Study of Boundary-Layer Development in a Two-Stage Low-Pressure Turbine

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Nomenclature

H = shape factor, δ^*/θ
S = arc length
Tu = freestream turbulence level
U_∞ = freestream velocity
u = local velocity
δ^* = displacement thickness

Subscripts

ex = exit value
wet = wetted distance
∞ = freestream value

Introduction

EXPERIMENTAL data from jet-engine tests have indicated that unsteady blade-row (wake) interactions and separation can have a significant impact on the efficiency of turbine stages. The effects of these interactions can be intensified in low-pressure turbine stages because of the low-Reynolds-number operating environment. Measured turbine efficiencies at takeoff can be as much as two points higher than those at cruise conditions.[1] Thus, during the last decade a significant amount of effort has been put into determining the effects of transition and turbulence on the performance of low-pressure turbine stages. Experimental investigations have been performed, for example, by Hodson et al.[2] and Halstead et al.[3] These investigations have helped identify/clarify the roles that factors such as the Reynolds number, freestream turbulence intensity, pressure gradient, and curvature have in the generation of losses. In parallel to the experimental investigations, there have been significant analytical efforts to improve the modeling of transition. Examples of such efforts include the works of Mayle[4] and Gostelow et al.[5] These newer models show promise of providing accurate transition predictions over a wide range of flow conditions,[6] although they have yet to be implemented into the numerical flow analyses used by the turbine design community. Some recent computational investigations of interest include the works of Chernobrovkin and Lakshminarayana[7] and Eulitz and Engel.[8]

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The focus of the current effort has been to use a viscous, unsteady quasi-three-dimensional Navier–Stokes analysis to study boundary-layer development in a two-stage low-pressure turbine. A two-layer algebraic turbulence model, along with a natural transition model and a bubble transition model, have been used. The geometry used in the simulations has been the subject of extensive experiments.[3] The predicted results have been compared with experimental data, including airfoil loadings and time-averaged/unsteady integral boundary-layer quantities.

Algorithm

In the numerical analysis the flowfield is divided into two types of zones. O-type grids are used to resolve the flowfield near the airfoils. The O grids are overlaid on H grids, which are used to resolve the flowfield in the passages between airfoils. The H grids are allowed to slip relative to one another to simulate the relative motion between rotors and stators. The thin-layer or full Navier–Stokes equations are solved on both the O and H grids. The governing equations are cast in the strong conservation form. A fully implicit, finite difference method is used to advance the solution of the governing equations in time. A Newton–Raphson subiteration scheme is used to reduce the linearization and factorization errors at each time step. The convective terms are evaluated using a third-order-accurate upwind-biased Roe scheme. The viscous terms are evaluated using second-order accurate central differences, and the scheme is second-order accurate in time. Details of the solution procedure and boundary conditions are discussed in Ref. 9.

Turbulence and Transition Models

The two-layer algebraic model based on the work of Baldwin and Lomax (BL) was used to model turbulence.[10] Several modifications were made to the original BL model based on previous experiences with compressor and turbine geometries:

1) The switchover location between the inner and outer models cannot move more than a specified number of grid points between adjacent streamwise locations. This eliminates nonphysical gradients in the turbulent viscosity near separation points.

2) A second derivative smoothing function is used on the turbulent viscosity field in separated flow regions. This also helps remove nonphysical gradients in the turbulent viscosity in separation regions.

3) A cutoff value is imposed on the turbulent viscosity (nominally 1200 times the freestream laminar viscosity).

The comparison of predicted and experimental integral boundary-layer quantities warrants discussion of the technique used to determine the location of the boundary-layer edge in the simulations. The following steps, based on the work of Davis et al.,[11] were used to determine the edge of the boundary layer:

1) Determine the minimum value of $|U_\infty - u|$, where U_∞ is the freestream velocity based on isentropic conditions and u is the local velocity.

2) Correct the location based on where the local vorticity exceeds a specified limiting value.

3) Within the new range determine where u is greater than U_∞.

4) Determine where the local velocity is 99% of the freestream value.

The low-Reynolds-number environment in low-pressure turbines suggests that the flow may be transitional. The natural transition model of Abu-Ghannam and Shaw has been used in the current study.[12] In the region between the start and end of transition, the intermittency function is determined using the model developed by Dhawan and Narasimha.[13] For cases involving separation bubbles the model developed by Roberts[14] and modified by Davis et al.,[15] is used. Instantaneous transition is assumed using the bubble model.

Geometry and Grid

The test article used in this study has been studied extensively by Halstead et al.[3] The turbine is typical of the those found in modern aircraft engines. The experimental turbine contains 82 first-stage nozzles, 72 first-stage rotors, 108 second-stage nozzles, and

72 second-stage stators (i.e., a 82-72-108-72 blade count ratio). For modeling purposes a blade count ratio of 78-78-104-78 was assumed, thus requiring the use of 3 first-stage nozzles, 3 first-stage rotors, 4 second-stage nozzles, and 3 second-stage rotors in the simulations. The complete grid topology contained 329,997 grid points. The average value of y^+, the nondimensional distance of the first grid point above the surface, was approximately 1.0 for all four blade rows. The boundary layers for all four blade rows were discretized with approximately 20–30 grid points.

The simulations were run on Silicon Graphics Inc. (SGI) Origin 200 workstations with 195-MHz processors. The average computation time was 4×10^{-5} s/grid point/iteration. The simulation was run for 20 global periods at 18,000 time steps per global period. A global period is defined as the second rotor moving through a distance equal to 4-s nozzle pitches or, similarly, the first rotor moving through a distance equal to 3 first nozzle pitches. The 20 global periods allowed the efficiency, losses, and integral boundary-layer quantities to become time periodic.

Results

The operating point studied corresponds to takeoff conditions. In accordance with the experiments, the freestream turbulence level (used in the transition models) was set at $Tu = 3\%$.

Numerical and experimental time-averaged loadings on the second nozzle and second rotor are shown in Figs. 1 and 2, respectively. The predicted results exhibit good agreement with the experimental

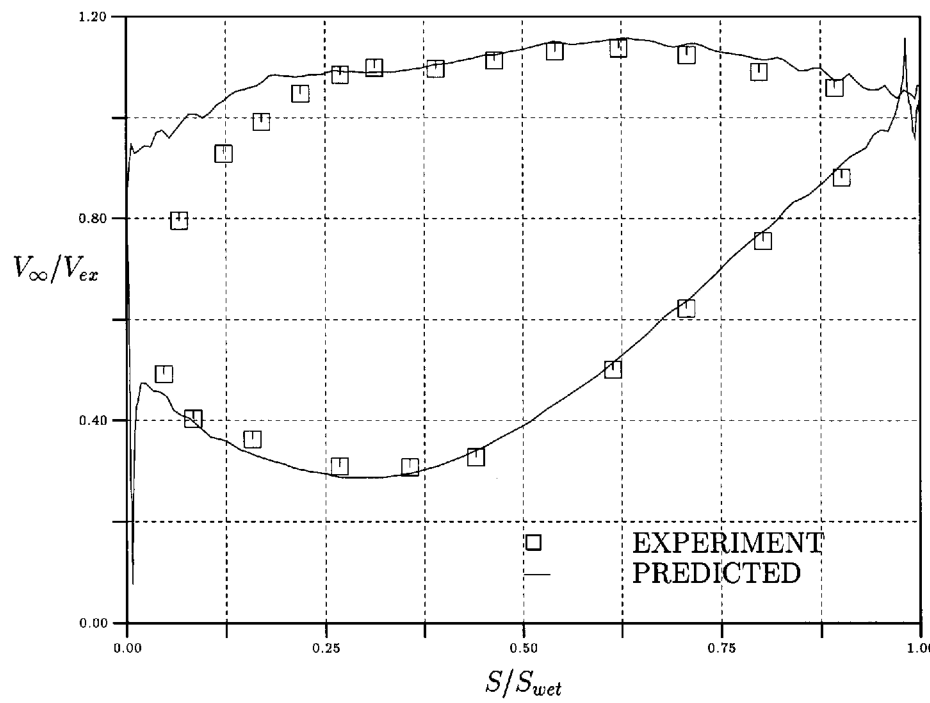

Fig. 1 Normalized loading on nozzle 2.

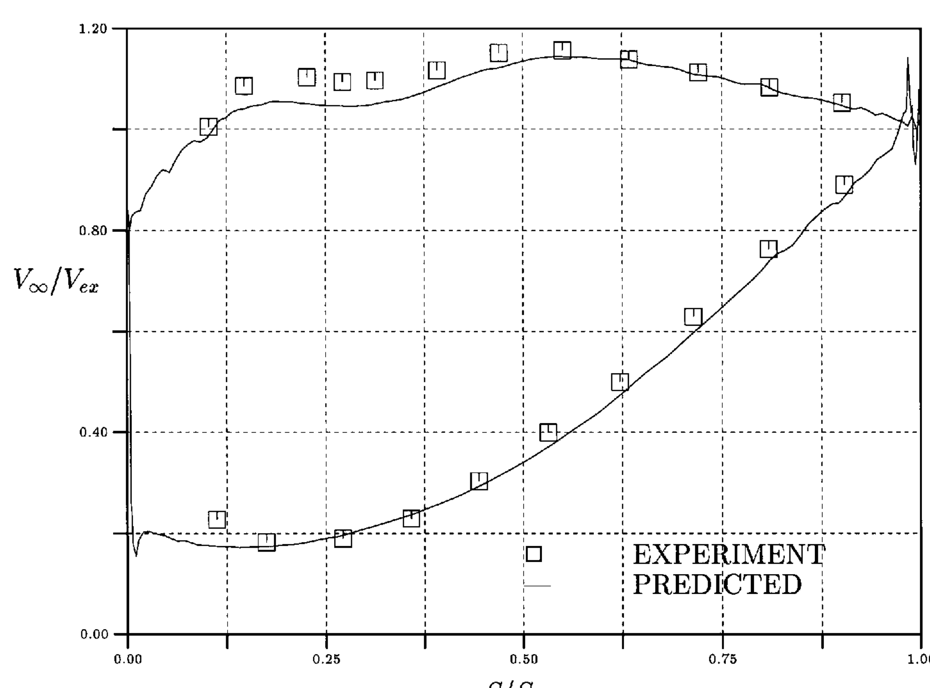

Fig. 2 Normalized loading on rotor 2.

data, except in the suction surface leading-edge region of the second nozzle. The differences in this region suggest the flow entering the second nozzle in the simulations has somewhat greater positive incidence. On the second rotor both the numerical results and experimental data show an acceleration region near the suction surface leading edge followed by a zone of constant velocity, a second acceleration region, and finally a deceleration zone as the flow moves downstream of the throat into the uncovered portion of the passage.

Figure 3 contains the time history of the unsteady displacement thickness at 82% of the suction surface length on the second nozzle. Included in these figures are the predicted results using the Abu-Ghannam and Shaw transition model,[12] as well as the experimental data. There is generally good agreement between the predicted results and the experimental data.

Minimum, maximum, and time-averaged distributions of the displacement thickness on the suction surface of the second nozzle are shown in Fig. 4, whereas the corresponding time-averaged shape factor distributions are shown in Fig. 5. The time-averaged values obtained with the Abu-Ghannam and Shaw model show excellent agreement with the experimental data.

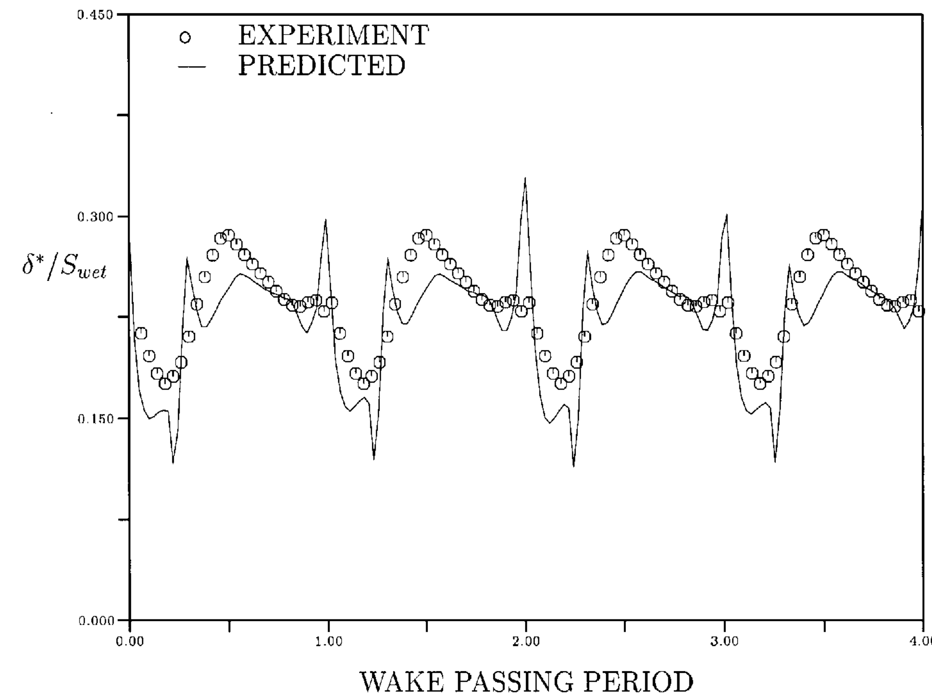

Fig. 3 Unsteady displacement thickness, nozzle 2, 82% suction surface length.

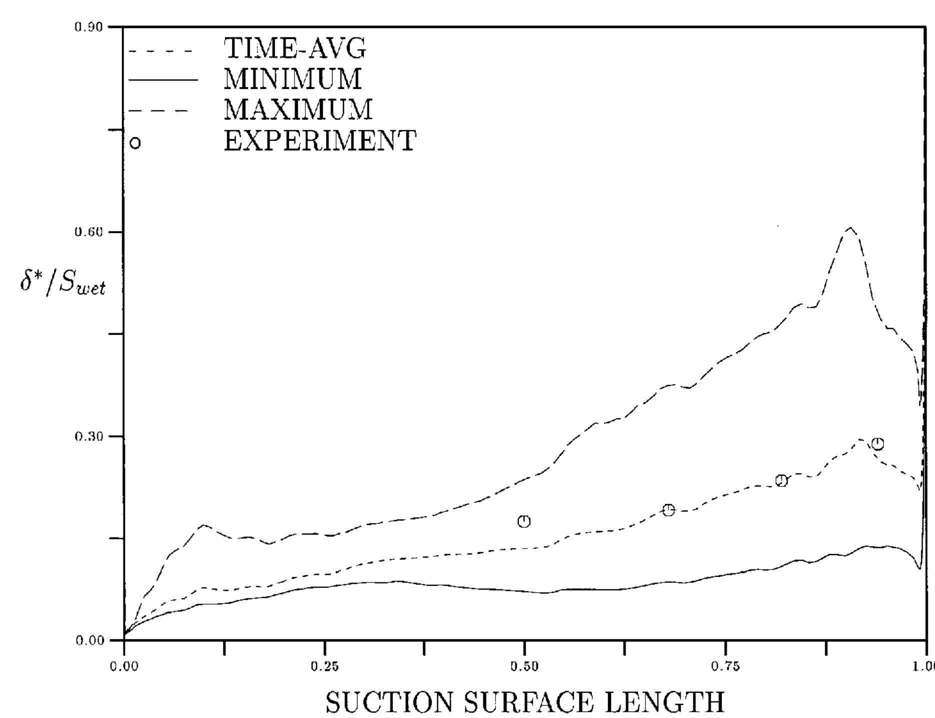

Fig. 4 Displacement thickness envelope, nozzle 2.

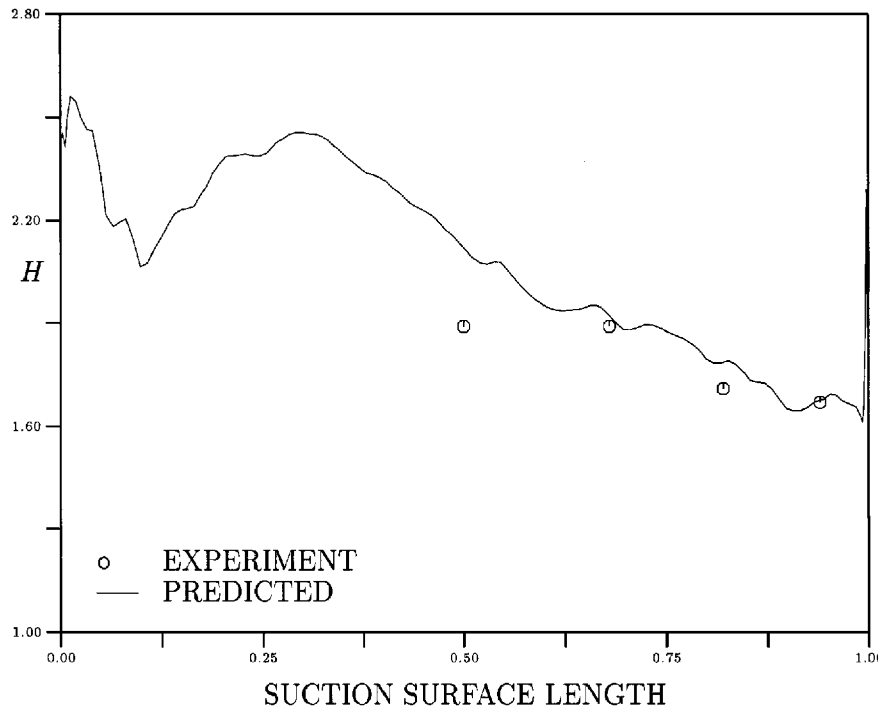

Fig. 5 Time-averaged shape factor, nozzle 2.

Conclusions

Quasi-three-dimensional numerical simulations have been performed for flow through a two-stage low-pressure turbine. The simulations were performed for takeoff operating conditions and employed natural and bubble transition models. The results of this study have shown that the Abu-Ghannam and Shaw transition model[12] yields accurate results for the transient and time-averaged integral boundary-layer quantities.

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