Flowfield Prediction of Separating Turbulent Shear Layers

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Abstract

THIS paper is concerned with the prediction of turbulent shear layers for the case of a steady freestream, incompressible, two-dimensional mean flow over a streamlined or gently curved body or surface with a developed turbulent boundary layer upstream of the separation zone. The separation of the boundary layer is due to an adverse pressure gradient. Experimental observations indicate that when separation occurs near the trailing edge, there is strong interaction between the wakes of the suction and pressure sides, since the thickness and velocity scales are not greatly different. When it occurs well upstream of the trailing edge, the velocity and pressure just outside the seperated shear layer approach the free-streamline condition of constant pressure and velocity in this fully stalled flow. Here we discuss the prediction of the turbulent shear flow downstream of the separation zone for this latter case.

This free-streamline behavior between the separation zone and the trailing edge is supported by measurements using a directionally sensitive laser anemometer. Downstream of intermittent separation or where backflow first occurs on an intermittent basis, the inner 15% of the shear layer has mean velocity profiles that are rather flat and of small magnitude. The local turbulence intensity remains large, but the mean momentum and kinetic energy are small. The pressure gradient undergoes a rapid reduction and approaches the freestream zero magnitude. No law-of-the-wall velocity profile is observed for the backflow. Evidently the low-velocity region in the separated shear layer just serves to satisfy continuity requirements after the energetic flow near the freestream has deflected away from the wall upon separation to reduce pressure gradients. This physical picture is preserved in the development of a numerical prediction model for high-Reynolds number flow.

Contents

Simpson and Collins[1] describe modifications to the boundary layer prediction program of Bradshaw et al.[2] to predict the flow upstream of intermittent separation. In the present paper, the Bradshaw model is further modified and used in conjunction with a potential flow model to predict mean velocity and shear profiles downstream of intermittent separation. Predictions are compared to the experimental results of Simpson et al.[3]

A finite-difference potential flow model is used to determine the stream function in the potential flow exterior to the shear flow. For the test flow the domain is defined by the upstream uniform flow at the entrance to the test section, the perforated plate exit of the test section, and the displacement thicknesses on the upper and lower walls of the test section. At the exit, a pressure drop proportional to the dynamic pressure with an experimentally determined resistance coefficient is used. On the test wall the displacement thickness from the attached boundary layer is used up to the beginning of intermittent separation. Downstream of this location the lower wall displacement thickness is computed with the requirement that the streamwise pressure gradient be minimized; this is accomplished by determining the displacement thickness distribution without information from the separated shear flow. A cubic polynominal model is used to approximate the displacement thickness variation downstream of intermittent separation. Two of the unknown polynominal coefficients are determined from the displacement thickness and its streamwise gradient at the point of intermittent separation from the upstream attached boundary layer. Exit flow continuity and uniformity requirements are used to determine a third coefficient, while the last coefficient was selected to minimize the pressure gradient downstream of intermittent separation. The predicted tangential U_e and normal V_e components of velocity at the outer edge of the shear layer closely agreed with experimental results only when the pressure gradient was minimized.

The shear flow has several regions shown in Fig. 1: the downstream outer separated flow region, an intermediate separated flow region, and the separated flow-wall region. The outer separated flow is divided from the intermediate separated flow by the outgoing characteristic II′ that originates at the wall at intermittent separation, the last characteristic that is directly independent of the downstream turbulence structure. The characteristic method of the modified Bradshaw model discussed in Ref. 1 is used with a matching of velocity conditions at the outer edge of the boundary layer to predict conditions in the separated flow for points with streamwise velocities in excess of 0.3 U_e. At distances closer to the wall where backflow is possible, a simple parabolic mean-velocity profile that can degenerate to a straight line is used. A parabolic shearing stress profile model is also used in this near-wall region. Matching the velocity and shear at this $0.3U_e$ position, Y_j and the no-slip condition at the wall and preservation of mass continuity determines the coefficients in the parabolic profiles.

Figures 2 and 3 show some of the comparisons of the predictions with experimental data. Several of the predicted

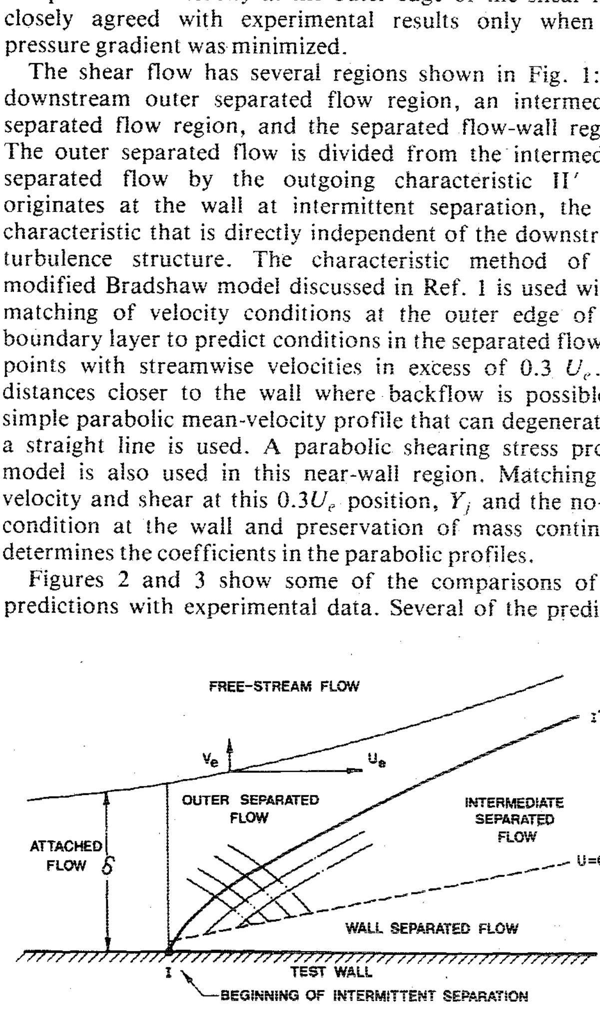

Fig. 1 Schematic of the several mean-velocity flow regions of the separated flow model (not to scale).

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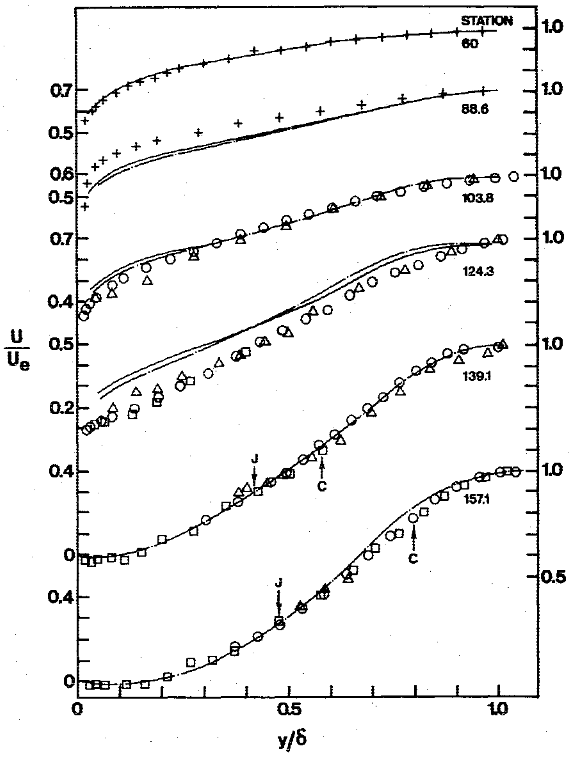

Fig. 2 Mean-velocity profiles: symbols—experimental results; solid lines—upstream predictions unmodified Bradshaw method; broken lines—model 1 predictions[1] upstream of separation; smoothed shear profile predictions for two downstream separated flow profiles. J and C denote Y_j and Y_c.

quantities are in good agreement with the measurements: 1) the mean velocity profiles; 2) the boundary-layer thickness δ; 3) the location from the wall at which the mean velocity is half the local freestream velocity; 4) the location of the maximum shearing stress; 5) the shape factor H; 6) the location where the mean backflow is divided from the forward flow Y_b; and 7) the magnitude of the backflow. Figure 3 also shows the predicted locations of Y_j and Y_c, the distance of II' from the wall. Shearing stress profiles are not in as good agreement, although there is possibly some uncertainty in the experimental values determined with a hot film nearer the wall due to the presence of a small amount of intermittent backflow.

Since values of the normal freestream velocity V_e at the outer edge of the boundary layer affect the predictions, its influence was examined. A 30% increase in this velocity produced, among other things, a 25% increase in the boundary-layer thickness gradient, a 5% higher maximum shear stress, and a 50% higher normal velocity V along the characteristic originiating at the intermittent separation point.

Modifications to Bradshaw's diffusion function were examined as well. One modification forced the diffusion to zero between the wall and point of maximum shear, while another rescaled the diffusion in the interior of the shear layer while maintaining the entrainment rate at the outer edge of the boundary layer. Both these modifications produced approximately a 5% decrease in the boundary-layer thickness and a 20% increase in the maximum shear stress, although the

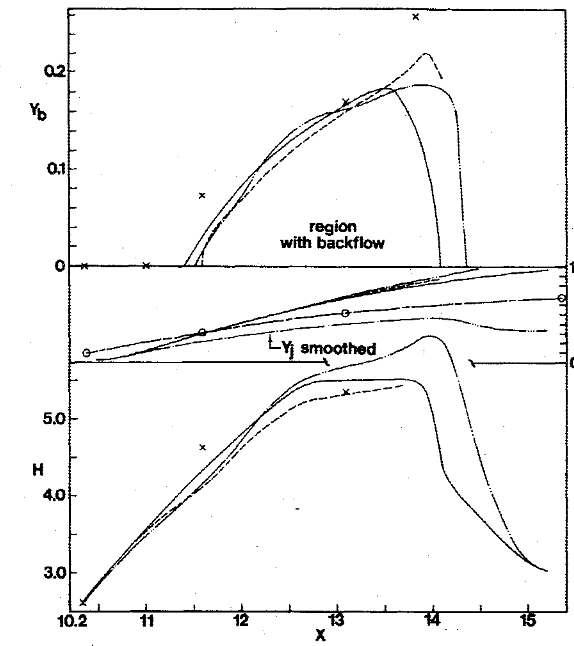

Fig. 3 Results comparison: x-experiments; o-experimental location maximum fluctuation. Predictions with experimental V_e: solid line—smoothed shear profile; dashed lines—unsmoothed shear. Prediction with predicted V_e and smoothed shear-dotted broken line.

shear stress was about 20% lower at a distance of 0.9 of the boundary layer.

Bradshaw's dissipation length function L was also modified to assume a constant value across the boundary layer. Velocity profiles and various length parameters differ by no more than 5% when L/δ is 0.1 or 0.2. Because of the tradition of using a constant dissipation length across a free shear layer, $L/\delta = 0.1$ was used for the results presented here.

We have shown that separated shear-flow predictions can be made using the modified Bradshaw model discussed in Ref. 1. Calculations are properly begun at intermittent separation where pressure gradient relief first begins. For fully stalled flows, such as the Simpson et al.[3] flow, which have relatively short distances between intermittent and fully developed separation, one can effectively use flow conditions at intermittent separation and an assumed functional form for the displacement thickness downstream of intermittent separation to predict the flow downstream of separation.

Acknowledgment

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References

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