THE ROLE OF SEPARATION BUBBLES ON THE AERODYNAMIC CHARACTERISTICS OF AIRFOILS, INCLUDING STALL AND POST-STALL, AT LOW REYNOLDS NUMBERS

by

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Abstract

Airfoils at high Reynolds numbers, in general, have small separation bubbles that are usually confined to the leading edge. Since the Reynolds number is large, the turbulence model for the transition region between the laminar and turbulent flow is not important. Furthermore, the onset of transition occurs either at separation or prior to separation and can be predicted satisfactorily by empirical correlations when the incident angle is small and can be assumed to correspond to laminar separation when the correlations do not apply, i.e., at high incidence angles.

This is not the case at low Reynolds numbers. For chord Reynolds numbers between 100,000 and 500,000, rather large separation bubbles may occur on the airfoil even at low incidence angles: the onset of transition occurs inside the bubble and is separation induced. The turbulence model for the transition region becomes important[1,2] and plays a significant role in the prediction of the aerodynamic characteristics of an airfoil.

The present paper describes a turbulence model for the transition region at low Reynolds numbers. This model is incorporated into the Cebeci-Smith

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algebraic eddy-viscosity formulation and is used in a calculation method that is based on the solutions of inviscid and boundary-layer equations with the onset of transition computed with the e^n-method based on linear stability theory.[3,4] Results will be presented for airfoils with large separation bubbles to demonstrate the ability of the turbulence model to predict the location of laminar separation and turbulent reattachment points. Results will also be presented to show the ability of the method to predict stall and post-stall flows on airfoils at low Reynolds numbers. These calculations will be performed with an improved Cebeci-Smith model that accounts for flows with strong pressure gradient and separation.

References

1. Walker, G.J., Subroto, P.H. and Platzer, M.F., "Transition Modeling Effects on Viscous/Inviscid Interaction Analysis of Low Reynolds Number Airfoil Flows Involving Laminar Separation Bubbles," ASME Paper 88-GT-32, Amsterdam, June 1988.
2. Walker, G.J., "The Role of Laminar-Turbulent Transition in Gas Turbine Engines: A discussion," Journal of Turbomachinery, Vol. 115, p. 207, April 1993.
3. Cebeci, T., "Essential Ingredients of a Method for low Reynolds Number Airfoils," AIAA Journal, Vol. 27, p. 1680, 1989.
4. Cebeci, T., Roknaldin, F., Carr, L.W., "Prediction of Stall and Post-Stall Behavior of Airfoils at Low and High Reynolds Numbers," AIAA Paper No. 93-3502, AIAA Applied Aerodynamic Meeting, Monterey, August 9-11, 1993

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PURPOSE OF THE STUDY

- Study the calculation of separation bubbles on airfoils.
  - Examine the modelling of the transitional region.
  - Calculate transition as part of the solution procedure.

- Study the ability and the accuracy of the calculation method to predict the lift and drag characteristic of airfoils including low-drag airfoils.

CALCULATION METHOD, 1

- Based on stability/transition and interactive boundary-layer (IBL) approach in which the solutions of the panel and inverse boundary-layer methods are coupled to a transition prediction method based on linear stability theory using the e^n procedure.

- Turbulence model is based on the algebraic eddy-viscosity formulation of Cebeci-Smith (CS) with two improvements:

    1. Modelling of the transitional region

    2. Improving the accuracy of the model in strong adverse pressure gradient flows and flows with separation

CALCULATION METHOD, 2

To model the transitional region, consider

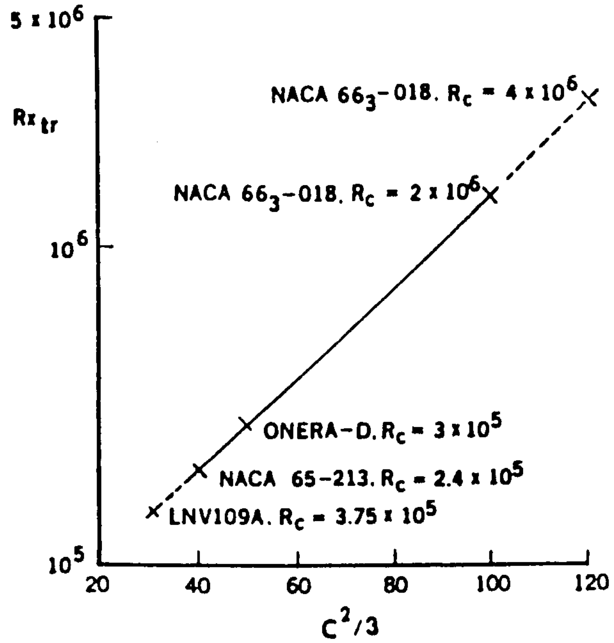
$$\gamma_{tr} = 1 - \exp\left[G(x - x_{tr}) \int_{x_{tr}}^{x} \frac{dx}{u_e}\right] \qquad (7b)$$

where

$$G = \frac{3}{C^2} \frac{u_e^3}{\nu^2} R_{x_{tr}}^{-1.34} \qquad (7c)$$

for separation-induced transition

$$C^2 = 213[\log R_{x_{tr}} - 4.7323] \qquad (19)$$



CALCULATION METHOD, 3

For strong adverse pressure gradient flows and flows with separation, consider

$$(\varepsilon_m)_o = \alpha \left| \int_0^\delta (u_e - u)dy \right| \gamma_{tr}\gamma$$

express α by

$$\alpha = \frac{0.0168}{F^{2.5}} \qquad (14)$$

where

$$F = 1 - \beta \frac{\partial u/\partial x}{\partial u/\partial y} \qquad (15b)$$

$$\beta = \begin{cases} \dfrac{6}{1 + 2R_t(2 - R_t)} & R_t < 1.0 \\ \dfrac{1 + R_t}{R_t} & R_t \geq 1.0 \end{cases} \qquad (16b)$$

so that

$$\alpha = \frac{0.0168}{[1 - \beta(\partial u/\partial x)/(\partial u/\partial y)]^{2.5}} \qquad (17)$$

In some ways, this improvement is similar to the Johnson-King model used for the CS model.

RESULTS FOR SEPARATION BUBBLES, 1

Take the Eppler airfoil as an example and conduct studies for $R_c = 200{,}000$ and 300,000 for the data of McGee et al.

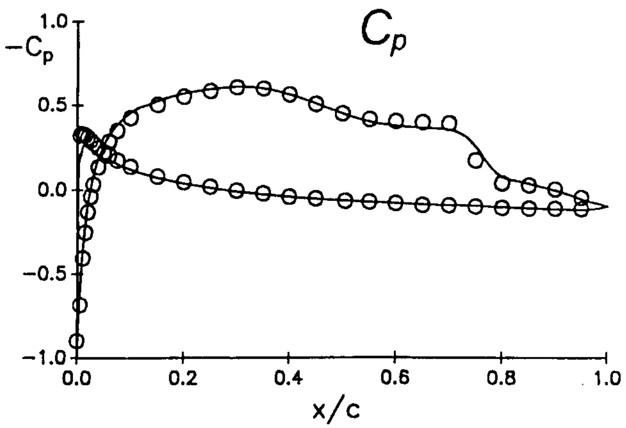
$$R_c = 200{,}000$$

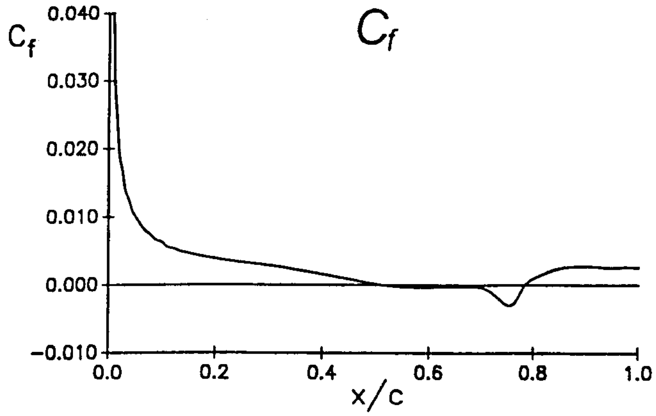
	Calculated			Experiment	
α	LS	$(x/c)_{tr}$	TR	LS	TR
-2	0.56	0.748	0.835	0.53	0.80
0	0.51	0.688	0.785	0.48	0.74
2	0.46	0.624	0.716	0.43	0.67
4	0.415	0.564	0.65	0.40	0.62
5	0.40	0.526	0.60	0.38	0.59
6	0.39	0.467	0.52	0.37	0.55

RESULTS FOR SEPARATION BUBBLES, 2

$R_c = 200{,}000$

$\alpha = 0°$


C_p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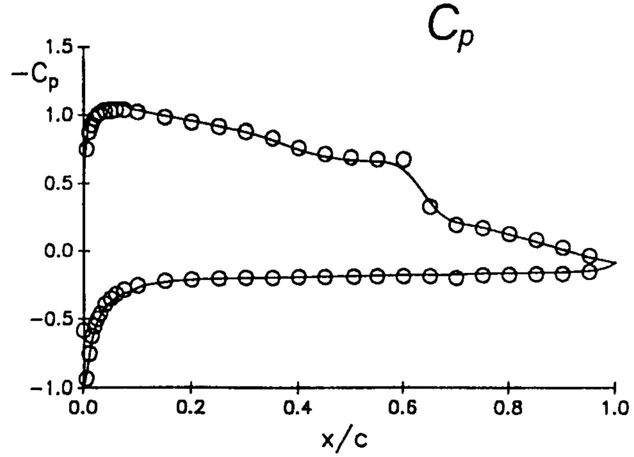
$\alpha = 4°$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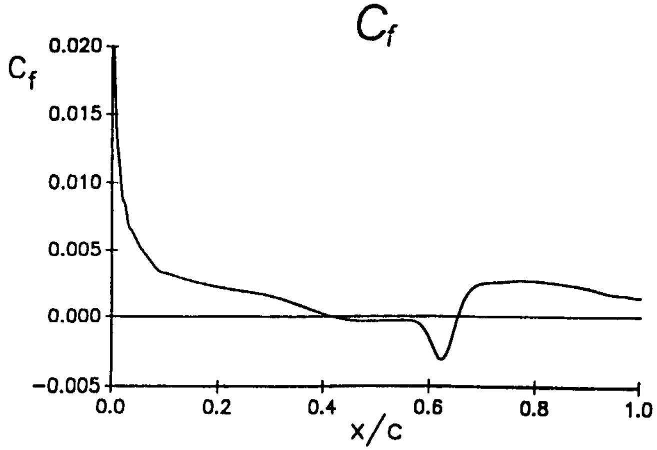
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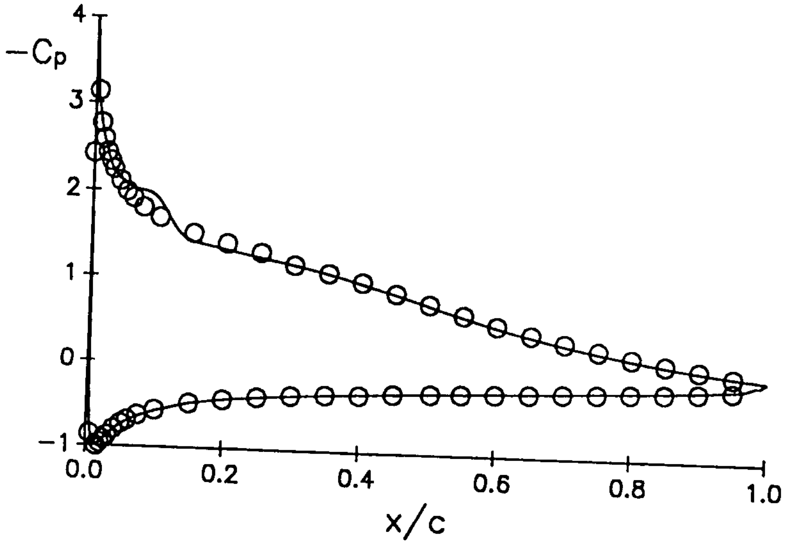
RESULTS FOR SEPARATION BUBBLES, 3

$R_c = 200{,}000$

$\alpha = 8°$

C_p



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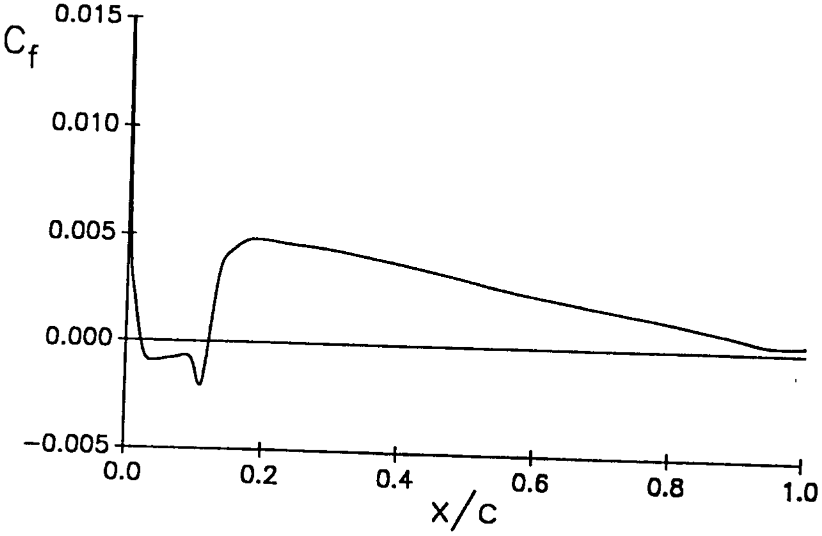


RESULTS FOR SEPARATION BUBBLES, 4

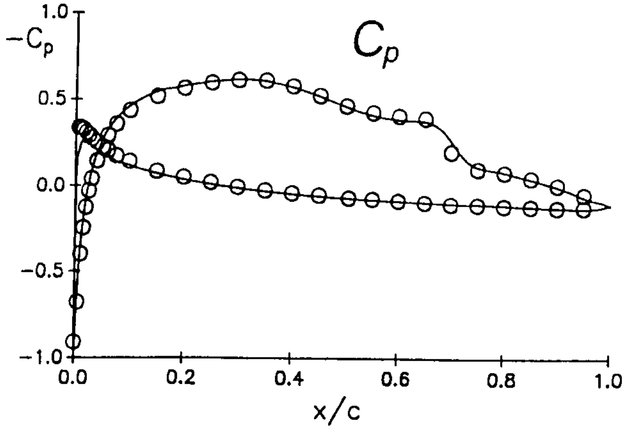
$R_c = 300{,}000$

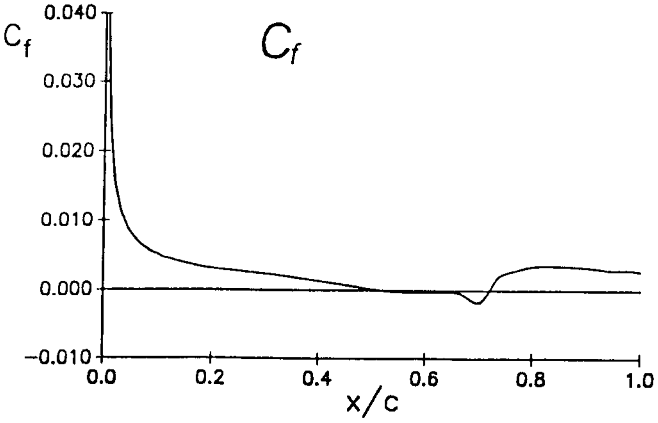
	Calculated			Experiment	
α	LS	$(x/c)_{tr}$	TR	LS	TR
-2	0.56	0.714	0.785	0.53	0.74
0	0.515	0.653	0.72	0.48	0.69
2	0.465	0.604	0.676	0.45	0.62
4	0.42	0.541	0.60	0.40	0.58
5	0.415	0.495	0.544	0.39	0.55
6	0.41	0.427	0.45	0.38	0.50
8	0.008	0.061	0.085	-	-

RESULTS FOR SEPARATION BUBBLES, 5

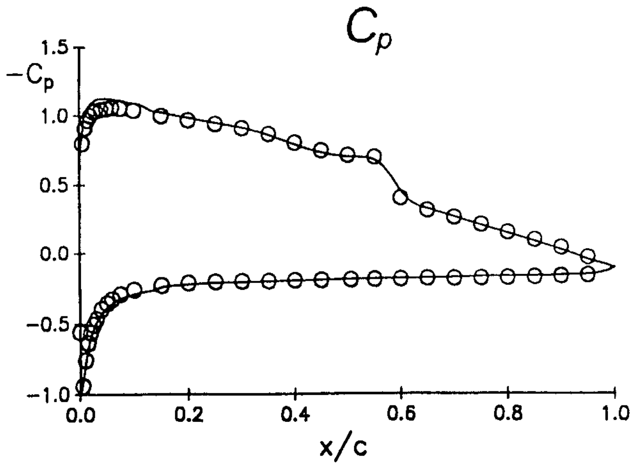
$R_c = 300{,}000$

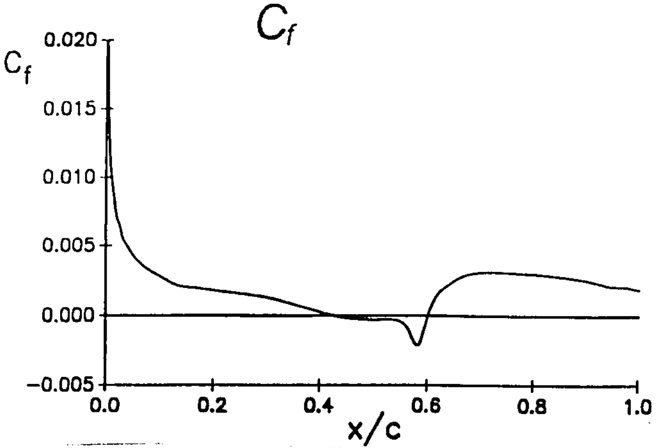
$\alpha = 0°$





$\alpha = 4°$



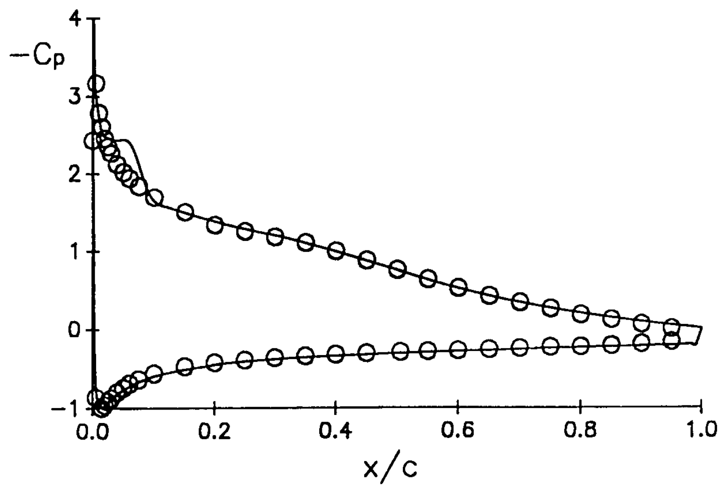


RESULTS FOR SEPARATION BUBBLES, 6

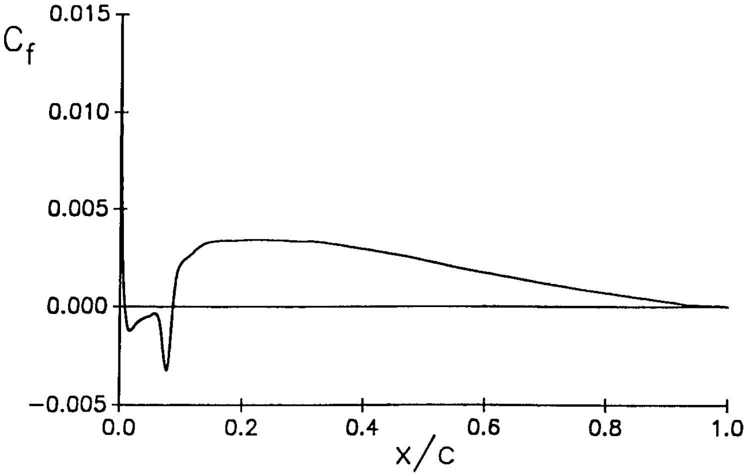
$R_c = 300{,}000$

$\alpha = 8°$

C_p



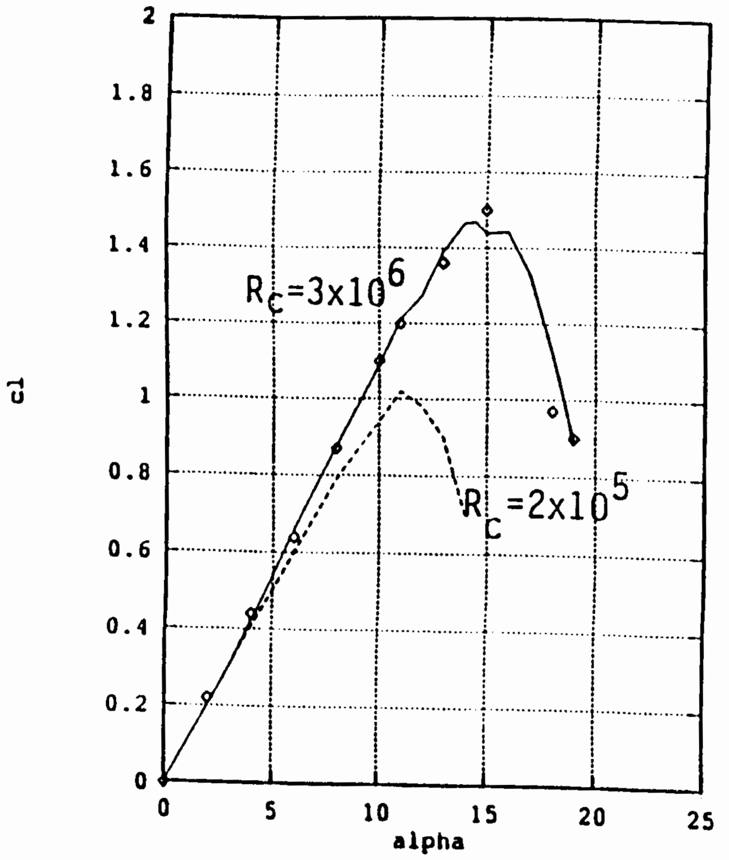
C_f



RESULTS FOR AERODYNAMIC CHARACTERISTICS, 1

Recent study

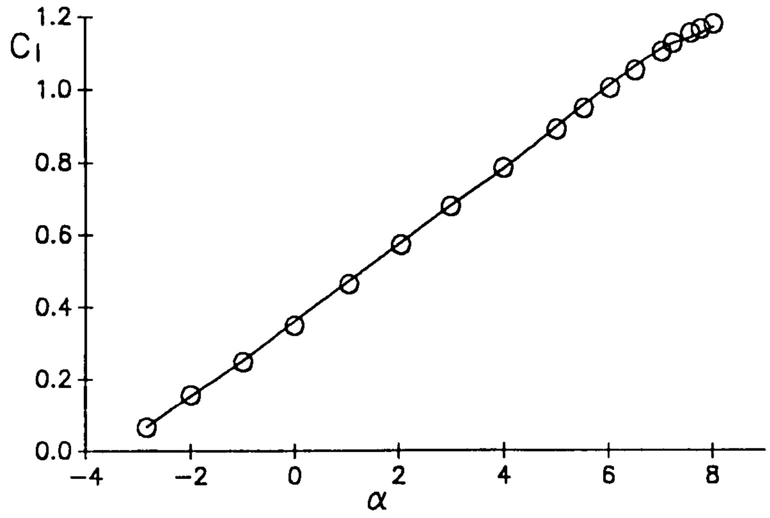
NACA 0012 Airfoil

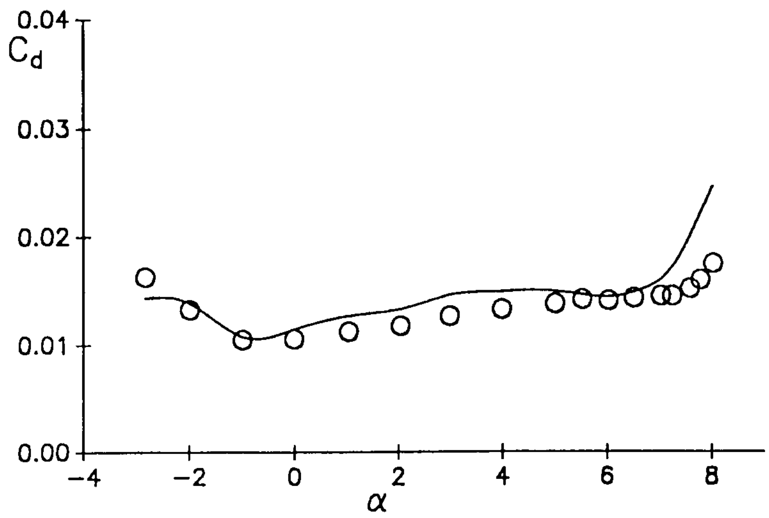


RESULTS FOR AERODYNAMIC CHARACTERISTICS, 2

Eppler Airfoil: Low Drag

$R_c = 200{,}000$

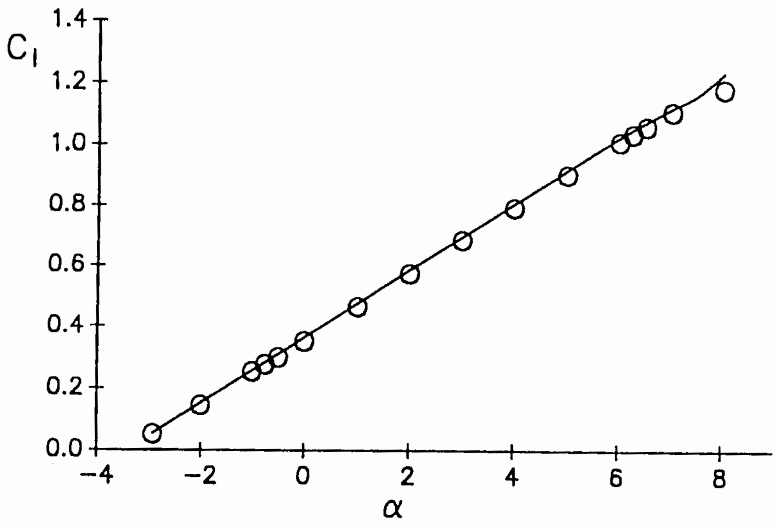


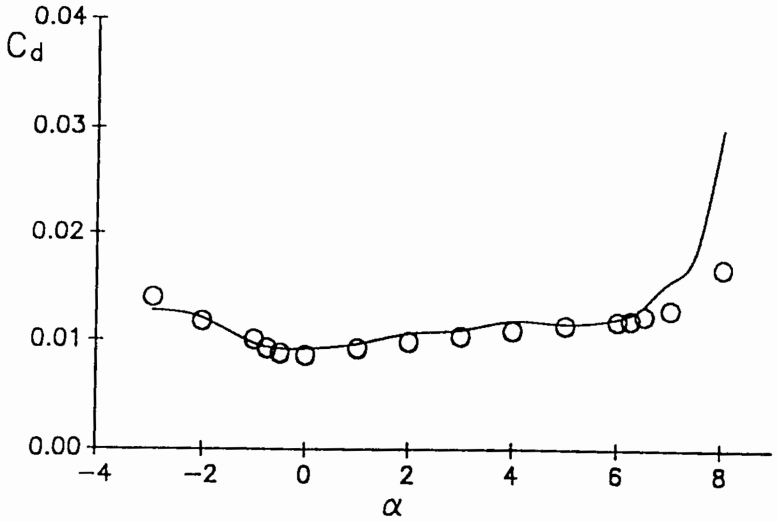


RESULTS FOR AERODYNAMIC CHARACTERISTICS, 3

Eppler Airfoil: Low Drag

$R_c = 300{,}000$





COMMENTS ON THE RESULTS

Features of this airfoil:

- Separation bubbles away from the leading-edge of the airfoil at low and moderate α.
- Leading-edge separation bubbles at higher α, close to stall. Solutions are sensitive to transition location.

CONCLUSIONS

At low Reynolds numbers

- The improved CS model, when incorporated into the calculation method based on a combination of e^n and IBL, is able to accurately predict separation bubbles on airfoils.
- For conventional airfoils, lift and drag can accurately be predicted for all angles of attack, including stall and post-stall.
- For low-drag airfoils, lift and drag can accurately be predicted for angles of attack up to stall.