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Introduction

An accurate numerical analysis of the flows associated with rotor-stator configurations in turbomachinery can be very helpful in optimizing the performance of turbomachinery. Such analyses tend to be computationally expensive and extremely complex because of the following reasons: 1) the flow is inherently unsteady, 2) the geometries involved are complicated, 3) the flow periodically transitions between laminar and turbulent flow and 4) there is relative motion between the stator and rotor rows. However, a clear understanding of the aerodynamic processes associated with turbomachinery can aid the design process considerably, and hence, the rather large computer costs of simulating the three-dimensional unsteady flows associated with turbomachinery are completely justified.

Several calculations of cascade flow already exist in the literature. These studies include two and three-dimensional calculations using both the Euler and Navier-Stokes equations. References (1)-(5) constitute a typical cross-section of the work done previously and are by no means a complete review of earlier efforts. While analyses of flows through isolated rows can be used to study many of the fluid mechanical phenomena in turbomachinery, such analyses do not yield any information regarding the unsteadiness arising out of the interaction of moving and stationary rows of airfoils. These interaction effects become increasingly important as the distance between successive rows is decreased. The experimental results of (6) show that the temporal pressure fluctuation near the leading edge of the rotor can be as much as 72% of the exit dynamic pressure when the axial gap is reduced to 15% of the chord length (for the operating conditions and geometry chosen). Thus, the need for treating the rotor and stator airfoils as a system in cases where interaction effects are predominant is obvious.

From a computational point of view one major difficulty in simulating rotor-stator flows arises because of the relative motion of the rotor and stator airfoils. A single grid that wraps around both the rotor and stator would have to distort considerably to accommodate the motion of the rotor and may result in inaccurate calculations. For small values of the axial gap between the rotor and stator airfoils such an approach may even be altogether impractical. The obvious solution to this problem is to use several grids which move relative to each other. Typically one would use a set of stationary grids to envelop the stator airfoils and a set of moving grids (stationary with respect to the rotor) to envelop the rotor airfoils. Information is then transfered between the several grids employed with the help of specialized boundary conditions.

Reference (7) presents rotor-stator interaction results obtained using the Euler equations. The various natural boundary conditions such as inlet, discharge, blade surface and periodicity boundary conditions that are required for rotor-stator calculations are presented and the unsteady flow through a fan stage is calculated. However, there are several areas that have not been addressed in (7), namely, 1) a general methodology of information transfer between the multiple grids employed, 2) viscous effects and 3) the three-dimensionality of the flow. Viscous effects can contribute significantly towards the unsteady component of the flow because of the passage of the second set of airfoils through the wakes of the first set. Endwall and tip leakage effects and the geometry of the airfoils may contribute significantly to the three-dimensionality of the flow. Hence, an accurate simulation of the flow within turbomachinery requires the time-accurate solution of the unsteady Navier-Stokes equations in three-dimensions.

In the multiple grid approach the calculation is performed on several grids that are either patched together or are overlaid. The boundary conditions used to transfer information from one grid to another must satisfy several requirements before they can be used effectively. Some of these requirements are listed below. The boundary conditions must be

1) numerically stable,

2) spatially and temporally accurate,

3) easily applicable in generalized coordinates,

4) conservative so that flow discontinuities can move from one grid to another without any distortion. The conservative property although desirable is not required in the case of flows without discontinuities.

The boundary conditions required to transfer information from patch to patch in the patched-grid approach are developed in detail in (8)-(10). In (8) a conservative patch boundary condition is developed for first-order accurate explicit schemes. Results demonstrating the conservative property of the new boundary condition and the quality of solutions possible with patched-grids are presented. In (9) and (10), this boundary condition is extended to work with implicit second-order accurate schemes. The modifications to the boundary scheme that are required to transfer information between two patches that are moving relative to each other are also developed in (9) and (10). Preliminary results for a rotor-stator configuration are presented in (10).

The patched-grid technique as developed in (8)-(10) is used to simulate the flow past a two-dimensional rotor-stator configuration of an axial turbine in (11). The airfoil geometry and flow conditions used are the same as those in (6). The unsteady, thin-layer, Navier-Stokes equations are solved in a time-accurate manner to obtain the unsteady flow field associated with this configuration. The numerically obtained results are compared with the experimental results of (6). A good comparison between theory and experiment is obtained in the case of time-averaged pressures on the rotor and stator. Pressure amplitudes (corresponding to the pressure variation in time) were also found to compare well with experiment thus indicating the validity of the computed unsteady component of the flow.

In the present study the approximation of two-dimensionality is removed and three-dimensional airfoil geometries are used. In addition the hub, outer casing and rotor tip clearance are all included in the calculation. A system of patched and overlaid grids are used to discretize the rather complex geometry of the three-dimensional configuration. An implicit, upwind third-order accurate method is used in all the patches. The equations solved are the unsteady, thin-layer Navier-Stokes equations in three dimensions. The turbulence model used is a modification of the Baldwin- Lomax model (12) that is developed in (13).

The presentation will include a brief description of the grid generation procedure, the integration method and the various boundary conditions used including the patch and overlay boundary conditions. Results in the form of hub to tip variations of time-averaged pressures and velocity fields to show the various vortical structures (horseshoe vortices at the hub and tip for the stator) will also be presented. Comparisons with the experimental data of (6) will be made. A sample of the results obtained are presented in the next section.

Results

In this section results obtained for the rotor-stator configuration shown in Fig. 1 are presented. Approximately five cycles (a cycle corresponds to the motion of the rotor through an angle equal to 2π /N where N is the number of stator or rotor airfoils) were required to eliminate the initial transients and establish a solution that was periodic in time. The calculation was performed at a constant time step value of about 0.04 (this translates into 2000 time-steps/cycle). The inlet Mach number used for this calculation was 0.07. The rotor velocity is determined from the desired flow coefficient (0.78 in this case) and the inlet axial velocity (u_∞). The Reynolds number used for this calculation was 100,000/in.

Midspan Time-Averaged Pressures

The available experimental data, for an axial gap of 15% , includes time-averaged pressures and pressure amplitudes on the rotor and stator airfoils at midspan (6). Figure 2 shows the predicted and experimental time-averaged pressure coefficient values (C_p) as a function of the axial distance along the stator. The pressure coefficient is defined as

$$C_p = \frac{p_{avg} - (p_t)_{inlet}}{\frac{1}{2}\rho_{inlet}\omega^2}$$

where p_{avg} is the static pressure averaged over one cycle. $(p_t)_{inlet}$ and ρ_{inlet} are the average total pressure and density, respectively, at midspan at the inlet and ω is the velocity of the rotor at midspan. The comparison between theory and experiment is good. A small separation bubble was found on the trailing edge circle of the stator in the numerical results. This is seen as a spatial fluctuation in pressure towards the trailing edge of the stator. Figure 3 shows the midspan time-averaged C_p distribution for the rotor. As in the case of the stator, the comparison between theory and experiment is good. A small separation bubble was predicted on the trailing edge circle of the rotor. The bubble is seen as a sharp dip and rise in the pressure curve.

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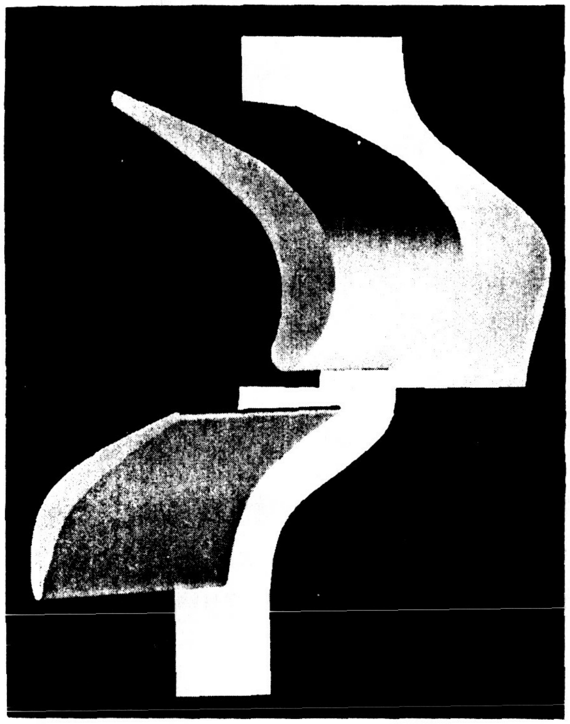
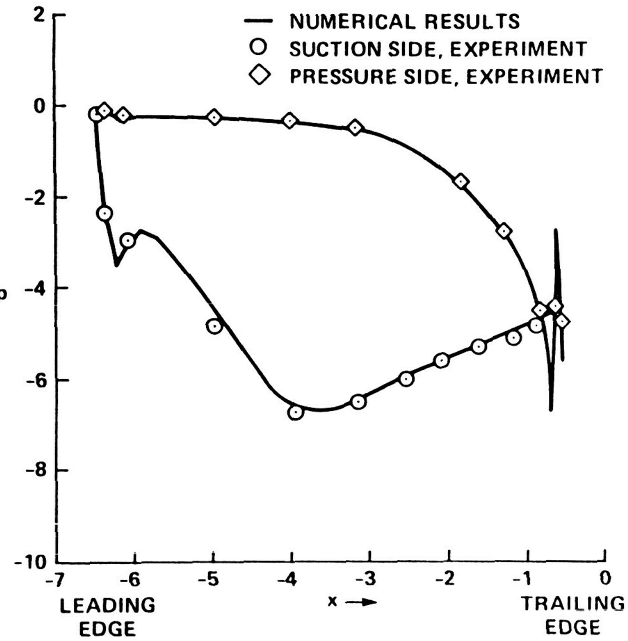
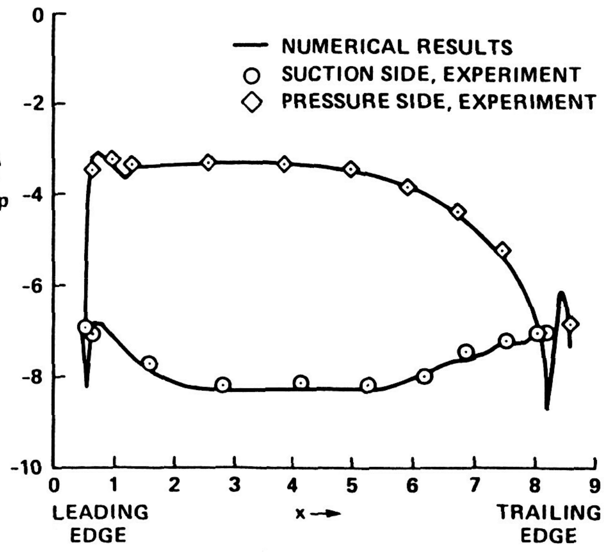


1. Rotor-Stator Geometry of (6).



2. Time-averaged pressure distribution on the stator at midspan.



3. Time-averaged pressure distribution on the rotor at midspan.

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16. Abstract

Fluid flows within turbomachinery tend to be extremely complex in nature. Understanding such flows is crucial to improving current turbomachinery designs. The computational approach can be used to great advantage in understanding turbomachinery flows. This study presents a finite-difference, unsteady, thin-layer, Navier-Stokes approach to calculating the flow within an axial turbine stage. The relative motion between the stator and rotor airfoils is made possible with the use of patched grids that move relative to each other. The calculation includes endwall and tip leakage effects. An introduction to the rotor-stator problem and sample results in the form of time-averaged surface pressures are presented. The numerical data are compared with experimental data and the agreement between the two is found to be good.

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