THE SM701 AIRFOIL AN AIRFOIL FOR WORLD CLASS SAILPLANES

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INTRODUCTION

In 1989, the International Gliding Commission (IGC) of the Federation Aeronautique Internationale (FAI) created a new class of sailplanes, the World Class. The goals of this class are significantly different from those of the Standard, 15-Meter, and Open Classes. (See refs. 1 and 2.) Accordingly, the performance of existing airfoils (e.g., ref 3) does not provide a good match to the requirements of World Class sailplanes. Therefore, a 16-percent-thick, laminar flow airfoil has been designed specifically for World Class sailplanes. This paper is a condensation of the report entitled "The SM701 Airfoil," which is available from the authors.

SYMBOLS

b	wingspan, m
C_p	pressure coefficient
c	airfoil chord, m
c_d	section profile-drag coefficient
c_l	section lift coefficient
c_m	section pitching-moment coefficient about quarter-chord point
$c_{m,0}$	zero-lift pitching-moment coefficient
L.	lower surface
L/D	aircraft lift-to-drag (glide) ratio
MU	transition mode
R	Reynolds number based on free-stream conditions and airfoil chord
S	wing area, m^2
S.	separation location, $1 - s_{sep}$
s_{sep}	arc length along which boundary layer is separated
s_{turb}	arc length along which boundary layer is turbulent including s_{sep}

T. transition location, 1- s_{turb}
t airfoil thickness, m
U. upper surface
v aircraft speed, km/h
v_s aircraft sinking speed, m/s
W aircraft mass, kg
x airfoil abscissa, m
y airfoil ordinate, m
α angle of attack relative to chord line, degrees

Subscripts:
ll lower limit
rough rough leading edge
ul upper limit

AIRFOIL DESIGN

OBJECTIVES AND CONSTRAINTS

The design specifications for this airfoil are contained in table I. Two primary objectives are evident from the specifications. The first objective is to obtain a maximum lift coefficient of 1.6 for a Reynolds number of 500,000. This objective is determined by the minimum-speed requirement for World Class sailplanes (i.e., 65 km/h), assuming a sufficient wing loading for adequate performance at inter-thermal penetration speeds. There are two requirements related to this objective. First, the maximum lift coefficient should not decrease below 1.4 with a rough leading edge. This requirement limits the increase in stall speed due to a contaminated leading edge to less than 5 km/h. Second, the airfoil should exhibit docile stall characteristics because one of the primary markets for World Class sailplanes will probably be low-time pilots. The second objective is to obtain low profile-drag coefficients over the range of lift coefficients from 0.2 to 1.5, which correspond to high-speed cruise and thermalling, respectively. It should be noted that these specifications coincide well with those presented in reference 2.

TABLE I.-AIRFOIL DESIGN SPECIFICATIONS

Parameter	Objective/ Constraint	Reynolds Number
Minimum lift coefficient $c_{l,min}$	0	4.0×10^6
Maximum lift coefficient $c_{l,max}$	1.6	0.5×10^6
Maximum lift coefficient rough $(c_{l,max})_{rough}$	≥ 1.4	0.5×10^6
Low-drag, lift-coefficient range:		
Lower limit $c_{l,ll}$	0.2	3.0×10^6
Upper limit $c_{l,ul}$	1.5	1.5×10^6
Zero-lift pitching-moment coefficient $c_{m,0}$	≥ -0.1	
Thickness t/c	≥ 0.16	

In addition to these objectives, three major constraints were placed on the design of this airfoil. First, the airfoil thickness should be at least 16-percent chord for structural reasons. Second, the zero-lift pitching-moment coefficient should be no more negative than -0.1. Although this constraint could not be satisfied, the pitching moment was kept as small as possible to encourage the acceptance of this airfoil in light of the commonly-held belief that large pitching moments lead to high trim drag and structurally unacceptable wing torsion. Third, the airfoil must be unflapped to satisfy World Class requirements.

PHILOSOPHY

Given the above objectives and constraints, certain characteristics of the design are evident. A drag polar which meets the goals for this design is illustrated in figure 1.

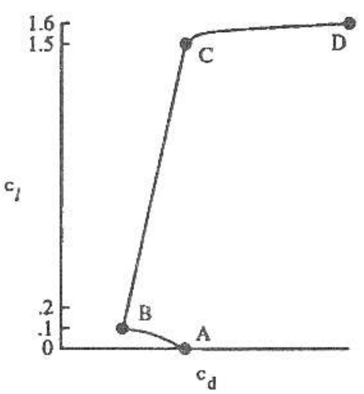

FIGURE 1.-Objective drag polar.

The desired airfoil shape can be traced to the pressure distributions which occur at the various points in figure 1. Point A represents the minimum lift coefficient. Point B is the lower limit of the low-drag, lift-coefficient range. Note that the lift coefficient at point B is lower than the objective (0.2) specified in table I. The difference is intended as a margin against such contingencies as manufacturing tolerances, finite-wing effects, operational deviations, and inaccuracies in the theoretical method. The drag at point C, the upper limit of the low-drag, lift-coefficient range, is not as low as at point B, unlike the polars of many other laminar-flow airfoils, where the drag within the laminar bucket is nearly constant. This characteristic is related to the elimination of significant (drag-producing) laminar separation bubbles on the upper surface. (See ref. 4.) It is acceptable because the portion of the total aircraft drag attributable to the profile drag decreases with increasing lift coefficient. Point D is the maximum lift coefficient.

From the preceding discussion, the pressure distributions along the polar can be deduced. The pressure distribution at point B should look something like that shown in figure 2.

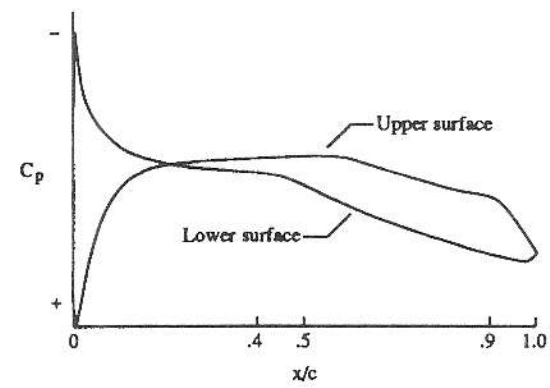

FIGURE 2-Conceptual pressure distribution at a lift coefficient of 0.1.

To achieve low drag, a favorable pressure gradient is desirable along the upper surface to about 55-percent chord. Aft of this point, a short region of adverse pressure gradient ("transition ramp") is desirable to promote the efficient transition from laminar to turbulent flow (ref. 5). Thus, the initial slope of the pressure recovery is relatively shallow. This short region is followed by a steeper, nearly linear pressure recovery. The slightly concave pressure recovery represents a compromise among high lift, low drag, and docile stall characteristics. The steep, adverse pressure gradient on the upper surface aft of about 90-percent chord is a 'separation ramp,' originally proposed by F. X. Wortmann, which confines turbulent separation to a small region near the trailing edge. By controlling the movement of the separation point at high angles of attack, high lift coefficients can be achieved with little drag penalty. This feature has the added benefit that it too promotes docile stall characteristics. (See ref. 6.)

Along the forward portion of the lower surface, the pressure gradient is initially very adverse and then decreasingly so. Thus, transition is imminent over the entire forward 40-percent chord of the lower surface. (See ref. 7.) This concept increases the amount of camber in the leading-edge region while maintaining low drag at the lower limit of the laminar bucket. The forward camber serves to balance, with respect to the pitching-moment constraint, the aft camber, both of which contribute to the achievement of the maximum lift-coefficient objective. This region is followed by a curved transition ramp (ref. 4) which is longer than that on the upper surface. Such a ramp is necessary because of the unfavorable variation of Reynolds number with lift coefficient and, therefore, pressure gradient which occurs on the lower surface. The transition ramp is followed by an essentially linear pressure recovery.

The amounts of pressure recovery on the two surfaces are determined by the airfoil-thickness and pitching-moment constraints.

At point C, the pressure distribution should look like that shown in figure 3.

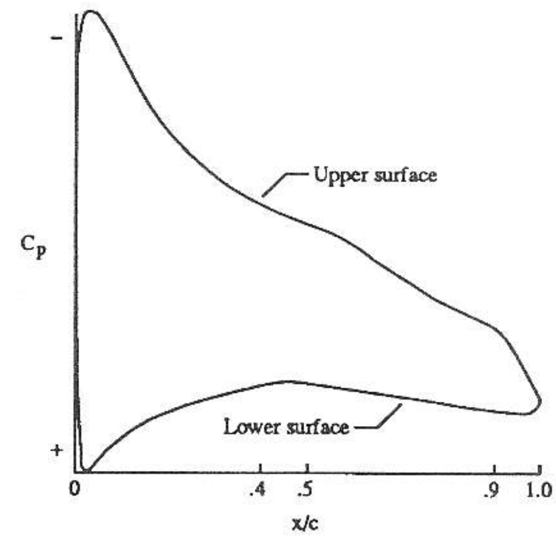

FIGURE 3. Conceptual pressure distribution at a lift coefficient of 1.5.

No suction spike exists at the leading edge. Instead, a rounded peak occurs aft of the leading edge. This feature is the result of incorporating increasingly favorable pressure gradients toward the leading edge. It is important because it allows higher lift coefficients to be reached without significant separation.

EXECUTION

Given the pressure distributions previously discussed, the design of the airfoil is reduced to the inverse problem of transforming the pressure distributions into an airfoil shape. The Eppler Airfoil Program System (refs. 8-11) was used because of confidence gained during the design, analysis, and experimental verification of several other airfoils.

The airfoil is designated the SM701. The airfoil shape is shown in figure 4 and the coordinates are contained in table II.

DISCUSSION OF RESULTS

PRESSURE DISTRIBUTIONS

The inviscid (potential-flow) pressure distributions for various angles of attack are shown in figure 4.

TRANSITION AND SEPARATION LOCATIONS

The variation of transition location with lift coefficient for Reynolds numbers of 500,000, 1,500,000, and 3,000,000 are shown in figure 5. It should be remembered that the method of references 8 through 11 'defines' the transition location as the end of the laminar boundary layer whether due to natural transition or laminar separation. Thus, for conditions which result in relatively long laminar separation bubbles (low lift coefficients for the

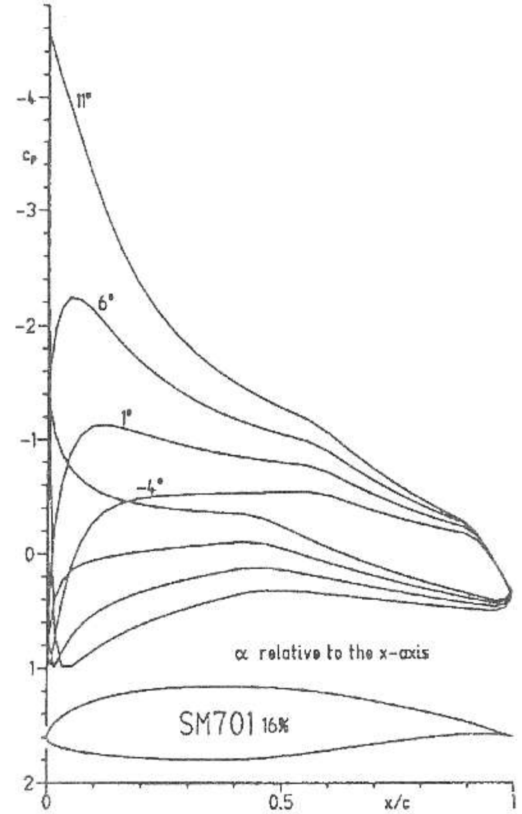

FIGURE 4. Inviscid pressure distributions.

upper surface and high lift coefficients for the lower surface and/or low Reynolds numbers), poor agreement between the predicted 'transition' locations and the locations measured experimentally can be expected. This poor agreement is worsened by the fact that transition is normally confirmed in the wind tunnel or in flight only by the detection of attached turbulent flow. For conditions which result in shorter laminar separation bubbles (high lift coefficients for the upper surface and low lift coefficients for the lower surface and/or high Reynolds numbers), the agreement between theory and experiment should be quite good. (See ref. 12.)

The variation of turbulent-separation location with lift coefficient for Reynolds numbers of 500,000, 1,500,000, and 3,000,000 are shown in figure 5. A small separation is predicted on the upper surface at high lift coefficients. This separation, which is caused by the separation ramp (fig. 4), increases in length with a rough leading edge. Separation is predicted on the lower surface at low lift coefficients. The lower-surface separation is not considered important because it occurs for conditions (lift-coefficient and Reynolds number combinations) which are not relevant to World Class sailplanes. Also, such separation usually has little effect on the section characteristics. (See ref. 12.)

TABLE II.-SM701 AIRFOIL COORDINATES

Upper Surface		Lower Surface	
x/c	y/c	x/c	y/c
0.00168	0.00771	0.00016	−0.00212
.00736	.01910	.00435	−.00981
.01701	.03121	.01501	−.01632
.03055	.04344	.03127	−.02244
.04794	.05534	.05277	−.02800
.06915	.06648	.07923	−.03294
.09417	.07658	.11036	−.03726
.12295	.08544	.14575	−.04101
.15541	.09296	.18488	−.04418
.19133	.09914	.22722	−.04670
.23041	.10397	.27222	−.04849
.27229	.10746	.31929	−.04943
.31654	.10964	.36784	−.04938
.36268	.11055	.41726	−.04803
.41019	.11018	.46727	−.04488
.45853	.10853	.51811	−.03983
.50714	.10557	.56979	−.03340
.55548	.10120	.62191	−.02623
.60323	.09517	.67386	−.01887
.65041	.08760	.72497	−.01182
.69676	.07903	.77446	−.00553
.74171	.06990	.82144	−.00041
.78466	.06055	.86497	.00324
.82498	.05125	.90406	.00526
.86207	.04221	.93768	.00567
.89529	.03348	.96489	.00463
.92431	.02493	.98462	.00262
.94922	.01669	.99624	.00073
.96999	.00946	1.00000	.00000
.98605	.00405		
.99640	.00095		
1.00000	.00000		

SECTION CHARACTERISTICS

Reynolds-Number Effects

The section characteristics for Reynolds numbers of 500,000,1,500,000, and 3,000,000 are shown in figure 5. It should be noted that the maximum lift coefficient predicted by the method of references 8 through 11 is not always realistic. Accordingly, an empirical criterion should be applied to the computed results. This criterion assumes that the maximum lift coefficient has been reached if the drag coefficient of the upper surface is greater than 0.0240 or if the length of turbulent separation along the upper surface is greater than 0.10. Thus,

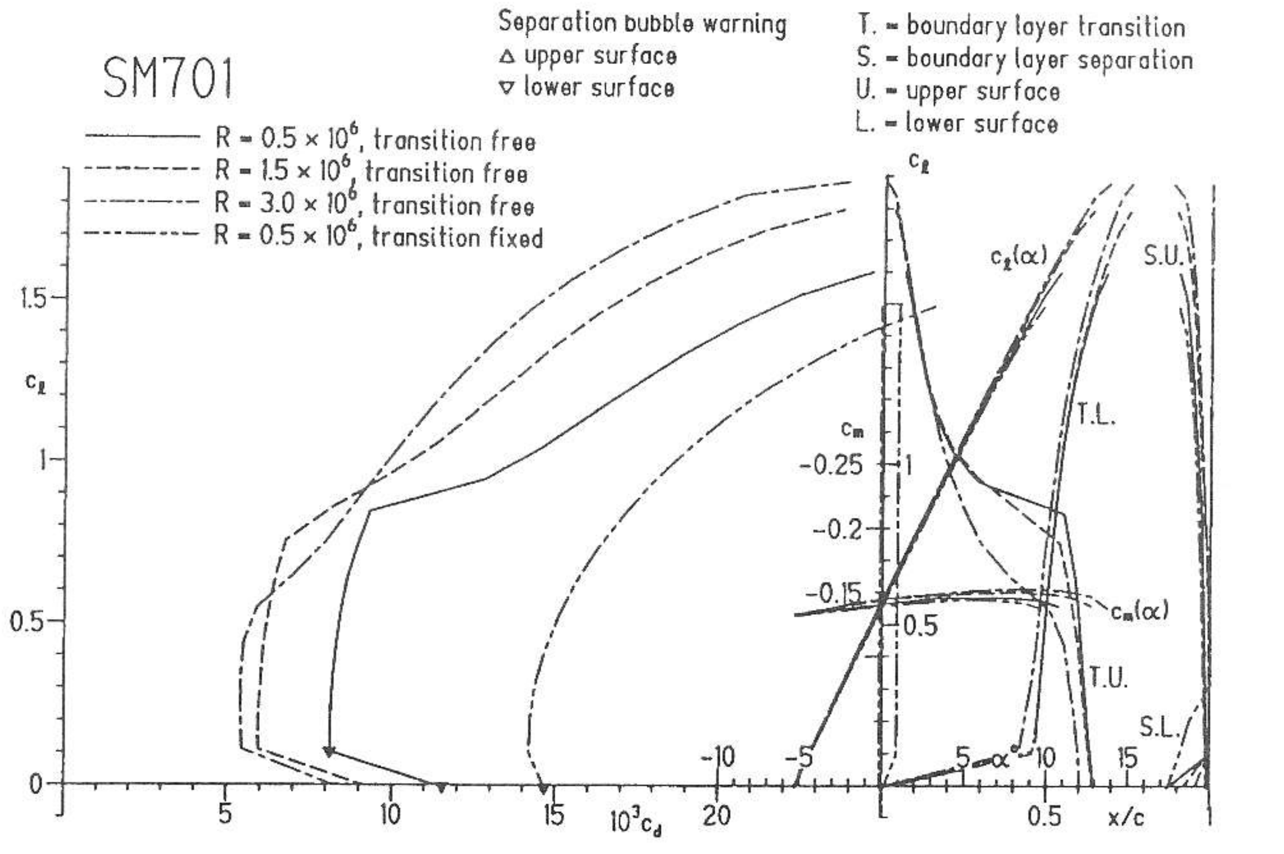

FIGURE 5. Effects of Reynolds number and roughness on section characteristics.

the maximum lift coefficient for a Reynolds number of 500,000 is predicted to be 1.60, which meets the design objective. Based on the movement of the upper-surface separation point, the stall characteristics are expected to be docile, which satisfies the design requirement. Significant (drag-producing) laminar separation bubbles are predicted on the lower surface at lift coefficients below about 0.2. These bubbles are inconsequential because the flight Reynolds numbers which correspond to these lift coefficients are higher.

The zero-lift pitching-moment coefficient is predicted to be -0.1333, which exceeds the design constraint of -0.1. The method of references 8 through 11 generally overpredicts the pitching-moment coefficient by about 10 percent. Thus, the actual zero-lift pitching-moment coefficient should be about -0.12, which still exceeds the design constraint. It was found during the design of this airfoil that a maximum lift coefficient of 1.6 and an airfoil thickness of 16 percent chord with acceptably low profile-drag coefficients could not be achieved without violating the pitching-moment constraint.

For a Reynolds number of 1,500,000, the upper limit of the low-drag range occurs at a lift coefficient of about 0.8, which is well below the design objective.

During the design process, it was determined that an upper-limit lift coefficient of 1.5 is inconsistent with the other design objectives and constraints which are considered of higher priority. Accordingly, the upper limit was reduced to a lift coefficient around that corresponding to the maximum lift-to-drag ratio of a sailplane. For a Reynolds number of 3,000,000, the lower limit of the low-drag range occurs at a lift coefficient of 0.1, which meets the design objective.

An additional analysis (not shown) indicates that significant (drag-producing) laminar separation bubbles should not occur on either surface for any flight condition.

Effect of Roughness

The effect of roughness on the section characteristics for a Reynolds number of 500,000 is shown in figure 5. The 'rough' results were obtained using transition mode MU = 9 (ref. 9), which simulates distributed roughness due to, for example, leading-edge contamination by insects or rain. At the higher lift coefficients, this transition mode is probably comparable to NACA (National Advisory Committee for Aeronautics) Standard Roughness which "is considerably more severe than that caused by the usual manufacturing irregularities or deterioration in service" (ref. 13). The maximum lift coefficient for a Reynolds number of 500,000 decreases to 1.47 rough (fig. 5), which exceeds the design requirement of 1.4. The drag coefficients are, of course, adversely affected by the roughness.

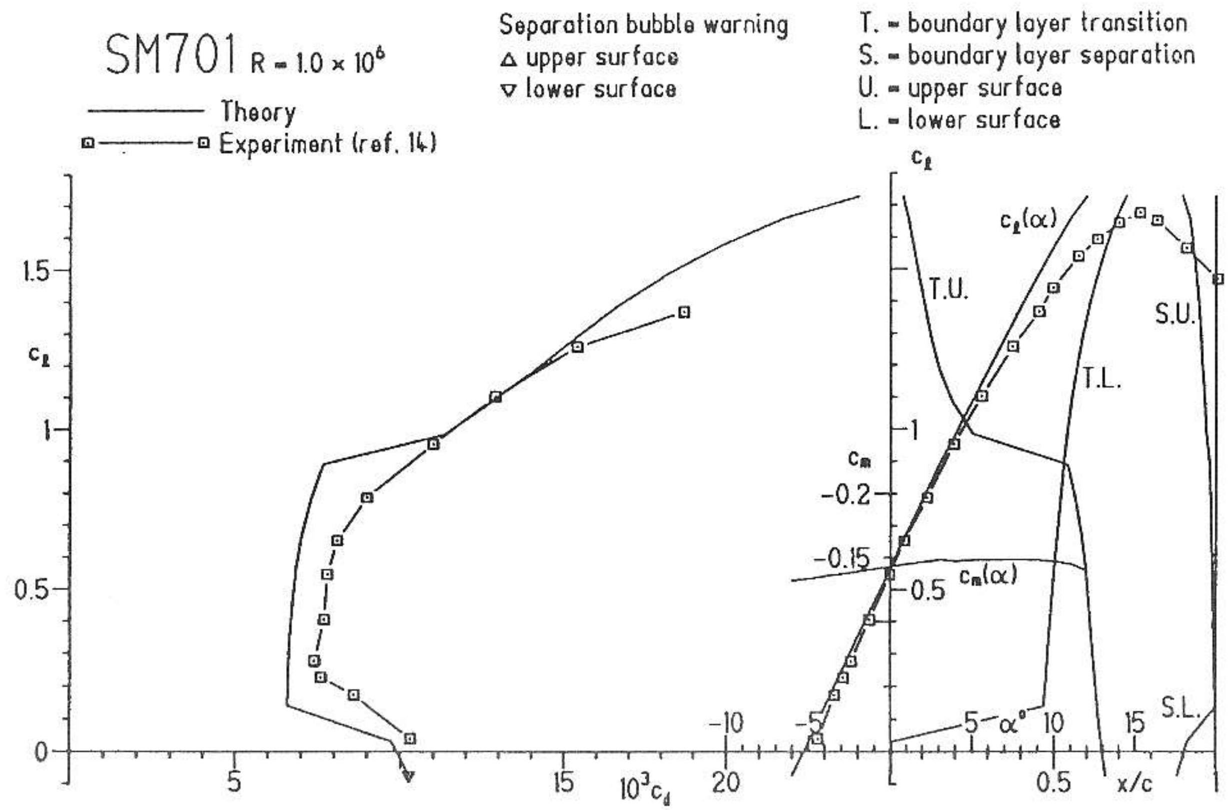

FIGURE 6. Comparison of theoretical and experimental section characteristics smooth for $R = 1.0 \times 10^6$.

COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

The predicted section characteristics for a Reynolds number of 1,000,000 are compared with measurements made in the Laminar Wind Tunnel of Universitat Stuttgart (ref. 14) in figure 6. The lift-curve slope and maximum lift coefficient are predicted quite accurately. The zero-lift angle of attack is, however, overpredicted because a boundary-layer displacement iteration was not performed. The agreement between the predicted and measured drag coefficients is reasonably good.

The comparison of theoretical and experimental section characteristics for a Reynolds number of 1,500,000 is shown in figure 7. The lift-curve slope is again predicted well. The zero-lift angle of attack and the pitching-moment coefficients are again overpredicted because no displacement iterations were performed. The maximum lift coefficient is also overpredicted, which is not typical of the method of references 8 through 11. (See, for example, ref. 12.) The agreement between the predicted and measured drag coefficients is again reasonably good.

SAILPLANE POLAR WITH SM701 AIRFOIL

An analysis of a "generic" World Class sailplane was performed using the method of references 8 through 11. The characteristics of this sailplane are given in table III. The largest unknown is the parasite-drag area (ref. 9). A value of 0.06 square meters was selected as being representative of a fairly unrefined sailplane (i.e., fixed landing gear, poor wing-root juncture, etc.). The predicted speed polar for this sailplane, incorporating the SM701 airfoil, is shown in figure 8. The results, which include a minimum speed of about 56 km/h, a minimum sinking speed of about 0.63 m/s, and a maximum glide ratio of about 35, along with good high-speed performance, confirm the achievement of the airfoil design objectives.

An additional analysis (not shown) using data from reference 15 indicates that the trim-drag penalty incurred by exceeding the pitching-moment constraint is outweighed by the increase in sailplane performance, particularly at low speeds.

CONCLUDING REMARKS

A 16-percent-thick, laminar-flow airfoil for World Class sailplanes, the SM701, has been designed and analyzed theoretically. As verified by wind-tunnel measurements, the primary objectives of a high maximum lift coefficient and low profile-drag coefficients, with restrained pitching-moment coefficient, have been achieved. In addition, the airfoil should exhibit docile stall characteristics. An analysis of a generic World Class sailplane incorporating the SM701 airfoil confirms the achievement of the objectives.

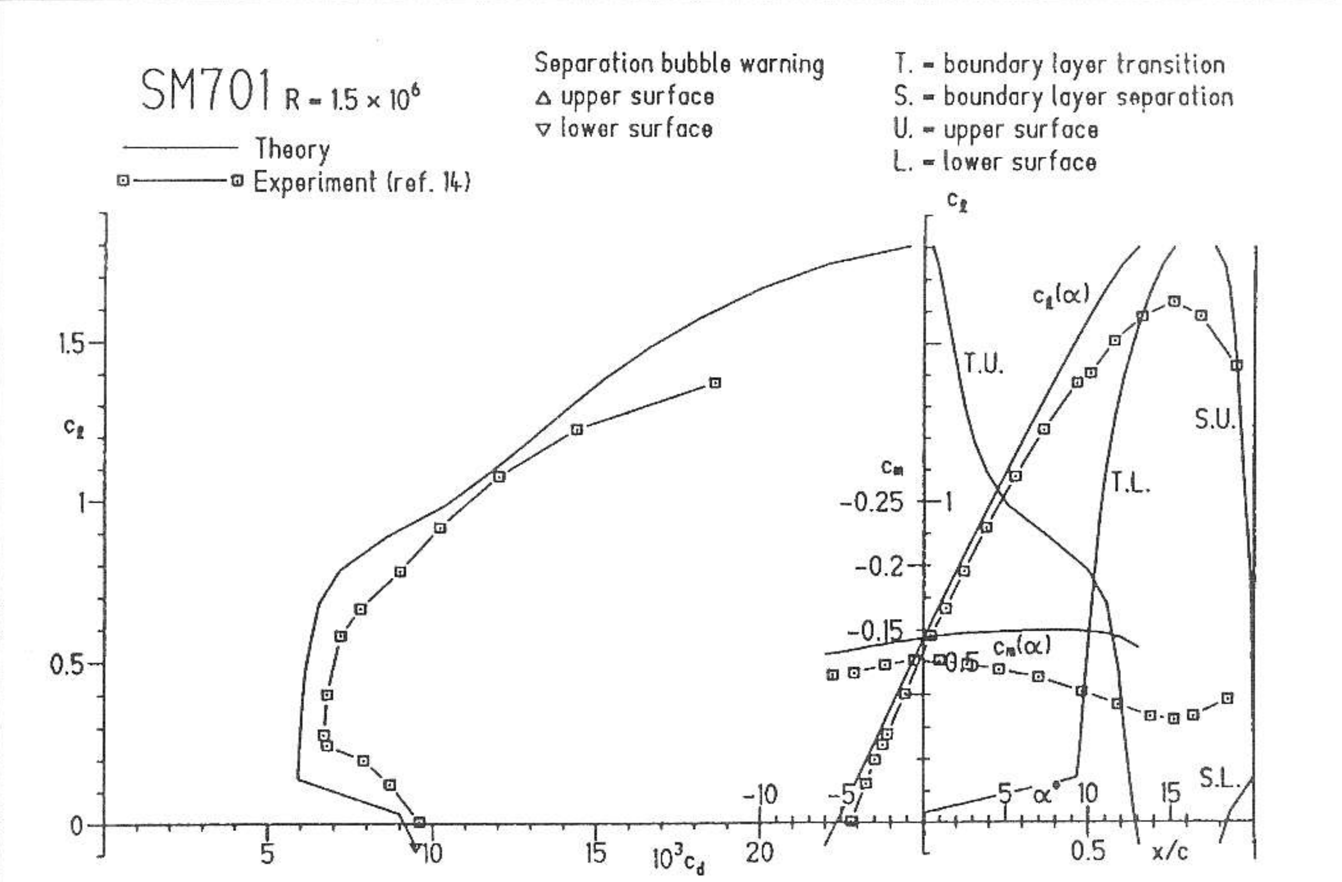

FIGURE 7. Comparison of theoretical and experimental section characteristics smooth for R = 1.5 X 10[6].

ACKNOWLEDGMENT

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TABLE III.-SPECIFICATIONS OF GENERIC WORLD CLASS SAILPLANE.

Wingspan b	15.00 m
Wing area S	11.25 m^2
Aspect ratio	20.00
Root chord	1.00 m
Tip chord	0.50 m
Taper ratio	0.50
Twist	0
Aircraft mass W	281.25 kg
Wing loading	25.00 kg/m^2
Parasite-drag area (ref. 9)	0.06 m^2
Altitude	Sea level

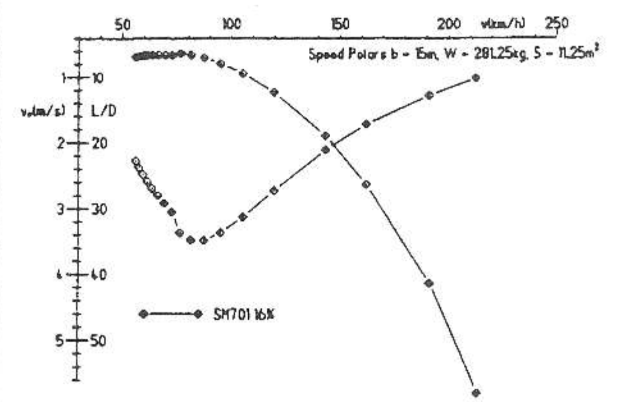

FIGURE 8. Speed polar for generic World Class sailplane.

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