. IMPROVED WINGLET AIRFOIL COORDINATES

Upper Surface		*Lower Surface*	
x/c	*z/c*	*x/c*	*z/c*
.00048	.00360	.00074	-.00413
.00502	.01263	.00657	-.01079
.01396	.02210	.01797	-.01714
.02731	.03157	.03448	-.02296
.04507	.04075	.05594	-.02811
.06718	.04948	.08215	-.03256
.09346	.05764	.11283	-.03630
.12370	.06511	.14763	-.03931
.15762	.07182	.18614	-.04160
.19488	.07766	.22791	-.04312
.23510	.08258	.27241	-.04384
.27785	.08649	.31912	-.04369
.32270	.08934	.36746	-.04254
.36916	.09107	.41699	-.04016
.41674	.09161	.46740	-.03650
.46494	.09091	.51813	-.03142
.51322	.08886	.56927	-.02444
.56121	.08525	.62152	-.01618
.60869	.08005	.67451	-.00814
.65554	.07332	.72697	-.00126
.70169	.06550	.77769	.00405
.74666	.05728	.82550	.00760
.78968	.04907	.86931	.00937
.83006	.04110	.90614	.00948
.86717	.03351	.94109	.00812
.90046	.02643	.96721	.00561
.92941	.01994	.98569	.00280
.95358	.01403	.99648	.00073
.97283	.00858	1.00000	0.00000
.98731	.00397		
.99669	.00098		
1.00000	0.00000		

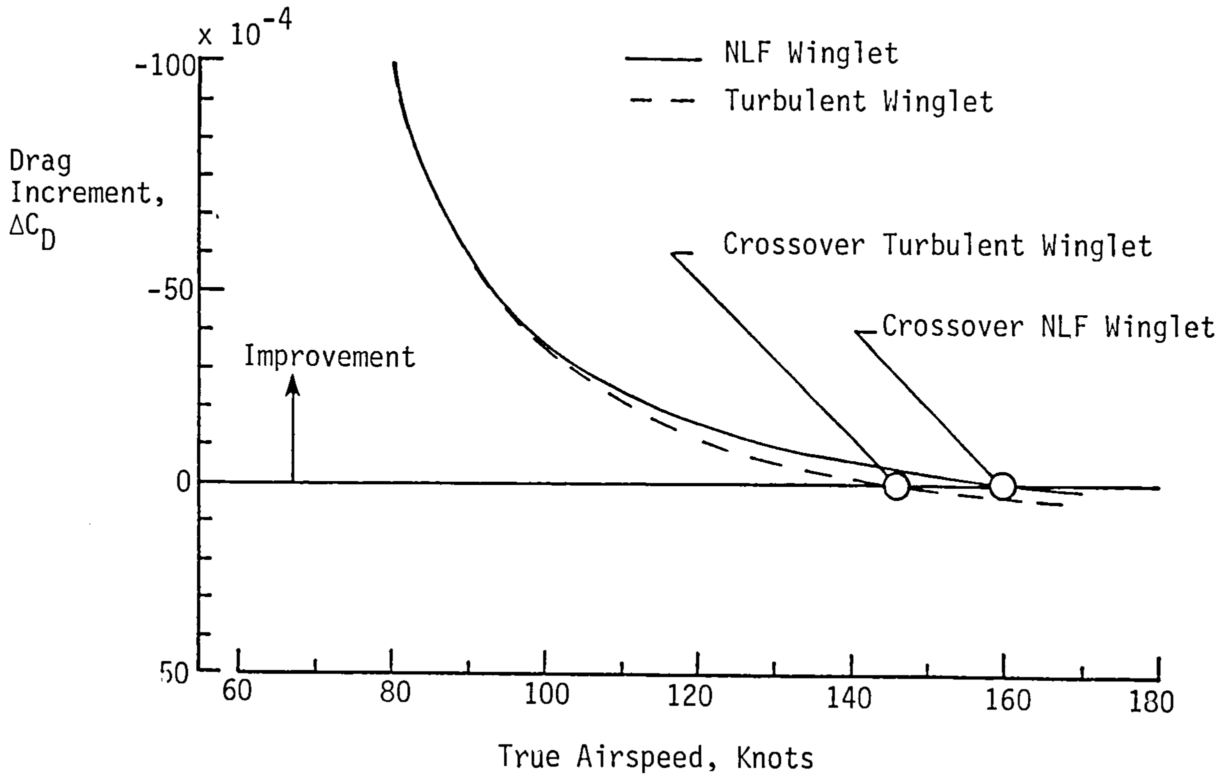

Figure 1. Influence of Winglets on Cruise Performance of a Single Engine, Six-Passenger Airplane. Cruising Altitude = 5,000 ft and W = 3600 lb.

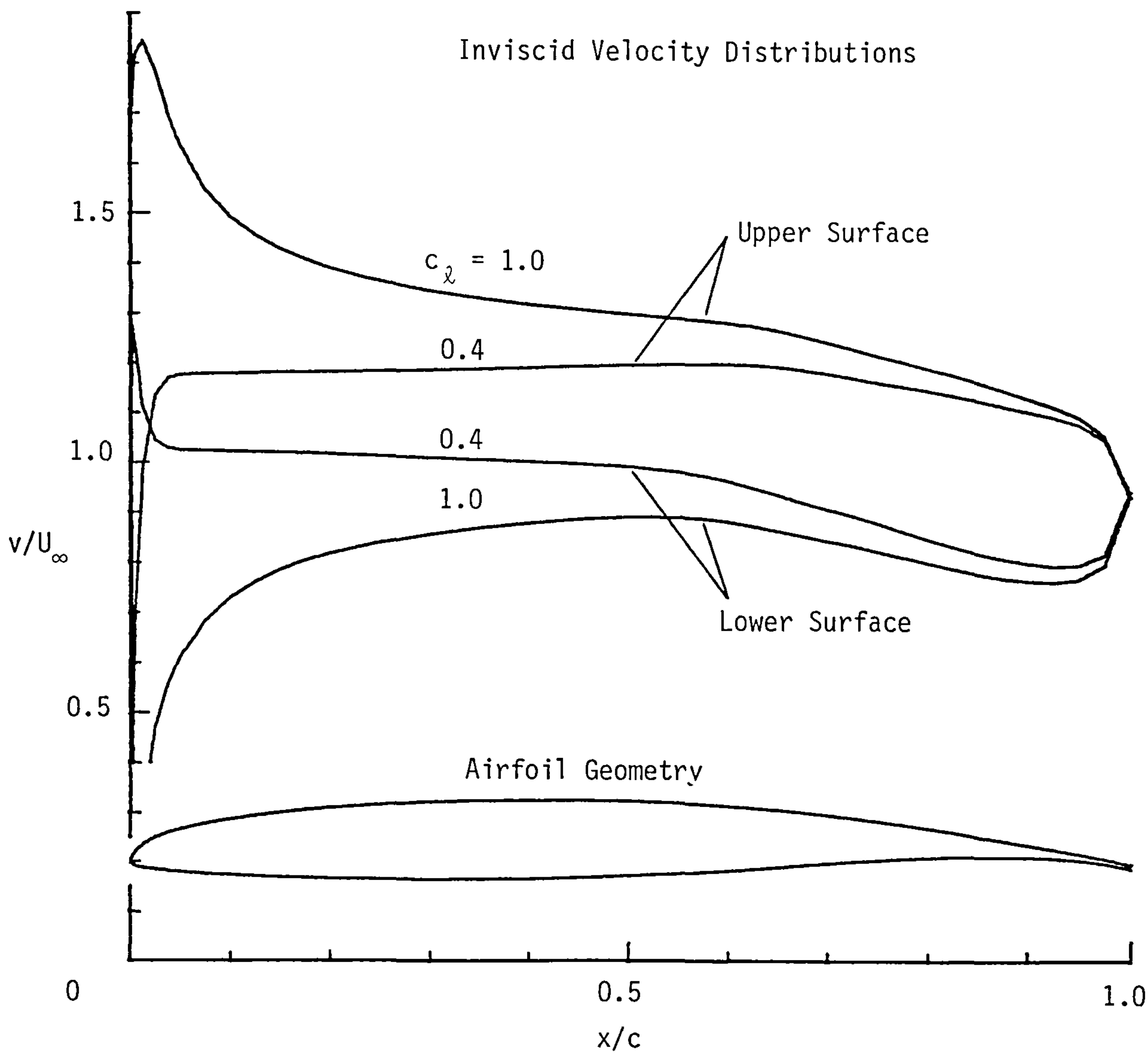

Figure 2. Supercritical Winglet Airfoil Geometry and Inviscid Velocity Distributions.

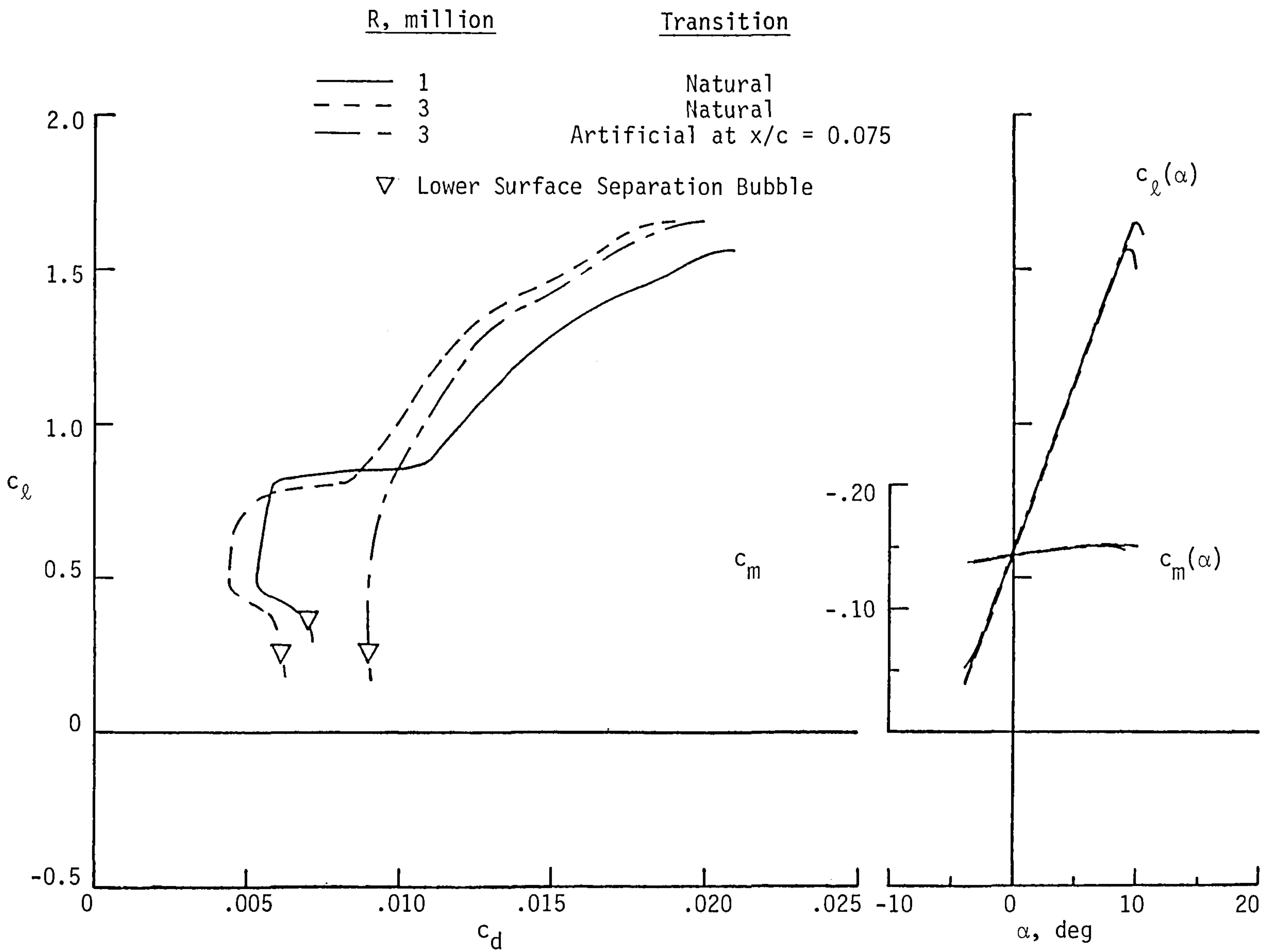

Figure 3. Supercritical Winglet Airfoil Section Characteristics.

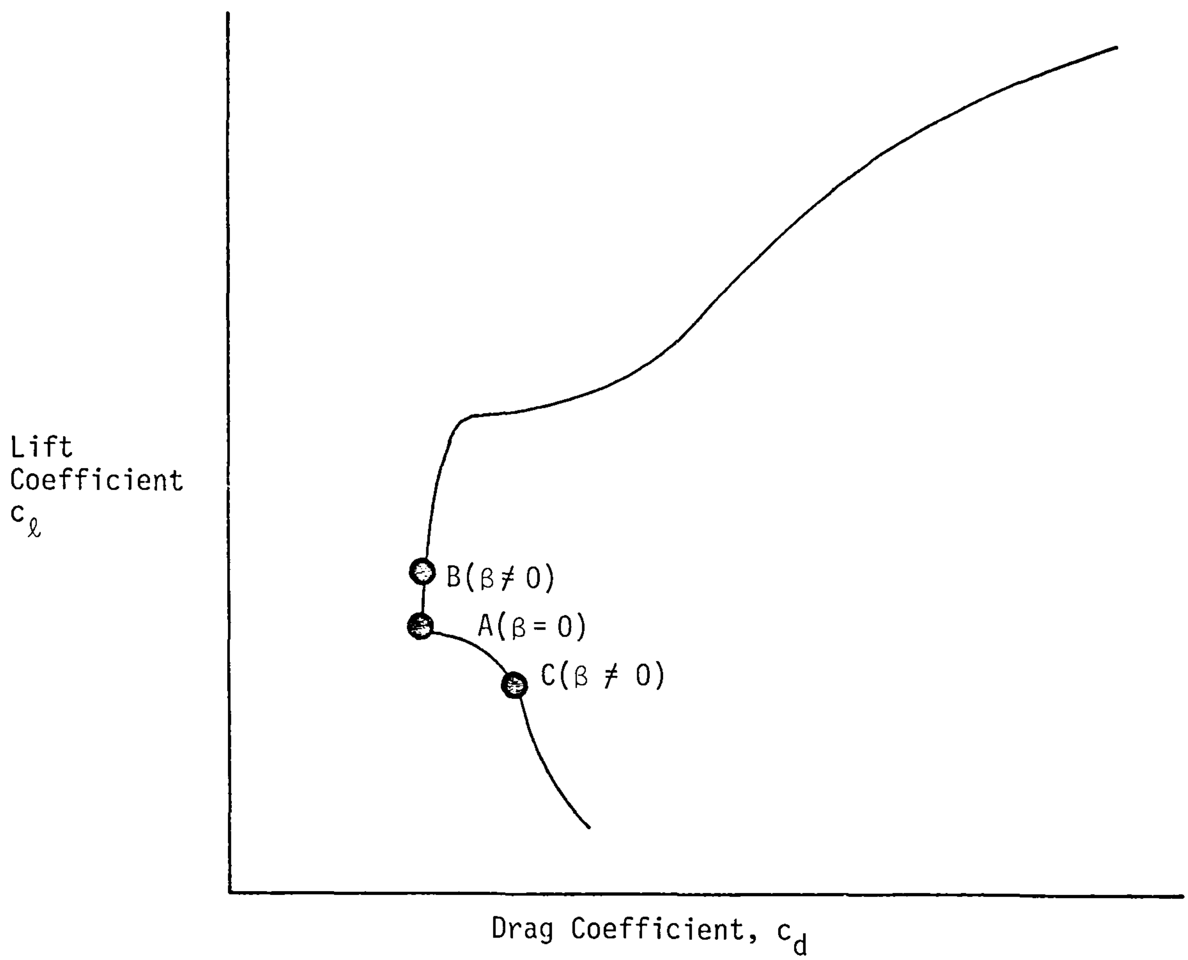

Figure 4. Drag Polar of a Winglet Airfoil Section with a Sharply Defined Drag Bucket.

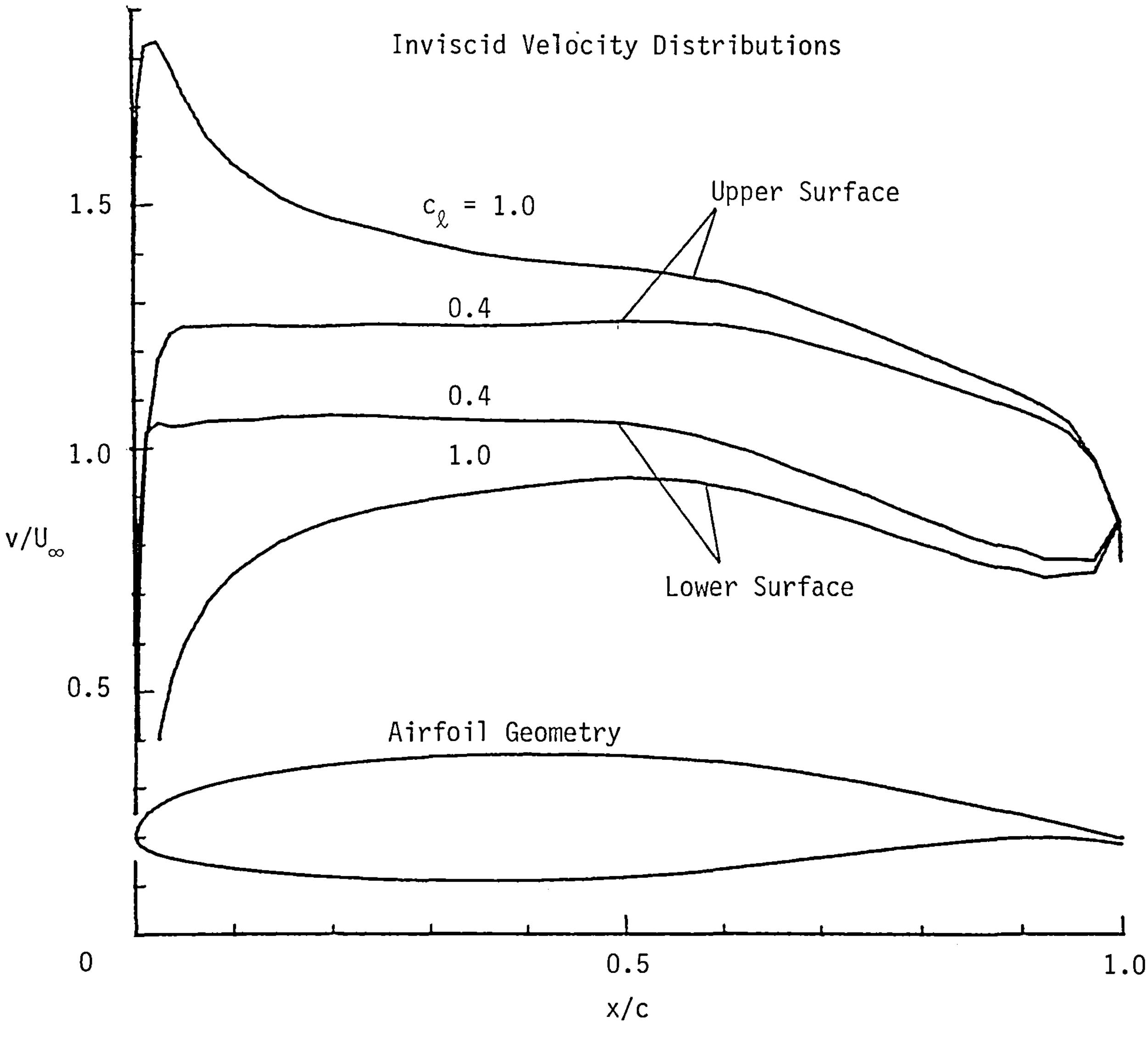

Figure 5. Inviscid Velocity Distributions and Section Geometry of the LS(1)-0413.

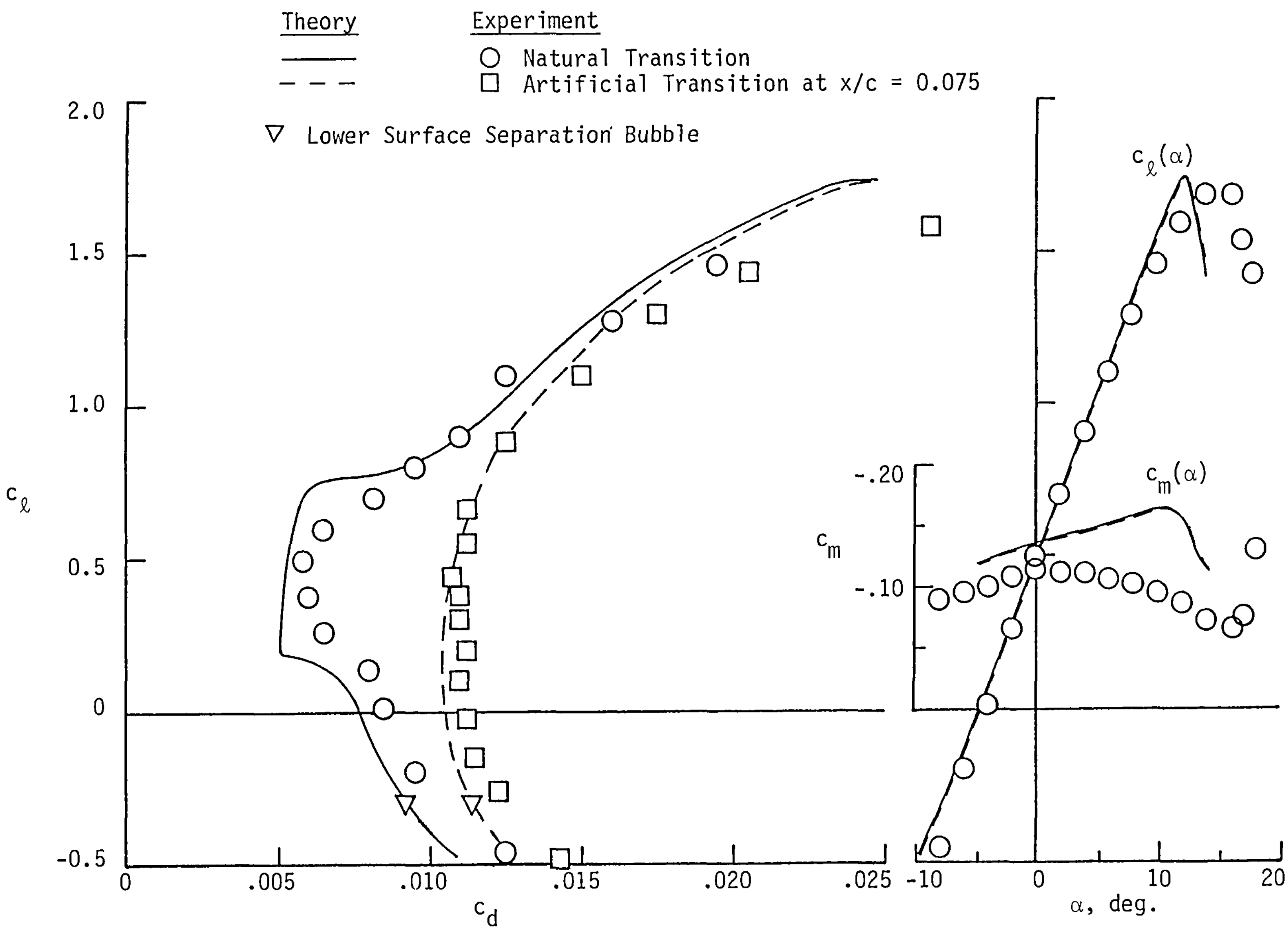

Figure 6. Comparison of Theoretical and Experimental LS(1)-0413 Section Characterisitics at R = 2.1 Million and M = 0.15.

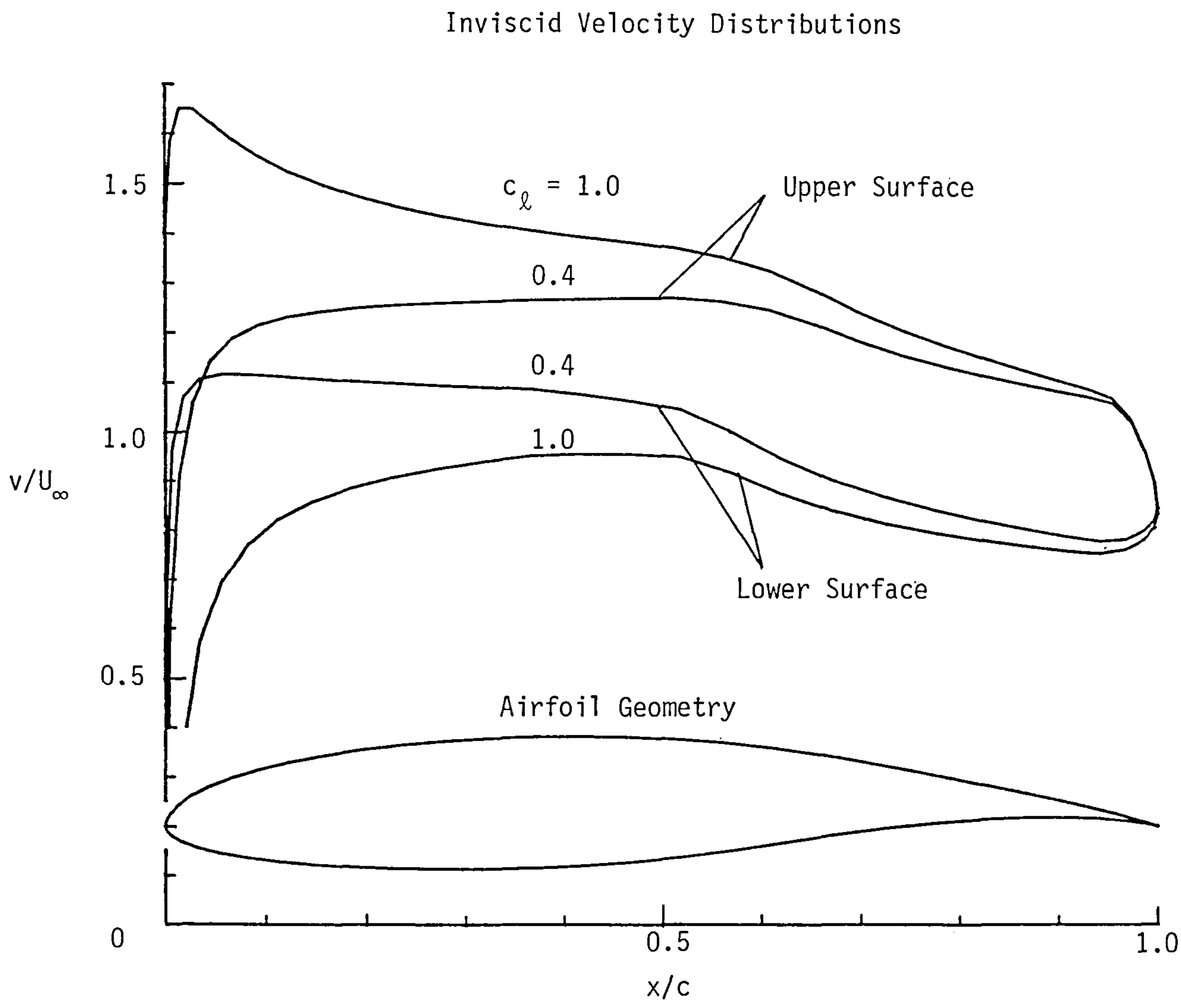

Figure 7. Airfoil Geometry and Inviscid Velocity Distributions of Improved Low-Speed Winglet Airfoil.

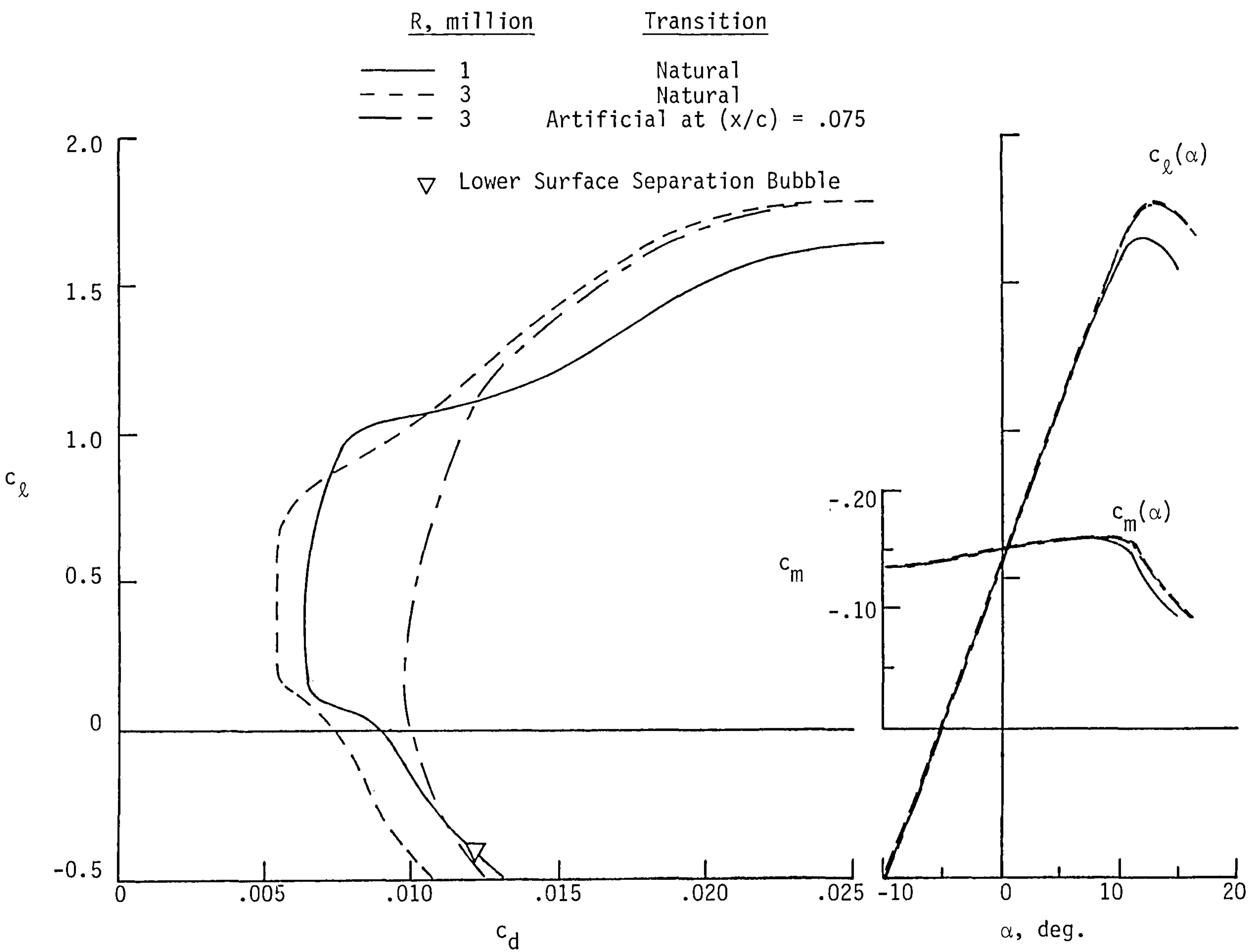

Figure 8. Section Characteristics for Improved Winglet Airfoil.

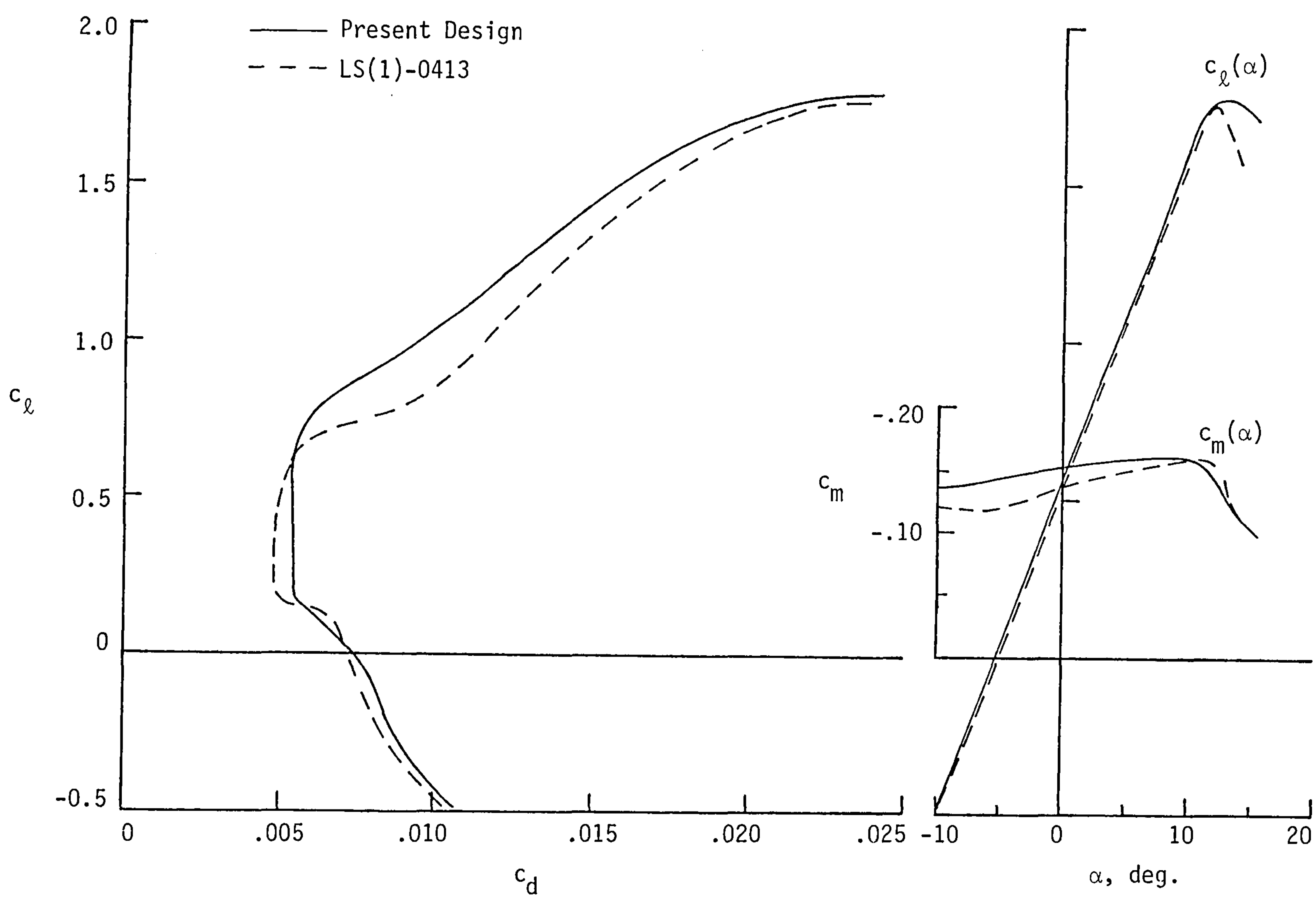

Figure 9. Comparison of Section Characteristics for LS(1)-0413 and Improved Winglet Airfoil. Natural Transition and R = 3.0 Million.

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16. Abstract

Winglet airfoil section characteristics can significantly influence cruise performance and handling qualities of an airplane. A good winglet design requires an airfoil section with a low cruise drag coefficient, a high maximum lift coefficient, and a gradual and steady movement of the boundary-layer transition location with angle of attack. The first design requirement provides a low crossover lift coefficient of airplane drag polars with winglets off and on. The other requirements prevent nonlinear changes in airplane lateral-directional stability and control characteristics. These requirements were taken into consideration in the design of a natural laminar flow airfoil section for winglet applications and chord Reynolds numbers of 1-4 million.

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