Engineering Notes

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Separated Flows Developing Under Increasingly Adverse Pressure Gradients

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Nomenclature

c = chord of the airfoil
c_p = pressure coefficient on the surface
M = freestream Mach number
Re = freestream Reynolds number
u = mean velocity
u_c = characteristic velocity scale, Eq. (3)
u_e = freestream velocity at the edge of the boundary layer
u_m = maximum shear stress velocity
u_n = maximum mean back-flow velocity
u_o = wall shear stress velocity
u_τ = friction velocity
x = distance on the upper surface of the airfoil
y = distance from the wall
y_c = characteristic distance corresponding to u_c
y_0 = airfoil coordinate
y_2 = characteristic distance in the boundary layer
α = angle of attack
ν_t = eddy viscosity
ρ = density
τ = shear stress
τ_0 = wall shear stress
τ_m = maximum shear stress
η = similarity parameter, Eq. (2)
ξ = similarity parameter, Eq. (4)

Introduction

SEVERAL studies exist on the separated boundary layer.[1,2] However, very little experimental data exist for the case of an airfoil flow that features an increasingly adverse pressure gradient.[3] Furthermore, few studies exist on the reversed flow region downstream of separation.[4] As pointed out by Clauser,[5] near and after separation, a two-parameter description that employs a velocity scale and length scale to describe turbulent boundary layers encounters severe difficulties. This is because near separation wall shearing stress approaches zero, and with it the velocity scale based on the wall shear stress. In order to overcome this difficulty, Perry and Schofield[6] suggest that the appropriate velocity scale for boundary layers developing in the adverse pressure gradient was related to maximum shear stress in the flow [$u_m = (\tau_m/\rho)^{1/2}$], rather than to the wall shear stress [$u_o = (\tau_0/\rho)^{1/2}$]. The similarity relations based on these scales have been shown to give good description of mean profiles in moderate to strong adverse pressure flows.

These concepts of similarity were further extended by Schofield,[7] which include the detached flow ($u>0$) as well as the back flow ($u<0$) in a separated boundary layer. In this study, back flowfield similarity relationships were developed that, when combined with the Perry and Schofield[6] relations for the detached flow, gave complete descriptions of the entire separated profile.

The primary objective of this Note is to present experimental results on separating flow over a NASA GA(W)-1 airfoil[8] having 2% trailing-edge thickness. The emphasis here is on the mean velocity data as they demonstrate flowfield similarity downstream of separation.

Experimental Facilities

The experiments were carried out on a 17%-thick NASA GA(W)-1 airfoil in the research wind tunnel facility at Lockheed-Georgia. Figure 1a depicts a schematic of the airfoil section. As can be seen, a blunt trailing-edge airfoil was fabricated by removing the last 7% of the chord length from the corresponding sharp trailing-edge airfoil. The resulting blunt trailing-edge airfoil section had a chord length of 0.26 m and a span of 0.76 m. On the airfoil surface, a total of 40 static pressure taps were provided to facilitate surface static pressure measurements.

Total pressure data in the boundary layer were acquired by a special dual-purpose pressure sensor that consists of two probes, with one probe pointing downstream and the other facing upstream. Both of the probes were fabricated of 0.0013 m tubing that was flattened to 0.00065 m at the end. A semicircular disc-type pressure probe (0.0032-m diam; 0.0016-m thickness) was used for static pressure measurements.

Prior to taking boundary-layer measurements in the tunnel, several complete mean velocity profile measurements were repeated in the wall-jet calibration facility using a round total head tube with a frontal area approximately equal to the flattened total head tube. The agreement between the mean velocity profiles acquired using round and flattened total head tubes was found to be better than ±2%.

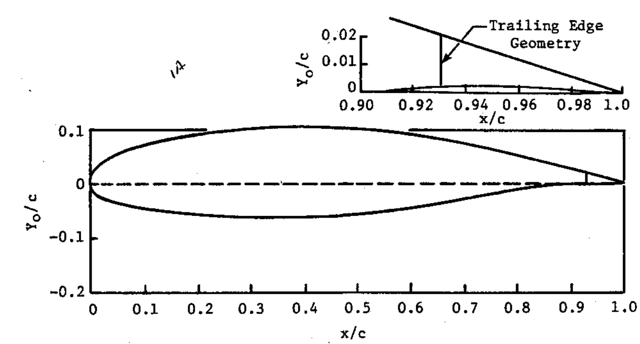

Fig. 1a Schematic of the NASA GA(W)-1 airfoil.

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Experimental Results and Analysis

All of the results are discussed in Ref. 9. Also, some of the results have been partially published in Mehta and Goradia.[10] Consequently, those data that are relevant to the general theme of this paper are presented here.

Figure 1b shows the average surface pressure distribution compared with the theoretical distribution[9] at $\alpha = 14.4$ deg. The computed pressure distribution is found to differ significantly from the measured data due to presence of separation near the trailing edge. Figure 2a depicts chordwise development of mean velocity profiles on the upper surface of the airfoil at $\alpha = 14.4$ deg. The measurements correspond to $Re = 2 \times 10^6$ and $M = 0.18$. Several attempts were made to identify various regions of the separated profile for flowfield similarity. For this it was divided into three regions, as shown in Fig. 2b. These regions, termed as the wall region W, the transition region T, and the mixing region M, arise due to distinguishing momentum transport mechanisms in each of the regions. The wall region is an equilibrium layer where turbulent energy production locally balances dissipation; the mixing region is where the inertial and shear stresses balance; and the transition region is one that includes maximum back-flow velocity. The transition region stretches from having a zero thickness at the onset of separation to a finite thickness at the trailing edge. The rate at which this region grows is determined by the imbalance of the inertial stresses to the wall shear stresses.

Schofield[7] considered only the positive flow region ($u > 0$) for the outer flowfield similarity. Although excellent correlations were obtained, the velocity and length scales used were found inadequate in describing the region where the outer flow matched the reversed wall flow. As a result, in this analysis, the outer flowfield is also considered to include the region where it matches the reversed wall flow. In terms of Fig. 2b, the present analysis defines M as the outer flowfield, and the region that comprises W and T as the reversed (back) flowfield.

For M, the scaling parameters were selected as follows:

$$f(\eta) = (1 - u/u_e)/(1 - u_n/u_e) \tag{1}$$

where

$$\eta = (y - y_2)/(y_c - y_2) \tag{2}$$

In the present analysis, y_c was selected to be the distance from the wall such that

$$u_c = 0.75u_e[1 + (u_n/u_e)] + u_n \tag{3}$$

A detailed explanation on the manner in which y_2 was selected is given later in this section.

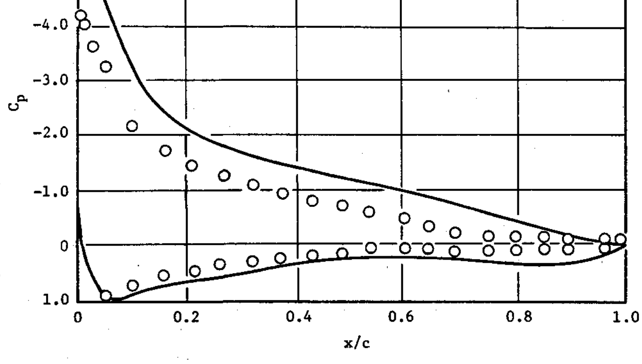

Fig. 1b Measured surface pressure distribution on the airfoil.

Figure 3a shows additional separated boundary layer profiles. These and the profiles of Fig. 2a were analyzed according to Eqs. (1-3). As seen in Fig. 3b, a good correlation for the mixing region profiles is obtained.

This evidence suggests that the outer flow maintains its similarity irrespective of what is happening underneath it at the wall. And separation, in fact, far from destroying or altering the outer similarity just provides a different wall matching condition for it.

It would now be fruitful to seek similarity relations for the back flow near the wall. If this region demonstrates the flowfield similarity, then it would be significant and potentially

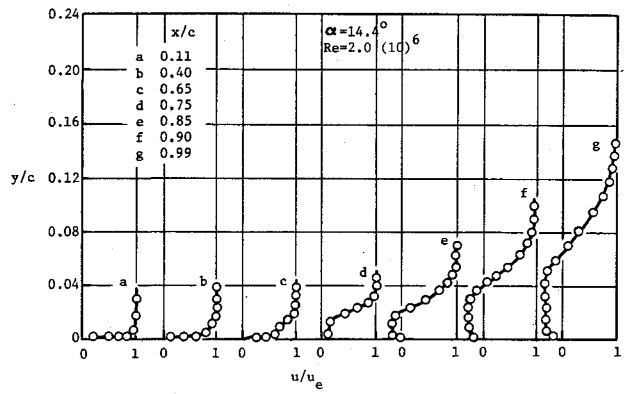

Fig. 2a Boundary-layer velocity profiles on the surface of the airfoil.

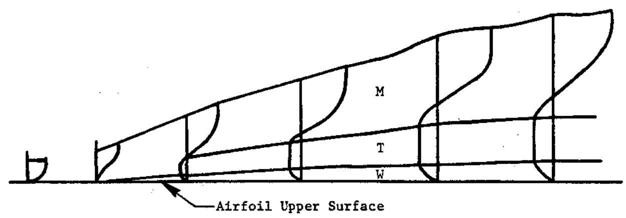

Fig. 2b Schematic of the separated velocity profile development.

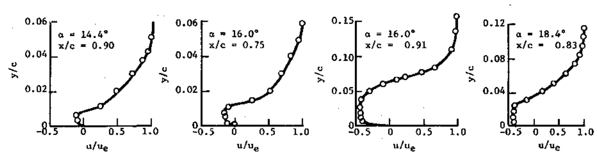

Fig. 3a Typical separated velocity profiles on the surface of the airfoil.

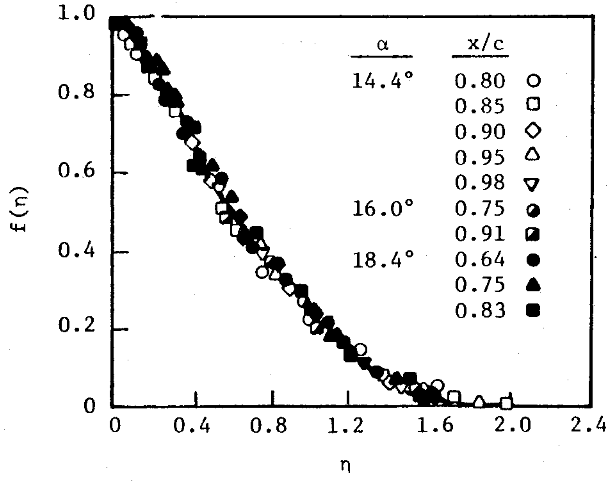

Fig. 3b Similarity parameter for the mixing region of the separated velocity profile.

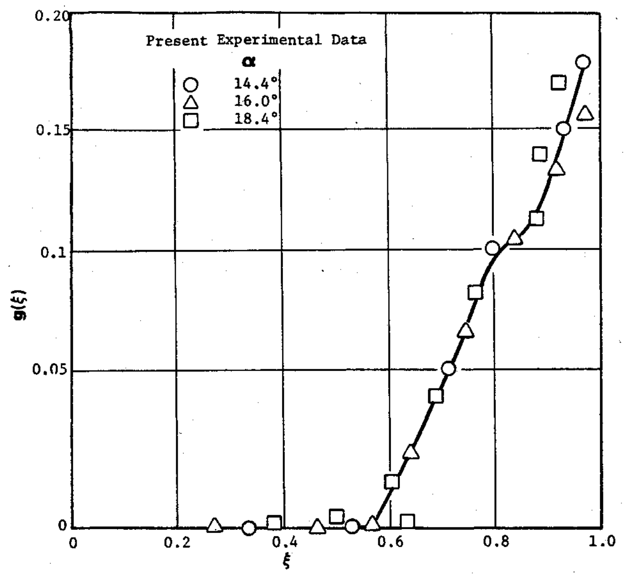

Fig. 4 Similarity parameter for the back-flow region of the separated velocity profile.

useful in developing calculation methods for separated boundary layers.

The reversed flow is influenced by a number of factors. First, the back flow could be considered a wall flow with scales based on wall shear stress. Simpson et al.[11] showed that these scales could not correlate their data. They also demonstrated that downstream flowfield conditions influence the magnitude of the back flow in a nonattaching separated boundary layer. Therefore, it seems that the back flow is a complex regime in which wall and outer flow variables in addition to downstream conditions may be important. Hence, it appears that the flow scales form on local variables. Simpson et al.[11] proposed the maximum back-flow velocity and its distance from the wall as two scales. These gave a fair correlation of their data.

In the present analysis, u_n was used as the velocity scale. However, y_2 as defined in Eq. (4) was selected as the length scale in contrast to studies by Simpson et al.[11] As seen in Figs. 2a and 3a, the maxima in the back-flow profiles tend to be rather flat ($du/dy \sim 0$). As a result, it was decided to curve-fit this data numerically and select y_2 as a distance where du/dy became positive. This length scale was selected for the following reasons. First, it provided the required matching point between the outer, mixing region flow and the back flow. Second, the length scale selected by Simpson et al.[11] would be more representative of the wall region only, and would incorporate the influence of the outer flow to a lesser degree. In contrast, y_2 incorporates the influence of the outer flow. As a result, it would seem to be an appropriate choice for the length scale in the back-flow region.

Figure 4 depicts the back-flow velocity plotted in the similarity coordinates:

$$\xi = (y_2 - y)/y_2 \tag{4}$$

$$g(\xi) = (u_n - u)/u_n \tag{5}$$

As can be seen, even with a limited amount of data in this region a good correlation is obtained.

It must be pointed out that for the airfoil flow (increasingly adverse pressure gradient) both u_n and y_2 increase in the streamwise direction. In contrast, the law-of-the-wall length scale ν/u_τ varies inversely with its velocity scale u_τ.

Concluding Remarks

Separated flow measurements on the upper surface of the NASA GA(W)-1 airfoil show that it is possible to divide the separated velocity profile into three viscous regions: the wall boundary layer, the transition region, and the external half wake. In the back-flow region, the mean velocity is found to demonstrate self-similarity behavior that is distinct from the law-of-the-wall for the turbulent boundary layers. In addition, the mixing region profiles show self-preserving behavior such that the chordwise development of the mean velocity is found to be reducible to a universal curve.

Acknowledgment

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Self-Preservation of Turbulent Wakes

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Nomenclature

b = half wake-width
c = chord of the airfoil
$h(\zeta)$ = wake similarity parameter
M = freestream Mach number
Re = freestream Reynolds number
u = mean velocity
w = wake velocity defect

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