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STUDY OF A VISCOUS SUBLAYER MODEL IN THE ANALYSIS OF 3-D SHOCK/ BOUNDARY LAYER INTERACTION FLOW FIELDS

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At high Reynolds number, it has been experimentally and computationally well-confirmed that the 3-D interactive physics is vertically organized into the triple-deck type of structure. The governing integral-type equations that characterize the non-reversed flow portion of the interactive wall layer model are formulated in the form of a set of nonlinear partial first order differential equations, including three-dimensional aspects. Also modeled was the splitting of the layer into an upper region of non-reversed flow and an underlying region of slow, reversed flow. The shock structure and nonlinear rotational inviscid flow behavior of the overlying region were explored by means of a suitable 3-D shock/boundary layer approach which include separation. The NASA Langley code "Laura" was modified to include these new wall layer equations.

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INTRODUCTION

Assessements by several in-depth workshops[1,2] have conclusively affirmed the importance of continued research on 3-D Shock Turbulent Boundary Layer Interaction ("SBLI") to the aerodynamical engineering of both external flow fields on hypersonic vehicles such as the NASP and the internal flows within air-breathing engine inlets. This conclusion has been further emphasized recently by a strong surge of interest in the accurate prediction of inlet flows for air breathing engines on very high Mach number hypersonic flight vehicles.

The present research involved a study of 3-D interactions including <u>flow separation</u> from nonaidabatic surfaces, wherein we sought to develop a generalized interactive "wall sublayer" model of the laminar plus turbulent disturbance shear stress physics that embraces the combined presence of streamwise flow reversal, cross-flow and heat transfer. According to the testimony of both experimental and CFD workers,[3,4] such a "super wall layer" model would not only provide valuable insight to observed interactive skin friction line behaviour and its Mach number dependence, but would also greatly enhance computational efficiency as an "underlay" to a computer code (say a 3-D Euler code) that numerically solves all the remaining outer portion of the flow field. Indeed, the need for providing a careful treatment of the near-wall region, because of the great difficulty and expense in providing sufficiently-fine streamwise as well as normal numerical mesh spacing at high Reynolds numbers, has been stressed by a number of experts. Our research originally proposed has three main technical goals within the scope of a three year effort:

(1) The development of such a generalized wall layer model in the form of

a set of first order partial differential equations that globally characterize the interactive displacement thickness, skin friction and heat transfer due to the near-wall viscous/turbulence shear-disturbance physics; (2) Incorporation of this model as a wall layer underlay in a suitable 3-D Euler (or Navier Stokes) code, followed by validation with data from several basic experimental studies of shock/boundary layer interactions on isolated single fins and ramps; (3) Application of the resulting composite code to the prediction and analysis of double fin[5] ("crossing shock") interactions typical of the actual inlet flow field in air breathing engine inlets (Fig 1).

Owing to the abrupt and unexpected termination of the supporting grant after only one year, only part of goal (2) and none of the work toward goal (3) could be carried out. This report describes the progress that was achieved regarding goals (1) and (2).

SUMMARY OF PROGRESS

At high Reynolds number, it has been experimentally and computationally well-confirmed that the 3-D interactive physics is vertically organized into the triple-deck type of structure illustrated in Fig. 2, which contains at its bottom a thin inner shear disturbance deck which provides the appropriate matching boundary condition at the bottom of the overlying middle deck and contains much of the interactive displacement thickness effect plus all of the important skin friction and heat transfer disturbances and underlying flow separation zones. It is the detailed flow modelling of this lower deck that constitutes the generalized global wall layer concept of this research.

a) We completed the formulation of the governing integral-type equations that characterize the non-reversed flow portion of interactive wall layer model in the form of a set of nonlinear partial first order differential equations, including the three-dimensional aspects of the flow (the cross flow velocity component) via lateral momentum balance : see appendix A.

b) A significant aspect of the wall layer theory is the further splitting of the layer into an upper region of non-reversed flow and an underlying lower region of slow, reversed flow (see Fig 3), the two regions being divided by a locus $y_u(x,z)$ whose unknown shape is determined from the upper/lower shear stress and normal velocity matching across it. Incorporation of this bi-regional aspect of the wall layer provides the proper interactive viscous/turbulent physics that underlies regions of 3-D SBLI-induced separation. We have also completed the formulation of the 3-D equations that govern <u>this</u> aspect of our interactive wall layer model (Appendix A) along with a paper describing their validation and application in the case of laminar 2-D flow (Appendix B)

c) An important feature is to capture the shock structure and nonlinear rotational inviscid flow behaviour of the overlying region by means of a suitable 3-D shock/boundary layer applications which include separation. After many discussions, we established a collaboration with Dr Peter Gnoffo at NASA Langley to use his "Laura" code[6]. This code was made operational at ISU including its adaptation to accept the matching conditions that allow the aforementioned wall layer equations to be inserted as an "interactive overlay" including a User Manual we have written for this ISU version with the interactive underlay modification aspects (Appendix C).

Regarding this part of the work, several unique aspects of our wall layer underlay approach are noteworthy. First, by virtue of our previous experience with 3-D interactive flows[7-10] we can provide particularly effective initial conditions that are analytically derived from steady triple deck theory, rather than just arbitrary numbers, thereby significantly accelerating time-convergence of the solution. Second, we would have been able to independently check out the 3-D Euler code solution convergence in the regime of weaker shock strengths at lower supersonic external flow Mach numbers by means of the analytical 3-D small disturbance middle-deck theory developed previously by the author. Third, (see Fig. 4) we are able to avoid the near wall difficulties experienced by Euler codes within nonuniform flow regions such as a boundary layer profile; using a wall layer underlay, such codes need not be solved all the way to the floor, but only down to some cutoff height $h(x,z)>0$ where $u(x,h,z)$ and $w(x,h,z)$ are non-zero. We further avoid a spurious normal mass, momentum and energy fluxes into the flow at this height by not choosing h arbitrarily but rather equal to the interactive displacement thickness $y_w(x,z)$ of the interactive wall layer that actually underlies the middle deck. This manner of incorporating the effect of the wall region shear disturbance physics not only provides computational advantages but is unique to our approach.

d) Having completed the detailed theoretical formulation of the wall layer model and its combination with a code for the overlying middle/outer deck rotational-flow regions, the resulting united programme had begun to be applied to the analysis of several specific interacting flow problems for which extensive experimental data and CFD Navier-Stokes numerical solutions results are available for validating comparisons. As a first step, we completed the calculation of a set of interactive solutions for adiabatic 2-d laminar flow past a compression corner that include substantial separation (see Appendix D); the results for local skin friction and pressure, which provide a significant test of the coupling of our wall layer model and its ability to handle reversed flow, are in excellent agreement with the Navier-Stokes solutions of Rizzetta. This work, the last to be completed before Grant expiration, is being written up as a technical paper.

REFERENCES

1 L Smits (Ed), "Meeting of the Working Group on 3-D Shock Wave/Turbulent Boundary Layer Interation "Princetown Univ, July 1988

2 NASA-Lewis Workshop on 3-D Shock Wave/Turbulent Boundary Layer Interactions, Cleveland Sept 1988

3 Kutler P "A Perspective of Theoretical and Applied Computational Fluid Dynamics" March 1985 pp 328-341 (See also Kutler, Steger and Bailey in AIAA Paper 87-1135)

4 Jameson A "Successes and Challenges in Computational Aerodynamics" AIAA Paper 87-1184

5 AIAA 91-0649 "Crossing Shock Wave-Turbulent Boundary Layer Interactions N Narayanswami and D Knight, Rutgers University. S M Bogdonoff, Princetown University. C C Horstman, NASA Ames Research Center.

6 Weilmunster K J "High Angle of Attack Inviscid Flow Calculations over a Shuttle-Like Vehicle AIAA Paper 83-1798.

7 Inger G R "Analytical Investigation of Swept Shock-Turbulent Boundary Layer Interaction in Supersonic Flow" AIAA Paper 84-1555 1985.

8 Inger G R "Supersonic Viscous-Inviscid Interaction of a Swept Compression Ramp with a Turbulent Boundary Layer" Turbulent Shear Layer/Shock Wave Interaction IUTAM Symposium Palaiseau 1985 (Ed J Delery) Springer Berlin-Heidelberg 1986.

8 Inger G R "The Role of Law of the Wall/Wake Modeling in Validating Shock-Boundary Layer interaction Predictions AIAA Paper 88-3581 July 1988.

9 Inger G R "Spanwise Propagation of Upstream Influence in Conical Swept Shock/Boundary Layer Interactions AIAA Journal 25 Feb 1987 pp 287-293.

10 Inger G R "Incipient Separation and Similitude Properties of Swept Shock/Turbulent Boundary Layer Interactions AIAA Paper 86-0345 Reno Jan 1986.

11 Inger G R and S Ahmed "Nonisotropic Effects in the Wall Region of a Three Dimensional Turbulent Boundary Layer" AIAA Paper 87-0285 Reno Jan 1987.

Appendix A

Summary of the Governing Equations characterizing the Interactive Wall Layer Model as a CFD Underlay.

To bring out the physical essentials, we further adopt the following assumptions. (1) The incoming undisturbed turbulent boundary layer is characterized by a steady compressible two-dimensional Law of the Wall/Law of the Wake structure. (2) The turbulent mean flow within the interactive wall sublayer obeys Morkovins Hypothesis as regards compressibility effects and is modeled in the first approximation by Law of the Wall mixing length concept (3). The laminar and turbulent Prandtl numbers are both unity. (4) The normal pressure gradient ($\partial p/\partial y$) and non-boundary layer type stress terms are negligible across the interactive wall layer.

Non-Reversed Flow Region

Under the aforementioned assumptions, the 3-D interactive flow in the non-separated portion of the wall layer is governed by the following set of equations:

Continuity
$$\frac{\partial(\rho u)}{\partial x}+\frac{(\partial \rho v)}{\partial y}+\frac{(\partial \rho w)}{\partial z}=0 \tag{7}$$

x-momentum
$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)+\frac{\partial p}{\partial x}=\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}+\rho v_t D_u\right) \tag{8}$$

y-momentum
$$\frac{\partial p}{\partial y}\equiv 0;\ p\equiv p_w(x,z) \tag{9}$$

z-momentum
$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)+\frac{\partial p}{\partial x}=\frac{\partial}{\partial y}\left(\mu\frac{\partial w}{\partial y}+\rho v_t D_w\right) \tag{10}$$

Energy
$$\rho\left(u\frac{\partial H}{\partial x}+v\frac{\partial H}{\partial y}+w\frac{\partial H}{\partial z}\right)\equiv\frac{\partial}{\partial y}\left[(\mu+\rho v_t)\frac{\partial H}{\partial y}\right] \tag{11}$$

where $H = C_pT + 1/2\ (u^2 + w^2)$ and

$$D_u\equiv\frac{\partial u}{\partial y}+(1-T_R)w\left(\frac{u\frac{\partial w}{\partial y}-w\frac{\partial u}{\partial y}}{u^2+w^2}\right) \tag{12a}$$

$$D_w\equiv\frac{\partial w}{\partial y}+(1-T_R)u\left(\frac{u\frac{\partial w}{\partial y}-w\frac{\partial u}{\partial y}}{u^2+w^2}\right) \tag{12b}$$

$$v_t=\ell^2\sqrt{\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2+(T_R-1)\frac{\left(w\frac{\partial u}{\partial y}-u\frac{\partial w}{\partial y}\right)^2}{\left(u^2+w^2\right)}} \tag{12c}$$

$$\ell=.41\ y[1-\mathrm{EXP}(-y/A)] \tag{12d}$$

$$A = 26\,\nu_w \rho_w^{1/2} \Big/ \left(\tau_{wx}^2 + \tau_{wz}^2\right)^{1/4} \tag{12e}$$

Relations (12) represent Rotta's non-isotropic Law of the Wall turbulent eddy viscosity model[11] which includes both pressure gradient effects and a non-isotropy factor T_R(where T_R = 1 for the isotropic case). For non-adiabatic wall conditions, especially at hypersonic external Mach numbers, we retain (unlike classical asymptotic deck theory) the variable density effect across the inner deck. The solutions of Eqs. 6-12 must satisfy boundary conditions with respect to y that the disturbance shear stresses vanish beyond some inner sublayer thickness $\delta_{SL}(x,z)$ and that on y = 0 we have the impermeable floor no-slip boundary conditions V (x,z) = U (x,z) = W(x,z) = 0. In addition, we impose the upstream condition that the flow pass over to the given compressible turbulent Law of the Wall/Wake boundary layer profile; on the basis of the Reference Temperature version of Waltz's formulation, for example, these profiles in the general non-adiabatic wall case are described analytically by

$$\frac{U_o}{U_e} = 1 + \frac{1}{.41}\sqrt{\frac{C_{f_o}}{2}\left(\frac{T_w}{T_e}\right)}\left[\left(\frac{R}{1+R}\right)\eta^2(1-\eta) - 2\pi + 2\pi\,\eta^2 \bullet (3-2\eta) + \ln\left(\frac{1+R\eta}{1+R}\right) - (.215 + .655R\eta)e^{-3R\eta}\right] \tag{13}$$

$$T_0(y) = T_w + (T_e - T_w)\frac{U_o(y)}{U_e} + \left(\frac{\gamma-1}{2}\right)M_e^2\left(\frac{U_o}{U_e} - \frac{U_o^2}{U_e^2}\right) \tag{14}$$

Where $\eta = y/\delta_o$, $R \equiv 4.1\, Re_{\delta_o}/[(1+\pi)(T_w/T_e)^{1+\omega}]$ with $\omega \equiv .76$ and π is Coles' wake function linked to Cf_o and Re_{δ_o} by the relation

$$2\pi + .215 + \ln(1+R) = .41 / \sqrt{\frac{C_{f_e}}{2}\left(\frac{T_w}{T_e}\right)} \tag{15}$$

Equation (13) for η >.10 yields a Law of the Wake behaviour with $U_o/U_e \rightarrow 1$ and $dU_o/dy \rightarrow 0$ as $\eta = 1$, while for very small η it assumes a Law of the Wall-type behavior consisting of a logarithmic term that is exponentially damped out into the linear sublayer profile $u/u_e = R\eta$ as $\eta \rightarrow o$.

Reversed Flow Region

Turning to a consideration of any reversed disturbance flow that might occur in the lower region of the wall layer, we propose to treat it on the basis of a negligible inertial approximation that is appropriate to such slow wall-dominated flows. Thus, we must solve the following equations by a y-integration of Eqs. 8-11 with the convective acceleration terms dropped:

$$\mu\frac{\partial u}{\partial y} + \rho v_t D_u = \tau_{x_w} + y\frac{\partial p_w}{\partial x} \tag{16}$$

$$\mu\frac{\partial w}{\partial y} + \rho v_t D_w = \tau_{B_w} + y\frac{\partial p_w}{\partial z} \tag{17}$$

$$(\mu + \rho v_t)\frac{\partial H}{\partial y} = \mu_w\left(\frac{\partial H}{\partial y}\right)_w \equiv -\dot{q}_w \tag{18}$$

Where we have used the fact that γ_t vanishes at the wall. Equations 16-18 are to be solved up to the vertical height $y_u(x,z)$ of the $U_N = 0$ locus (unknown priori) where $U_N = U \sin \Lambda - W \cos \Lambda$ and Λ is the angle of the local separation line as shown in Fig 5.

Outline of the Wall Solution Method

Addressing first the reversed flow region-aspect of this wall layer for $0 \leq y \leq y_u\ (x,z)$, the velocity and temperature (and density) field solutions are to be obtained by further integrations wrt y of Eqs. 16-19 along with equations 12a-e. When the resulting expression for U_N is equated to zero, we additionally get a pair of expressions governing the unknown locus $Y_U(x,z)$ of the form

$$\frac{\partial y_u}{\partial x} + \frac{\partial p_w}{\partial x} \cdot k_{x_1} = k_{x_2}(\tau_{x_w}, \tau_{z_w}, y_u) \qquad (19A)$$

$$\frac{\partial y_u}{\partial z} + \frac{\partial p_w}{\partial z} \cdot k_{z_1} = k_{x_2}(\tau_{x_w}, \tau_{z_w}, y_u) \qquad (19B)$$

where the various K's here are detailed functionals resulting from the integration. An additional integration of the continuity Equation then yields an expression for the transpiration mass flux $\dot{m}_u$ across Y_U of the form

$$\dot{m}_u \equiv \rho v(x, y_u, z) = \int_0^{y_u(x,b)} -\left[\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho w)}{\partial z}\right] dy$$

$$= \tau_{x_w} j_{x_1} + y_u^2 \frac{\partial p_w}{\partial x} j_{x_2} + j_{x_3}(\tau_{x_w}, \tau_{z_w}, y_u) \qquad (20)$$

$$+ \tau_{z_w} j_{z_1} + y_u^2 \frac{\partial p_w}{\partial z} j_{z_2} + j_{z_3}(\tau_{x_w}, \tau_{z_w}, y_u)$$

Where the J's are further integration-functionals. Along with us, we note that a further y-integration of Eqs. 16-18 yield relationships between the wall shear components and the shears along the Y_u in terms of $\partial p/\partial x$ and $\partial p/\partial z$ of the form

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layer for purposes of a CFD underlay, we obtain a solution of the equations by an integral method approach: this not only enables an efficient matching between the upper and lower wall layer regions across Y_u but also formulates the wall layer model in the desired form of a set of first order partial differential equations governing the 3-D disturbance wall shear, heat transfer and displacement thickness $Y_w(x,z)$. Indeed, some unpublished earlier work by R T Davis reveals that it yields relationships of the form

$$\frac{\partial\tau_x(y_u)}{\partial t} = F_{x_1}\frac{\partial\tau_x(y_u)}{\partial x} + F_{x_2}\frac{\partial\tau_x}{\partial z}(y_u) + F_{x_3} \tag{26}$$

$$\frac{\partial\tau_x(y_u)}{\partial t} = F_{z_1}\frac{\partial\tau_z(y_u)}{\partial x} + F_{z_2}\frac{\partial\tau_z}{\partial z}(y_u) + F_{z_3} \tag{27}$$

$$\frac{\partial\dot{q}(y_u)}{\partial t} = F_{Q_1}\frac{\partial\dot{q}(y_u)}{\partial x} + F_{Q_2}\frac{\partial\dot{q}}{\partial z}(y_u) + F_{Q_3} \tag{28}$$

where the various F_x, F_z and F_Q here are functionals of $\tau_x(y_u)$, $p_w(x,y)$ and $y_u(x,z)$ given by the details of the momentum and energy equation integral analyses with suitable profiles. When combined with Eqs. 19-25 that link $\tau_x(y_u)$, $\tau_z(y_u)$ and $q(y_u)$ along $y = y_u$ to their local counterparts along the wall $y = 0$, Eqs. 26-28 provide in principle a trio of relationships governing the local interactive skin friction and wall heat transfer of the form

$$\frac{\partial\tau_{xw}}{\partial t} = f_{\tau_1}\frac{\partial\tau_{xw}}{\partial x} + f_{\tau_2}\frac{\partial\tau_{xw}}{\partial z} + f_{\tau_3} \tag{29}$$

$$\frac{\partial\tau_{zw}}{\partial t} = f_{\tau_4}\frac{\partial\tau_{zw}}{\partial x} + f_{\tau_5}\frac{\partial\tau_{zw}}{\partial z} + f_{\tau_6} \tag{30}$$

$$\frac{\partial\dot{q}_w}{\partial t} = f_{q_1}\frac{\partial\dot{q}_w}{\partial x} + f_{q_2}\frac{\partial\dot{q}_w}{\partial z} + f_{q_3} \tag{31}$$

With the aforementioned analysis of the entire wall layer completed, we close the problem by obtaining the overall vertical velocity field from an integration of continuity Eq 6 across $0 \leq y \geq y_u$ and then beyond the viscous thickness of the wall layer δ_{SL} where the disturbance shear stresses become vanishingly small; this procedure yields

$$v(x,y>\delta_{SL},z)=\rho^{-1}(x,y,z)^{\times}\left\{\dot{m}_u-\int_{y_u}^{\delta_{SL}}\left[\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho w)}{\partial z}\right]dy-\int_{\delta_{SL}}^{y}\left[\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho w)}{\partial z}\right]dy\right\} \quad (32)$$

When the right side of this Equation is equated to zero, the result provides a determination of the y(x,z) locus along which the "far field" v emerging from the wall layer vanishes, ie, the effective inviscid wall position (or displacement thickness) $y_w(x,z)$ (see again fig 4.). The resulting expression for y_w that emerges is of the general form.

$$y_w(x,z,t)=f_{y_1}\frac{\partial y_w}{\partial x}+f_{y_2}\frac{\partial y_w}{\partial z}+f_{y_3} \quad (33)$$

Eq. 33 completes the formulation by providing the desired coupling mechanism to the overlaying numerical Euler solution of the middle deck. Moreover, the detailed evaluation of Eq. 32. at the outer edge of the proposed generalized wall layer also permits a careful examination of the important property of the upwash (vertical velocity) behaviour right above 3-D skin friction line confluence. This is very helpful in further illuminating the actual physical behavior of the flow as it ostensibly leaves the surface ("separates") along such a confluence.

Appendix B

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A Theory for the Reversed Flow in a Laminar Separation Bubble

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Appendix C

Users Manual Suppliment for LAURA

Louis L. LeGrand

May 15, 1991

1 INTRODUCTION

The program LAURA was written at NASA Langley by Peter Gnoffo. Any questions not answered by this paper can be directed to him at his E-mail address "gnoffo@abcfd01.larc.nasa.gov" or by telephone at (804) 864-4380. He is very helpful and very patient. Peter and I did most of our interaction through E-mail. I sent him questions, and he sent me answers and program modifications.

The code itself is very, very large, and consists of about 90 separate Fortran files. Peter mailed these files to my *Project Vincent* account, and we went to work trying to get a working version here at ISU. Getting the program to compile took several weeks of interaction since it had originally been compiled on a different machine, and a few of the options had been stripped (i.e. reacting flow and multitasking capabilities). Finally, however, we did get the program to work.

Although the program is capable of modeling 3-D, viscous, supersonic/hypersonic flow in thermochemical nonequilibrium, we will be primarilly interested in 2-D, inviscid supersonic, nonreacting flow with vorticity.

2 INPUT

2.1 wingbdy.f

The geometry of the body is contained in the *file* "wingbdy.f". The example body that is stored there now is a 2-D cylindrially blunted 15 degree wedge, which was chosen so that the shock will be curved, and the flow will have vorticity.

2.2 Input File

The the input file is used to customize the flow and run parameters. An example input file is shown in Figure 1. The variable names and their significance is given

⋮

5.3 Inger.q

Dr. Inger is doing work that requires certain information at or near the surface of the body. Therfore, Peter has modified LAURA to produce a formatted output file containing this information called "inger.q".

The first row of this file contains a single number "1". This denotes that the block of information that follows is at the body surface. Several lines down from this single "1" is another row that contains a single number "2". This "2" denotes that the block of information that follows is for the cells that are a step away from the body. After the "2" block, there is a "3" block that is one more step away from the body. By selecting the proper block, the user can use the flow properties at the body surface or somwhere above the body surface.

Each block of information contains several rows of information. Each row has the following eleven elements:

[illegible]

Appendix D

ABSTRACT

Separation Bubble Modeling in Compression Ramp-Generated Viscous-Inviscid Interactions

G. R. Inger and B. Nath*

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INTRODUCTION

Correct treatment of the near wall viscous flow physics, and especially the separation bubble region, is an important aspect of the calculation of the interacting flow field generated around a deflected control surface on a high speed aerodynamic body. Such near wall features are often difficult and expensive to resolve with a CFD/Navier-Stokes code without fine grained sub-mesh refinement schemes. It would therefore be of value in practical design-type codes if an analytical underlay to them could be supplied that resolves the near wall viscous flow physics including the reversed flow portion of the separation bubble. This paper presents such an underlay theory for the simplified trial problem of 2-D steady laminar supersonic flow past a compression corner.

OUTLINE OF THE THEORETICAL APPROACH

Consider the vicinity of a high Reynolds number compression ramp flow as schematically illustrated in Fig. 1: here, as is well-known,[1] the local strong viscous-inviscid interaction generates a triple deck structure outside and inside the incoming boundary layer profile, consisting of an outer region of disturbed irrotational inviscid flow, a middle deck of rotational perturbation flow, and an inner deck of non-reversed viscous disturbance flow. This triple deck in turn can be imagined to lie on top of the portion of the separation bubble that contains a reversed (viscous) flow.

Our treatment of this situation consists of two parts. In the overlying triple deck of non-reversed flow, we have developed a unique defect-type of integral method which describes the overall local features of the deck in terms of a set of ordinary differential equations. As shown in Thus if p_w, δ, Ui denote the local wall pressure, thickness and edge slip velocity,

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* Professor and graduate student, respectively, Dept. of Aerospace Engineering and Engineering Mechanics

respectively of the deck, these equations for supersonic outer deck flow are as follows in terms of the well-known non-dimensional triple deck variables (Ref. 1):

$$p_w + \frac{U_i^2}{2} = \delta \frac{U_i}{3} - \int_{-\infty}^{X} V_u \, dX \qquad (1)$$

$$\frac{d}{dX}\left(\frac{\delta^2 U_i}{6} - \frac{7}{15}\delta U_i^2\right) - U_i V_u = 2\frac{U_i}{\delta} - U_i \frac{d}{dX}\left(\frac{U_i \delta}{3}\right) \qquad (2)$$

$$p = \frac{dU_i}{dX} + \alpha \cdot H(X) + \frac{dY_u}{dX} \quad \left\{ \begin{array}{ll} H(X) = 0, & X < 0 \\ = 1, & X \geq 0 \end{array} \right\} \qquad (3)$$

where α is the ramp angle, Yu(x) is the underlying separation bubble locus upon which this deck rests (see Fig.1) and Vu is the corresponding transpiration velocity across Yu(x) into the bottom of the deck from the reversed flow region. It is seen that the solution of Eqs. (1)-(3) is necessarily coupled to the behavior (unknown apriori) of the reversed separation bubble properties.

The second aspect of our theory is thus to provide a comparable analytical treatment of the reversed flow zone whereby its Yu(x) and Vu(x) are appropriately linked to the properties of the overlying triple deck. This has been done using a method of successive inertial approximations;[2] according to the detailed analysis to the full paper, the results are the following :

$$\left. \begin{array}{ll} Y_u = 0 & \text{if } 2U_i/\delta < 1 \\ = 2(2U_i/\delta - 1)/(dp_w/dX) & \text{otherwise} \end{array} \right\} \qquad (4)$$

$$V_u = \frac{d}{dX}\left[Y_u^3 (dp_w/dX)/12 \right] \qquad (5)$$

The simultaneous solution of Eqs. (1)-(5) for the five unknowns p, Ui, δ, Vu and Yu comprises the matched treatment of the entire interaction zone including the reversed flow aspect of the separation bubble that occurs for large enough compression corner angles.

VALIDATION OF THE THEORY

The reversed flow portion of the foregoing theory has been validated by comparison with the now classical exact Navier-Stokes numerical solutions by Briley for a typical separation bubble flow.[3] As shown in Fig. 2, the present theory gives very accurate results for the Yu locus in such a flow, and hence should provide a faithful representation of the reversed flow aspect of the above-described interaction theory.

The foregoing triple deck theory of the reversed flow region also has been shown to be in good agreement with exact numerical solutions : an example is illustrated in Fig. 3. In the case $\bar{\alpha} = 2.50$.

TYPICAL RESULTS

In Figure 4 are illustrated a set of representative results obtained by a Runga-Kutta method solution of Eqs. (1)-(5) for a separated flow case with $\bar{\alpha} = 2.2$. The significant local alterations of the interactive pressure and skin friction by the corner-smoothing displacement effect of the bubble are closely seen. Currently this work is being extended to address: (a) hypersonic external flow, (b) non-adiabatic wall conditions with heat transfer across the separation bubble, (c) three dimensional flows and (d) turbulent flow including turbulence modeling within the reversed flow region.

REFERENCES

1. Stewartson, K., "Multistructured Boundary Layers," in Adv in App. Mech. 14, 1974.
2. Inger, G. R. and L. Legrand, "A Theory for the Reversed Flow in a Laminar Separation Bubble," Proc. 7th International Conf. on Numerical Methods in Laminar and Turbulent Flow, Stanford Univ., July 1991.
3. Briley, K. R., "A Numerical Study of Laminar Separation Bubbles Using the Navier-Stokes Equations," J.F.M. 47, 1971.

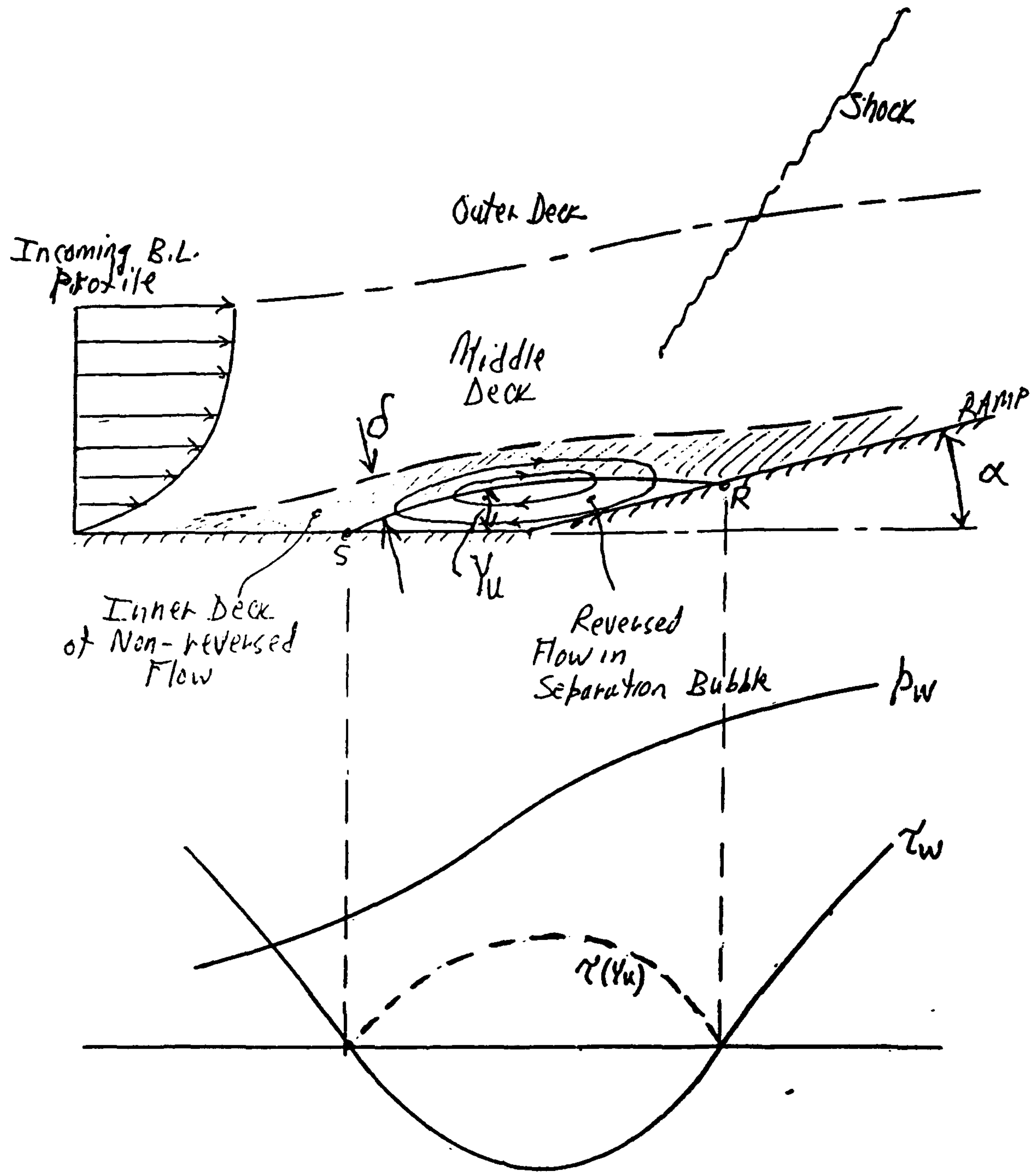


Fig. 1 Multiple-Decked Configuration of Compression Corner Interaction Region

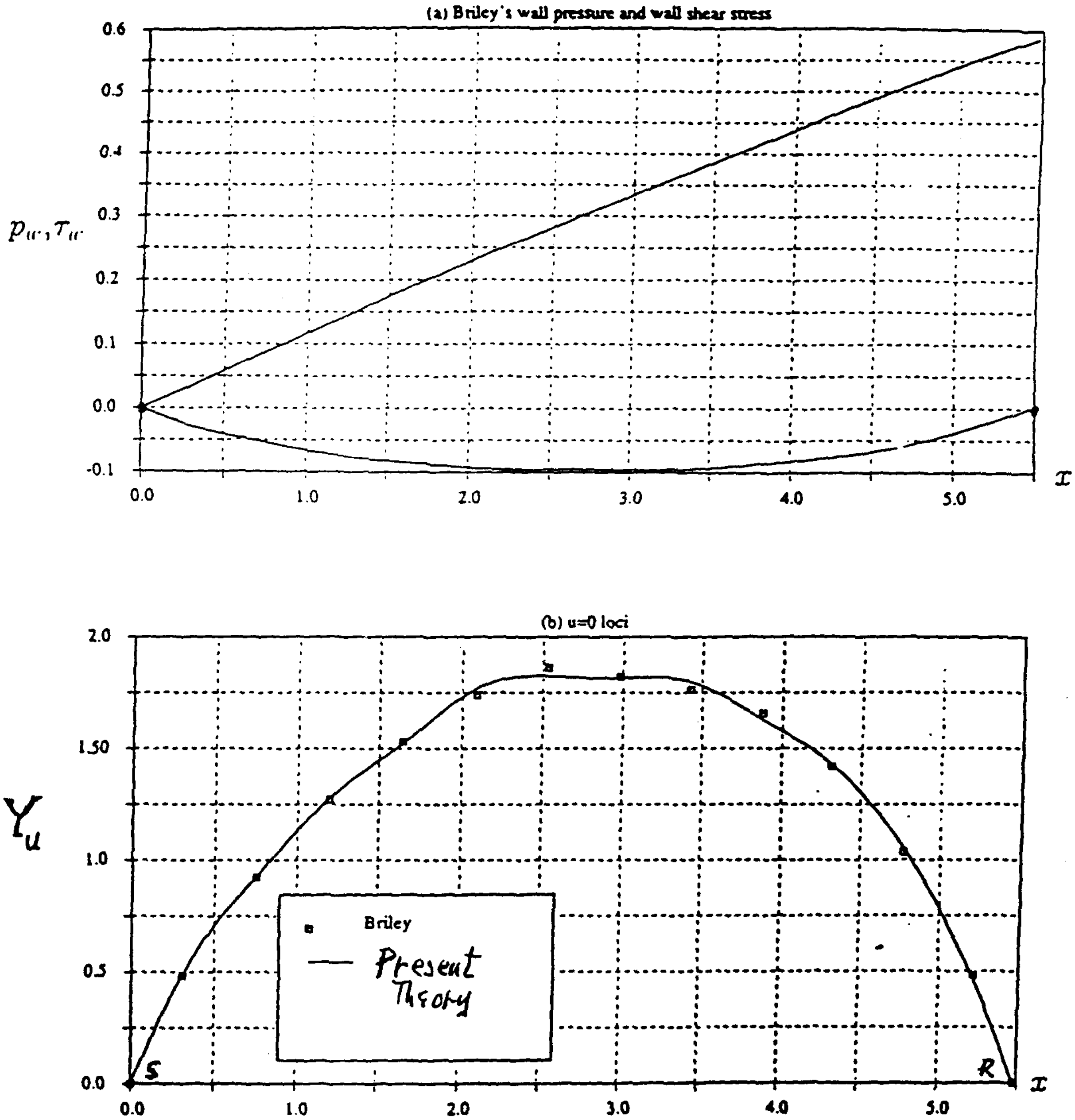


Fig. 2. Comparison of Present Reversed Flow Region Theory with Brileys Exact Navier Stokes Solution for a Separation Bubble

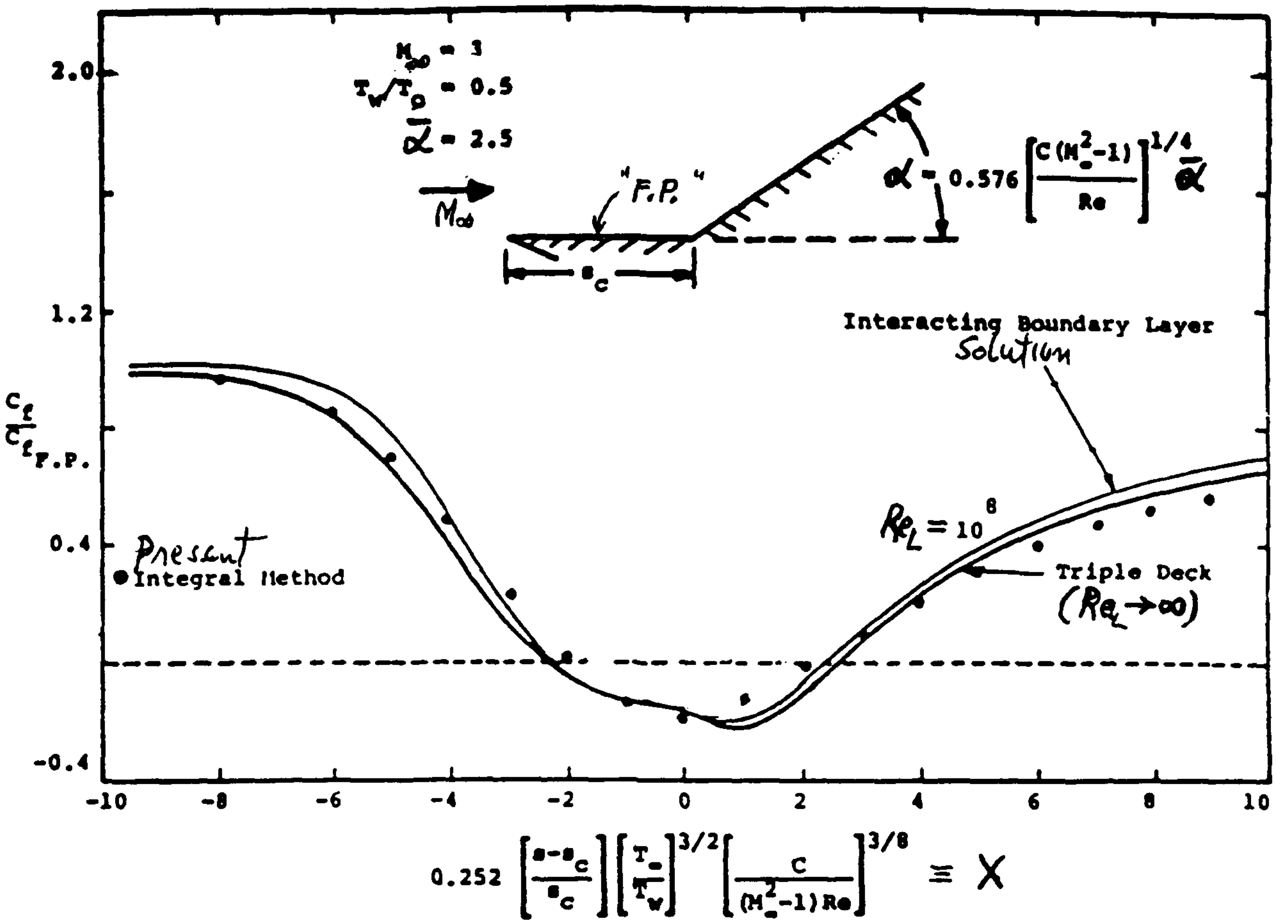
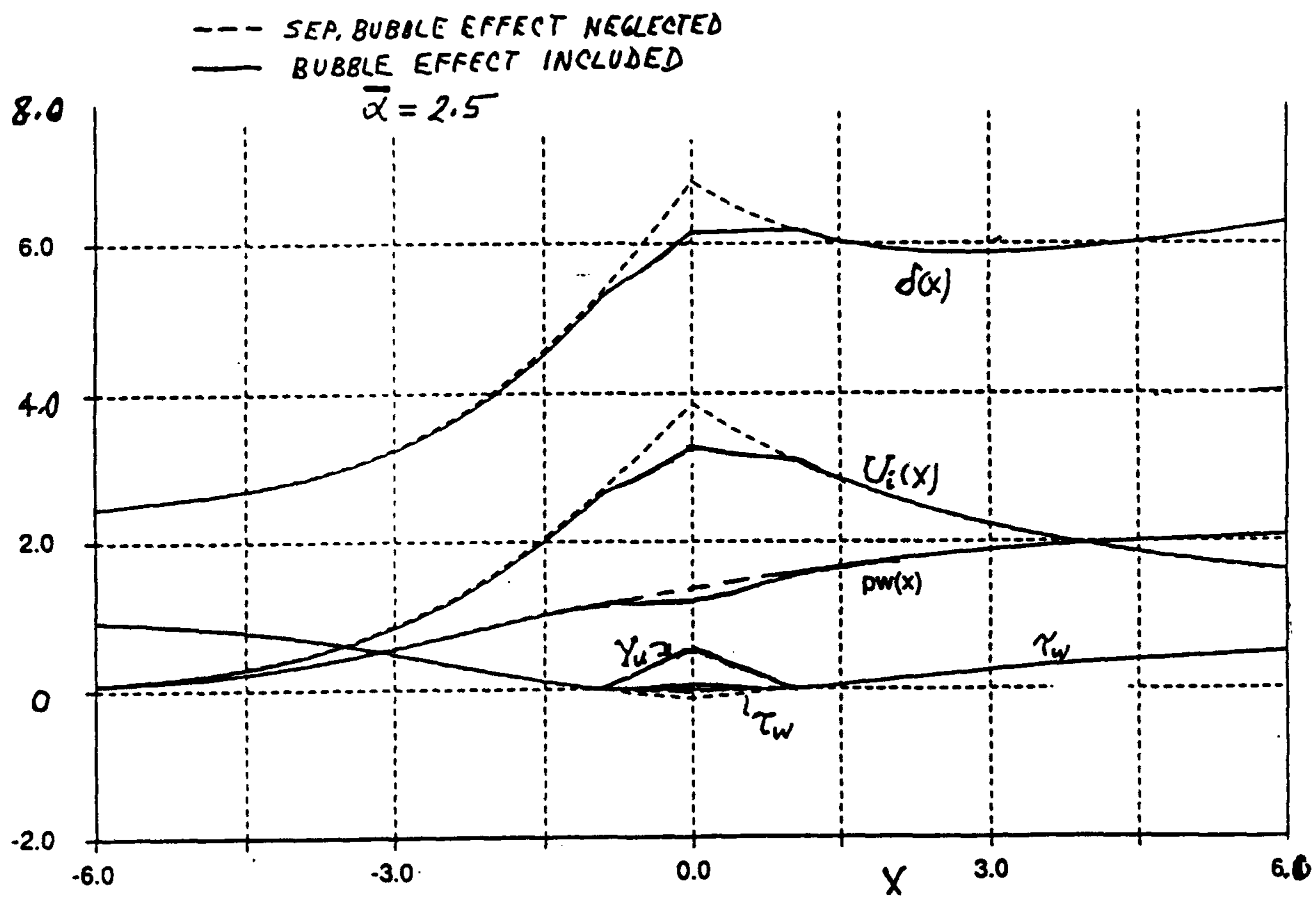


Fig. 3 Comparison of Present Interaction Solution with Separation with Exact Solutions of Rizzetta



Figures for Report

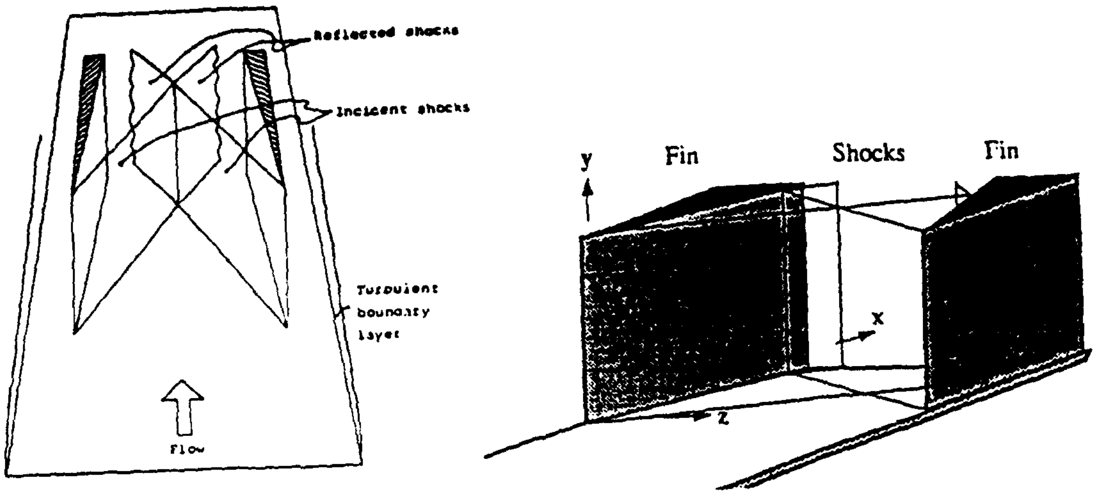


Fig. 1 Crossing-Shock Interaction Problem for High Speed Inlets

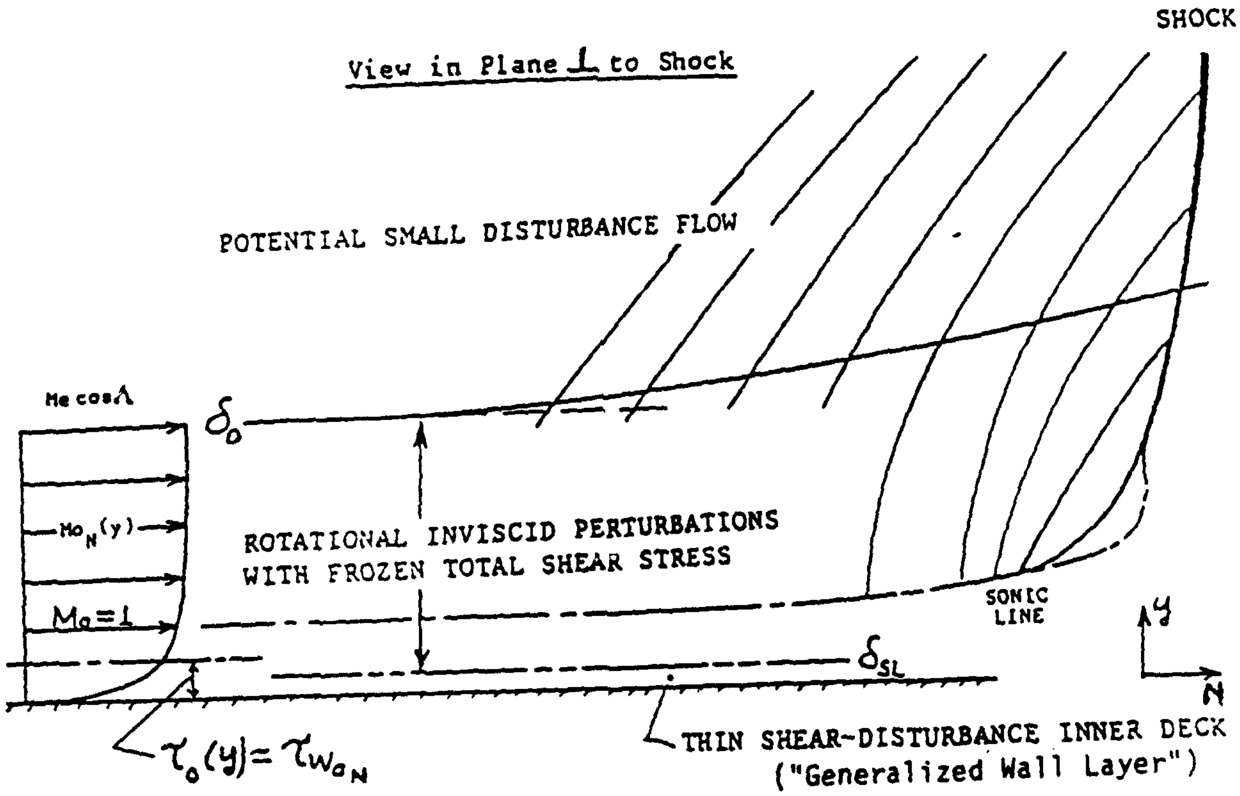


Fig. 2 Typical Triple-Deck Structure of a Shock/Boundary Layer Interaction Zone

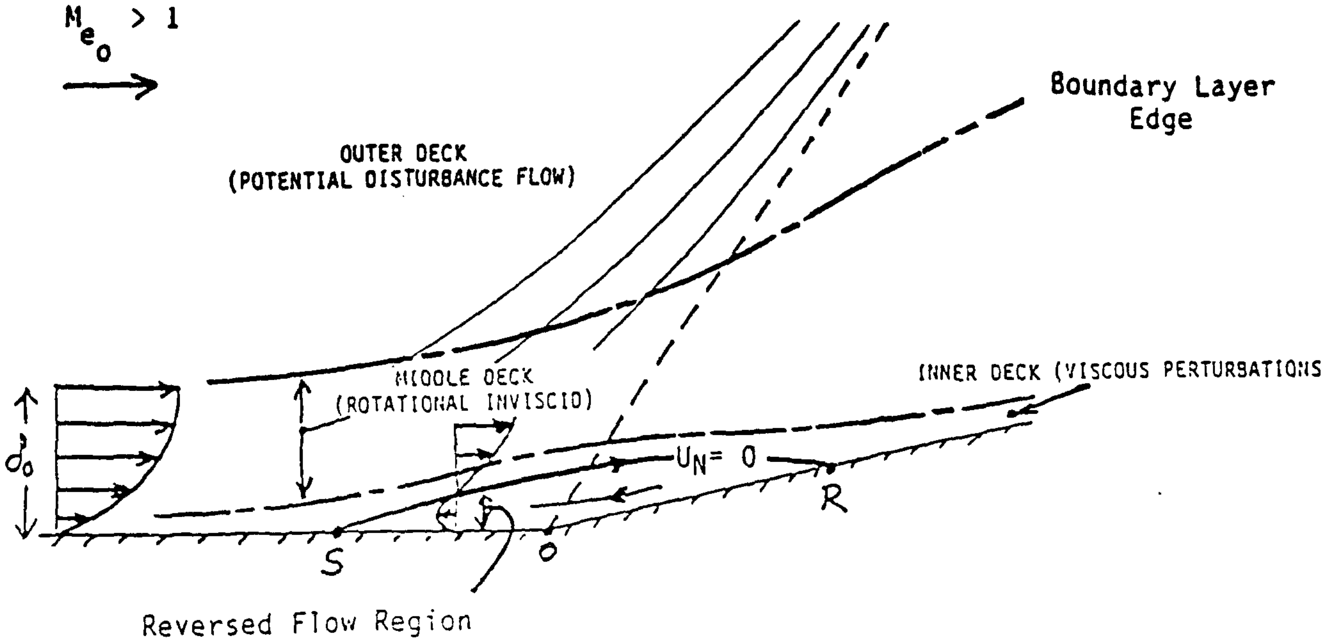


Fig. 3 Detail of Reversed Flow Structure at Bottom of Wall Layer

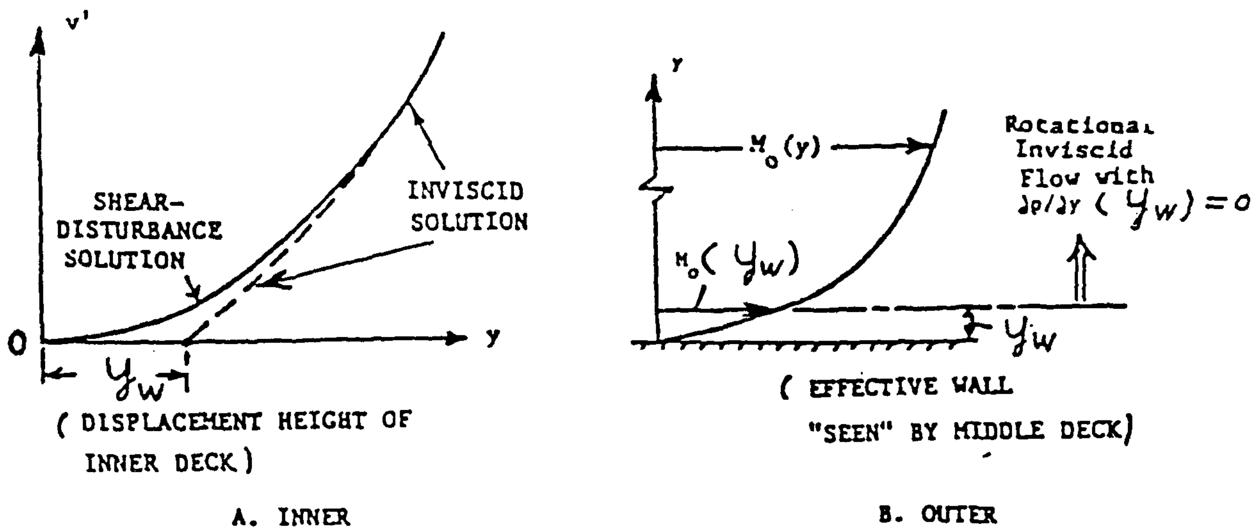


Fig. 4 Middle Deck Matching to the Wall Layer by the Displacement Thickness Concept

Top View