Numerical Study of Separated Turbulent Flows

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Theme

SUPERSONIC, turbulent, boundary-layer separation has been studied numerically in six time-marching finite-difference calculations based on the Saffman-turbulence-model equations. Separation of a turbulent flat-plate boundary layer is predicted in all six cases. In three, boundary-layer interaction with an oblique shock wave induces separation; in the other three flowfields, flow into a flat plate-ramp compression corner causes separation. For the shock-wave boundary-layer interactions, computed flow properties agree with corresponding experimental data. However, computed and measured compression-corner flow properties differ noticeably. This Synoptic reviews the computations and makes comparisons between numerical and experimental data for one of the shock-wave boundary-layer interactions.

Contents

Calculations were performed with an explicit time-marching computer code called AFTON 2PT,[1] which generates solutions to the time-dependent Saffman-turbulence model equations[2] for plane transient two-dimensional turbulent fluid motion; steady flow conditions were obtained as the long-time limit of a time-varying field. Flow conditions for the six flowfields are given in Table 1 which includes Reynolds number based on boundary-layer thickness just upstream of the interaction region (Re_δ), inviscid static pressure rise (p_f/p_i), freestream flow deflection (θ) for shock-wave boundary-layer interactions (SWBLI's), and wedge angle (ϕ) for compression-corner (CC) flows.

Results for the $\theta = 9.87°$ SWBLI calculation have been reported previously by Wilcox.[3] Good agreement between numerical and experimental data was shown, although a slight Reynolds-number mismatch caused differences in separation-bubble length and sonic-line location. The $Re_\delta = 10^6$ SWBLI virtually duplicates one of the Reda-Murphy[4,5] experiments and thus provides a more definitive comparison between theory and experiment. Reda and Murphy actually present two sets of data with which computational results are compared. The first set, referred to as the G1 data, is given in Ref. 4. The G1 data exhibit nontrivial three-dimensional effects caused by side-wall

Table 1 Freestream flow conditions

Flow	$\theta, \phi(°)$	Re_δ	p_f/p_i
SWBLI	9.87	$2.5 \cdot 10^5$	3.72
SWBLI	12.75	$2.5 \cdot 10^5$	5.10
SWBLI	12.75	$1.0 \cdot 10^6$	5.10
CC	20.0	$2.5 \cdot 10^5$	3.72
CC	26.0	$2.5 \cdot 10^5$	5.10
CC	26.0	$1.0 \cdot 10^6$	5.10

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Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Jets, Wakes, and Viscid-Inviscid Flow Interactions.

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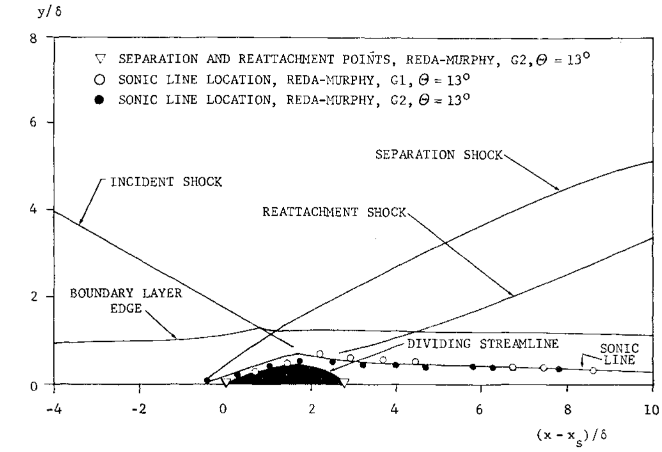

Fig. 1 Computed flowfield structure for the interaction of an oblique shock wave with a turbulent flat-plate boundary layer; $M_\infty = 2.96$, $\theta = 12.75°$, $Re_\delta = 1.0 \times 10^6$.

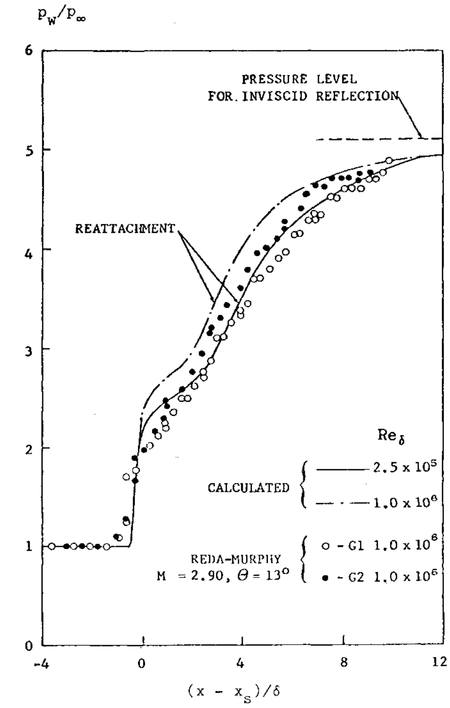

Fig. 2 Comparison of calculated surface pressure distributions with experimental data; $M_\infty = 2.96$, $\theta = 12.75°$.

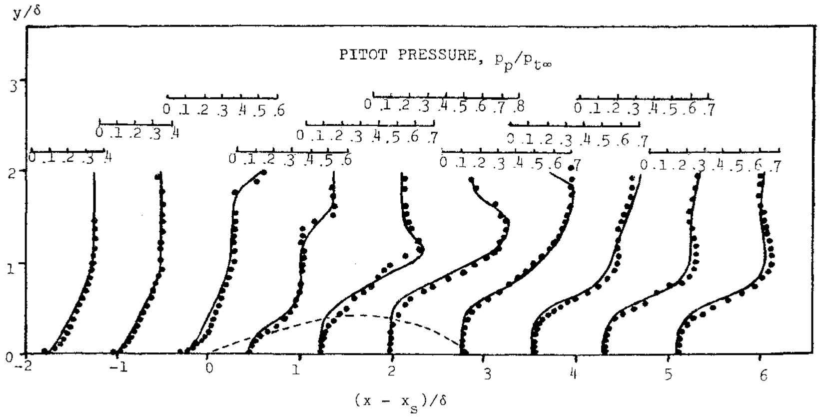

Fig. 3 Comparison of computed pitot-pressure profiles with measured profiles of Reda and Murphy; $\theta = 12.75°$, $Re_\delta = 1.0 \times 10^6$; dashed line denotes dividing streamline.

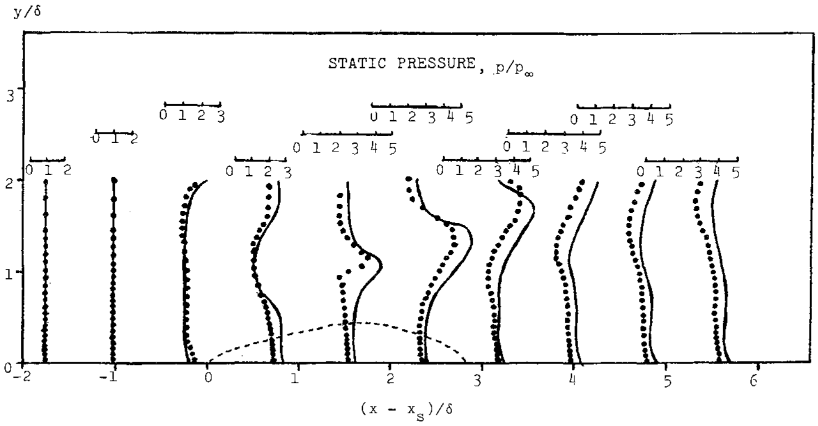

Fig. 4 Comparison of computed static-pressure profiles with measured profiles of Reda and Murphy; $\theta = 12.75°$, $Re_\delta = 1.0 \times 10^6$; dashed line denotes dividing streamline.

boundary layers in the rectangular channel where the measurements were made. The second set, referred to as the G2 data, was obtained in a subsequent study by Reda and Murphy;[5] side plates were mounted on the channel side-walls to suppress side-wall boundary-layer—and hence, three-dimensional—effects.

A flowfield schematic for the computed SWBLI is shown in Fig. 1. The reference point on the plate chosen for the computation is the value of x (distance from the plate-leading edge) at which the boundary layer separates, x_s. All important qualitative features of a separated SWBLI are predicted, e.g., the boundary layer separates, inducing separation and reattachment shocks to appear, and the sonic line remains significantly distant from the plate for many boundary-layer thicknesses downstream of reattachment. The numerical and experimental flowfields are in close quantitative agreement. The measured (G2) separation bubble length of 2.81δ is within 0.5% of the calculated value. The numerical sonic line passes within 5% of corresponding G1 and G2 data (Fig. 1).

Numerical and experimental surface-pressure distributions are shown in Fig. 2. The theoretical pressure distribution is generally 5–10% higher than the G2 data except in the immediate vicinity of the separation region where differences of about 18% are noted. Interestingly, the numerical distribution generally lies closer to the (more three-dimensional) G1 distribution.

Figures 3 and 4 compare computed and experimental (G2) pitot and static pressure profiles throughout the interaction region. Inspection of Fig. 3 shows close agreement between computed and measured pitot pressure profiles; corresponding profiles generally differ by less than 5%. Although calculated static pressures (Fig. 4) are somewhat higher than measured, the predicted profile shapes display all important details of the experimental profiles (e.g., location of pressure peaks and inflection points); deviations between calculated and measured static pressures are no more than 15% of scale.

Results of the compression corner computations are less satisfactory than those of the SWBLI's. While all salient features of compression-corner flow structure have been predicted, quantitative comparisons with corresponding experimental data for the same flow conditions[6] are poor, particularly for the 26° ramps; the most notable discrepancies are in separation-bubble sizes and the surface-pressure distributions. The numerical separation bubbles are from 50–100% smaller than the measured bubbles when $\phi = 26°$, while the separation-bubble length is accurately predicted for $\phi = 20°$. Computed surface pressures above the separated region are 20–30% higher than measured in all three computations.

The most important conclusion drawn in this study is that, *with no adjustment in parameters,* the Saffman turbulence model provides an accurate description of both flow structure and local flow details for shock-induced, turbulent boundary-layer separation for the cases considered. However, the computer code and/or the turbulence model will apparently require further modification in order to achieve accurate computation of turbulent compression-corner flows.

References

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