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SOME NEW AIRFOILS FOR ROTORCRAFT

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AUGUST 2010

ABSTRACT

Ten, natural-laminar-flow airfoils, the S406, S407, S409, S410, S411, S412, S413, S414, S415, and S418, intended for rotorcraft applications, have been designed and analyzed theoretically. Five of the airfoils, the S406, S407, S411, S414, and S415, have been experimentally verified. The measurements have been compared with predictions from two, widely used airfoil codes as well as from two, computational fluid dynamics codes.

INTRODUCTION

Ten airfoils intended for rotorcraft applications have been designed and analyzed theoretically. To complement the design effort, investigations were conducted in The Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel (ref. 1) to obtain the basic, low-speed, two-dimensional aerodynamic characteristics of five of the airfoils, selected based on their priority to the U.S. Army. The measurements have been compared with predictions from the method of references 2 and 3 (PROFIL07) and from the method of reference 4 (MSES 3.0) as well as from two, computational fluid dynamics (CFD) codes (ref. 5).

This report provides an overview of the airfoils, which are described in detail in references 6 through 13.

SYMBOLS

Values are given in both SI and U.S. Customary Units. Measurements and calculations were made in U.S. Customary Units.

C_p pressure coefficient, $\frac{p_l - p_\infty}{q_\infty}$

c airfoil chord, mm (in.)

c_c section chord-force coefficient, $\oint C_p d\left(\frac{z}{c}\right)$

c_d section profile-drag coefficient, $\int_{\text{Wake}} c_d' d\left(\frac{h}{c}\right)$, except post stall,
 $c_n \sin \alpha + c_c \cos \alpha$

c_d' point drag coefficient

c_l section lift coefficient, $c_n / \cos \alpha - c_d \tan \alpha$

c_m section pitching-moment coefficient about quarter-chord point,
 $-\oint C_p \left(\frac{x}{c} - 0.25\right) d\left(\frac{x}{c}\right) + \oint C_p \left(\frac{z}{c}\right) d\left(\frac{z}{c}\right)$

c_n	section normal-force coefficient, $-\oint C_p d\left(\frac{x}{c}\right)$
h	horizontal width in wake profile, mm (in.)
M	free-stream Mach number
p	static pressure, Pa (lbf/ft ²)
q	dynamic pressure, Pa (lbf/ft ²)
R	Reynolds number based on free-stream conditions and airfoil chord
t	airfoil thickness, mm (in.)
x	airfoil abscissa, mm (in.)
z	airfoil ordinate, mm (in.)
α	angle of attack relative to x-axis, deg

Subscripts:

dd	drag divergence
l	local point on airfoil
ll	lower limit of low-drag range
max	maximum
min	minimum
S	separation
T	transition
ul	upper limit of low-drag range
0	zero lift
∞	free-stream conditions

Abbreviations:

L.	lower surface
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LSLTT	The Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel
LTPT	NASA Langley Low-Turbulence Pressure Tunnel
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
S.	boundary-layer separation location, x_S/c
SNLF	slotted, natural laminar flow
T.	boundary-layer transition location, x_T/c
U.	upper surface

EXPERIMENTAL VERIFICATION

As a prerequisite to the experimental verifications, the E 387 airfoil (ref. 14) was investigated in The Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel (LSLTT) to validate the facility and the test technique, particularly for low Reynolds numbers. The results have been compared to those obtained for the same airfoil in the NASA Langley Low-Turbulence Pressure Tunnel (LTPT). See figure 1 and reference 15.

The models of the airfoils designed under the present effort were tested over a range of Reynolds numbers with transition free (smooth), with transition fixed near the leading edge to simulate full-chord, turbulent flow, and, for the S406 and S415 airfoils, with scaled, NACA standard roughness to simulate more severe, leading-edge contamination. The measured model contours were within 0.13 mm (0.005 in.) of the prescribed shapes. The pressures measured on the models were reduced to standard pressure coefficients and numerically integrated to obtain section normal-force and chord-force coefficients and section pitching-moment coefficients about the quarter-chord point. Section profile-drag coefficients were computed from the wake total and static pressures. Standard, low-speed, wind-tunnel boundary corrections were applied to the data.

The test Mach numbers and Reynolds numbers were generally much lower than the operational values of the intended applications. (The present investigations serve as prerequisites to more costly, high Mach number and Reynolds number verifications.)

AIRFOILS

Almost all airfoils in use on rotorcraft today were developed under the assumption that extensive laminar flow is not likely on a rotor. (See ref. 16, for example.) For the present effort, however, given the low to moderate Reynolds numbers, the achievement of laminar

flow warranted exploration, acknowledging that concerns remain about the effects of sweep and radial pressure gradients.

The airfoils were designed using the Eppler Airfoil Design and Analysis Code (refs. 2 and 3) because of its unique capability for multipoint design and because of confidence gained during the design, analysis, and experimental verification of many other airfoils. For the S414 airfoil, the MSES code (ref. 4) was used to refine the initial fore-element shape, designed using the Eppler code, in the two-element configuration.

The airfoils and their intended applications are listed in the following table. The airfoils that have been experimentally verified are shown in italics. Representative section characteristics are shown in figures 2 through 6. (It should be noted that the compressibility correction incorporated in the method of refs. 2 and 3 is invalid if the local flow is supersonic and, accordingly, only subsonic results are shown.)

Application	Airfoil			Figure	Reference
	Primary	Tip	Root		
Small helicopter	<i>S406</i>	—	—	2	6
High-altitude, tandem-rotor helicopter	<i>S407</i>	S409	S410	3	7 and 8
Small helicopter	<i>S411</i>	S412 S413	<i>S411</i>	4	9 and 10
Small helicopter having torsionally stiff blade	<i>S414</i>	—	—	5	11
Slowed-rotor helicopter	<i>S415</i> <i>S418</i>	—	—	6	12 and 13

The airfoil design specifications (table I) were provided by, and refined during discussions with, Preston B. Martin of the U.S. Army Aeroflightdynamics Directorate (AFDD), Research, Development and Engineering Command (RDECOM). The airfoil shapes and their coordinates are available from Airfoils, Incorporated.

Several airfoils are related. Two airfoil families were designed and three of the primary airfoils have similar design specifications.

For the S407, S409, and S410 airfoil family, the positive pitching-moment coefficient of the root airfoil, the S410, is used to balance the negative pitching-moment coefficient of the primary airfoil, the S407. This allows the performance of the primary airfoil to be maximized while maintaining an appropriate pitching moment for the entire blade.

For the S411, S412, and S413 airfoil family, the primary airfoil, the S411, was initially designed with a trailing-edge shape that geometrically and aerodynamically approximated the

required tab. This shape was then modified to the specified tab geometry. Accordingly, the performance of the final, tabbed airfoil is likely better than that of an airfoil altered by the addition of a relatively arbitrary tab. The outboard and tip airfoils, the S412 and S413, respectively, were derived from the S411 airfoil to increase the aerodynamic and geometric compatibilities of the three airfoils. Because of the design requirements, the S412 and S413 airfoils are symmetric.

The S406, S411, and S414 airfoils have similar design specifications, except for the zero-lift pitching-moment constraint. Thus, these airfoils allow the effect of pitching moment on rotor performance to be evaluated. For the S414 airfoil, which has no pitching-moment constraint, the slotted, natural-laminar-flow (SNLF) airfoil concept (ref. 17) was employed. The SNLF airfoil concept allows the extent of natural laminar flow to be increased beyond the previously established limit. Thus, the concept exhibits low section profile-drag coefficients without having to resort to the complexity and cost of laminar flow control. It also achieves a high maximum lift coefficient without variable geometry (i.e., the aft element need not be deflected).

Finally, the S415 and S418 airfoils are intended for the blade of a slowed-rotor helicopter. The S415 airfoil, designed for the hover condition, is “unmorphed” into the S418 airfoil, which is more suitable for forward flight.

CONCLUDING REMARKS

Ten, natural-laminar-flow airfoils, intended for rotorcraft applications, have been designed and analyzed theoretically. Five of the airfoils have been experimentally verified. The measurements have been compared with predictions from two, widely used airfoil codes as well as from two, computational fluid dynamics codes.

ACKNOWLEDGMENTS

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TABLE I.- AIRFOIL DESIGN SPECIFICATIONS

(a) S406 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,\min}$	0.10	0.59	2.12×10^6	Low
Maximum lift coefficient $c_{l,\max}$	1.30	0.30	1.14×10^6	High
Lower limit of low-drag, lift-coefficient range $c_{l,\text{ll}}$	0.20	0.59	2.12×10^6	Medium
Upper limit of low-drag, lift-coefficient range $c_{l,\text{ul}}$	0.70	0.46	1.63×10^6	High
Zero-lift pitching-moment coefficient $c_{m,0}$	≥ -0.05	0.59	2.12×10^6	Low
Thickness t/c	0.1425			High
Other: Maximum lift coefficient $c_{l,\max}$ independent of leading-edge roughness Docile stall characteristics				

TABLE I.- Continued

(b) S407 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,min}$	0.15	0.70	552,000	Low
Maximum lift coefficient $c_{l,max}$	1.20	0.20	147,000	High
Lower limit of low-drag, lift-coefficient range $c_{l,ll}$	0.20	0.70	552,000	High
Upper limit of low-drag, lift-coefficient range $c_{l,ul}$	1.00	0.50	368,000	Medium
Zero-lift pitching-moment coefficient $c_{m,0}$	≥ -0.15	0.70	552,000	Low
Thickness t/c	> 0.06			Low
Other: Maximum lift coefficient $c_{l,max}$ independent of leading-edge roughness Docile stall characteristics				

TABLE I.- Continued

(c) S409 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,min}$	0.00	0.76	409,000	Low
Maximum lift coefficient $c_{l,max}$	1.00	0.55	303,000	High
Lower limit of low-drag, lift-coefficient range $c_{l,ll}$	0.10	0.76	409,000	High
Upper limit of low-drag, lift-coefficient range $c_{l,ul}$	0.90	0.58	319,000	Medium
Zero-lift pitching-moment coefficient $c_{m,0}$	≥ 0.00	0.76	409,000	Medium
Thickness t/c	> 0.05			Low
Other: Maximum lift coefficient $c_{l,max}$ independent of leading-edge roughness Docile stall characteristics Drag-divergence Mach number $M_{dd} > 0.78$ at $c_l = 0.00$				

TABLE I.- Continued

(d) S410 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,\min}$	0.10	0.425	437,000	Low
Maximum lift coefficient $c_{l,\max}$	1.00	0.18	185,000	High
Lower limit of low-drag, lift-coefficient range $c_{l,\text{ll}}$	0.20	0.425	437,000	High
Upper limit of low-drag, lift-coefficient range $c_{l,\text{ul}}$	0.80	0.20	206,000	Low
Zero-lift pitching-moment coefficient $c_{m,0}$	≥ 0.05	0.425	437,000	Medium
Thickness t/c	> 0.05			Low
Other: Maximum lift coefficient $c_{l,\max}$ independent of leading-edge roughness Docile stall characteristics				

TABLE I.- Continued

(e) S411 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,\min}$	0.00 ¹	0.70	2.26×10^6	Low
Maximum lift coefficient $c_{l,\max}$	1.25 1.20	0.30 0.40	0.97×10^6 1.29×10^6	High
Lower limit of low-drag, lift-coefficient range $c_{l,\text{ll}}$	0.10	0.70	2.26×10^6	Medium
Upper limit of low-drag, lift-coefficient range $c_{l,\text{ul}}$	0.65	0.45	1.45×10^6	Medium
Zero-lift pitching-moment coefficient $c_{m,0}$	0 ± 0.002 ¹ 0 ± 0.005 ²	0.75 0.45	2.42×10^6 1.45×10^6	High
Thickness t/c	0.14 with tab			Medium
Other: Maximum lift coefficient $c_{l,\max}$ independent of leading-edge roughness Docile stall characteristics 5-percent-chord tab with thickness of 0.352-percent chord				

¹With transition fixed at 10-percent chord on upper and lower surfaces.²With transition free.

TABLE I.- Continued

(f) S412 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,min}$	-0.05	0.78	2.51×10^6	Low
Maximum lift coefficient $c_{l,max}$	1.00	0.40	1.34×10^6	High
Lower limit of low-drag, lift-coefficient range $c_{l,ll}$	0.00	0.78	2.51×10^6	High
Upper limit of low-drag, lift-coefficient range $c_{l,ul}$	0.50	0.58	1.88×10^6	Medium
Zero-lift pitching-moment coefficient $c_{m,0}$	0 ± 0.002	0.78	2.51×10^6	High
Thickness t/c	0.12			Medium
Other: Maximum lift coefficient $c_{l,max}$ relatively independent of leading-edge roughness Docile stall characteristics Trailing-edge thickness of 0.352-percent chord				

TABLE I.- Continued

(g) S413 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,\min}$	-0.10	0.80	2.61×10^6	Low
Maximum lift coefficient $c_{l,\max}$	1.00	0.40	1.34×10^6	Medium
Lower limit of low-drag, lift-coefficient range $c_{l,\text{ll}}$	0.00	0.80	2.61×10^6	High
Upper limit of low-drag, lift-coefficient range $c_{l,\text{ul}}$	0.50	0.61	1.98×10^6	High
Zero-lift pitching-moment coefficient $c_{m,0}$	0 ± 0.002	0.80	2.61×10^6	High
Thickness t/c	0.10			Medium
<p>Other:</p> <p>Maximum lift coefficient $c_{l,\max}$ relatively independent of leading-edge roughness</p> <p>Docile stall characteristics</p> <p>Trailing-edge thickness of 0.352-percent chord</p>				

TABLE I.- Continued

(h) S414 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,min}$	0.00	0.70	2.26×10^6	Low
Maximum lift coefficient $c_{l,max}$	1.25 1.20	0.30 0.40	0.97×10^6 1.29×10^6	High
Lower limit of low-drag, lift-coefficient range $c_{l,ll}$	0.10	0.70	2.26×10^6	Medium
Upper limit of low-drag, lift-coefficient range $c_{l,ul}$	0.65	0.45	1.45×10^6	Medium
Zero-lift pitching-moment coefficient $c_{m,0}$	—			
Thickness t/c	0.14			Medium
<p>Other:</p> <p>Maximum lift coefficient $c_{l,max}$ independent of leading-edge roughness</p> <p>Docile stall characteristics</p> <p>Objectives and constraints identical to those for S411 airfoil without $c_{m,0}$ constraint</p>				

TABLE I.- Continued

(i) S415 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,\min}$	0.40	0.50	5.00×10^6	Medium
Maximum lift coefficient $c_{l,\max}$	1.50			High
Lower limit of low-drag, lift-coefficient range $c_{l,\text{ll}}$	0.60			Medium
Upper limit of low-drag, lift-coefficient range $c_{l,\text{ul}}$	1.40			High
Pitching-moment coefficient c_m at $c_l = 1.50$	≥ -0.10	0.40	4.00×10^6	Low
Thickness t/c	—			—
<p>Other:</p> <p>Maximum lift coefficient $c_{l,\max}$ relatively independent of leading-edge roughness</p> <p>Docile stall characteristics at $M = 0.2$ and $R = 2.0 \times 10^6$ (i.e., verifiable in The Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel)</p>				

TABLE I.- Concluded

(j) S418 airfoil

Parameter	Objective/ Constraint	Mach Number M	Reynolds Number R	Priority
Minimum lift coefficient $c_{l,min}$	0.00	0.72	7.20×10^6	Medium
Maximum lift coefficient $c_{l,max}$	0.80	0.60	6.00×10^6	Low
Lower limit of low-drag, lift-coefficient range $c_{l,ll}$	0.02	0.70	7.00×10^6	High
Upper limit of low-drag, lift-coefficient range $c_{l,ul}$	0.10			Medium
Zero-lift pitching-moment coefficient $c_{m,0}$	≥ -0.02	0.72	7.20×10^6	High
Thickness t/c	$(t/c)_{S415}$			Constraint
<p>Other:</p> <p>Maximum lift coefficient $c_{l,max}$ relatively independent of leading-edge roughness</p> <p>Drag-divergence Mach number $M_{dd} \geq 0.75$ at $c_l = 0.00$</p>				

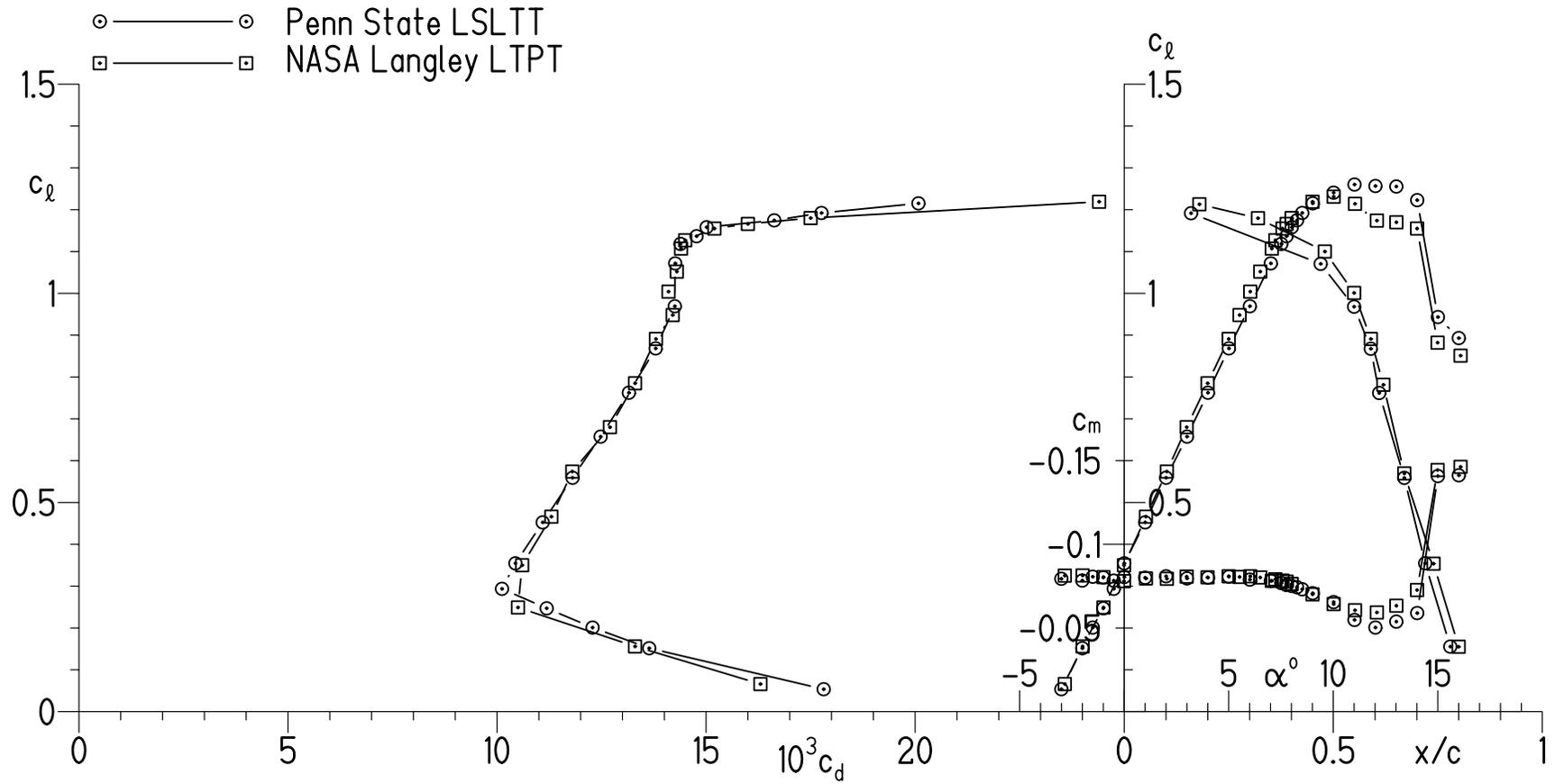
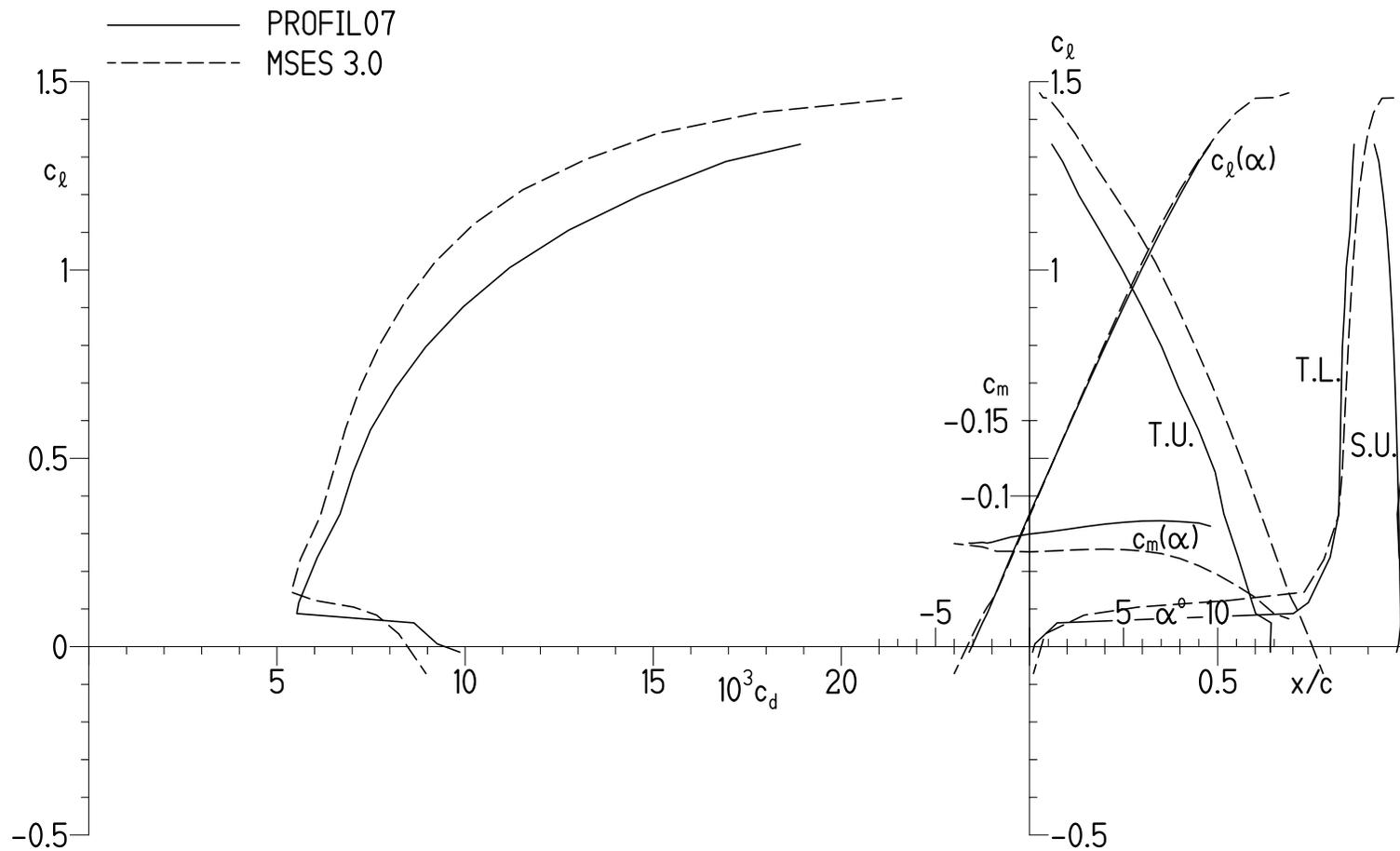
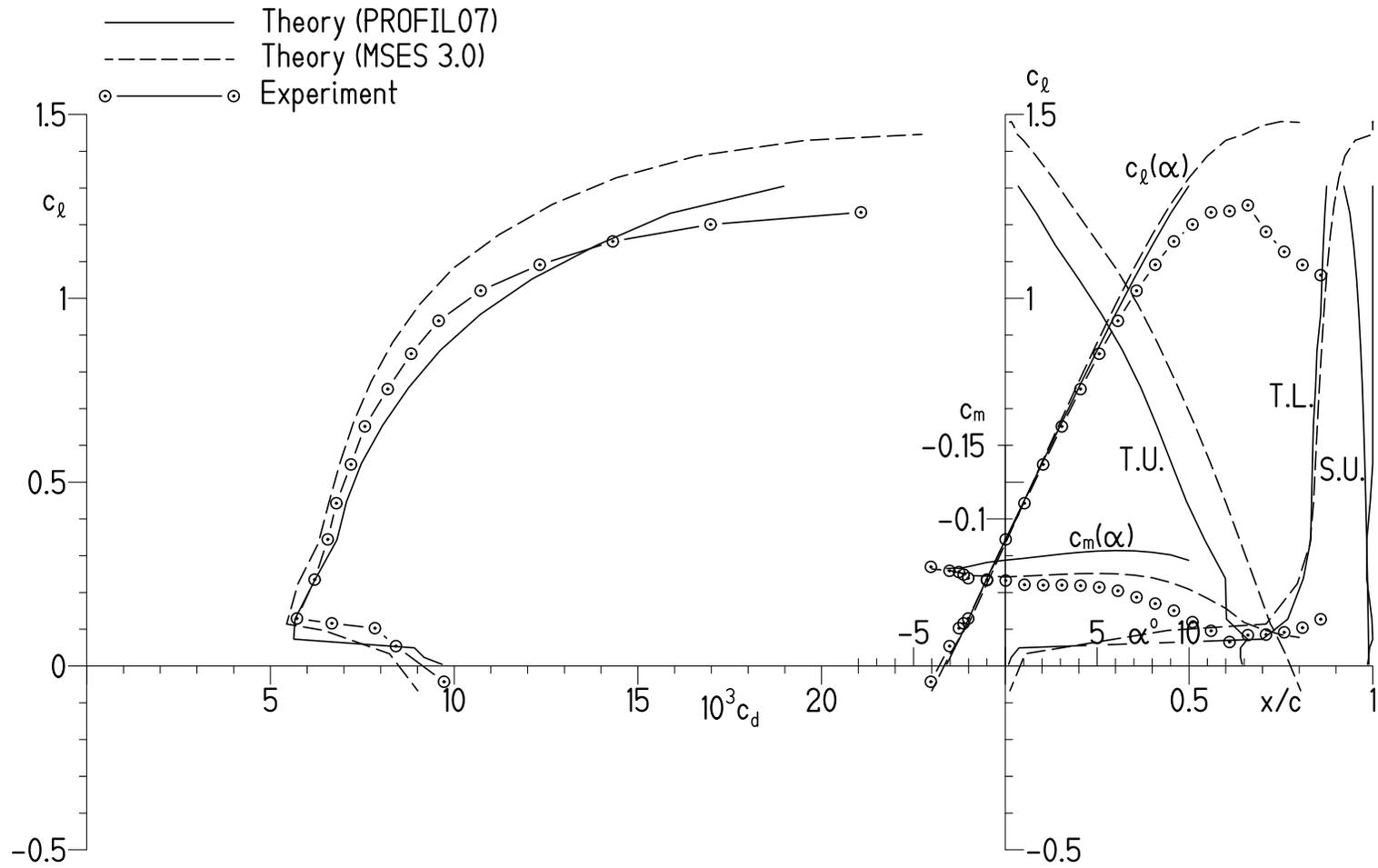


Figure 1.- Comparison of section characteristics of E 387 airfoil for $R = 200,000$ with transition free.



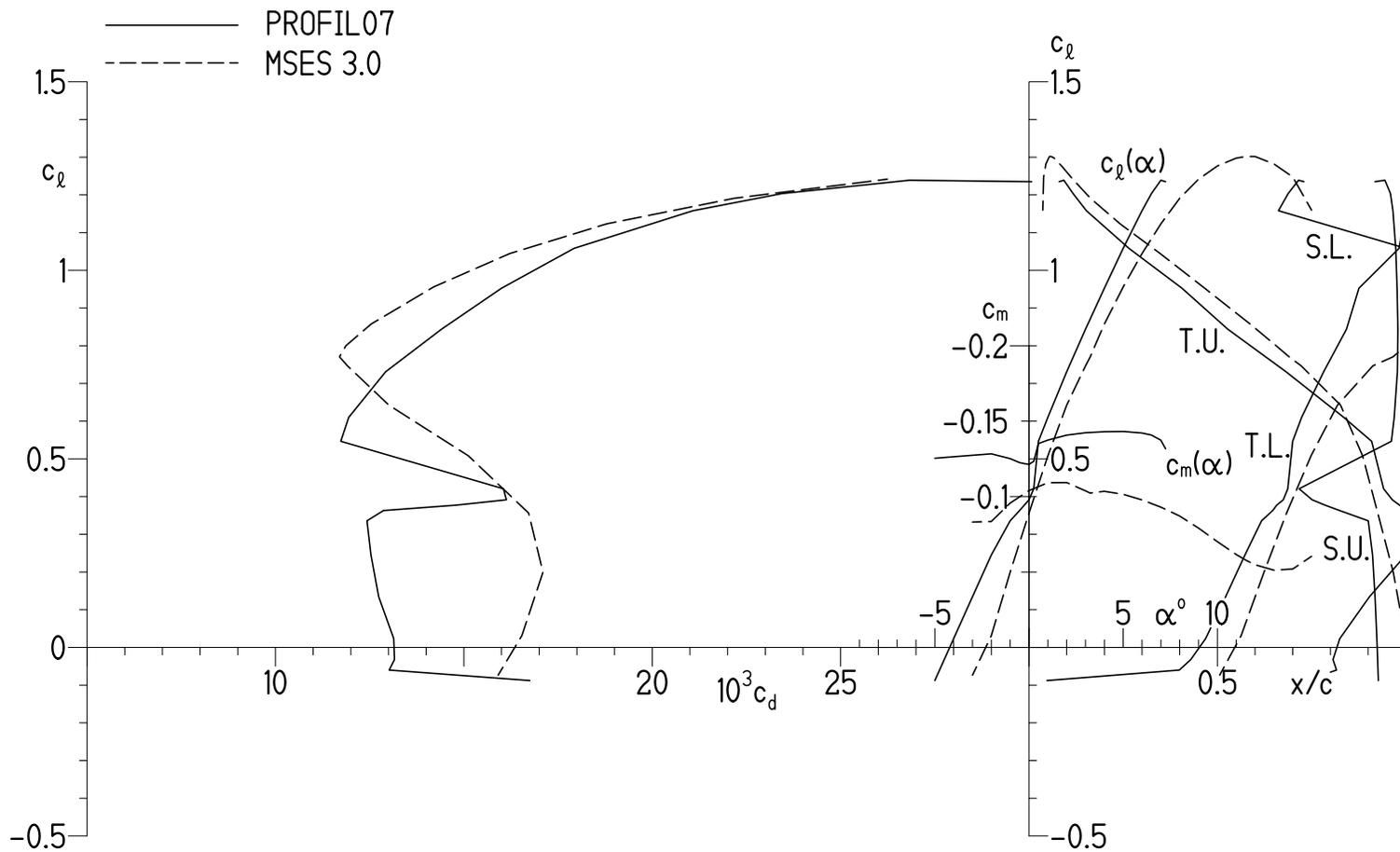
(a) $M = 0.30$ and $R = 1.14 \times 10^6$.

Figure 2.- Section characteristics of S406 airfoil with transition free.



(b) $M = 0.11$ and $R = 1.00 \times 10^6$.

Figure 2.- Concluded.



(a) S407 airfoil at $M = 0.20$ and $R = 147,000$.

Figure 3.- Section characteristics of S407, S409, and S410 airfoils with transition free.

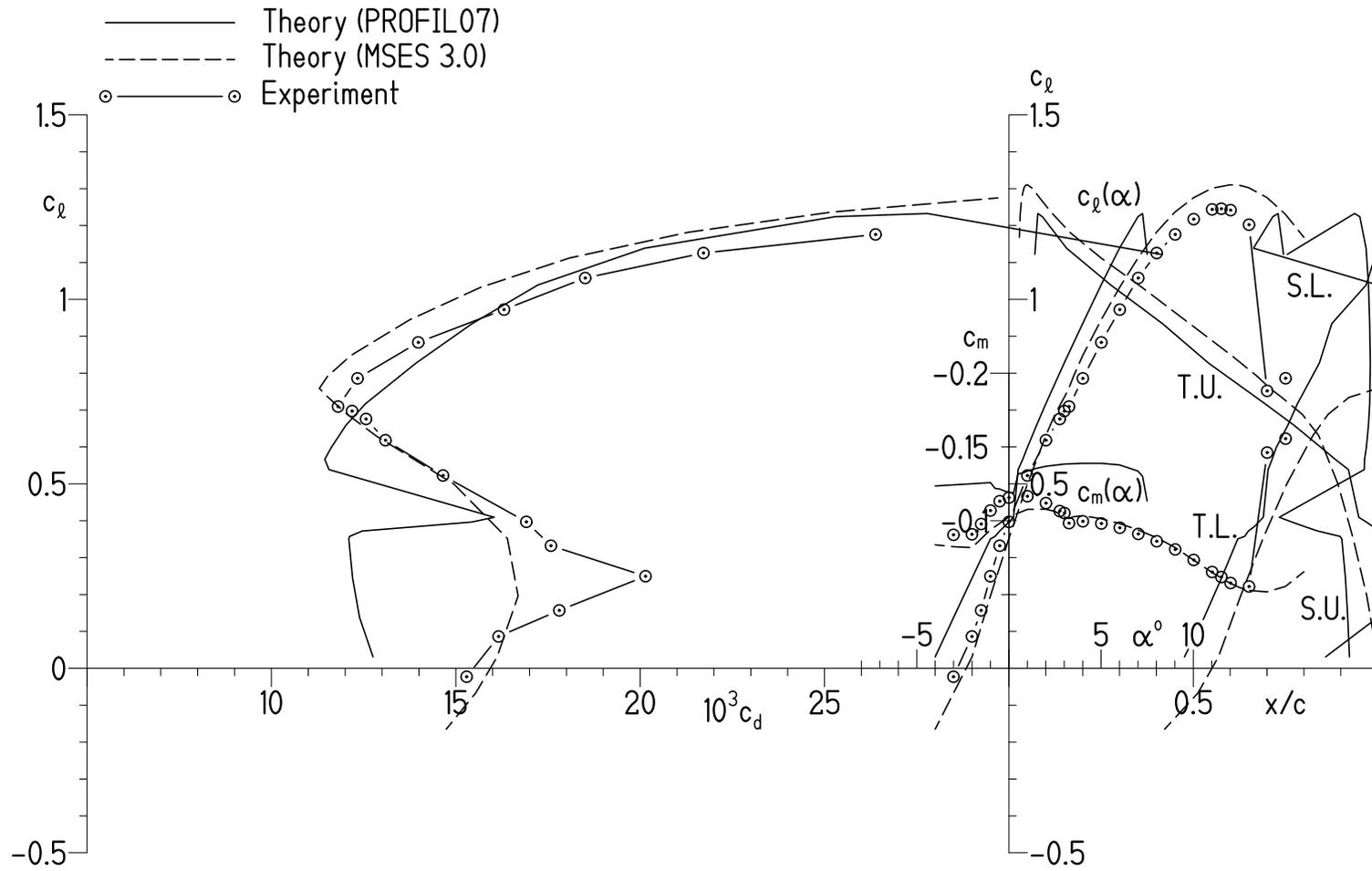
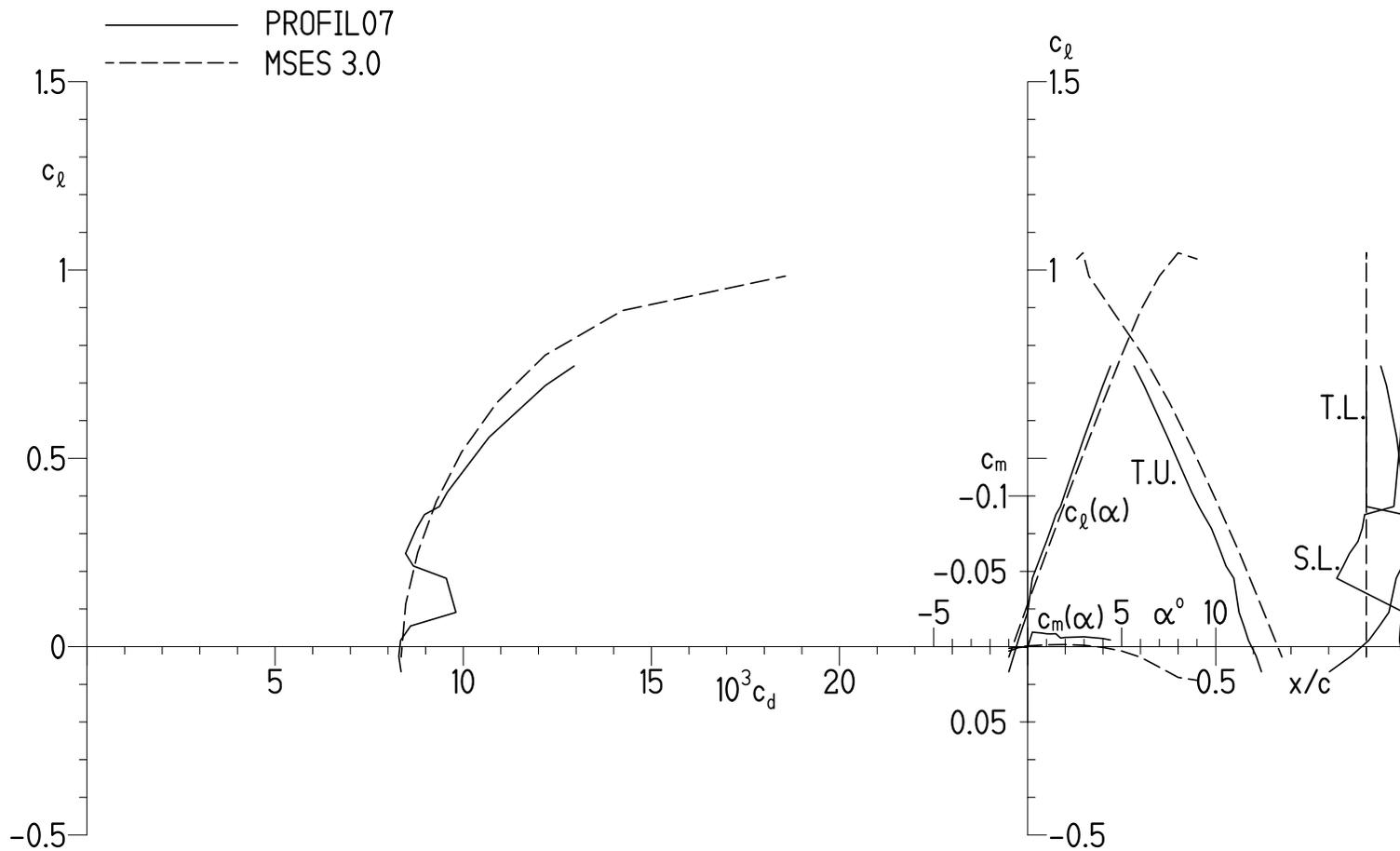
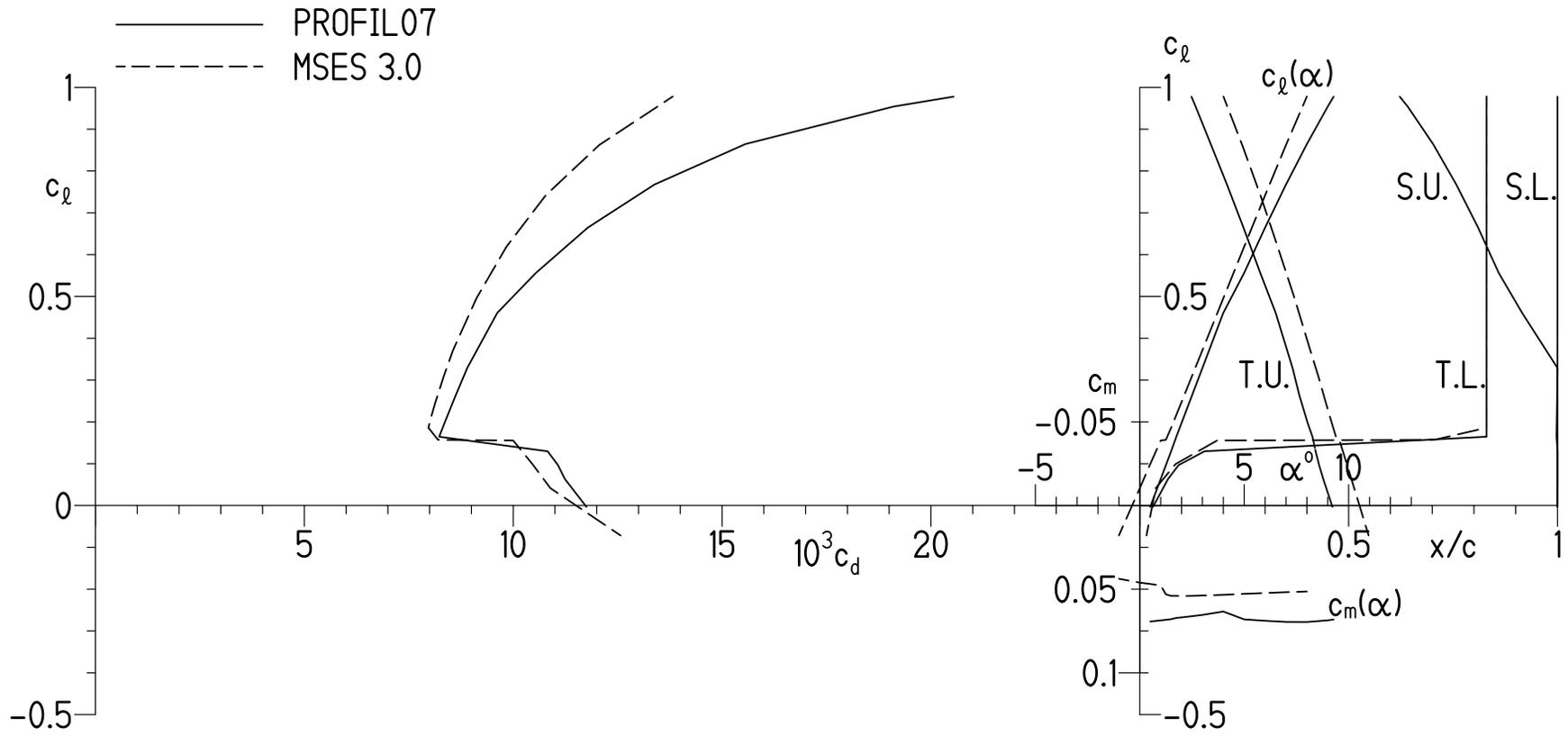
(b) S407 airfoil at $M = 0.04$ and $R = 150,000$.

Figure 3.- Continued.



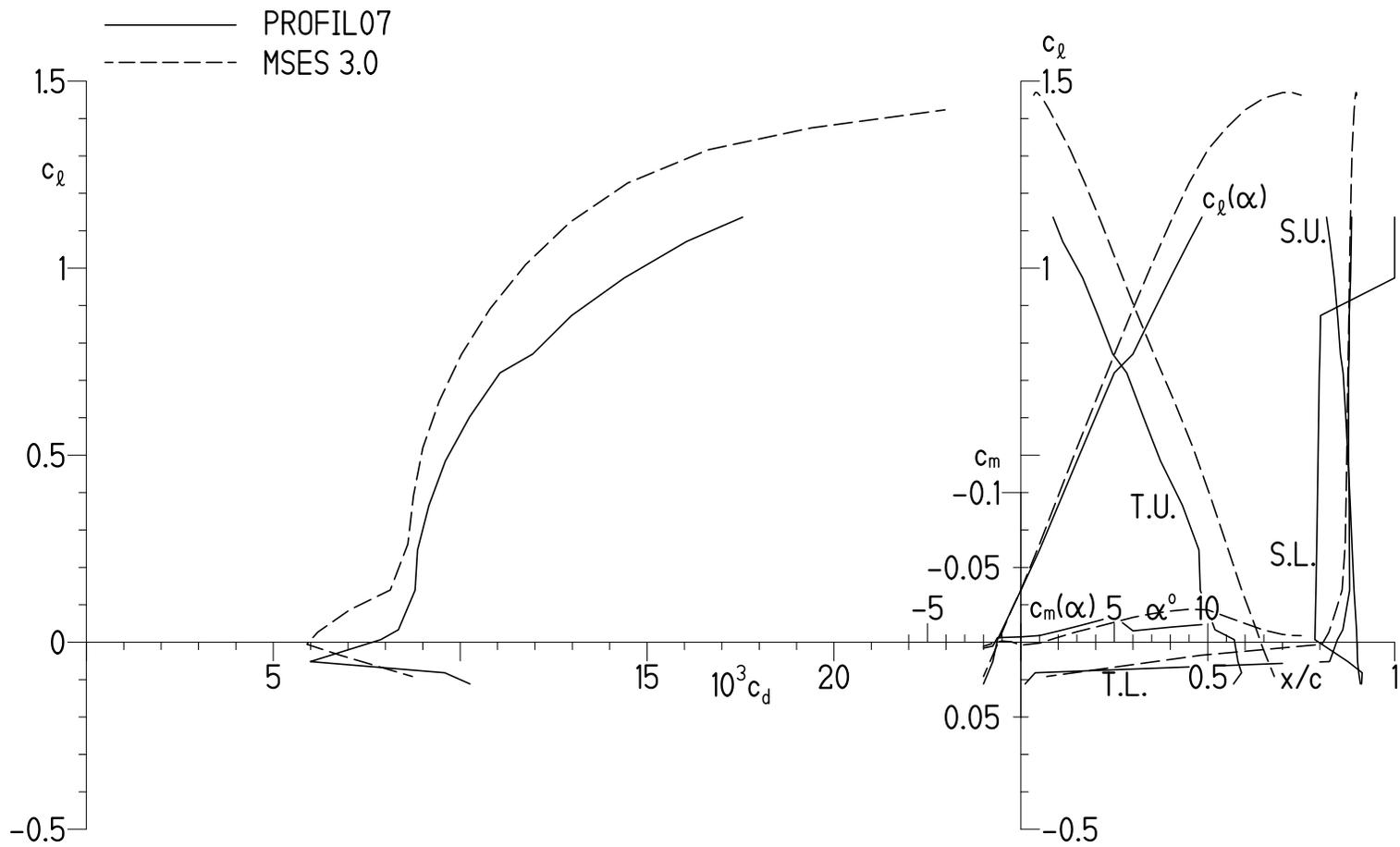
(c) S409 airfoil at $M = 0.55$ and $R = 303,000$.

Figure 3.- Continued.



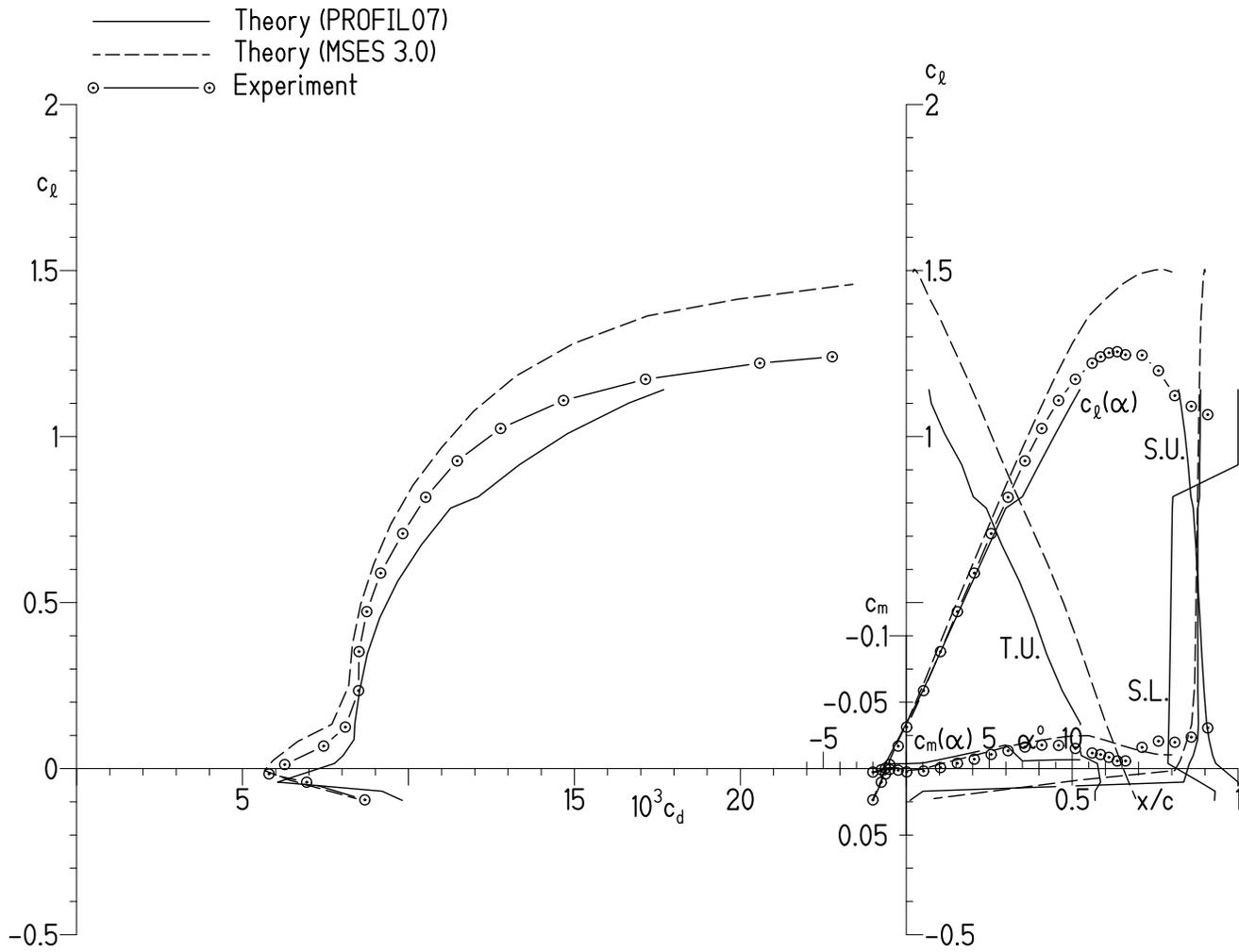
(d) S410 airfoil at $M = 0.425$ and $R = 437,000$.

Figure 3.- Concluded.



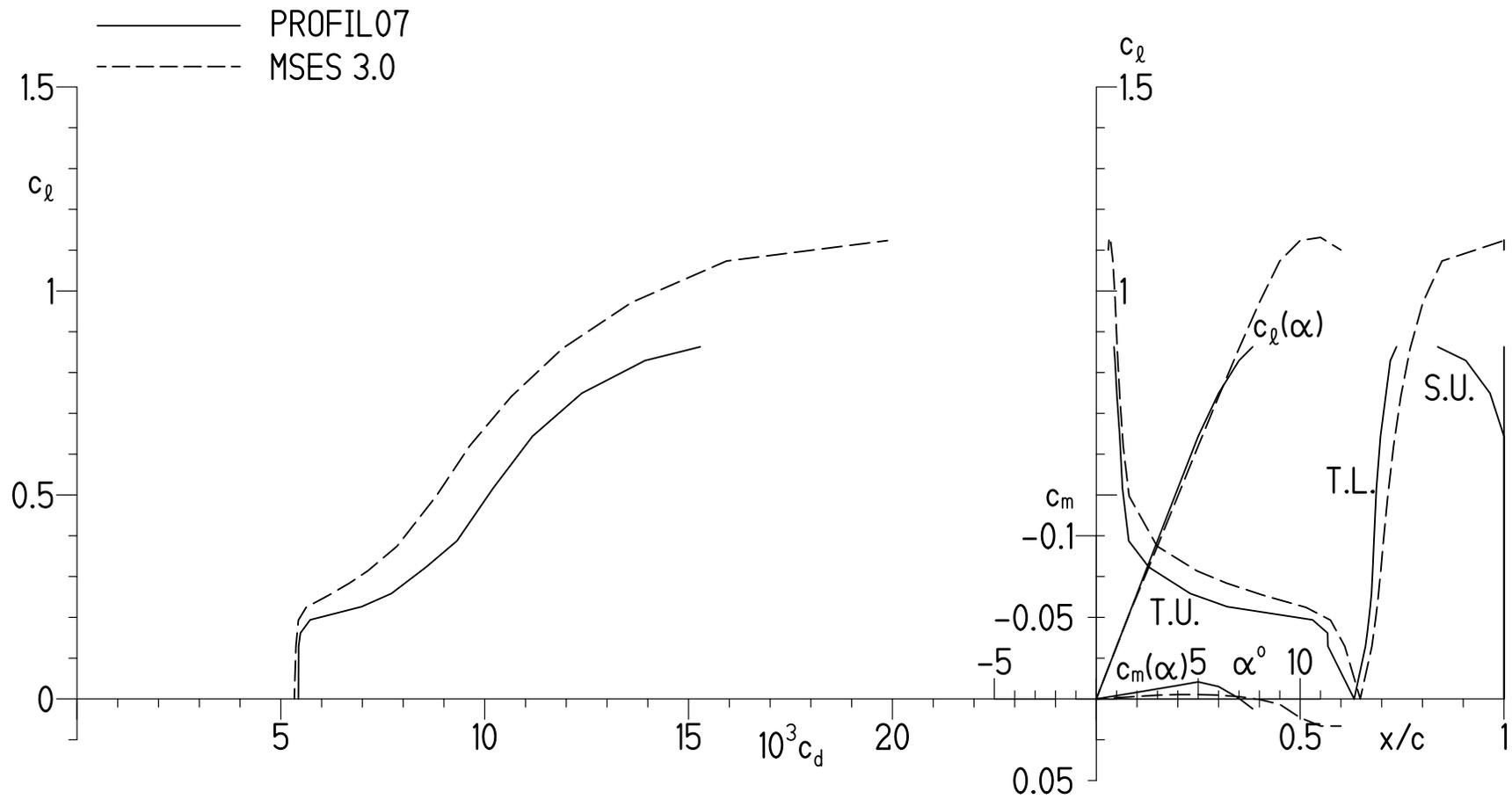
(a) S411 airfoil at $M = 0.30$ and $R = 0.97 \times 10^6$.

Figure 4.- Section characteristics of S411, S412, and S413 airfoils with transition free.



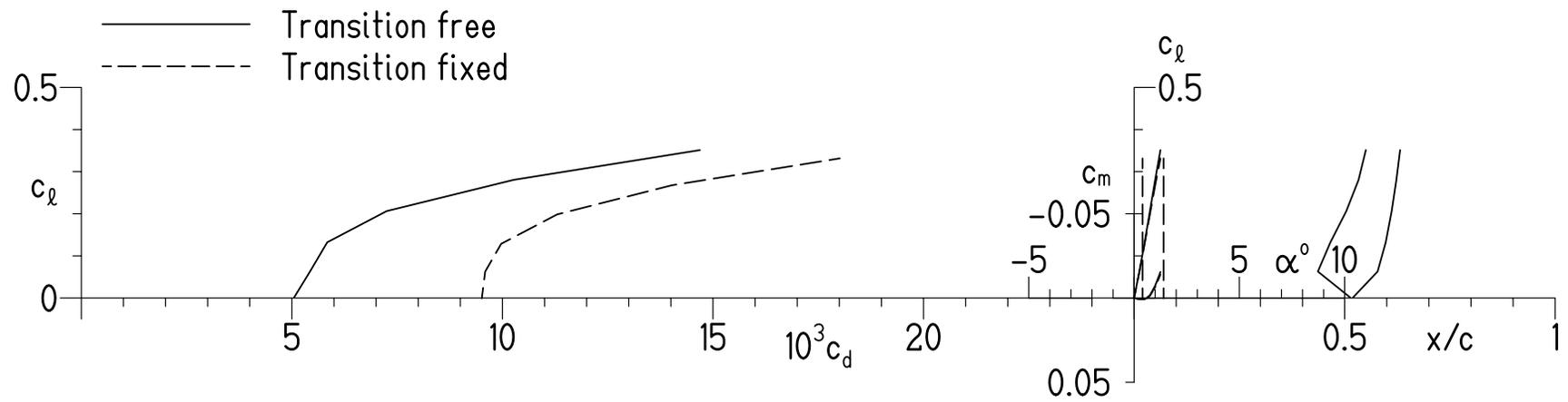
(b) S411 airfoil at $M = 0.10$ and $R = 1.00 \times 10^6$.

Figure 4.- Continued.



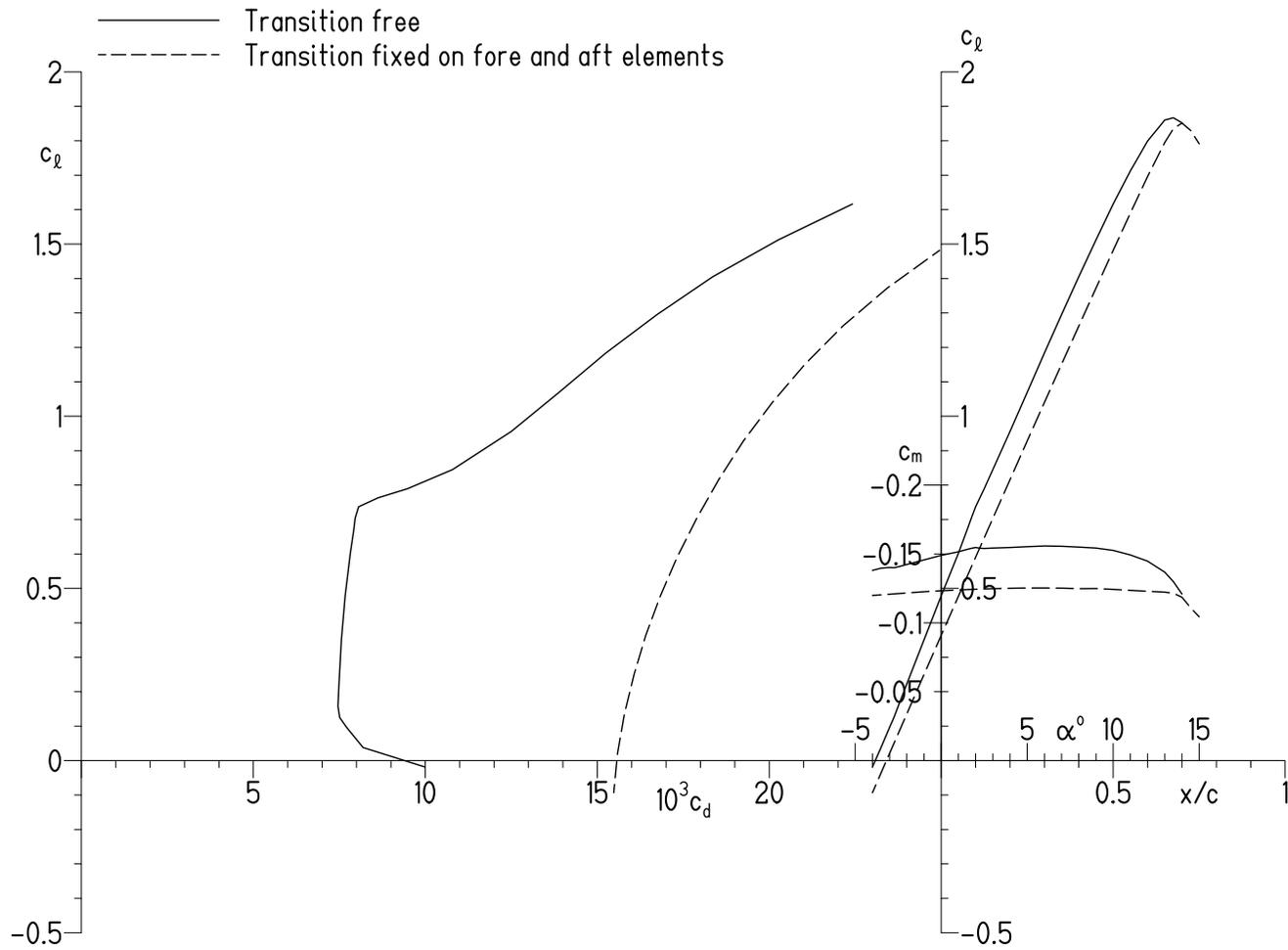
(c) S412 airfoil at $M = 0.40$ and $R = 1.34 \times 10^6$.

Figure 4.- Continued.



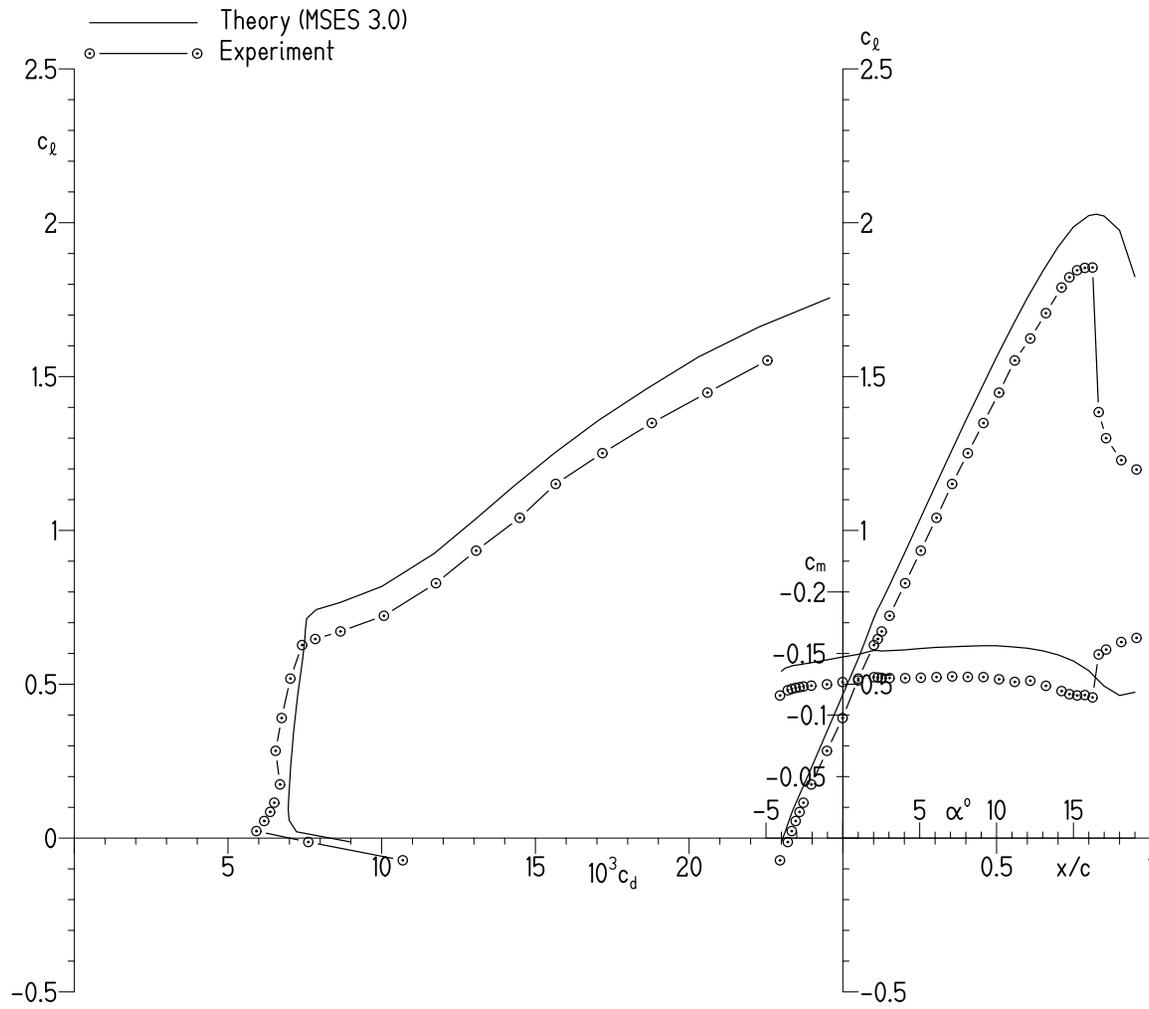
(d) S413 airfoil at $M = 0.80$ and $R = 2.61 \times 10^6$.

Figure 4.- Concluded.



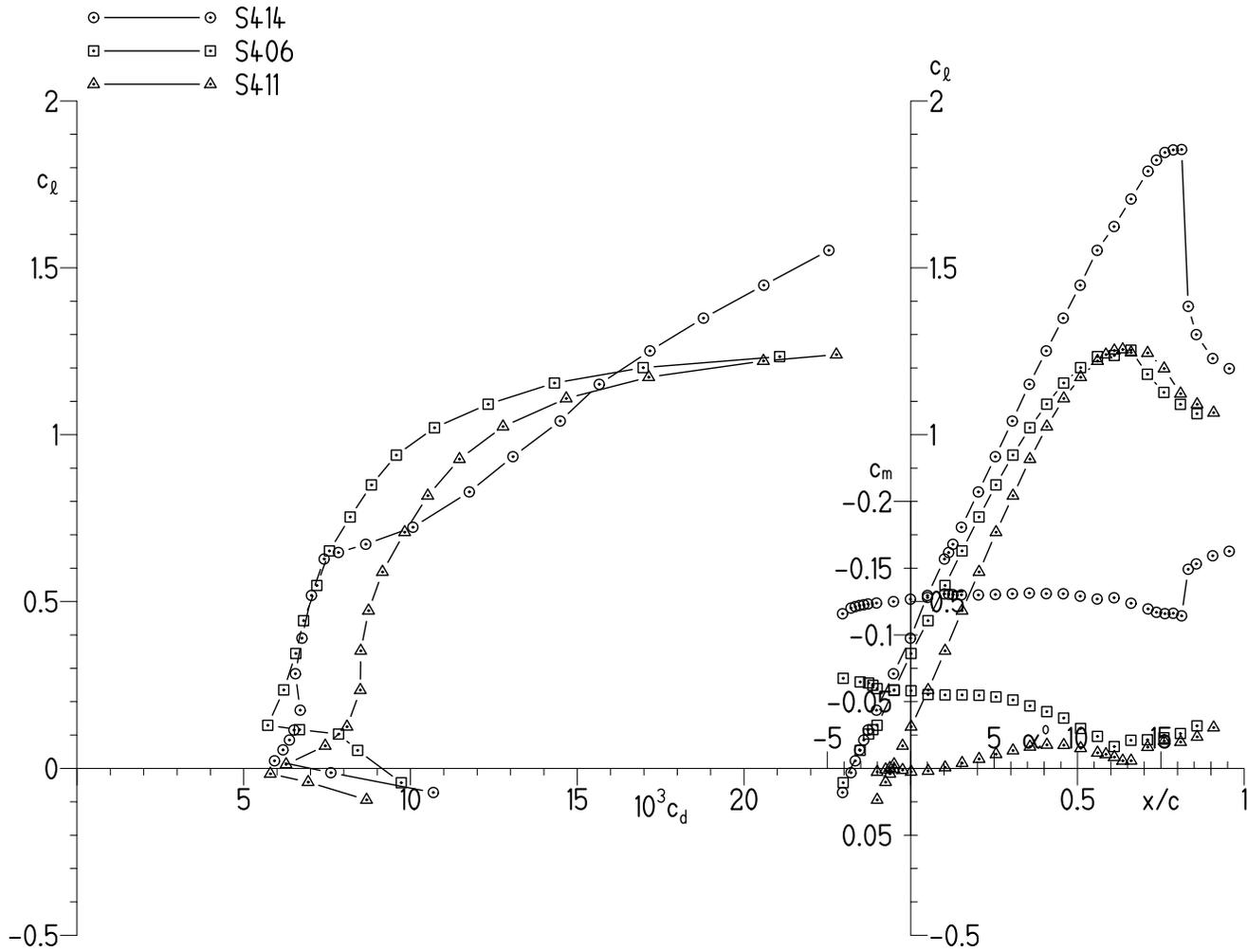
(a) $M = 0.30$ and $R = 0.97 \times 10^6$.

Figure 5.- Section characteristics of S414 airfoil with transition free.



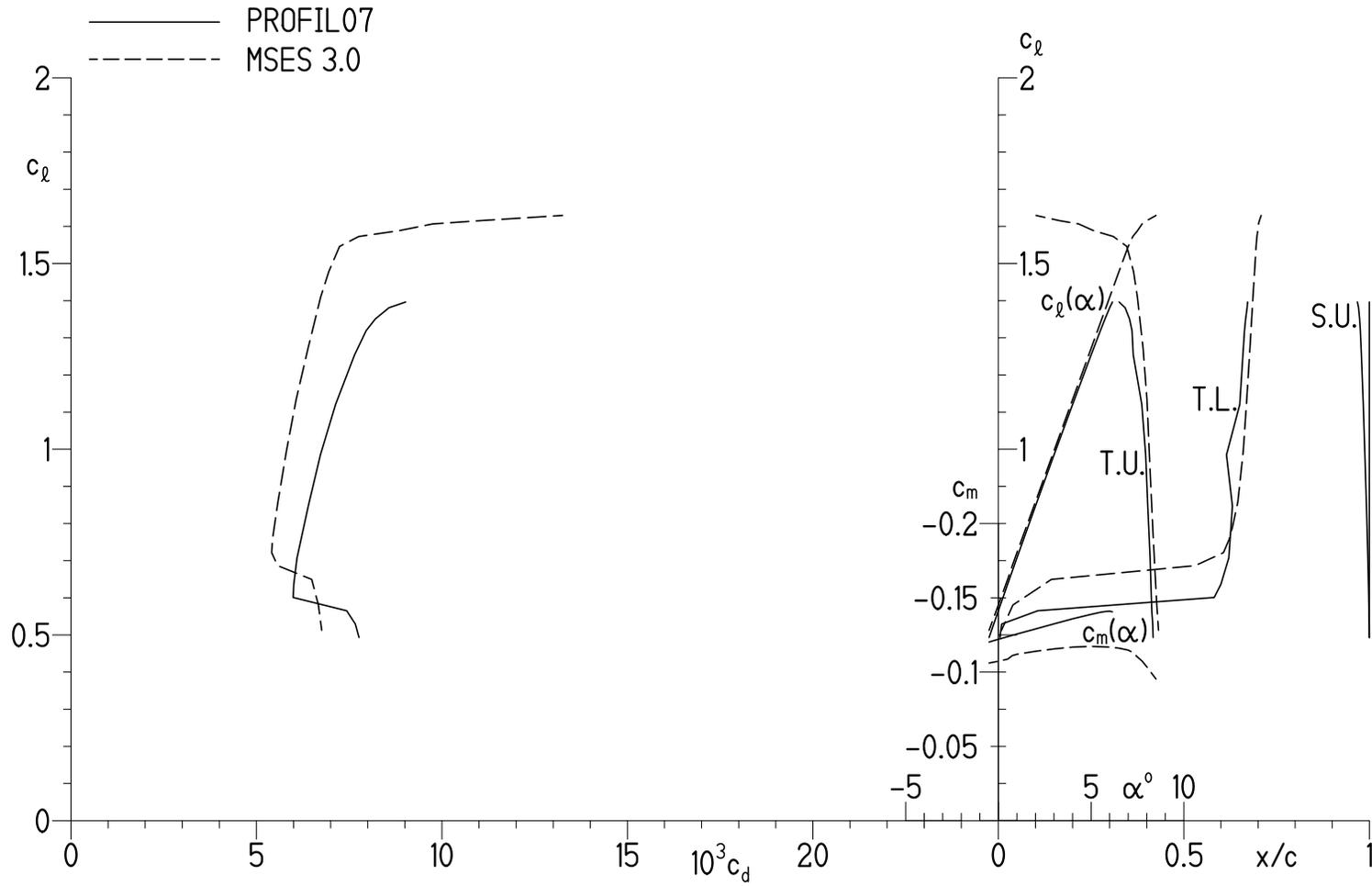
(b) $M = 0.10$ and $R = 1.00 \times 10^6$.

Figure 5.- Continued.



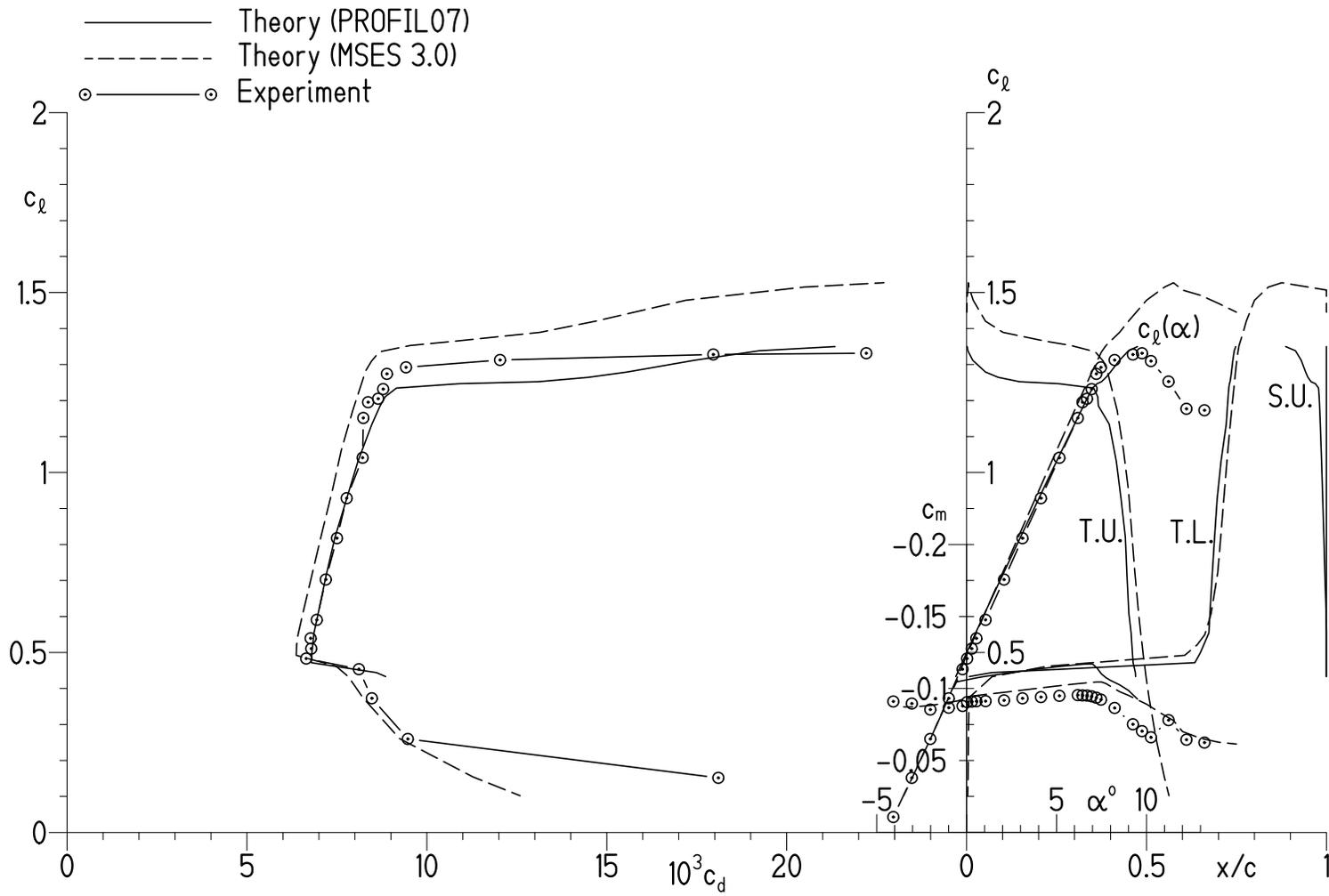
(c) $M = 0.1$ and $R = 1.0 \times 10^6$.

Figure 5.- Concluded.



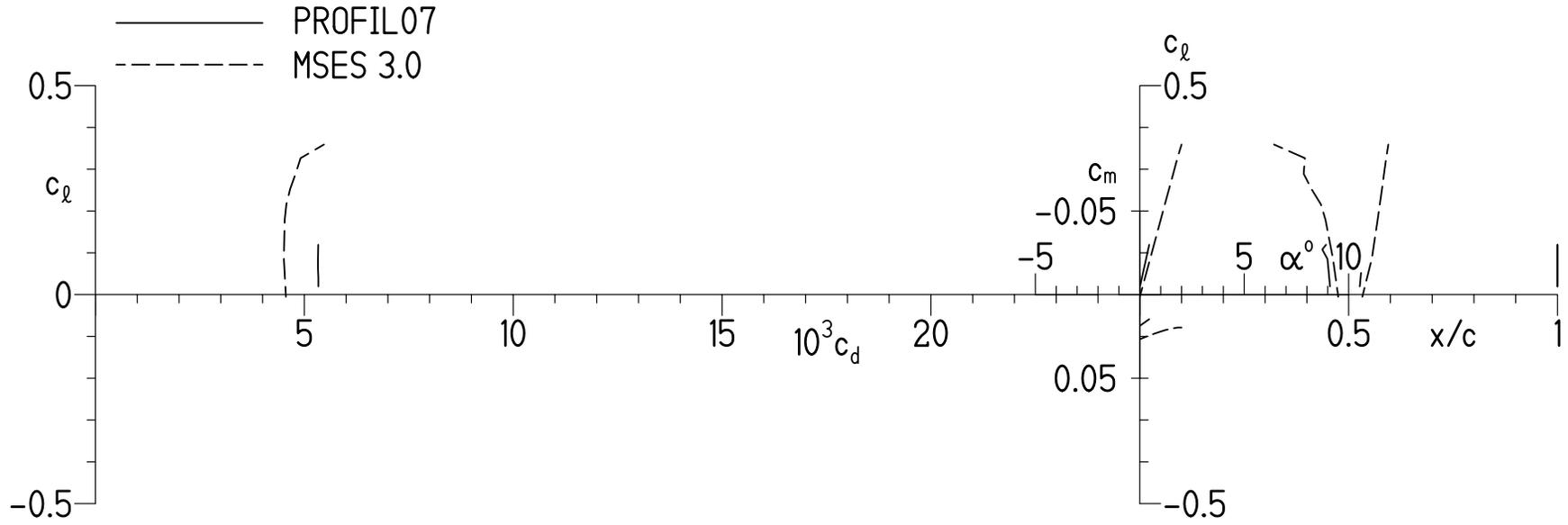
(a) S415 airfoil at $M = 0.50$ and $R = 5.00 \times 10^6$.

Figure 6.- Section characteristics of S415 and S418 airfoils with transition free.



(b) S415 airfoil at $M = 0.12$ and $R = 1.50 \times 10^6$.

Figure 6.- Continued.



(c) S418 airfoil at $M = 0.70$ and $R = 7.00 \times 10^6$.

Figure 6.- Concluded.

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14. ABSTRACT

Ten, natural-laminar-flow airfoils, the S406, S407, S409, S410, S411, S412, S413, S414, S415, and S418, intended for rotorcraft applications, have been designed and analyzed theoretically. Five of the airfoils, the S406, S407, S411, S414, and S415, have been experimentally verified. The measurements have been compared with predictions from two, widely used airfoil codes as well as from two, computational fluid dynamics codes.

15. SUBJECT TERMS

Airfoils, rotorcraft, laminar flow, wind tunnel

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