Technical Notes

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AIAA 81-4179

Effects of Suction on Ramp-Induced Laminar Boundary-Layer Interaction

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Nomenclature

a = speed of sound
B_1 = $H+(1+m_e)/m_e$
B_2 = $8+[2+6m_e/(1+m_e)]+(M_e^2-1)Z/[m_e(1+m_e)]$
C = Chapman-Rubesin parameter
d = slot opening width
G = $(1+m_e)\tan\theta/[m_e(1+m_\infty)C]$
H = θ_i/δ_i^*
J = θ_i^*/δ_i^*
m = $0.2M^2$
M = Mach number
P = pressure, or $\left[\dfrac{\partial(U/U_e)}{\partial(Y/\delta_i^*)}\right]_{Y=0}$
R = $2\delta_i^*\int_0^{\delta_i}[\partial(U/U_e)/\partial Y]^2 \mathrm{d}Y$
Re_c = plate Reynolds number, $(u/\nu)_\infty x_c$
$Re_{\delta_i^*}$ = $(u/\nu)_\infty(M_e/M_\infty)\delta_i^*$
T = temperature
$(u/\nu)_\infty$ = freestream unit Reynolds number
u,v = velocity components in x, y direction
U,V = transformed velocity components
x,y = longitudinal and normal coordinates
X,Y = transformed coordinates
Z = $(1/\delta_i^*)\int_0^{\delta_i}(U/U_e)\mathrm{d}Y$
β = $(\alpha_e/\alpha_\infty)(P_e/P_\infty)$
δ_i^* = incompressible displacement thickness
δ_i = incompressible boundary layer thickness
θ_i = incompressible momentum thickness
θ_i^* = incompressible mechanical energy thickness
θ = local streamline inclination

Subscripts

c = corner at hinge line of ramp
e = edge of boundary layer
ℓ = slot leading edge
o = onset of interaction
t = slot trailing edge, or total
w = inviscid wedge or wall conditions
∞ = freestream conditions

Introduction

WHENEVER there is an abrupt change in the direction of a supersonic external flow, the inviscid pressure distribution is modified by the boundary-layer development, and an interaction between the external flow and the boundary layer occurs. Impinging shock waves and oblique shocks caused by ramps are known to produce such interactions over a wide range of freestream conditions. A prominent feature of these flows is a region of reversed flow occurring in the interaction region as shown in Fig. 1. A typical pressure distribution is also presented in this figure to define certain terminology.

The integral moment method of Lee and Reeves[1] is a well established approximate calculation procedure for handling this type of shock/boundary-layer interaction in laminar flow. The purpose of the investigation reported here was to extend the Lees-Reeves method to include mass transfer at the wall and to investigate the effect of suction on the interaction of a laminar boundary layer with the supersonic external stream.

Analysis

The equations for conservation of mass and momentum for two-dimensional, adiabatic, boundary-layer flow of a compressible fluid were transformed into incompressible form via the Stewartson transformation. These equations together with a mechanical energy equation, obtained by multiplying the momentum equation by U, were integrated across the boundary layer to obtain a system of first-order differential equations describing the flow. These equations, including the effects of mass transfer at the wall, are presented next in a form similar to that used by Klineberg and Lees.[2]

Momentum

$$\delta_i^*\frac{\mathrm{d}H}{\mathrm{d}x}+H\frac{\mathrm{d}\delta_i^*}{\mathrm{d}x}+\delta_i^*\frac{(2H+1)}{M_e}\frac{\mathrm{d}M_e}{\mathrm{d}x}=\beta C\left(\frac{P}{Re_{\delta_i^*}}+\frac{V_w}{U_e}\right)$$

Moment of Momentum

$$\delta_i^*\frac{\mathrm{d}J}{\mathrm{d}H}\frac{\mathrm{d}H}{\mathrm{d}x}+J\frac{\mathrm{d}\delta_i^*}{\mathrm{d}x}+\delta_i^*\frac{3J}{M_e}\frac{\mathrm{d}M_e}{\mathrm{d}x}=\beta C\left(\frac{R}{Re_{\delta_i^*}}+\frac{V_w}{U_e}\right)$$

Continuity

$$\delta_i^*\frac{\mathrm{d}H}{\mathrm{d}x}+B_1\frac{\mathrm{d}\delta_i^*}{\mathrm{d}x}+B_2\frac{\delta_i^*}{M_e}\frac{\mathrm{d}M_e}{\mathrm{d}x}=\beta C\left(G-\frac{1}{m_e}\frac{V_w}{U_e}\right)$$

These equations can be solved by Cramer's rule for $\mathrm{d}H/\mathrm{d}x$, $\mathrm{d}\delta_i^*/\mathrm{d}x$, and $\mathrm{d}M_e/\mathrm{d}x$ and integrated numerically provided relations between the profile parameters H, J, P, R, and Z are known. Following Lees and Reeves[1] these relationships were computed from similarity solutions of the laminar boundary-layer equations without suction.

Received March 13, 1980; revision received Nov. 24, 1980.

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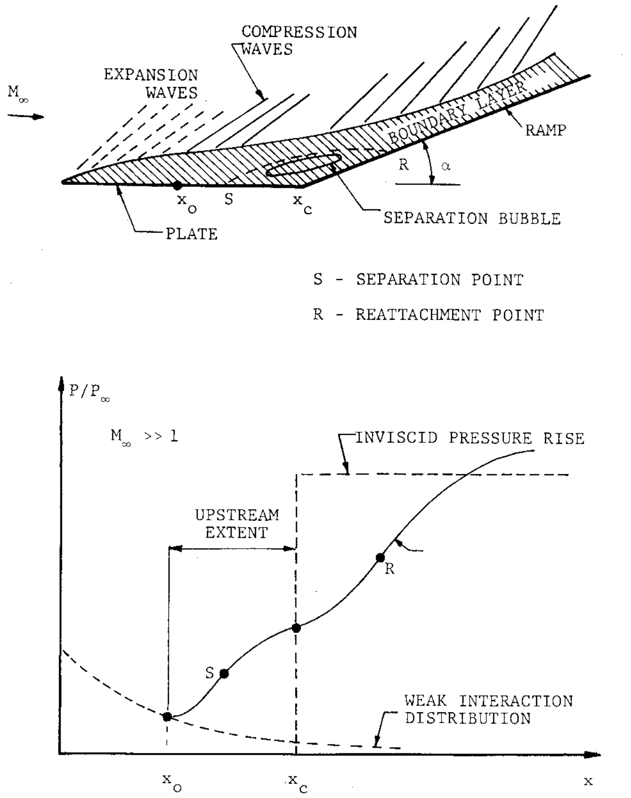

Fig. 1 Geometry and typical pressure distribution for ramp-induced laminar boundary-layer interaction.

The use of similarity solutions for an impermeable wall for calculations with suction is, of course, subject to question. However, a recent publication by Stock[3] indicates that laminar boundary-layer profiles with moderate suction or blowing can be reproduced by flows with a different, effective pressure gradient without mass transfer. Thus, the Falkner-Skan-Stewartson profile family is justified and avoids further complicating the calculation.

The present calculation procedure has been developed to model concentrated suction through a single slot such as used in the experiments of Ball[4,5] and Rhudy.[6] Assuming uniform flow in the slot leads to the following relation for the incompressible suction velocity:

$$\frac{V_w}{U_e} = -\frac{M_w(1+m_w)^{1/2}}{1+m_\infty}\left(\frac{T_{t,\infty}}{T_w}\right)^{1/2}\frac{(1+m_e)^{1/2}}{CM_e}$$

where

$$M_w = |v_w|/a_w$$

for suction.

The Mach number at the entrance of the slot M_w depends on the slot design and, even though the flow is choked, it is always less than one. For a slot with large inlet radius such as used by Ball, the value of M_w is determined by the area ratio of contraction. For the sharp-cornered slots used by Rhudy, the vena contracta effect essentially fixes the Mach number at the slot entrance. One-dimensional continuity considerations imply that $M_w = 0.375$ for all sharp-edged slots.

Initial conditions for the dependent variables H, δ_i^*, and M_e were established by two different procedures, depending on the level of suction. For small or no suction, the initial Mach number at x_o was assumed to be the tangent-wedge value obtained from the pressure ratio for a weak interaction. The initial values of δ_i^* and H were assumed to be linked through a similarity solution, and were obtained by an iteration to make $(dM_e/dx)_o = 0$.

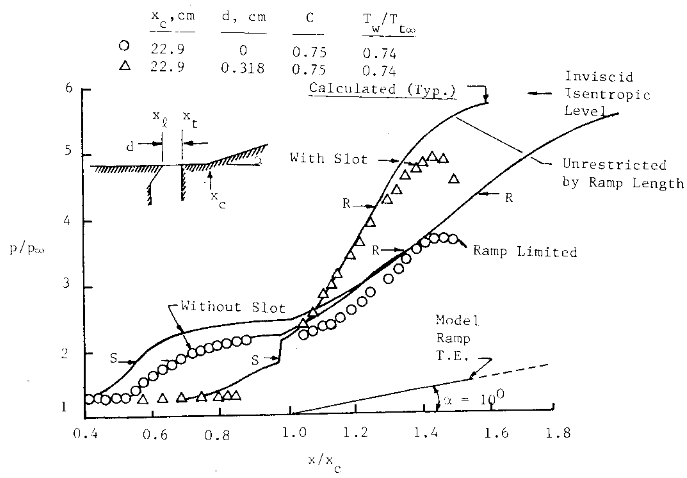

Fig. 2 Comparison of calculation results with data of Rhudy[6] at $M_\infty = 8$, $Re_c = 10^6$.

Without suction, this procedure always leads to the rapid, initial pressure rise induced by the displacement thickness growth that is observed experimentally. In contrast to this behavior is the interaction near the suction slot that is characterized by a flow expansion to pressures less than the freestream level. This interaction was observed by Rhudy[6] but only at conditions conducive to an effective disappearance of the separation bubble. It is postulated that, for this type of interaction, there are two extrema of the displacement thickness in the vicinity of the slot, since it is changes in the displacement thickness that produce the unusual pressure variations.

The procedure adopted for defining initial conditions for this interaction was to fix H at the flat-plate value and iterate for M_e that makes $d\delta_i^*/dx$ zero.

A unique solution is obtained when the derivatives of M_e and H on the ramp are both tending to zero and the Mach number is nominally equal to the value for an isentropic compression through the ramp angle. These conditions are satisfied in practice by an iterative adjustment of one parameter governing the initial conditions. With small or no suction, the iteration parameter is the location of the onset of interaction x_o, and with moderate to large suction it is the compressible displacement thickness δ_i^* at the slot leading edge x_ℓ. A solution is initially sought for a small suction interaction as long as $x_o < x_\ell$ provides solutions convergent to the downstream conditions. However, when it is indicated that $x_o > x_\ell$, initial conditions appropriate to large suction are applied and x_o is fixed at the slot leading edge.

Results

The computer code developed from the preceding analysis was verified for the no suction case by comparison with the experimental pressure data of Lewis et al.[7] at $M_\infty = 4.0$ and with theoretical calculations of Klineberg and Lees[2] at $M_\infty = 6.0$. These comparisons showed excellent agreement between the current calculation scheme and well-established results without suction.

Figure 2 shows a comparison of computed results with data obtained by Rhudy[6] at $M_\infty = 8$. Two no-bleed solutions are presented first for comparison, because the ramp pressures fall below the overall rise expected thus indicating that the ramp was too short. A ramp limited solution was obtained by relaxing the downstream boundary condition to allow M_e to be a minimum just upstream of the trailing edge. The agreement of this calculation with the data upstream of the hinge line is extremely good although considerable disparity still is evident on the ramp.

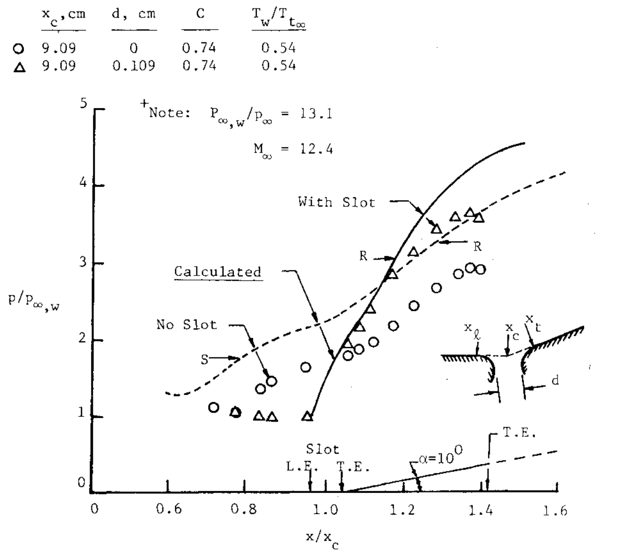

Fig. 3 Comparison of calculation results with data of Ball[4] at $M_{\infty,w} = 6.7, Re_{c,w} = 0.36 \times 10^6$.

A comparison with data obtained at the same freestream conditions but with bleed through a sharp-edge slot shows that the calculation correctly predicts the appreciable reduction in upstream extent produced by hinge-line bleed. However, this reduction is not as great as shown by the data. This difference is, to some extent, the result of the ramp being too short.

Figure 3 shows a comparison with the data of Ball[4] obtained with a pitched model that provided a tangent wedge Mach number of 6.7. The no-bleed data are drastically different from the calculated pressure distribution to an extent that also indicates that the ramp was too short. This indication, however, is misleading since subsequent tests[5] with longer ramps gave similar results. The most logical explanation for these results is lateral bleed caused by the pitched flat plate. This explanation is completely consistent with angle-of-attack data by Rhudy[6] that were obtained on a model with aspect ratio (2.2) nearly identical to Ball's. With this model Rhudy found that data equivalent to unpitched data could not be obtained by pitching.

Bleed data obtained with a contoured slot with a throat opening of $0.012x_c$ are also shown in Fig. 3 for comparison with the calculated results. The agreement is generally quite good with respect to both the reduction in upstream extent and the increase in pressure gradient on the ramp.

Conclusions

A series of calculations were made to determine the effect of Mach number, Reynolds number, and slot size on the pressure distribution for ramp-induced interactions with bleed. These calculations were all made for a sharp-edged slot ($d = 0.014x_c$) similar to Rhudy's with downstream edge fixed at $0.986x_c$ and a ramp angle fixed at 10 deg. The conclusions based on this series are summarized as follows:

1) The upstream extent of the interaction (or size of the reverse-flow bubble) can decrease with an increase in Reynolds number. That is, sufficient bleed reverses the characteristic Reynolds number effect.

2) The upstream extent increases with Mach number increase ($4.5 \leq M_\infty \leq 8.0$), and this too represents a trend reversal caused by sufficient bleed.

3) The ramp pressure gradient increases appreciably with increases in Reynolds number for a fixed bleed rate.

4) The upstream extent decreases with an increase in slot width until a critical size is reached. At this critical condition, the upstream extent decrease abruptly and the onset of interaction closely approaches the location of separation.

5) Despite the appreciable reduction in upstream extent possible through the application of hinge-line bleed, the reversed flow part of the velocity profile at the hinge line is larger with suction.

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AIAA 81-4180

The Nature of Differences in Some Forms of Transition in the Boundary Layer

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Introduction

ACCORDING to modern theory, transition from a laminar to a turbulent boundary layer may appear as the result of amplification of small disturbances in the wavy structure. The development of waves of low intensity (Tollmien-Schlichting waves) is well described by linear hydrodynamic stability theory.[1] With the increase in wave energy, the process is more complicated and may be connected with the nonlinear effects of wave evolution. The physical mechanisms include spontaneous amplification of spatial fluctuations, subharmonic generation, and nonequivalence of process character but, in general, are not well maintained. It has been shown[2] that the disturbance spectrum in the region of nonlinear development is made up of a set of harmonics of the main frequency with similar intensities and that spatially distributed eddy structures are formed in the flow. Under other conditions,[3] subharmonic frequencies are generated together with the successive formation of harmonics; spatial nonhomogeneity is lower and does not contain pronounced regularity. A similar fact was observed experimentally[4] by injecting disturbances in the form of localized wave packets.

Received April 9, 1980; revison received Jan. 12, 1981.

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