blade boundary layer occurred in a small bubble at the foot of the shock, no gross separation was present. This absence of gross separation can be attributed to the favorable pressure gradients in the trailing edge region.

4 Comparison Between Some Calculations and the Measurements

This section presents the results of a comparison between the measured flows and the numerical predictions from a limited number of calculation methods developed for inviscid flow. Initial calculations showed that direct comparisons of the measured and calculated flow fields at the same back pressure ratio were unsatisfactory. The reasons for the discrepancies are believed to be associated with the growth of the boundary layers on the tunnel side wall and with the presence of the wake. Instead, in the comparisons presented below the back pressure ratio in the calculations has been chosen to give the best overall agreement with the measured flow field in respect of both shock position and peak suction. The changes in back pressure ratio needed are relatively small and it should be pointed out that Denton’s fully three-dimensional method \(^2\) predicts flows developing in just the same way as in the experiments.

Figure 6 shows the measured isobars on the surface of the thin-thick-thin blade at each of two back pressures compared with corresponding sonic lines from Denton’s three-dimensional program at two slightly lower back pressures. The higher speed case is particularly interesting, showing the predicted shock to be planar, just as measured; there is, however, some discrepancy near the leading edge. A similar comparison for the swept blade is shown in Fig. 7, where, for clarity, only sonic-line positions are shown. The failure of the numerical method to reproduce the measured flow near the root is believed to be due to the coarse grid which had to be used because of computer storage restrictions.

Figure 8 shows a comparison between sonic lines calculated by Denton’s three-dimensional program and those calculated by a two-dimensional version of the program used in strip theory mode. These calculations were made at the same back pressure ratio and correspond to the measured results shown in Fig. 6. As will be seen the strip theory approach fails completely to reproduce the main features of the flow giving a highly three-dimensional shock far too close to the trailing edge.

All of the calculations were made on an IBM 370-165. The fully three-dimensional calculations used about 2800 nodes in the flowfield, this being the maximum for which storage was available. These nodes were distributed more-or-less uniformly throughout the flowfield with a certain amount of refinement near the blade leading and trailing edges. Computations were continued for about 1000 iterations, requiring about 12-15 minutes of c.p.u.

5 Conclusions

The test results reported in this paper show that it is possible to generate highly three-dimensional transonic flows with embedded shock waves using relatively simple test geometries. Furthermore, it has been demonstrated that it is possible to avoid gross viscous effects by suitable choice of test conditions. Thus the results would appear to form ideal test cases for the inviscid calculation methods currently available for treating flows in blade-blade passages.

From the limited comparisons made with the predictions of some of these methods it is clear that in order to calculate the main features of the highly three-dimensional flows it is essential to use fully three-dimensional methods. Simple strip theory approaches are shown to be completely inadequate and this has important implications for the use and applicability of simple two-dimensional cascade testing of blade sections.

References


DISCUSSION

G. S. Settles

Shock wave/turbulent boundary layer interactions are inherently complex phenomena. Transonic flow adds another order of complexity, and in the full three dimensions these interactions must surely be the most difficult of all. (The fact that chemical reactions are not involved is small comfort.) Thus the authors are congratulated for making a start in a useful area where very little is known.

The primary value of this work lies in its exploratory nature: some phenomenology of 3D transonic flows is revealed; suggesting directions for future work. In such a case one expects that more questions will be raised than answers provided.

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The authors are to be commended for undertaking a very difficult task. It is essential that experimental data of this type be generated to provide suitable test cases for three-dimensional transonic computational methods. Although the geometries used are simple, resulting flow fields have most of the features found in complex three-dimensional flow fields. It was the intent of this experimental investigation to reduce the viscous effects as much as possible which I feel was accomplished. However, it may not be possible to reduce them to the extent where they need not be included in a computation used for comparisons with the data. This can only be determined by testing both inviscid and viscous computations for these geometries.

Since the authors intended these data to be used to test computation methods, there are a few points left out of this paper which should be addressed. For transonic flows of this type the boundary conditions employed in the computations can sometimes dominate the computed flow fields. The use of solid walls in this experiment provide well documented top and side boundary conditions for the computer. However, little is mentioned about the upstream and downstream boundaries. Many of the test cases are choked which makes the downstream boundary condition extremely important. The axial locations of both boundaries must be stated along with the measured pressures at these boundaries. In a computation one would like to prescribe the Mach number and total pressure at the upstream boundary and fix the static pressure at the downstream boundary. A minor point which is not clear to me is how accurately one determines boundary layer transition from surface oil-flow studies. Also, the data from the oil-flow studies should be made available as a check for those using viscous computations.

The calculations presented are extremely disappointing since substantial changes in free stream mach number (0.02 to 0.04) were required to obtain qualitative agreement with the data. There could be several reasons for this. Were tunnel side walls included in the calculations and if so, was an allowance made for side wall boundary layer growth? What type of boundary conditions were applied up and down stream of the test section? These points should be addressed. Finally, it could be viscous effects on the test models which cause these differences. I believe that if one is "allowed" to vary the wind tunnel test Mach number in a computation to obtain agreement with the data, the computational method is not completely validated as a predictive tool.

**Authors' Closure**

The authors thank Dr. Settles and Dr. Horstman for their helpful and constructive comments. The authors agree that despite the effort taken to reduce the influence of viscous effects it is necessary to compute the flow with a method which includes some allowance for viscous effects, although it is hoped that these can be taken into account without using a fully interactive program. A certain amount to work has been carried out by other workers (e.g. [14]) since the completion of the present work to try and quantify the extent of the influence of viscosity (including wall effects).

The success of any given computation method is very dependent on the boundary conditions employed. The method (2) used by the present authors treats the upstream boundary by fixing the total pressure, total temperature and flow angle and extrapolates the static pressure from interior points. Since there are no loss mechanisms upstream of the blade (i.e. no changes in total pressure) and since the manner of specifying the upstream boundary allows for non-uniform velocity, pressure and density fields then the boundary need not be more than about a chord length upstream of the blade. At the downstream boundary the static pressure (the "back-pressure") is fixed and other variables extrapolated. The back-pressures quoted for the experiments are the asymptotic values measured downstream of the blade. In the calculations the downstream boundary was sited far enough downstream for further downstream movement of it not to affect significantly the calculated pressure distribution on the blade itself. Although of course sidewalls were included in the calculations, no allowance could be made for sidewall boundary layer growth. One of the present authors (WND) is currently coding and testing a computational method for viscous compressible flow [15] and it is his intention to apply this method to the experimental configuration when the method is sufficiently developed.

**Additional References**