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 important¹,² 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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** Professor and Chairman
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.\textsuperscript{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


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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

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

where

\[ G = \frac{3}{C^2 v^2} \frac{u_e}{R_x^{1.34}} \]  \hspace{1cm} (7c)

for separation-induced transition

\[ C^2 = 213[\log R_x^{x_{tr}} - 4.7323] \]  \hspace{1cm} (19)
CALCULATION METHOD, 3

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

\[( \epsilon_m)_o = \alpha \left[ \delta \int_0^{\delta} (u_e - u) dy \right] \gamma_{tr} \gamma \]

express \( \alpha \) by

\[ \alpha = \frac{0.0168}{F^{2.5}} \]  \hspace{1cm} (14)

where

\[ F = 1 - \beta \frac{\partial u/\partial x}{\partial u/\partial y} \]  \hspace{1cm} (15b)

\[ \beta = \begin{cases} 
\frac{6}{1 + 2R_t(2 - R_t)} & R_t < 1.0 \\
\frac{1 + R_t}{R_t} & R_t \geq 1.0 
\end{cases} \]  \hspace{1cm} (16b)

so that

\[ \alpha = \frac{0.0168}{[1 - \beta(\partial u/\partial x)/(\partial u/\partial y)]^{2.5}} \]  \hspace{1cm} (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.

$R_c = 200,000$

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<th>LS</th>
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<td>0.564</td>
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<td>0.52</td>
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RESULTS FOR SEPARATION BUBBLES, 2

\[ R_c = 200,000 \]

\[ \alpha = 0^\circ \]

\[ \alpha = 4^\circ \]
RESULTS FOR SEPARATION BUBBLES, 3

$R_c = 200,000$

$\alpha = 8^\circ$

$C_p$

$C_f$

![Graphs showing $C_p$ and $C_f$ versus $x/c$.]
## RESULTS FOR SEPARATION BUBBLES, 4

\[ R_c = 300,000 \]

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<th>( (x/c)_r )</th>
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<td>0.085</td>
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RESULTS FOR SEPARATION BUBBLES, 5

\[ R_c = 300,000 \]

\[ \alpha = 0^\circ \]

\[ \alpha = 4^\circ \]
RESULTS FOR SEPARATION BUBBLES, 6

\[ R_c = 300,000 \]

\[ \alpha = 8^\circ \]

\[ C_p \quad C_f \]
RESULTS FOR AERODYNAMIC CHARACTERISTICS, 1

Recent study

NACA 0012 Airfoil

\( \alpha \)

\( Re = 3 \times 10^6 \)

\( Re = 2 \times 10^5 \)
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 $\alpha$.

- Leading-edge separation bubbles at higher $\alpha$, 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.