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FLOW RESEARCH COMPANY

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Flow Research Note No. 118

Study of Design and Analysis Methods for Transonic Flow

by

Earll M. Murman

Final Report

Contract NAS2-8847

July 1977

Submitted to

NASA Ames Research Center

Moffett Field, California 94035

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Summary

During the contract period, three tasks were completed. Task I consisted of developing an airfoil design program and incorporating a boundary layer analysis. Task II involved deriving boundary conditions for ventilated transonic wind tunnels and performing transonic wind-tunnel wall calculations. Task III consisted of formulating a computational procedure for rotational transonic flow in engine inlet throats. The work accomplished during the contract, including significant conclusions, is summarized below by task.

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*Final Report, NASA Contract NAS2-8847.

1. Task I - Airfoil Design Program

An integral boundary layer method including a laminar boundary layer, transition, a turbulent boundary layer, and a first-order shock-wave boundary-layer interaction model was coded and coupled to the two-dimensional airfoil program TSFOIL. The boundary layer program is a modified version of the one written by McNalley (1970), which is well documented. A Nash-Hicks turbulent shear stress model was added to the program to account for "history effects" in the turbulent boundary layer. In addition, a shock-wave boundary-layer interaction model developed by Reshotko and Tucker (1955) also was added to the turbulent boundary layer code to account for the jump in displacement thickness through the shock. Smoothing of the resulting discontinuity was required to yield a realistic solution. Figure 1 shows a calculated boundary layer result. An empirical extrapolation of the displacement surface is required at the trailing edge. A copy of this computer program was delivered to the Project Technical Monitor, Mr. Ray Hicks.

The above program was coupled to TSFOIL, and calculations were done for an NACA 0012 airfoil. A viscous wedge model was used in the inviscid calculation to properly locate the shock wave. The formulation of this model and the computed examples were reported in the progress report for the sixth quarter of the contract. Coupling of the entire viscous-inviscid program to the optmization program COPES was formulated, and the subroutines were written. Flow charts for the boundary layer calculation and design program are shown in figures 2 and 3.

There are several tasks which could be done to extend the above work. The first is to incorporate the trailing edge "boundary layer" model of Melnik and Mead (1977) to avoid ad hoc smoothing of the boundary layer in this region. The second task is to couple the boundary layer program to Jameson's full potential equation code for two-dimensional airfoils by using the conservative finite-volume method. Some work was done in the early stages of this contract to accomplish this for FL06, but this work was not completed. The third task is to run more cases to be compared with experiment. The fourth task is to extend the entire method to transonic flows involving heat transfer, such as for turbine blades. The basic McNalley program already contains the heat transfer capability.

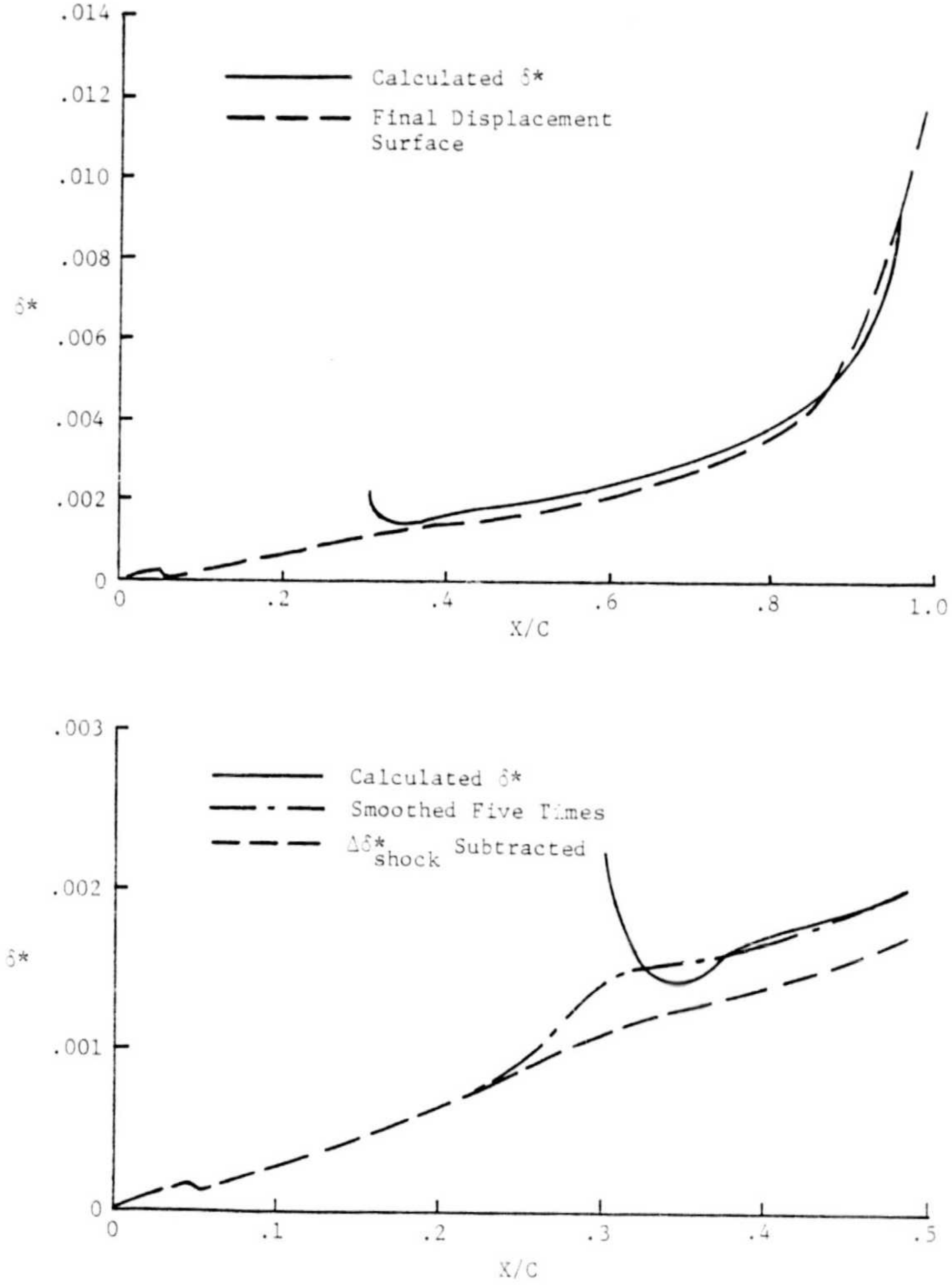


Figure 1 NACA 0012. M - .72, $\alpha = 2^{\circ}$.
Displacement Thickness Calculated Using McNalley Program and Roshotko-Tucker Jump Conditions -- Upper Surface Only

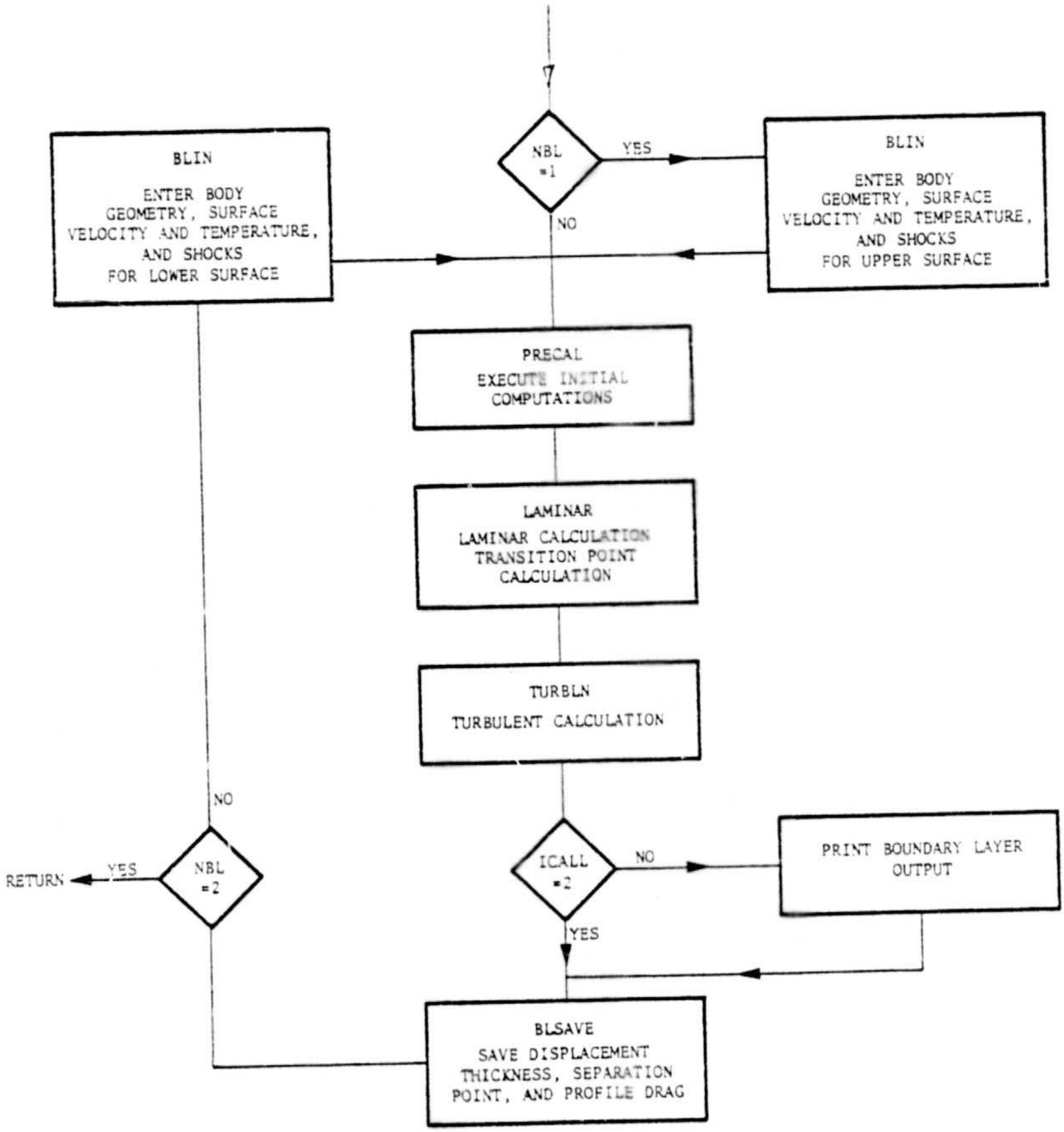


Figure 2   Flow Chart for Subroutine BLAYER

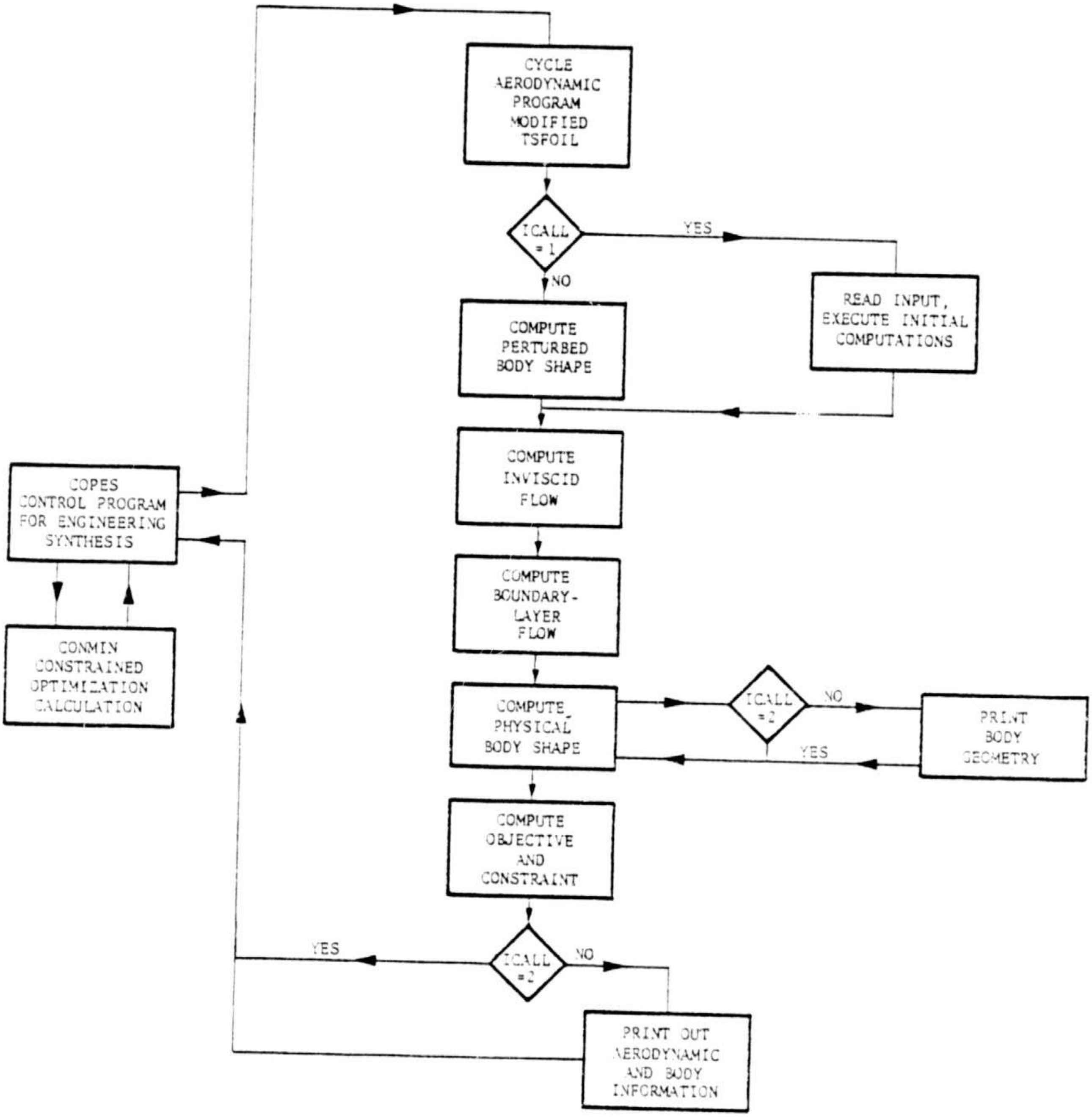
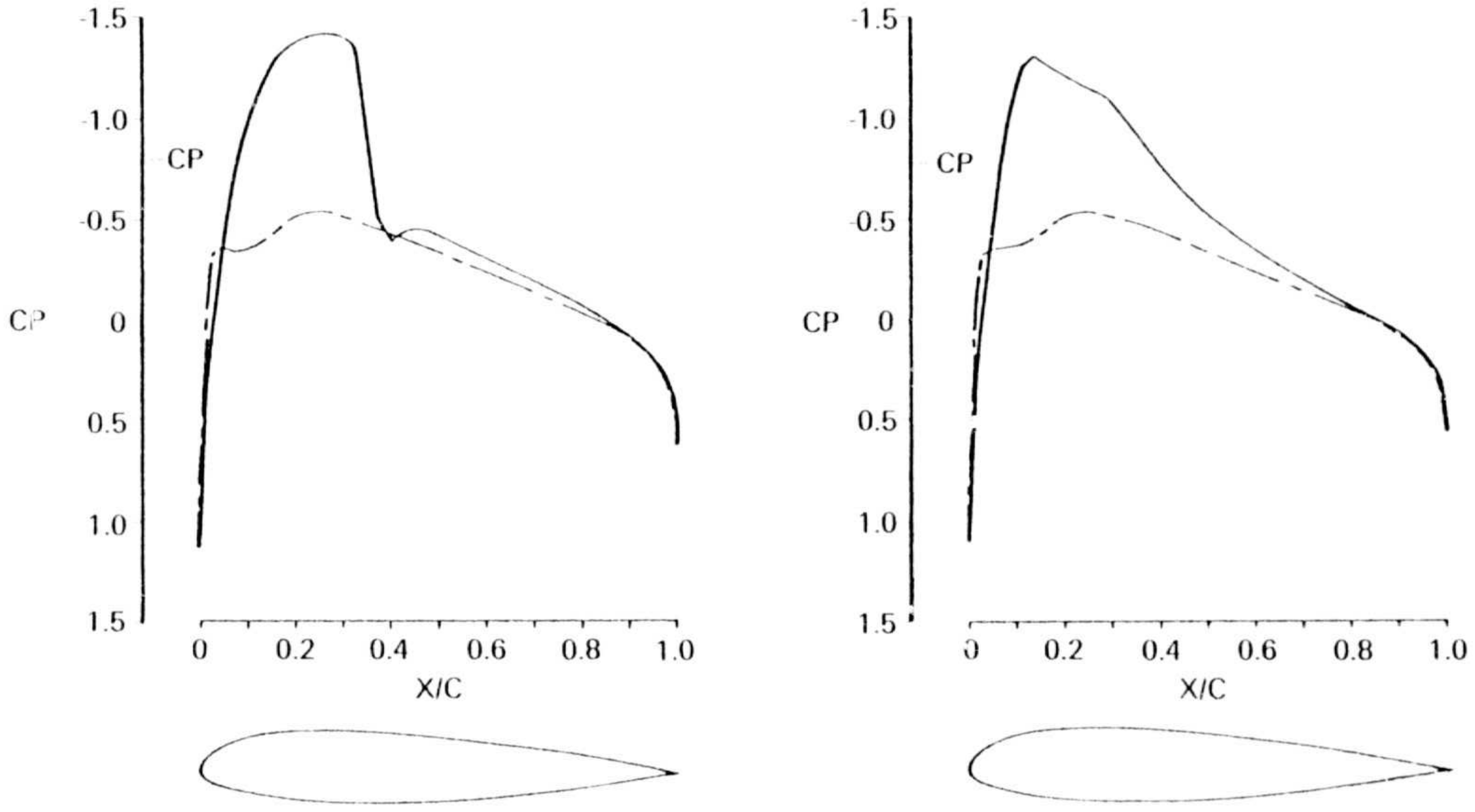


Figure 3 Flow Chart for Airfoil Design Program

Considerable effort was devoted to examining improved methods of parametrically representing the airfoil geometry for optimization calculations. These methods were fully reported in progress reports. The methods studied included cubic splines, polynomials, super ellipses, modified trigonometric functions, and quadratic splines. The most successful methods are ones that are defined, and are smooth and continuous over the entire airfoil surface. A calculation performed with the cubic spline method is shown in figure 4.



M = .700 ALPHA = 0.00°
CL = .25 CD = 0.0024 CM = -.006
INVISCID METHOD: Jameson-Conservative
BOUNDARY LAYER METHOD: NONE
NACA 23015

(a) Initial Airfoil

M = .700 ALPHA = 0.00°
CL = .26 CD = -.0005 CM = -.010
INVISCID METHOD: JAMESON-CONSERVATIVE
BOUNDARY LAYER METHOD NONE
NACA 23015 UPPER SURFACE MOD

(b) Optimum Airfoil

Figure 4 Design of Low Drag Transonic Airfoils Using Optimization Methods

2. Task II - Wind-Tunnel Wall Interference Study

Far-field formulae were derived for a source, doublet and vortex in a ventilated transonic wind-tunnel with contoured walls. These formulae may be used for upstream and downstream boundary conditions for finite-difference calculations of transonic wind-tunnel wall interference. The "derivation" of the equations and discussion of the results were reported by Smithmeyer and Murman (1976).

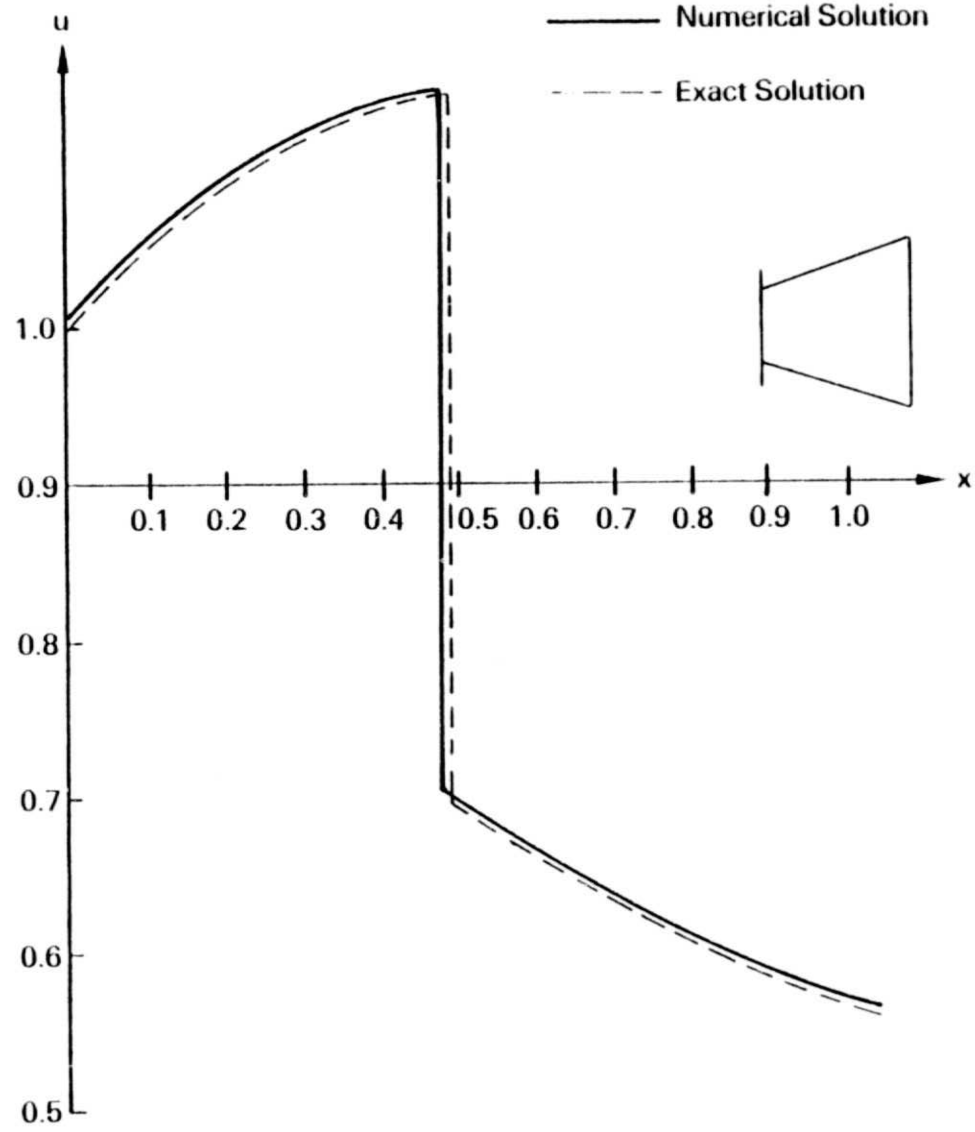
The general homogeneous wind-tunnel wall boundary condition was incorporated in the program TSFOIL, and several representative calculations were completed. Three finite-difference formulations were considered, and two were tested. The calculations converged for a low value of porosity (P = .25) but failed to converge for higher values of porosity.

A number of calculations were done to test the sensitivity of wind-tunnel wall calculations to the upstream and downstream boundary conditions. If the boundaries are located far from the airfoil, there is no significant effect on the airfoil pressure distribution. This result has led to the concept of modeling an actual test section by using $\phi_y = 0$ for the upstream boundary condition located at the test section entrance, and ϕ_x or $\phi_{xx} = 0$ on the downstream boundary located at the test section exit. Previous work had been directed at modeling tunnels extending to infinity in the upstream and downstream directions. The use of these simple upstream and downstream boundary conditions will allow the use of more complicated forumlae in place of the classical homogeneous tunnel wall boundary conditions to model the porous walls.

3. Task III - Rotational Flows

Several formulations for computing rotational inviscid transonic flows were studied. Results showed that internal transonic flows with subsonic exit boundary conditions are fundamentally different from external transonic flows. For example, for one-dimensional converging-diverging nozzle flows, it is well known that no isentropic solution exists for a wide range of downstream boundary conditions. In contrast to this, no such non-existence proofs are known for external flows. Thus, internal transonic flow calculations require some fundamentally different equations, difference algorithms and iteration procedures. These were studied in the course of the work and have been written in report form. The report by Rizk and Murman (1977) will be distributed soon. A one-dimensional calculation was completed and is shown in figure 5. This model problem uses the numerical procedures that will be extended to two-dimensional calculations under separate funding from NASA-Ames.

As part of the work of this task, the suitability of transonic small-disturbance theory for internal flows was critically examined. It was found that, because of the non-uniqueness of isentropic internal flows under some conditions, the range of applicability of small-disturbance theory to internal flows in solid wall channels is limited to a small class of flows. It is believed that if the exit conditions are subsonic, the usual small-disturbance theory may be restricted to conditions where the embedded supersonic zones do not extend all the way across the channel.



$(\varrho A\phi_x)_x = 0$

$\phi(0)$, $\phi_x(0)$ Given

$\phi(1)$ Given

Figure 5 One-Dimensional Numerical Example

4. Other Related Activities

Three talks were presented as a direct result of work done on this contract. They are:

Murman, E. M. "Review of Some Numeric Solutions of the Transonic Small-Disturbance Equation," presented at Symposium Transsoniccum II, Gottingen, Germany, September 1975.

Murman, E. M. "Calculations of the Transonic Small-Disturbance Equations," presented at the ONR Transonic Flow Conference, UCLA, March 1976.

Rizk, M. H. and Murman, E. M. "Rotational Transonic Flows in Ducts and Nozzles," presented at the Third AIAA Computational Fluid Dynamics Meeting, Albuquerque, New Mexico, June 1977.

Five visits were made to NASA Ames to work jointly with the project officer Ray Hicks and to execute computations on the Ames CDC 7600.

References

McNalley, W. D. (1970) "FORTRAN Program for Calculating Compressible Laminar and Turbulent Boundary Layers in Arbitrary Pressure Gradients," NASA TN D-5681.

Melnik, R. E. and Mead, H. R. (1977) "Theory of Viscous Transonic Flow Over Airfoils at High Reynolds Number," AIAA Paper 77-680, June.

Reshotko, E. and Tucker, E. (1955) "Effect of a Discontinuity on Turbulent Boundary Layer Thickness Parameters With Applications to Shock Induced Separation," NACA TN 3454.

Rizk, M. and Murman, E. M. (1977) Transonic Non-Insentropic Internal Flows, Flow Research note to be published.

Smithmeyer, M. G. and Murman, E. M. (1976) "Far-Field Boundary Conditions for Airfoils in Transonic Wind Tunnels." Flow Research Report No. 78, December.