Comparison of Measured and Predicted Transonic Flow Around an Airfoil

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Abstract

A TWO-DIMENSIONAL numerical solution using an inviscid time marching method has been compared with interferometric data obtained from image plane holograms. This has been done over the whole blade profile including the trailing edge shock region, but a particularly detailed analysis has been made of the leading edge. The data obtained show isodensity/iso-Mach contours ($\Delta M = 0.03$), with a spacing of typically 50 μm between them. It was found that a highly refined grid size of similar resolution was required to compute an accurate solution.

Contents

Description of Flow

The two-dimensional airfoil section which was based upon a NACA 0010-34 profile[1] was mounted at zero incidence in the center of the tunnel on two supports from below. These were located within the tunnel flow, causing a 12% blockage of the throat area beneath the blade. It may be thought that such a large blockage would generate three-dimensional effects; previous oil flow and pressure measurements show this not to be the case.[1] They also show that despite a 5-mm-thick sidewall boundary layer the flow on the upper surface of the blade is two-dimensional for 90% of its span.

As a result of the partial blockage of the blade at the leading edge, the stagnation point has moved toward the pressure surface. The flow is seen to accelerate around the leading edge up to a maximum speed of $M = 1.25$ (Fig. 1). This can be compared with the computed flow solutions shown in Figs. 2-4. The flow remains attached around the leading edge and subsequently decelerated to a minimum Mach number of 1.06 at 10% of the blade chord. The suction surface of the blade then behaves in a more conventional manner, the supersonic flow being accelerated by the convex surface of the blade profile up to $M = 1.26$. It is also noted that the boundary-layer thickness at the trailing edge is 2 mm. This thickness has not been taken into account in the inviscid calculations.

Optical System

The optical system used in this experiment was similar to that applied previously[2] to turbine cascade, image plane holography. The interferometric fringes formed in the holograms represent iso-density contours and, hence, in the isoentropic region of the flow, iso-Mach contours.

The image plane approach has the advantage over alternative holographic systems in that it can yield high resolution data with minimum aberrations caused by diffraction and refraction of the light rays. However, it is not possible to compensate completely for these effects, as can been seen in the region of extremely high density gradient within the first 1 mm of the suction surface leading edge, Fig. 1. It is estimated that at the blade surface where the density gradient is 0.4 kg/m^3/mm of blade chord length there is an underestimate of Mach number of approximately 5% and a positional uncertainty of ± 5 μm.

A second source of error is the three-dimensionality of the flow. In particular, the sidewall boundary-layer thickness δ is of the order of 5 mm for a tunnel span of 114 mm. It has been shown previously[2] that this effect would result in an error of less than 1% in the calculated path length.

The interferometric method applied in this two-dimensional flow case has several advantages over other techniques in that the typical spacing between interferometric fringes around the leading edge was 50 μm compared with pressure tapping holes of 200 μm or laser anemometer measurement areas of 300-500 μm.

Time Marching Scheme

The numerical scheme applied to this problem was the three-dimensional version of Denton's inviscid time marching program.[3] It allowed a variable grid size to be introduced. The grid size was varied from approximately 100 μm to 5 mm in the x direction and 300 μm to 20 mm in the perpendicular direction. The method used was a standard program for calculating three-dimensional flow through turbomachinery blade rows (fixed or rotating) with splitter blades. In this approach the central grid line is replaced by two coincident grid lines. The grid lines then separate to form the airfoil profile. The upper and lower wind tunnel walls are treated as main blades with solid surfaces.

In order to produce the partial blockage the lower side tunnel wall was profiled differently than the upper side by treating the walls as "main" blades with thickness shown in Fig. 4. The amount of blockage corresponded to that created by the airfoil supports. Although the numerical blockage does not simulate the actual flow exactly, which may account for the difference in the shape of the contour levels between Figs. 1 and 2, the main effect is the same; i.e., to produce a large velocity increase and a strong two-dimensional normal shock under the blade. The solution was obtained by an $88 \times 30 \times 3$ point grid on a Perkin Elmer 3230 minicomputer taking 600 times steps and 100 min of CPU time. This is equivalent to about 10 min CPU on a large mainframe computer. The cusp used in this type of numerical scheme, Fig. 2, exerts no force on the flow.

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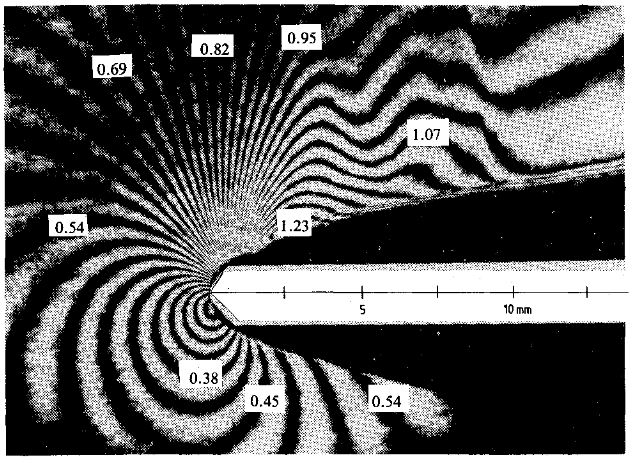

Fig. 1 Interferogram of blade leading edge.

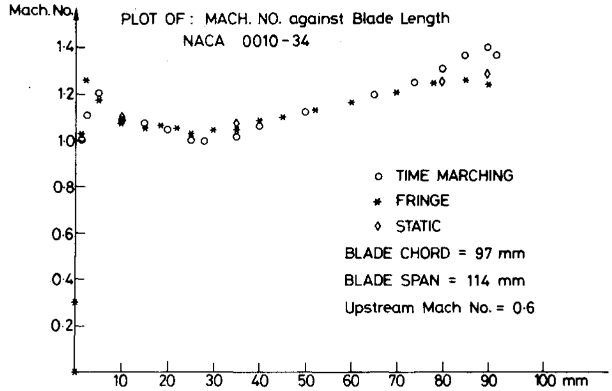

Fig. 3 Comparison between static pressure tappings, interferometric fringes, and time marching predictions over the airfoil for an inlet Mach number of 0.6.

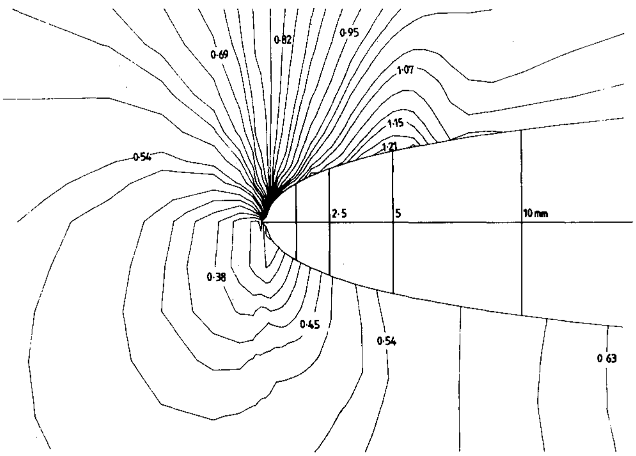

Fig. 2 Time marching prediction of blade leading edge.

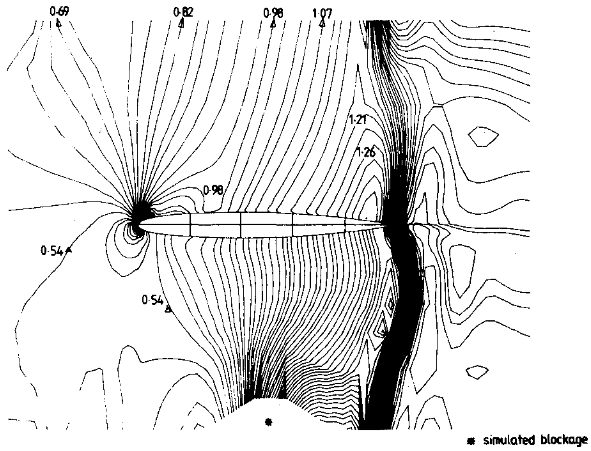

Fig. 4 Time marching prediction of the flow distribution.

Conclusions

The agreement between the calculated and measured flow around the airfoil section is good. The time marching scheme adopted predicts with high resolution the flow around the leading edge of the blade. The scheme is also in reasonable agreement over the remaining upper surface of the blade, including the trailing-edge region, although only a very coarse grid was used in this region.

The use of holographic interferometry in this experiment has been fundamental to the development and testing of the final scheme. It has produced high resolution data in a region of large acceleration around the leading edge of the blade.

References

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[3] Denton, J.D., "An Improved Time Marching Method for Turbomachinery Flow Calculation," ASME Paper 82-GT-239, April Meeting of the ASME International Gas Turbine Conference and Exhibition, Wembley, London, 1982.