COMPUTATION OF TRANSONIC FLOWS IN AND ABOUT TURBINE CASCADES WITH VISCOUS EFFECTS

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ABSTRACT

An inviscid-viscous interaction treatment has been developed to predict the flow through transonic axial turbine blade cascades. The treatment includes a trailing-edge base pressure model. This model is based on treating the area between the points of flow separation on the blade surfaces at the trailing-edge and the point of downstream confluence of the suction and pressure surface flows as a region of constant pressure. A time marching technique is used to calculate the inviscid flow and viscous flow is calculated by integral methods for laminar and turbulent boundary layers. Good agreement with experimental data has been obtained.

INTRODUCTION

The recent widespread adoption of the time marching (1-4) method for calculation of inviscid transonic turbomachine flow, including the prediction of shock waves, has led to improvements in the design of turbine blade profiles. However, relevant viscous effects, and in particular the effects of shock and boundary layer interactions, are important in the prediction of turbomachine flows. It has been demonstrated by the author (5 & 6) that considerable enhancement in the quality of flow computations in transonic turbines and compressors can be achieved by the inclusion of an integral blade surface boundary layer method in an inviscid time marching calculation for such flows. The boundary layer method used in the earlier flow calculation work (5,6) included a comparatively simple model for separated flows. It also used a relatively slow inviscid calculation technique with no special treatment of the base region for turbine blades.

Recently Denton (7) described an improved inviscid time marching method for the flow calculations in transonic turbine cascades. Based on this technique, an inviscid viscous treatment has been developed which can deal with shock and boundary-layer interactions and which also takes into account base pressure effects for turbine cascades. In the next section the main features of this treatment are described and in the subsequent sections inviscid and viscous methods are described. Comparisons between predictions and experimental data obtained for a number of transonic axial turbine blade cascades are then presented.

MAIN FEATURES

Essentially, the time marching method serves as a tool for determining the surface Mach number distribution (including shock waves where appropriate), this information being required for the blade surface boundary layer computation, which is an integral part of the iterative scheme. The computed surface boundary layers and downstream wake are then applied to the basic profile to produce a modified profile. This completes the first full iteration cycle. Modification of the profile alters the 'external' inviscid flow, but it is assumed that successive iterations will refine the interaction between the 'external' and boundary layer flows such that an equilibrium stage is eventually attained. For boundary layers which are attached or which approach separation only towards the rear part of the blade profile (attached up to 85% of the blade chord) this procedure is convergent. For turbine blade cascades with convergent passage this degree of attachment is normally the case. However, for blades with larger areas of turbulent separation (separation occurring earlier than 85% of the blade chord) an 'inverse mode', as suggested by Calvert (8) is used. In this mode the inviscid calculation is used to estimate the geometry required to produce a given velocity distribution and the boundary layer calculation finds the surface velocity distribution corresponding to that geometry. This inverse mode is used only up to the blade trailing edge. After the trailing edge a base pressure model is used. For blades with thick rounded trailing edge the flow is assumed to separate at the blend points of the trailing edge circle, see Fig. 1. Separation shocks followed by reattachment shocks may be present, depending on the overall pressure ratio. The area
between the points of flow separation (points A and B in Figure 1) on blade surfaces at the trailing edge and the point of downstream confluence (point C in Figure 1) of the suction and pressure surface flows is treated as a region of constant base pressure. This constant base pressure is estimated from Sieverding's (9) correlations.

TIME MARCHING METHOD FOR INVIScid FLOW CALCULATION

The inviscid free stream calculation is based on Denton's (7) improved time marching method. It is an opposed-difference scheme for solving the Euler-conservation-equations in finite volume form. It includes the effects of varying radius (with or without rotation) and varying stream-tube thickness with axial distance, i.e. the calculation is quasi-three-dimensional. The grid system is shown in Figure 2. In the cascade plane it is formed by a series of unevenly placed quasi-streamlines which are intersected by pitchwise lines at constant values of radius and axial position. The use of pitchwise lines greatly facilitates application of the periodicity condition between the bounding quasi-streamlines.
upstream of the blade passage. The direction of these bounding streamlines need not coincide with the flow inlet direction.

No mass is allowed to flow across the solid boundaries. Constant entropy conditions are applied for points on the blade surfaces. Entropy is allowed to increase only across shock waves. This reduces the effect of any numerical errors arising from the changes of flow properties which occur due to large leading edge radius of a blade.

Behind the trailing edge for the calculation in the base region, the flow is constrained to follow the separation streamlines e.g. lines A B and C B in Figure 3a. However, the exact location of the point B, both in the axial and in the tangential directions, and the shapes of the separation streamlines are not known. The only known quantity is the target base pressure (obtained from Sieverding's (9) correlation) along the separation streamlines.

In the present calculation for the sake of simplicity the separation streamlines are taken as straight lines. Starting from an initial guess for the point B, it is shifted both axially and tangentially till the static pressures along the lines A B and C B or along the lines A B1 and C B1 etc are equal to within 0.01% of the target base pressure. The shifting of the point B is done every 50 time steps as the iteration proceeds. The axial spacing of the pitchwise grid lines thus has to be very fine in the trailing edge region of the blade.

The following procedure is adapted to update the position of the point of confluence in its shifting cycle. Let us assume that the current cycle is the sixth, that the position B1 is to be determined (see Figure 3a) and that B2 and B3 were the positions in the previous two cycles i.e. in fifth and fourth respectively.

(a) on line A B determine the point which has the maximum drift from the target pressure (say point D).
(b) As shown in Figure 3b, using the relationship between the drift in pressure and the tangential location of the points D5 and D4 from the previous two cycles find the new location D6 which will make the drift in pressure equal to zero.
(c) Repeat the processes (a) and (b) for the pressure surface side of the base region and thus determine new location J6. It is worth noting that points of maximum drift on the suction side and the pressure side (points J5 and D5 in Figure 3a) need not be on the same pitchwise line.
(d) Join A with D6 and also C with J6 to obtain the new location for the point of confluence B1.
(e) Update the relationship between the drift in pressure and the tangential location, as shown in Figure 3b, for all the location points.

Downstream of the point B the orifice is taken to be of zero thickness but is treated as a solid boundary. It is moved in the tangential direction as the calculation proceeds in such a manner as to equalise the average pressure along the downstream suction and pressure wake boundaries.

**CALCULATION OF BOUNDARY LAYER**

An integral method is used to predict the blade surface boundary layers as these methods are considerably faster than differential methods and their results are of acceptable accuracy for the purposes of the aerodynamicist. The method can account for streamtube height variation along the blade surfaces. It also makes a correction for the pressure variation in the normal direction to the turbine cascades which arises due to large curvature changes of the blade. The method includes a simple procedure for calculating shock and boundary layer interaction effects. A full description of the boundary layer calculation can be found in references (5) and (6). Whilst calculating the boundary layer growth on a blade surface the method starts the computation from the stagnation point as a laminar boundary layer. This might undergo transition to the turbulent state before the trailing edge of the blade is reached. In the present calculation the transition, when it occurs, is taken as instantaneous such that the value of the boundary layer momentum deficit thickness is assumed unchanged.

**SOME RESULTS**

The method developed has been applied to determine the flow through a number of turbine cascades for which detailed experimental data is available.

For the results presented in the subsequent sections 19 x 75 grids were used. Run time per point per time step on an IBM 3081 was 1.07 x 10^-4 s. The first two test cases required 700 time steps for convergence. Compared to these Denton's 7) method needed 500 time steps for convergence. The number of time steps used for the final test case for convergence was 1350.

**NOZZLE GUIDE VANL**

In the first instance results for an NGL nozzle guide vane tested in a supersonic cascade are presented (figures 4 and 5). The vane possesses a convergent-divergent passage and has a low trailing edge wedge angle. The experimental results are described in detail by Litchfield et al (10). The predicted Mach number distribution around the blade surface is compared with the experimental data (see Figure 4). It can be seen that the comparison is excellent for both the blade surfaces. The predicted shock strength and its predicted position on the suction surface are in extremely good agreement with measurements. The predicted separation shocks at the trailing edge for both the blade surfaces agree

![FIG. 4 NOZZLE GUIDE VANL. HST CASE](image-url)
accurately with the experimental data. The Mach number distribution obtained from the basic Denton (7) time marching method for the same grid is also given in Figure 4. It can be seen that compared with the present method and experimental data the shock strength on the suction surface is under-predicted and the prediction is poor in the trailing edge region. Figure 4 also shows a plot of the computed displacement thickness for the suction surface only. This boundary layer transits from laminar to turbulent on interaction with the passage shock.

Figure 5 shows the computed contours of the passage Mach numbers. At the trailing edge the separation shocks and the reattachment shocks are shown. The final shape of the dead air region between the separation streamlines behind the trailing edge are also shown in this figure. It can be seen that the computed position of the apex of this triangle is such that a reattachment shock is predicted only on the pressure surface side of this triangle.

The second test case is for a VKI nozzle blade tested in a supersonic cascade which features a convergent-divergent section and concavity on the suction surface downstream of the throat (Figure 6). Experiments for this cascade were performed by Sieverding (9). Schlieren pictures taken of the cascade flow show that shock and viscous effects are present along the suction surface, firstly in the throat region and secondly, further downstream near the trailing edge. In the throat region a train of lambda shocks local to the suction surface appear to thicken the boundary layer such that a local expansion and recompression occurs. At the end of this interaction the boundary layer undergoes transition to turbulent flow. Further downstream, a shock emanating from the trailing edge of the blade interacts with the already thickened boundary layer on the suction surface of the adjacent blade. This interaction of the shock and now turbulent boundary layer results in the rapid thickening of the boundary layer till finally the trailing edge is reached. Figure 6 gives these features of the interaction in the form of displacement thickness plot for the suction surface only. Figure 6 also gives the surface Mach number distributions from the experiment, the present method and that due to Denton (7). It can be seen that of the calculated results for this cascade, the present method predicts the closest correspondence with experiment.

In the base region separation shocks are predicted which agree with the measurements.

STEAM TURBINE ROTOR BLADE

Finally, results for a transonic steam turbine rotor tip section are presented. The geometrical details for this blade along with experimental results are given by Sieverding (9). Figure 7 shows a plot of the displacement thickness for the suction surface as computed by the present method. The boundary layer is nearly all turbulent. Strong interaction between the passage shock wave and the boundary layer are predicted and this can be seen, in the plot, as the rapid thickening of the displacement...
thickness till the trailing edge is reached. Figure 7 also gives the surface Mach number distribution from the experiment and the present method. It can be seen that the method predicts a reasonably good agreement with the experimental data.

18 Separation

FIG. 7 STEAM TURBINE ROTOR BLADE TEST CASE

CONCLUDING COMMENTS

The inclusion of an integral blade surface boundary layer method, along with a novel trailing-edge base pressure model, in an inviscid time marching method has resulted in considerable enhancement in the quality of flow computations in and about transonic axial turbine blade cascades.

The trailing edge base pressure model has enabled the prediction of separation shocks and reattachment shocks, should these exist in this region.

The method developed has been applied to determine the flow through a number of transonic axial turbine blade cascades, and in all cases good agreement with experimental data has been obtained.

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REFERENCES


