Assessment of a 3-D Boundary Layer Code to Predict Heat Transfer and Flow Losses in a Turbine*

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The prediction of the complete flow field in a turbine passage is an extremely difficult task due to the complex three-dimensional pattern which contains separation and attachment lines, a saddle point and a horseshoe vortex (Fig. 1). Whereas, in principle such a problem can be solved using full Navier-Stokes equations, in reality methods based on a Navier-Stokes solution procedure encounter difficulty in accurately predicting surface quantities (e.g. heat transfer) due to grid limitations imposed by the speed and size of the existing computers. On the other hand the overall problem is strongly three-dimensional and too complex to be analyzed by the current design methods based on inviscid and/or viscous strip theories. Thus there is a strong need for enhancing the current prediction techniques through inclusion of 3-D viscous effects. A potentially simple and cost effective way to achieve this is to use a prediction method based on three-dimensional boundary layer (3-DBL) theory. The major objective of this program is to assess the applicability, using the data in Ref. 1, of such a 3-DBL approach for the prediction of heat loads, boundary layer growth, pressure losses and streamline skewing in critical areas of a turbine passage. A brief discussion of the physical problem addressed here along with the overall approach and some calculated results is presented in the following paragraphs.

In the present investigation, zonal concepts are utilized to delineate regions of application of 3-DBL theory -- these being the endwall surface, suction surface and pressure surface as shown by the shaded regions of Fig. 1. The zonal concept employed in this investigation implies that there exists a thin region near the surface dominated by wall pressure forces and friction forces so that boundary layer theory is valid provided that the proper inflow conditions and boundary layer edge conditions are applied. Although the pressure surface boundary layer shows weak three dimensional effects on a stationary blade, the endwall surface boundary layer shows strong three dimensional effects due to sweeping of the boundary layer across the passage from the pressure to the suction surface, and the suction surface boundary layer shows strong effects due to the nearby passage vortex which sweeps the boundary layer away from the endwall. These strong three dimensional effects should provide a rigorous test of the zonal application of 3-D boundary layer theory to this problem.

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The zonal approach requires three distinct analyses (See Fig. 2). A modified version of the 3-DBL code (Ref. 2), named "TABLET" (Three-Dimensional Algorithm for Boundary Layer Equations in Turbulent Flow) is used to analyze the boundary layer flow. This modified code solves the finite difference form of the compressible 3-DBL equations (including the energy equations) in a nonorthogonal surface coordinate system which includes coriolis forces produced by coordinate rotation. These equations are solved using an efficient, implicit, fully coupled finite difference procedure. The nonorthogonal surface coordinate system (including the metrics and direction cosines) is calculated using a general analysis based on the transfinite mapping of Gordon (Ref. 3) which is valid for any arbitrary surface. Experimental data is used to determine the boundary layer edge conditions. In this study the boundary layer edge conditions (free stream velocity and velocity gradients) are determined by integrating the boundary layer edge equations, which are the Euler equations at the edge of the boundary layer, using the known experimental wall pressure distribution. Starting solutions along the two inflow boundaries are estimated by solving the appropriate limiting form of the 3-DBL equations.

Test cases were selected from an experimental study by Graziani et.al.(Ref. 1) of a large scale turbine blade cascade. The solution of the boundary layer flow on the endwall surface is shown on Fig. 3. This solution, which is for the thick boundary layer case of Ref. 1, was started using locally similar solutions of the boundary layer equations along the two inflow boundaries assuming that the cross flow velocity can be neglected. The computational domain extends from just downstream of the saddle point to the blade trailing edge. Fig. 3 shows a comparison of the measured and calculated limiting streamlines, where the calculated streamlines are represented by the direction of the local wall shear force vector. A comparison of the measured and calculated local Stanton number was presented at a previous HOST workshop. Although the inflow conditions along the upstream boundary are not duplicated precisely because of the saddle point, the overall prediction of the flow direction and heat transfer (Stanton number) is encouraging.

The second test case is for the suction surface, described in (Ref. 1) and the results are shown on Figs. 4 through 7. Fig. 4 shows the surface coordinates used in this calculation generated by the coordinate analysis. The computational domain extends from a point downstream of the blade leading edge to the blade trailing edge and from the endwall to the midplane (which is a plane of symmetry). Again, local similarity solutions were used for the inflow boundaries, and the boundary layer edge conditions were obtained from the experimental pressure distribution. Fig. 5 shows the boundary layer edge conditions calculated by the boundary layer edge analysis using the experimental pressure distribution. The plotted velocity vectors show a strong crossflow produced by the passage vortex and no flow across the plane of symmetry. Fig. 6 shows a comparison of the measured wall limiting streamlines with the calculated wall shear force vector. Again the strong cross flow near the blade trailing edge is shown. The magnitude of the wall shear force vector indicates a boundary layer approaching separation near the trailing edge. A comparison of the measured and calculated heat transfer (Stanton number) is shown on Fig. 7. The predictions of flow angle are very encouraging. The predictions of heat transfer are more sensitive to inflow conditions and turbulence modeling and need further refinement.

It is planned to use this analysis for predicting the wall limiting streamlines and heat transfer on the pressure surface of a rotating turbine blade, which includes coriolis forces, to complete this preliminary assessment of the applicability of 3-DBL theory for analysis of viscous flow in a turbine passage using the zonal concept.

References

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3. Gordon, J. W. and Thiel, L. C.: Transfinite Mappings and Their Application to Grid Generation; Numerical Grid Generation, F. Thompson Ed., Elsevier Science Publishing Co. Inc., 1982.

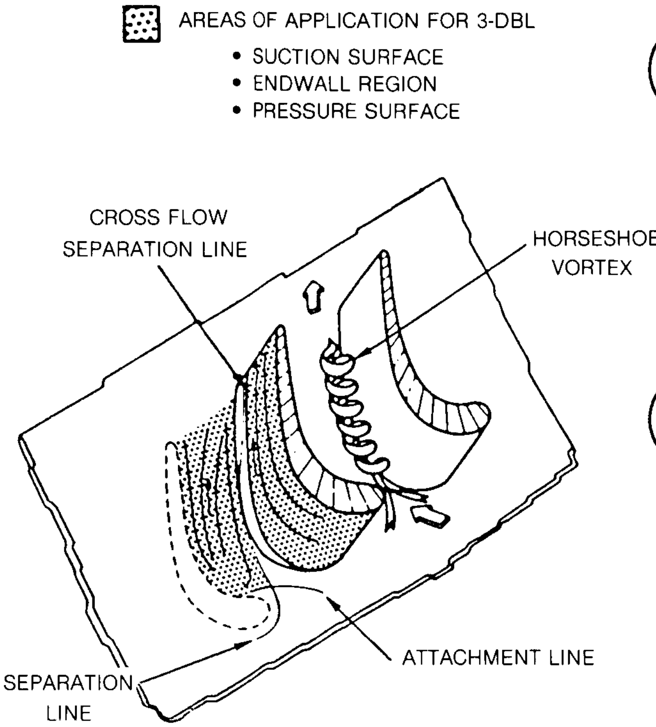

Fig. 1 Flow in a Turbine Passage

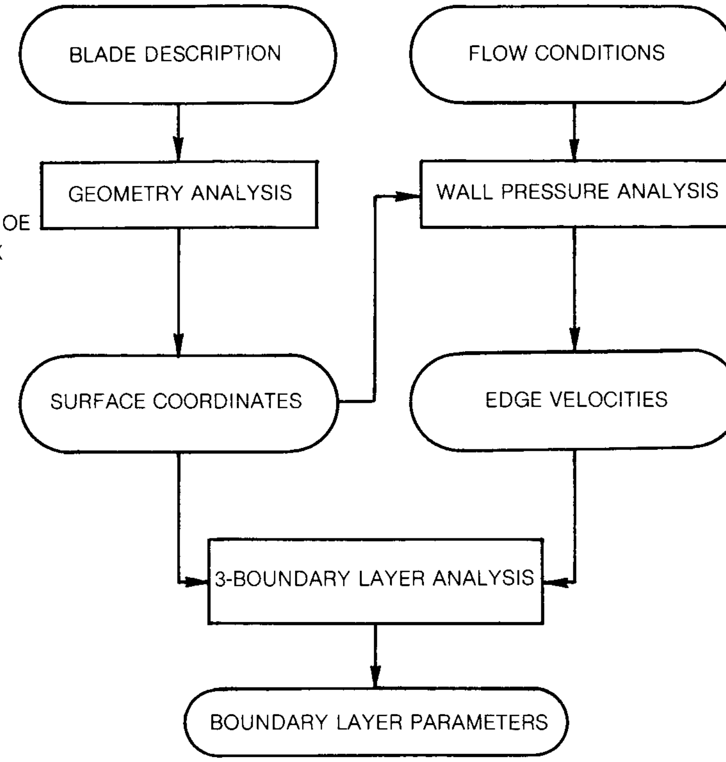

Fig. 2 Flow Chart of Geometry, Wall Pressure and 3-D Boundary Layer Analysis

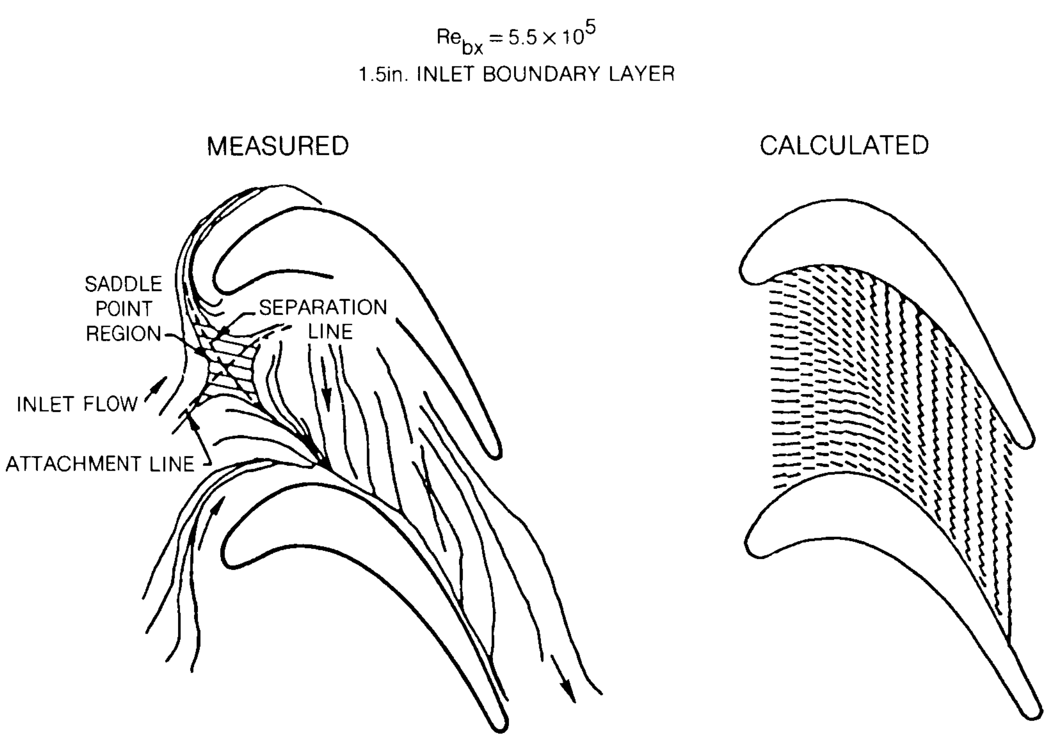

Fig. 3 Comparison of Measured and Calculated Endwall Limiting Streamlines

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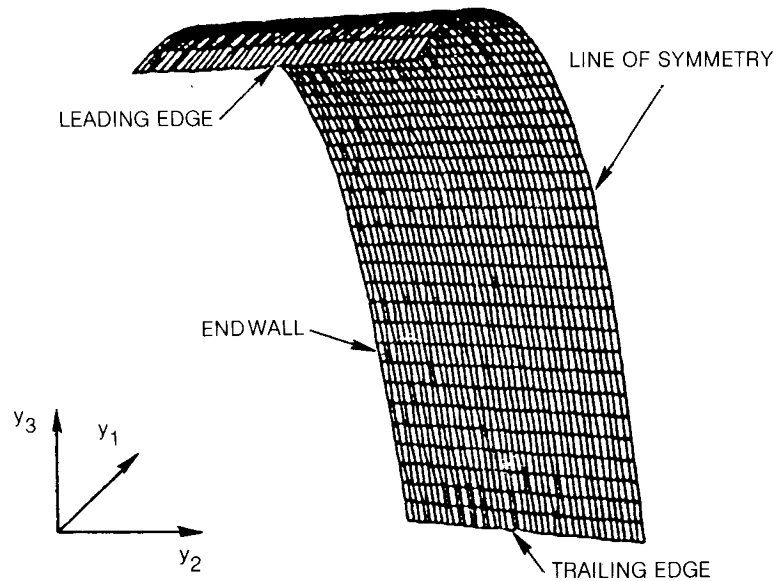

Fig. 4 Coordinate System Calculated for Suction Surface

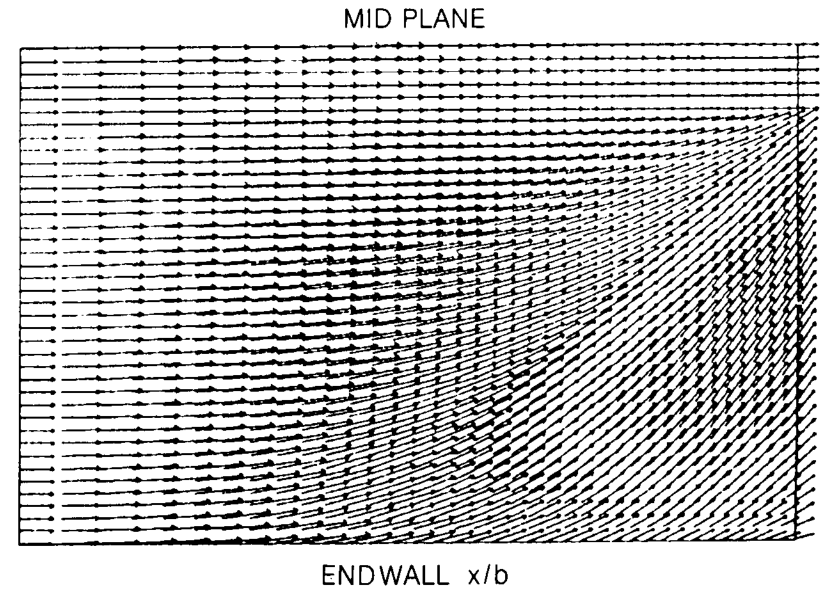

Fig. 5 Calculated Boundary Layer Edge Conditions

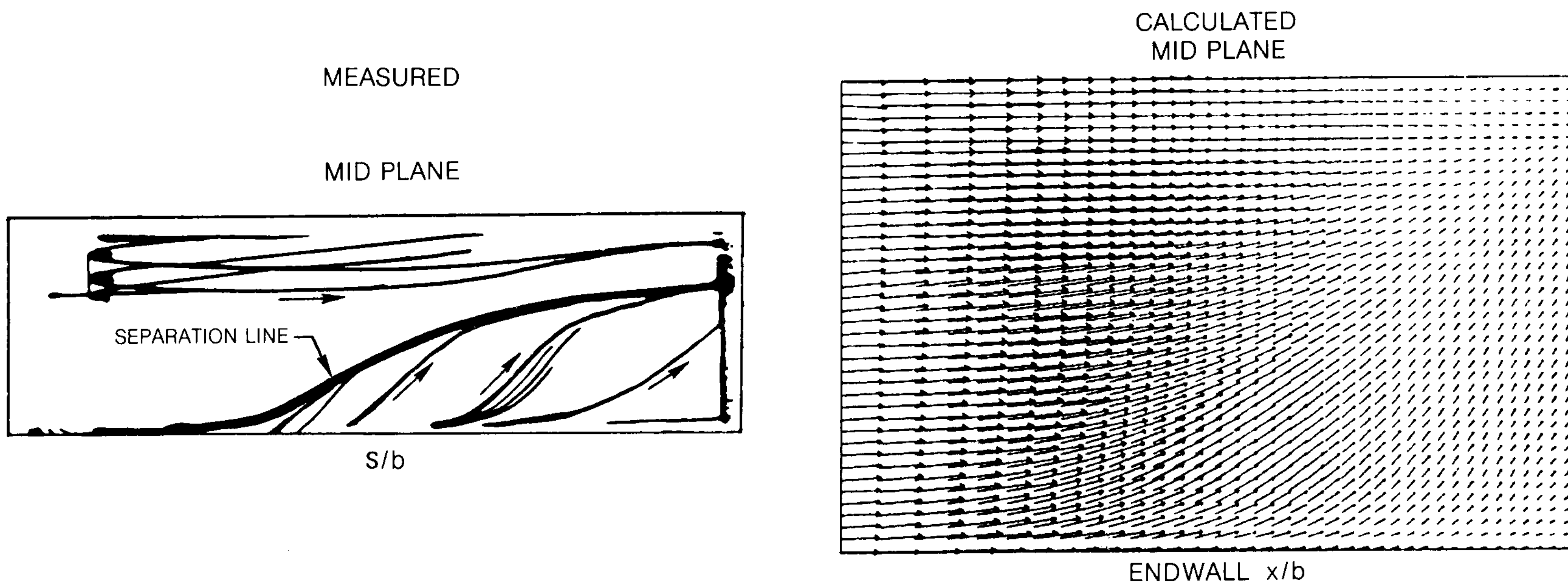

Fig. 6 Measured and Calculated Suction Surface Limiting Streamline

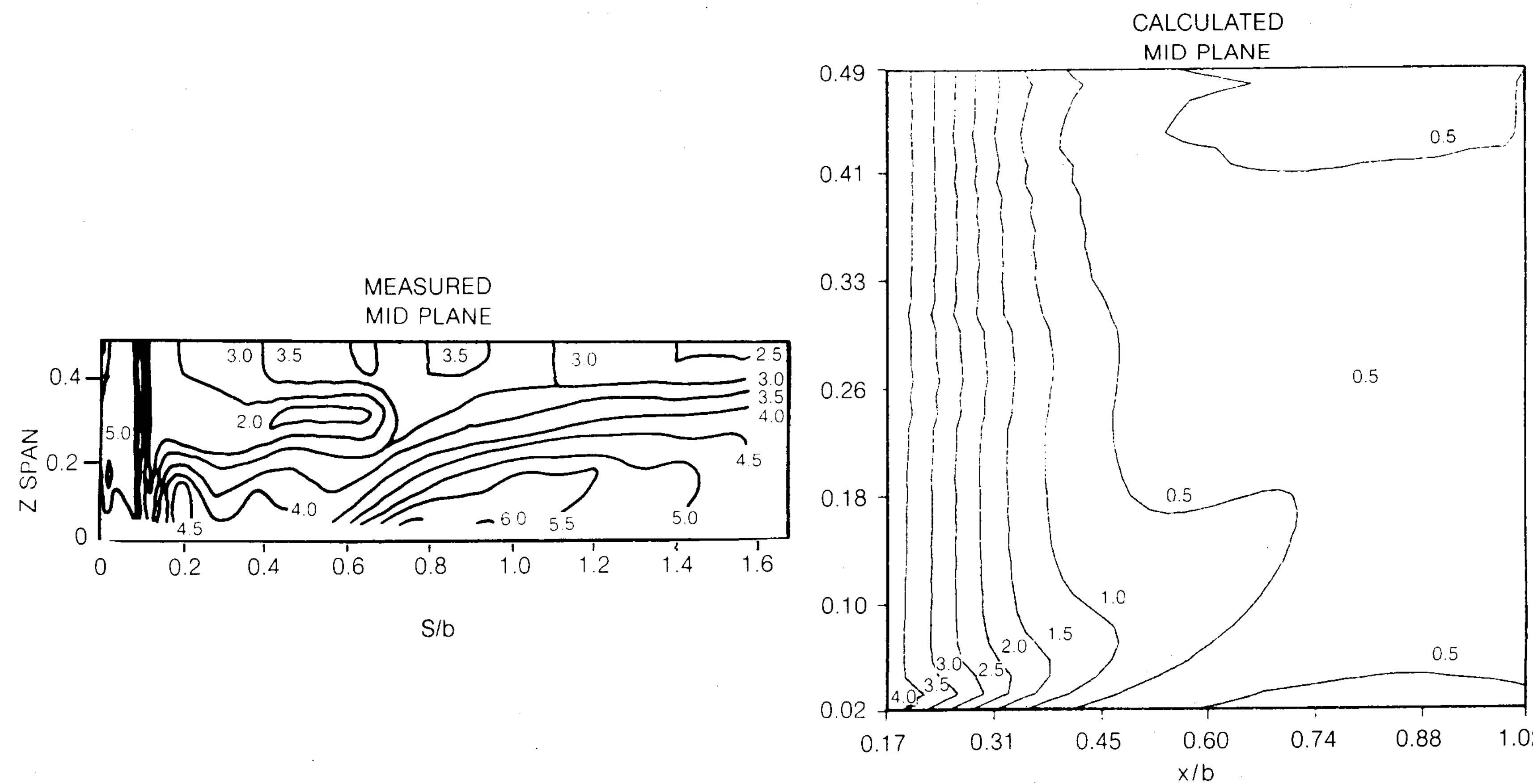

Fig. 7 Measured and Calculated Suction Surface Stanton No. Contours