Technical Notes

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Experimental Studies of the Separated Flow over a NASA GA(W)-1 Airfoil

Jayesh M. Mehta*
Illinois Institute of Technology, Chicago, Illinois
and
Suresh Goradia
Jafarabad, India

Introduction

THE abrupt change in rear geometry of blunt-based airfoil moving through a real fluid causes the external flow to separate from the body. This, in turn, results in significant changes of the configuration of the far wake, base drag, and the lift-drag characteristics of the airfoil. In a study by Kline,[1] the turbulent separation is found to have a spectrum of states; where the first onset of the separation is observed to be extremely unsteady, with a steady separation downstream. Upstream of the steady separation region, intermittent streaks of the backflow occur near the surface. The mean wall shear stress decreases rapidly in the intermittent region, and has a nonzero value until the fully separated flow is reached.

Several studies exist on separated boundary layers.[2,3] However, as pointed out by Samuel and Joubert,[4] very little experimental data exist for the case of an airfoil-type flow; that features an increasingly adverse pressure gradient, which causes the flow to decelerate until separation is reached. Furthermore, few studies exist that report on the reversed flow region downstream of the separation.[5]

As suggested by Sovran,[6] separated flow influences the freestream potential flow which, in turn, affects the upstream boundary layer. Therefore, to understand the influences of separation, it is imperative that experimental results for the turbulent separated flow are acquired and analyzed.

The primary objective of this Note is to present the experimental results of the separating flow over the NASA GA(W)-1 airfoil having 2% trailing-edge thickness. Emphasis is on the data, as they reveal significant features of the separating boundary layer under an adverse pressure gradient. The fully separated flow is examined in terms of surface pressure distributions, skin friction, mean velocity profiles, and the boundary-layer integral properties. Finally, mean velocity profiles downstream of the separation point are analyzed for the flowfield similarity.

Experimental Facilities

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

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*Research Assistant, Department of Mechanical Engineering.

The measurement of the total pressure in the boundary layer was made by using a special dual purpose pressure sensor, which consists of two probes with one probe pointing downstream and the other facing the upstream. Both of the probes were fabricated of 0.0013-m tubing, which was flattened to 0.00065 m at the end. A semicircular disk type pressure probe (diameter, 0.0032 m; thickness, 0.0016 m) was used for static pressure measurements. A hot-wire anemometer probe was also employed in order to complement the results obtained by pressure probes.

The wind tunnel facilities at Lockheed consist of a closed-circuit tunnel, permitting maximum air velocity of 92 m/s. The typical Reynold's number achievable in the test section (length, 1.09 m; width, 0.76 m; height, 1.22 m) is of the order

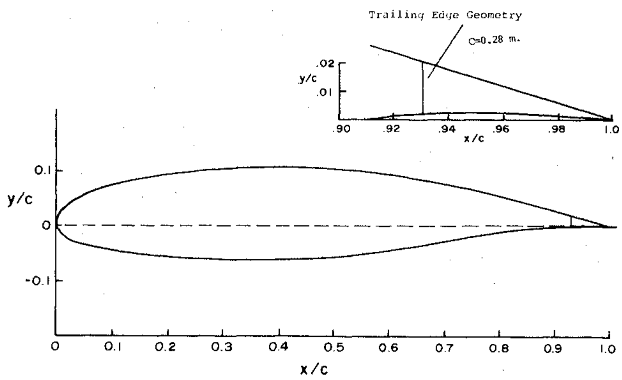


Fig. 1 Schematic of the NASA GA(W)-1 airfoil.

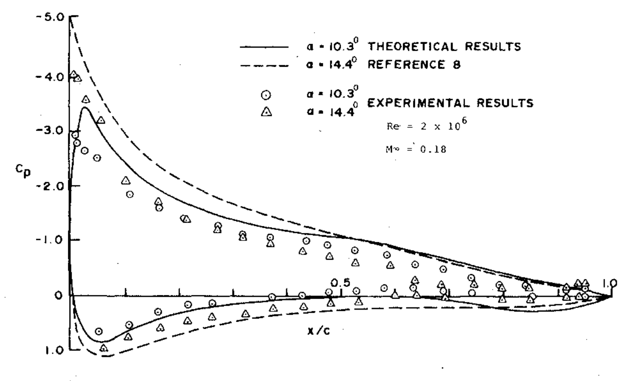
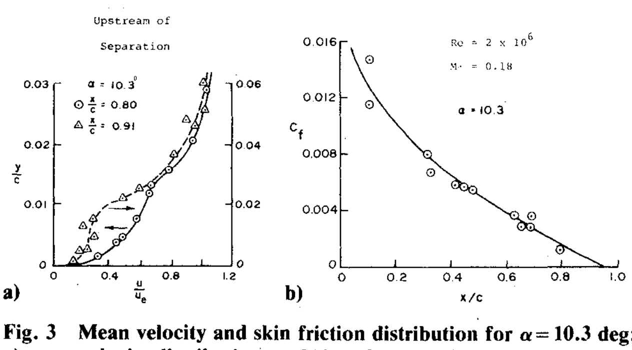


Fig. 2 Surface pressure distribution at $\alpha = 10.3$ and 14.4 deg.



a) b)

Fig. 3 Mean velocity and skin friction distribution for $\alpha = 10.3$ deg; a) mean velocity distribution, and b) surface skin friction.

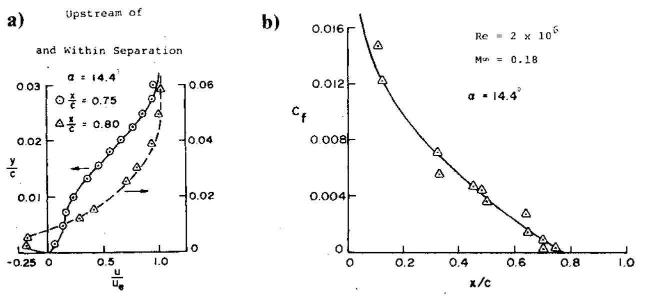


Fig. 4 Mean velocity and skin friction distribution for $\alpha = 14.4$ deg; a) mean velocity distribution, and b) surface skin friction.

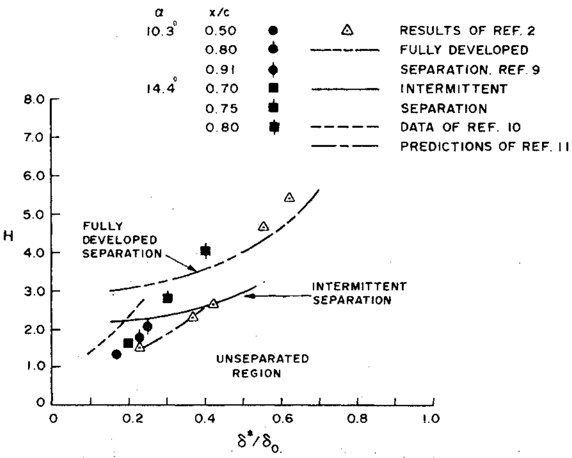


Fig. 5 Comparison of present results with the separation criteria based on several studies.

of 4.0(10^6), per meter of chord length. The test section is also equipped with the side wall boundary-layer control system, to prevent the separation of the boundary layer on the upper and lower side walls.

The details of the wind-tunnel facility, with the wall boundary-layer suction system, the pressure probes, and the crossed wire anemometry used in the experiment have been described in Ref. 7. Furthermore, the skin friction coefficient was inferred from the total and static pressure measurements at the same location.

Experimental Results and Analysis

Measurements were acquired for surface boundary layer at different angles of attack; ranging from 10.3 to 18.4 deg. These angles of attack were selected as their boundary-layer characteristics provide a wide spectrum of states; ranging from intermittent, unsteady separation at $\alpha = 10.3$ deg to full steady separation at $\alpha = 18.4$ deg. The measured values included surface pressure, boundary-layer total and static pressures, and mean velocities.

Figure 2 shows the average surface pressure distribution compared with the theoretical distribution[8] at $\alpha = 10.3$ deg and $\alpha = 14.4$ deg for a sharp trailing edge GA(W)-1 airfoil. Several interesting features are observed. Based only on the criterion that dC_p/dx on the surface is equal to zero at the onset and the downstream of separation, the intermittent separation seems to have occurred at about x/c of 0.80 for the lower angle of attack. This is further substantiated by the velocity profiles shown in Fig. 3a for x/c of 0.80 and 0.91. The velocity profiles at these points do not correspond to fully-developed separted flow. Furthermore, as depicted in Fig. 3b, the surface skin friction drops continuously but does not reach a vanishingly small value, which indicates the existence of intermittent separation at these conditions.

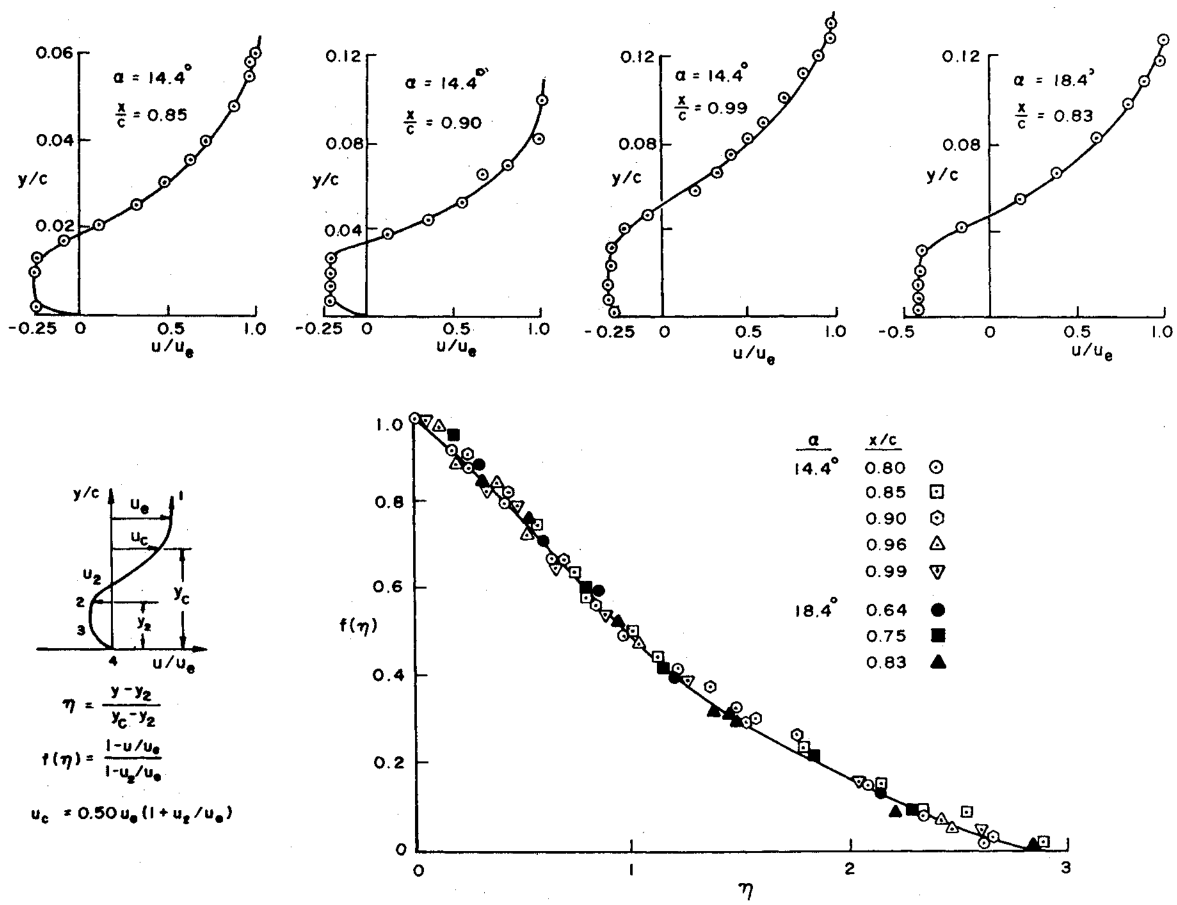


Fig. 6 Mean velocity profiles and similarity curve for the outer region of the fully-separated flow.

At the higher angle of attack, as shown in Fig. 2, the onset of intermittent separation seems to have occurred at about x/c of 0.65; the flow having reached full separation somewhere between x/c of 0.75 and x/c of 0.80, as can be inferred from velocity profiles as shown in Fig. 4a. This observation is further substantiated by the surface skin friction results as shown in Fig. 4b. Extrapolating skin friction data, one obtains the condition for full separation at x/c of 0.78.

Figure 5 depicts the comparison of the present results with the separation criteria as discussed by Sandborn and Kline.[9] The latter are based on the examination of several turbulent separation velocity profiles. For intermittent separation they have proposed the relation

$$H = 1 + (1 - \delta^*/\delta_{0.995})^{-1} \tag{1}$$

The present data are in good agreement with these criteria. At the lower angle of attack ($\alpha = 10.3$ deg), the velocity profiles indicate the presence of the intermittent separation at x/c of 0.91. The integral properties corresponding to this profile correlate well with the intermittent separation criterion. Although no velocity profile data were taken between x/c of 0.75 and 0.80, for $\alpha = 14.4$ deg, interpolation between these two points places x/c of 0.78 near the fully-developed separation line. Furthermore, the present data follow the results of Sandborn and Liu[10] more closely than the separation correlation of Perry and Schofield.[11] The data presented by Sandborn and Liu[10] and the present results are for the large change in curvature, unlike the Perry and Schofields' data.[11] This indicates that the surface curvature plays an important role in determining the path ($Hv/s\delta^*/\delta_{0.995}$) by which a boundary layer separates.

Downstream of separation the outer region velocity profiles behave similar to a two-dimensional mixing layer. Figure 6a shows the typical fully separated flow profiles for $\alpha = 14.4$ and 18.4 deg. If the outer region mean velocity profile, between the points 1 and 2 as shown in Fig. 6b, is expressed in terms of the following parameters:

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

and

$$f(\eta) = (1 - u/U_e)/(1 - u_2/U_e) \tag{3}$$

where, y_c is the distance from the airfoil surface, such that

$$u_c = 0.50U_e[1 + (u_2/u_e)] \tag{4}$$

then the chordwise development of the mean velocity is found to be reducible to a universal curve.

Conclusions

The separated flow velocity profiles, skin friction distributions, and boundary-layer integral properties are presented for a 17% thick NASA GA(W)-1 airfoil. The integral properties corresponding to separation agree well with the separation criteria of Sandborn and Kline.[9] Downstream of the separation the outer region velocity profiles show some similarity and the chordwise development of the mean velocity is found to be reducible to a universal curve.

Acknowledgments

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Separation Criteria for Three-Dimensional Boundary-Layer Calculations

H. C. Raven*
Netherlands Ship Model Basin, Wageningen, The Netherlands

Introduction

THE thin boundary-layer equations solved with a prescribed pressure distribution are often used to obtain a prediction of the three-dimensional viscous flow about streamlined bodies such as ship hulls or aircraft components. In many cases, the location and nature of the separation are also deduced from the solution. The question arises whether this is a correct deduction. It is possible that the calculated results are misleading in this respect, since in at least some situations the boundary-layer equations are singular at the separation line. This means that no valid solution can be obtained in the whole region of influence of this singularity. In the following, this is designated as the "forbidden region."

Related to this is the concept of inaccessibility. According to Cebeci et al.,[1] a point in the boundary layer is inaccessible from the forward stagnation point if the velocity field there cannot be computed in terms of the initial conditions at the

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*Research Engineer, Section Ship Powering Research.