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Two-Dimensional
Analysis Code
Throughflow

NASA Technical Memorandum 4141

Application of a Two-Dimensional Unsteady Viscous Analysis Code to a Supersonic Throughflow Fan Stage

Ronald J. Steinke
Lewis Research Center
Cleveland, Ohio

National Aeronautics and
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Information Division

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Summary

The Rai ROTOR1 code for two-dimensional, unsteady viscous flow was applied to a model of the NASA Lewis Research Center supersonic throughflow fan (SSTF) stage design of 1987. The axial Mach number for this SSTF design model increases from 2.0 at the inlet to 2.9 at the outlet, and both the rotor and stator have 52 blades. The Rai code uses overlapped O- and H-grids that are packed at the blade edges and surfaces, and arranged uniformly throughout the rotor-stator interface region. The Rai code was run on a Cray XMP computer, and the large output data files were postprocessed on a VM system (International Business Machines) and IRIS workstation (Silicon Graphics). Lewis GRAPH3D and Ames PLOT3D software were used for graphics. Contours of flow-field parameters and overall performance parameters are presented for a converged cycle.

Results from the Rai code analysis indicate that high viscous effects caused large blade wakes and low overall adiabatic efficiency. Only weak blade shock losses are indicated throughout the entire SSTF flow field. Entropy contours show strong rotor wakes uniformly traversing through the rotor-stator interface region and dispersing as they pass through the stator passage. Mach number contours show the flow to increase through the fan as designed, except in regions within the blade wakes where the flow is locally subsonic. The rotor flow is nearly steady since the entire flow field is supersonic, except within blade wakes and near blade surfaces. Pressure coefficient contours show both rotor and stator blades are front loaded as designed. As the rotor moves one cycle, overall efficiency varies 0.003 for the rotor and 0.032 for the stage.

For the rotor, comparisons were made to the Chima rotor viscous code (RVC) for steady flow. For rotor grids of similar density, the rotor total pressure ratio contours and efficiency distributions from the Rai and Chima codes compare well. Past experience with the Chima code indicates that the predicted rotor overall efficiency of 0.768 may be increased by 0.045 if grid density is increased by a factor of 4. Generally, two-dimensional viscous analysis codes such as those developed by Chima and Rai provide considerable insight into the flow physics of the SSTF design.

Introduction

In 1987 NASA Lewis Research Center finalized a design for a supersonic throughflow fan (SSTF) (refs. 1 and 2). Usually the design process for turbomachinery relies on numerous empirical models for blade element losses, deviation angle, and other factors. Such empirical correlations are usually derived from experimental test data for previously designed turbomachines that were built and tested. However, for the SSTF design, the usual empirical design correlations did not exist because of a complete lack of useful experimental data for this type of turbomachine. Therefore the design process for the SSTF relied on predictions from advanced computational fluid dynamics (CFD) codes.

Various types of CFD codes for steady flows were used to establish the SSTF design. Briefly, they included the Crouse axisymmetric compressor design and off-design codes (ref. 3), the Chima quasi-three-dimensional rotor viscous code (ref. 4), and the Denton three-dimensional Euler code with interactive boundary layer (ref. 5, and J.D. Denton, July 1983, ASME Turbomachinery Institute Course on Fluid Dynamics of Turbomachinery, lecture). These codes were used to iterate on the SSTF rotor and stator blade shapes until a reasonable design was established. The predicted blade-generated shock losses were low. Blade leading-edge shocks were contained within the blade passage by using high-solidity and long-chord blades. The validity of the SSTF design will, of course, not be fully established until the SSTF is built and successfully tested. But additional confidence in the design was achieved by comparing the SSTF flow predictions from different CFD codes. For steady flow, the SSTF Chima code predictions compared well with the Denton code predictions.

For unsteady flow, Jorgenson analyzed a model of the SSTF stage with the same number of rotor and stator blades (ref. 6). Jorgenson's work uses C-grids from the Sorenson GRAPE code (ref. 7). The results clearly show some important flow features: rotor wakes pass through the stator passage, the rotor flow appears to be independent of the stator position, and weak shocks are generated at the blade leading edges.

This report describes two-dimensional, unsteady viscous flow results obtained with the Rai ROTOR1 code (ref. 8) for a model of the SSTF that has the same number of rotor and stator blades. The Rai code uses overlapped O- and H-grids that can be packed at the blade edges and surfaces, and distributed uniformly throughout the entire rotor-stator interface region. The Rai code computations were performed on the Lewis Cray XMP computer. Graphics output and other data postprocessing were performed on the Lewis VM computer system and an IRIS workstation. Contours of flow field parameters and overall rotor and stage performance parameters are presented herein. For the SSTF rotor, comparisons are made to the Chima code prediction. Also presented are a brief description of the SSTF design and a brief nontechnical description of the Rai codes.

Supersonic Throughflow Fan Description

The SSTF flowpath and some overall design parameters are shown in figure 1. The flowpath's constant hub and tip radii were selected to minimize the possible detrimental effects of shocks caused by curved flowpath walls. The relatively high hub-to-tip radius ratio of 0.70 was intended to reduce radial flow gradients and streamline curvature effects.

The rotor design tip speed is 1500 ft/sec (457.3 m/sec), and the estimated overall stage pressure ratio is 2.45. The flow accelerates through the fan stage from an axial Mach 2.0 at the inlet to an axial Mach 2.9 at the outlet. There are 44 rotor blades and 52 stator blades. These blade numbers yield the high blade solidity necessary to control the flow within the blade passage. Figure 1 also shows the position of the 52-bladed rotor used to model the SSTF design. Rotor solidity was held constant when the SSTF rotor was scaled to 52 blades.

Rai Code Description

The following code descriptions are very brief and nontechnical and are intended for the code user.

Rai ROTOR1 Code

The Rai ROTOR1 code computes the two-dimensional, unsteady viscous flow for a rotor-stator stage. The code solves the unsteady, thin-layer Navier-Stokes equations in a time-accurate manner and uses the Baldwin-Lomax turbulence model. Because of the code's short length (3200 lines) and ample comment statements, it is possible to modify the code input and run the code without a conventional input data set or a user's manual. The code is capable of generating large amounts of output in the form of q-data (density, momentum, and energy) files. Therefore data postprocessing and graphics are needed to comprehend the code's output. For graphics, either the Lewis GRAPH3D software or the Ames PLOT3D software is useful.

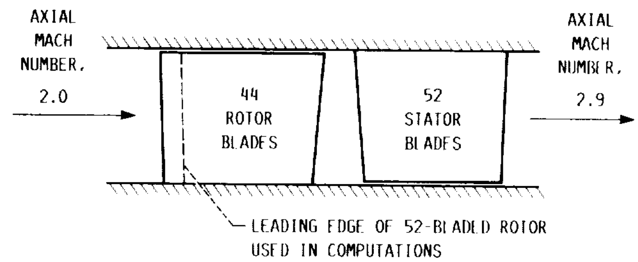

Figure 1.—Supersonic throughflow fan flowpath and overall design parameters. Constant hub and tip radius, tip speed, 1500 ft/sec (457.3 m/sec); stage pressure ratio, 2.45.

The version of the ROTOR1 code used for the computations in this report included two modifications that were suggested and provided by Rai (M.M. Rai, Apr. and Nov. 1988, NASA Ames Research Center, Moffett Field, CA, personal communications). Namely, the subroutine RHS34 was changed to render it total-variation-diminishing (TVD), and the subroutine MUTUR was changed to use relative velocities in place of absolute velocities for the turbulence model.

Rai Grid Code

The Rai grid code computes one O-grid and one H-grid for each blade. The Fortran listing is short at 1600 lines, and comment statements within the code permit the location and modification of the required input. The code contains options to pack the grids in critical flow regions such as the blade edges and surfaces, and in the rotor-stator interface region. At Lewis, the O-grid packing at the blade edges was modified with the help and advice of Wood (J.R. Wood, Dec. 1987, NASA Lewis Research Center, Cleveland, OH, personal communication). These modifications were made to permit increased control of grid packing for blades that have very sharp leading and trailing edges.

Supersonic Throughflow Fan Grids

The grids for the SSTF fan computation are shown in figure 2. Note again that these grids are for the SSTF rotor scaled to 52 blades, with the blade solidity held constant. The grid width equals one blade pitch. The grids are located at the mean-line flowpath height of 8.5 in. (21.6 cm). The grids shown in figure 2 are positioned pitchwise, relative to each other, at 75-percent cycle fraction (CF). As the rotor moves through a distance of one pitch, the CF varies from 0 to 100-percent.

There are two 151-by-31 O-grids and two 71-by-51 H-grids. For improved detail, figure 3 shows an enlarged view of the rotor grid, and figure 4 shows an enlarged view of the rotor leading-edge region. For improved flow computation, the O-grids are denser at the blade edges and near the blade surfaces. The O-grids overlap the H-grids by at least four cells.

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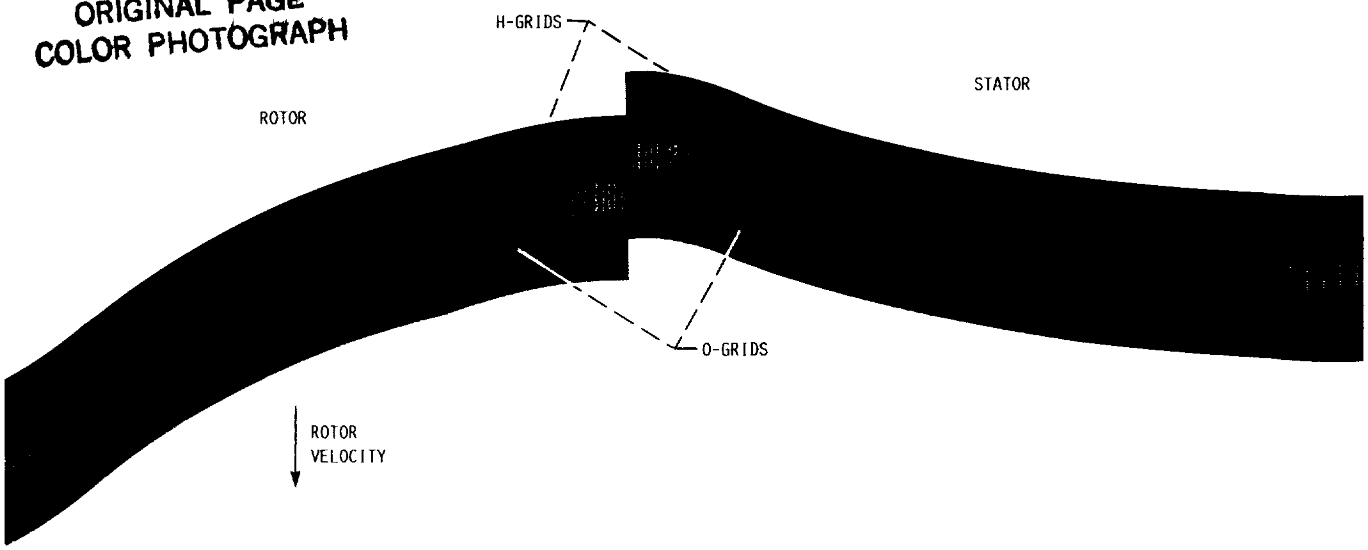


Figure 2.—Supersonic throughflow fan grid for the Rai code using PLOT3D graphics.

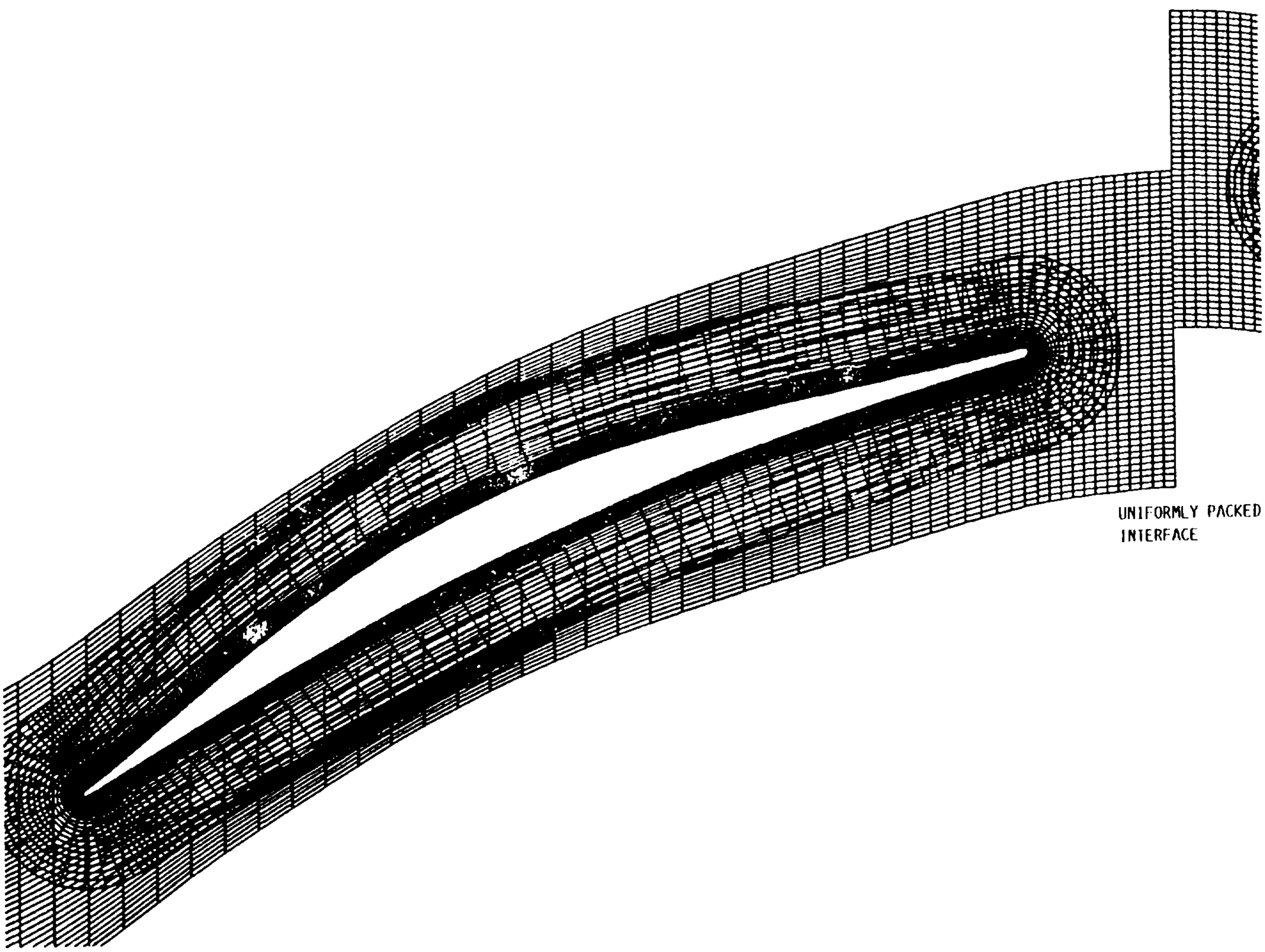


Figure 3.—Supersonic throughflow fan rotor grid for the Rai code. Enlarged view.

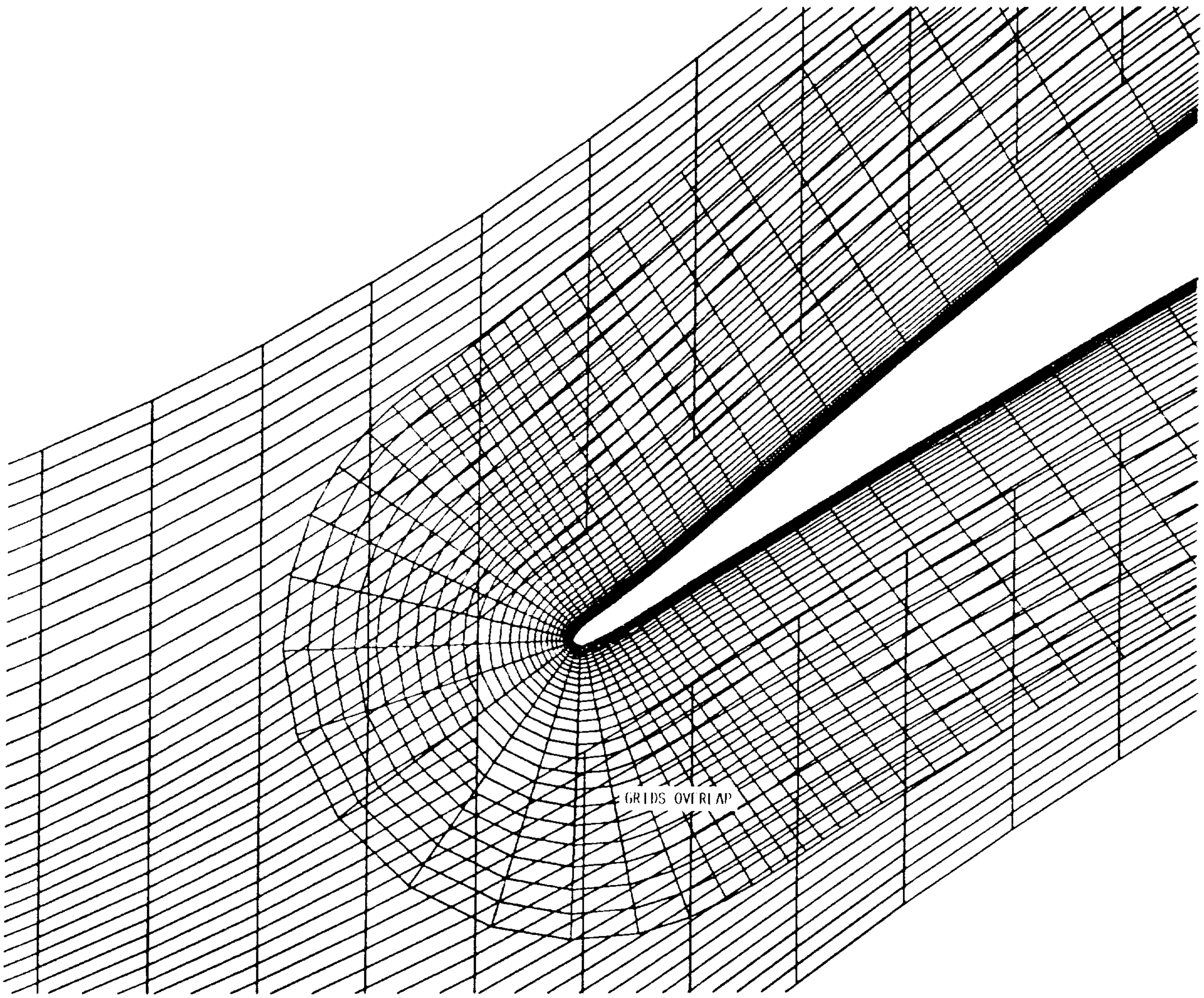


Figure 4.—Supersonic throughflow fan rotor leading-edge grid for the Rai code. Enlarged view.

In the critical rotor-stator interface region, the H-grids are denser. At the interface, there are 51 equally spaced H-grid lines in the pitchwise direction for both the rotor and stator. Since the H-grids are uniformly packed from the rotor trailing edge to the stator leading edge, the rotor wake should be consistently conveyed across the rotor-stator interface as the rotor moves a complete cycle.

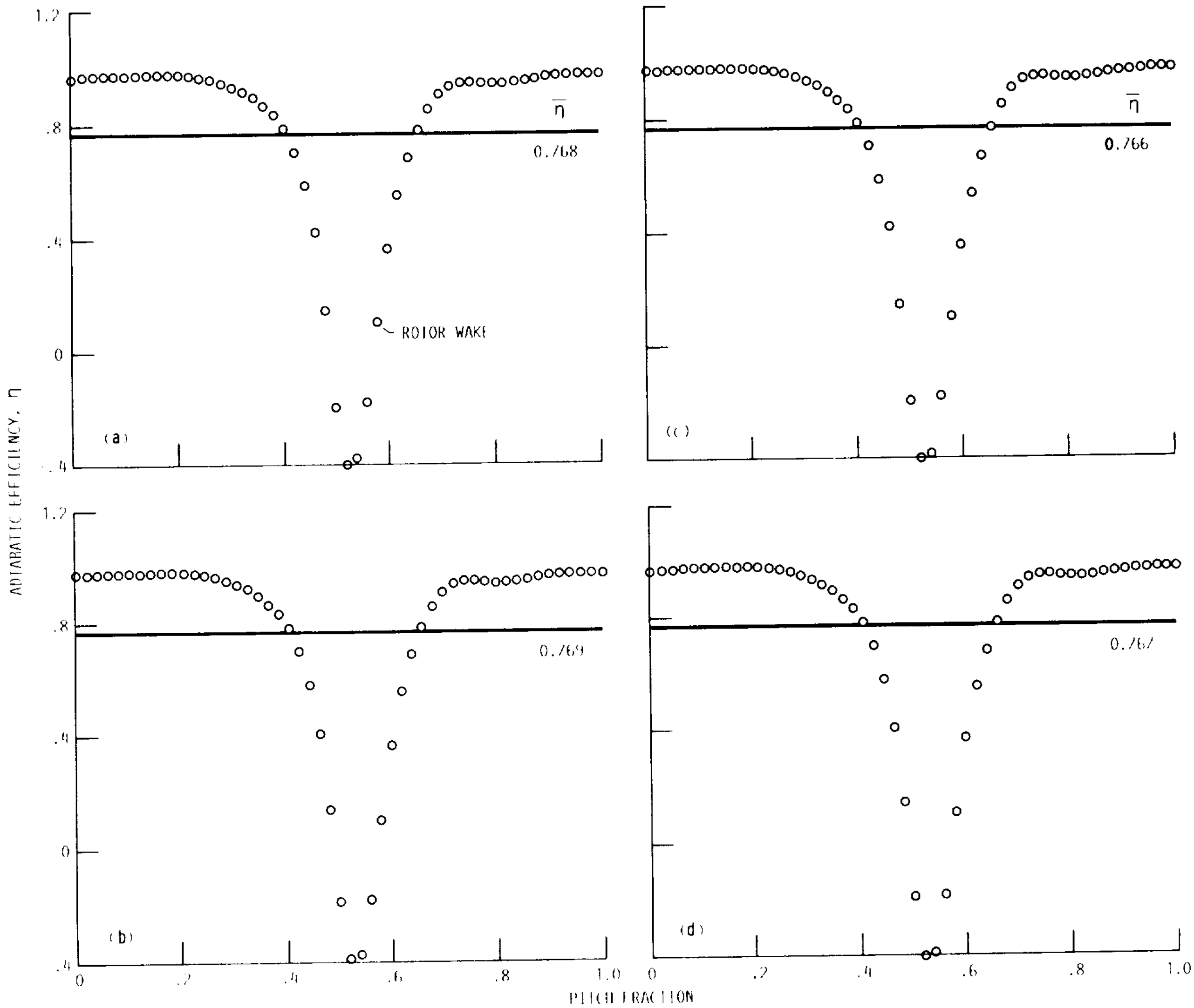
Results and Discussion

First, results from the Rai code are discussed in terms of adiabatic efficiency and entropy for several different cycle fractions covering one complete cycle. Then, additional flow details and flow predictions are presented at only 25-percent CF. Finally, Rai code predictions for the SSTF rotor are compared with the Chima code predictions. Note that the results presented represent only a small fraction of the total useful output produced by the code. A video movie, for example, would give a more complete description of the computed unsteady flow.

The results presented are for a converged cycle for which computations were performed for 1600 time steps with four subiterations per time step. The maximum change in normalized density after each time step is less than 0.01, and after the fourth subiteration it is less than 0.0001.

Efficiency Distributions

Figure 5 shows rotor adiabatic efficiency distributions over one pitch at 25-percent CF intervals. (Adiabatic efficiency is defined in the appendix.) Each distribution contains 51 values

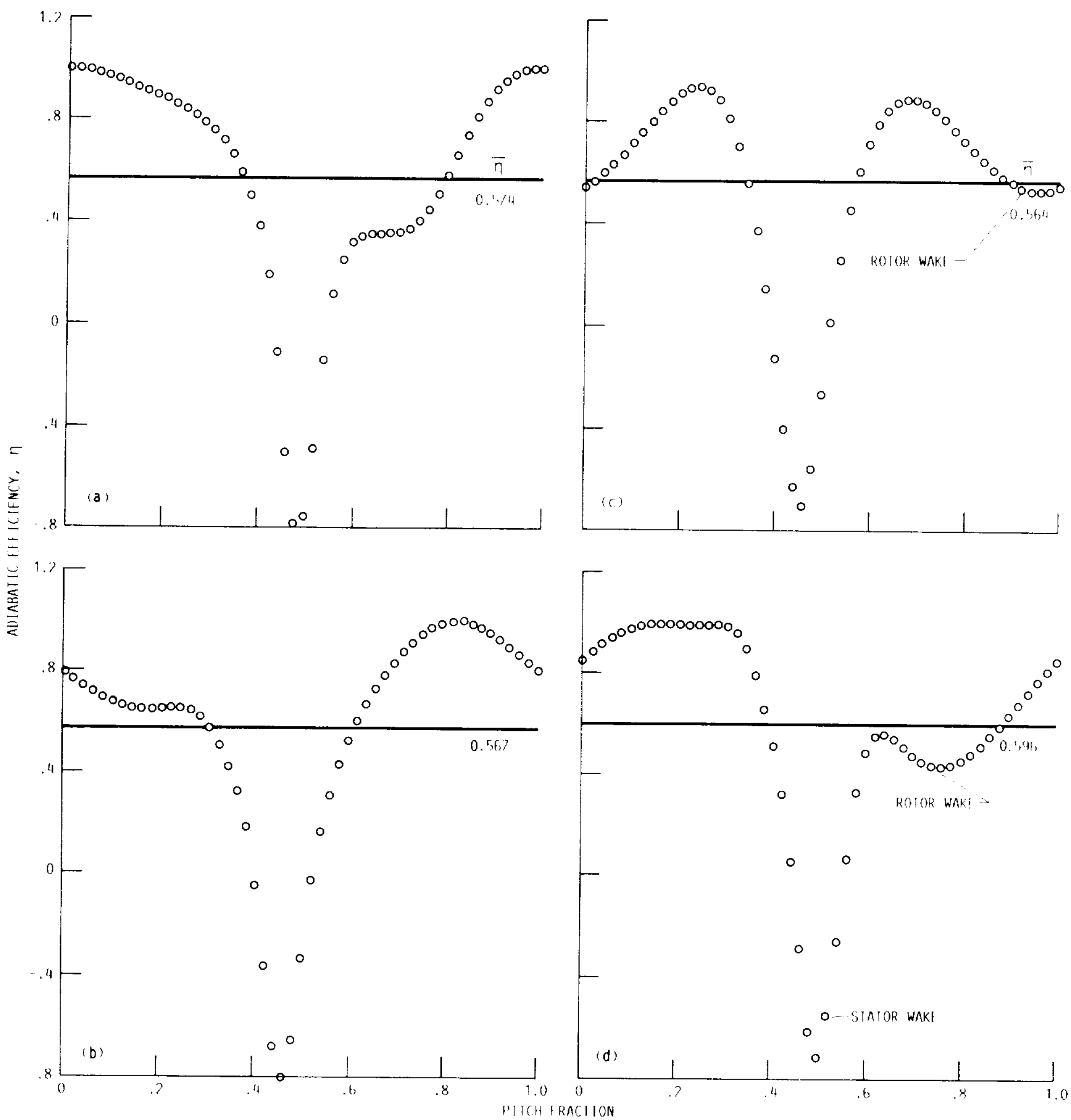


(a) 0-percent cycle fraction.
(b) 25-percent cycle fraction.
(c) 50-percent cycle fraction.
(d) 75-percent cycle fraction.

Figure 5.—Supersonic throughflow fan rotor adiabatic efficiency distributions from the Rai code.

from the rotor H-grid line at the rotor-stator interface. In addition to the efficiency distributions, a corresponding "averaged" overall rotor efficiency is shown. (The averaging method is discussed in the appendix.) For the rotor, these distributions are nearly independent of CF. The 0.003 variation in rotor overall efficiency could be attributed to the small subsonic rotor wake region or to the numerical limits of the "average" computation. The rotor wake region is easily identified by the sharp drop in rotor efficiency. Negative efficiencies occur within the wake region when the total pressure ratio is less than 1.0. The high efficiencies (near 1.0) in the flow region midway between rotor wakes indicate that only small shock losses are being calculated in the rotor.

Figure 6 shows stage adiabatic efficiency distributions over one pitch at 25-percent CF intervals. The efficiencies were calculated along the stator H-grid line located farthest downstream. Overall efficiencies are also shown. The stator wake is clearly shown as the lowest efficiency region, and its location is independent of CF. A dispersed rotor wake, with location varying with CF, is also apparent as a low-efficiency region with values ranging from 0.4 to 0.8. There is still a small region lying outside of the blade wakes where efficiencies approach 1.0. These efficiencies near 1.0 suggest that only weak shocks exist in the entire stage flow field. The stage overall efficiency varies by 0.032 as the rotor moves through one cycle.

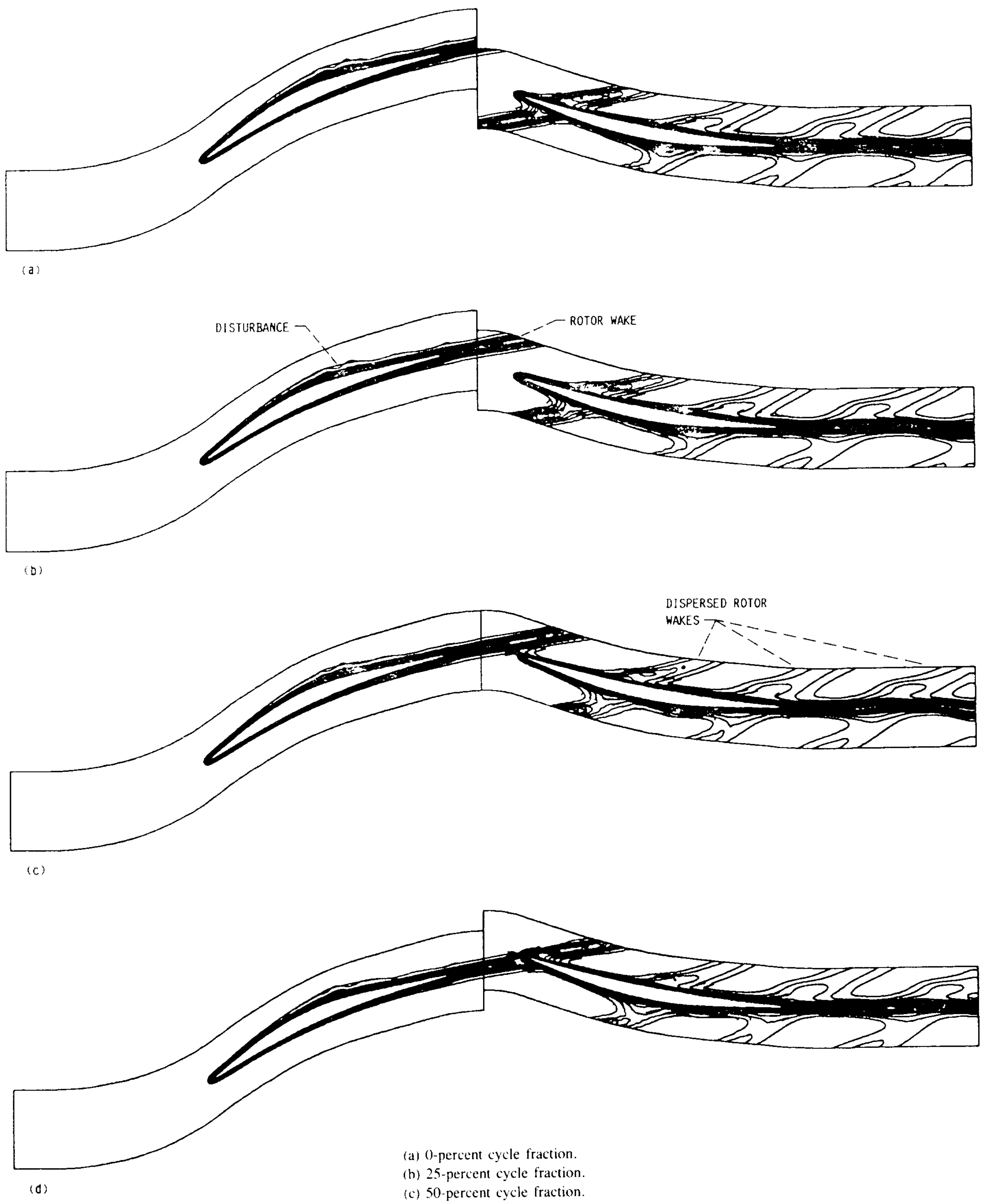


(a) 0-percent cycle fraction.
(b) 25-percent cycle fraction.
(c) 50-percent cycle fraction.
(d) 75-percent cycle fraction.

Figure 6.—Supersonic throughflow fan stage adiabatic efficiency distributions from the Rai code.

Contour Plots

Figure 7 shows entropy contours for the SSTF stage at 25-percent CF intervals. For the rotor, the entropy contours are nearly independent of CF, and downstream of the rotor trailing edge they show a distinct rotor wake. Notice that the rotor wake remains unchanged across the rotor stator interface and that it is dispersed as it passes through the stator passage. Generally the rotor entropy contours are smooth except near the rotor suction surface at about 60-percent chord where there are ripples in the contours. The SSTF stage entropy contours shown in figure 7 for 25-percent CF are also shown enlarged in figure 8 at around the rotor-stator interface region. These entropy contours show the excellent match across the rotor-



(a) 0-percent cycle fraction.
(b) 25-percent cycle fraction.
(c) 50-percent cycle fraction.
(d) 75-percent cycle fraction.

Figure 7.—Supersonic throughflow fan entropy contours from the Rai code.

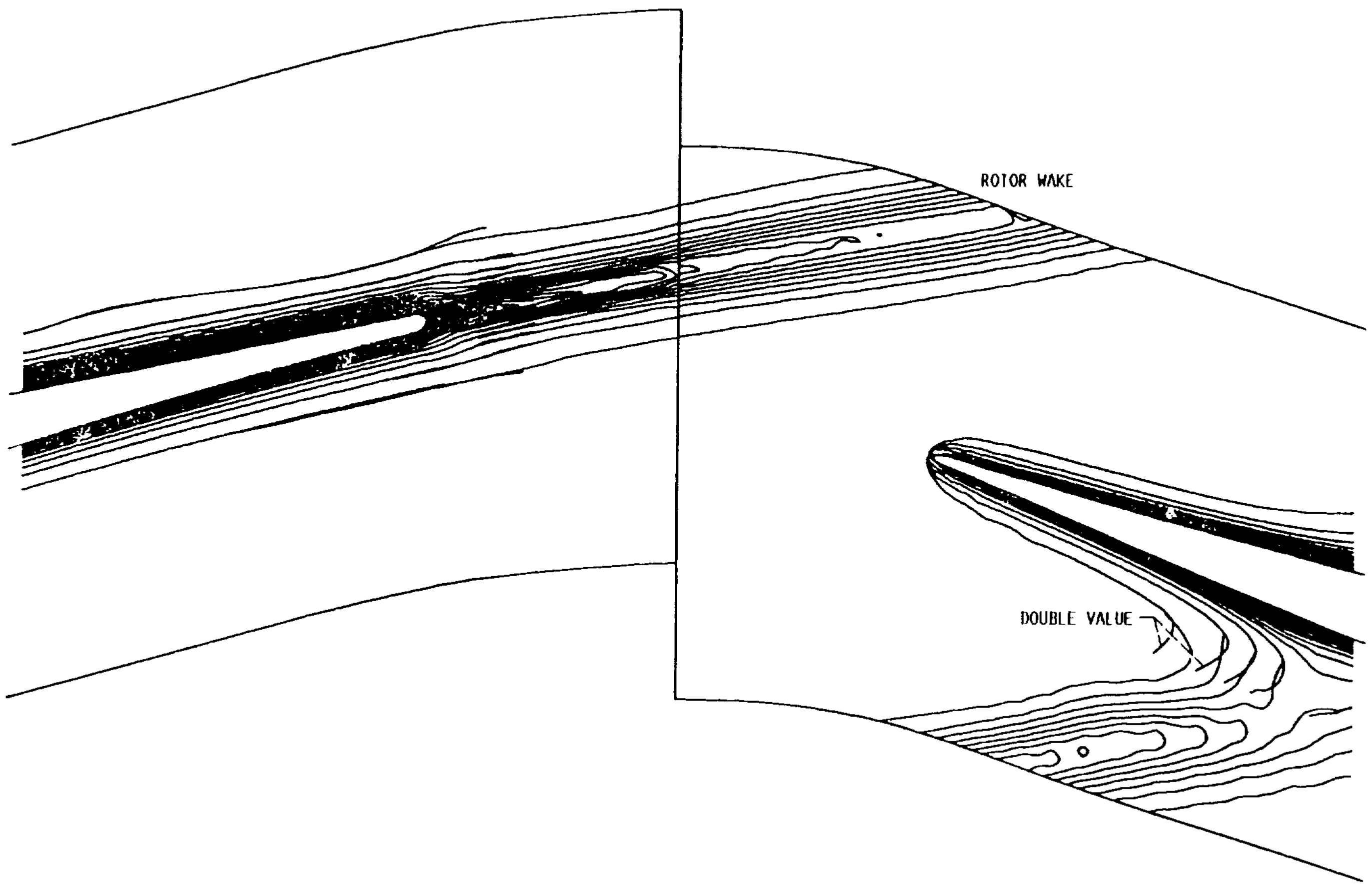


Figure 8.—Supersonic throughflow fan entropy contours at 25-percent cycle fraction from the Rai code in the rotor-stator interface region. Enlarged view.

stator interface of the H-grids. Note that entropy values in the O-H grid overlap region are double valued because of grid density differences. Figure 9 shows entropy contours for 25-percent CF generated by using PLOT3D software on an IRIS workstation, illustrating the advantage of color graphics over black and white graphics.

Absolute Mach number contours are shown in figure 10 where the Mach number can be seen to increase from the fan inlet to the outlet, as designed. The Mach contours also reveal the dispersed rotor wakes at the fan exit. Pressure coefficient (defined in the appendix) contours in figure 11 indicate only weak shock waves at the rotor and stator leading and trailing edges. Blade loading along the blade surfaces can also be observed from the pressure coefficient contours. Both rotor and stator blades are loaded more in the front than in the rear, which agrees with the design loading distributions.

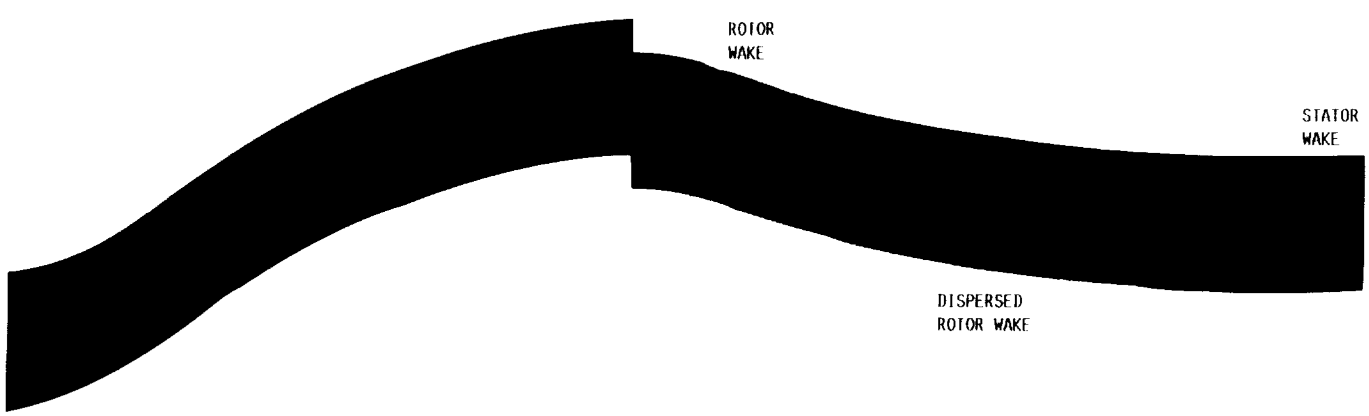


Figure 9.—Supersonic throughflow fan entropy contours at 25-percent cycle fraction from the Rai code using PLOT3D graphics.

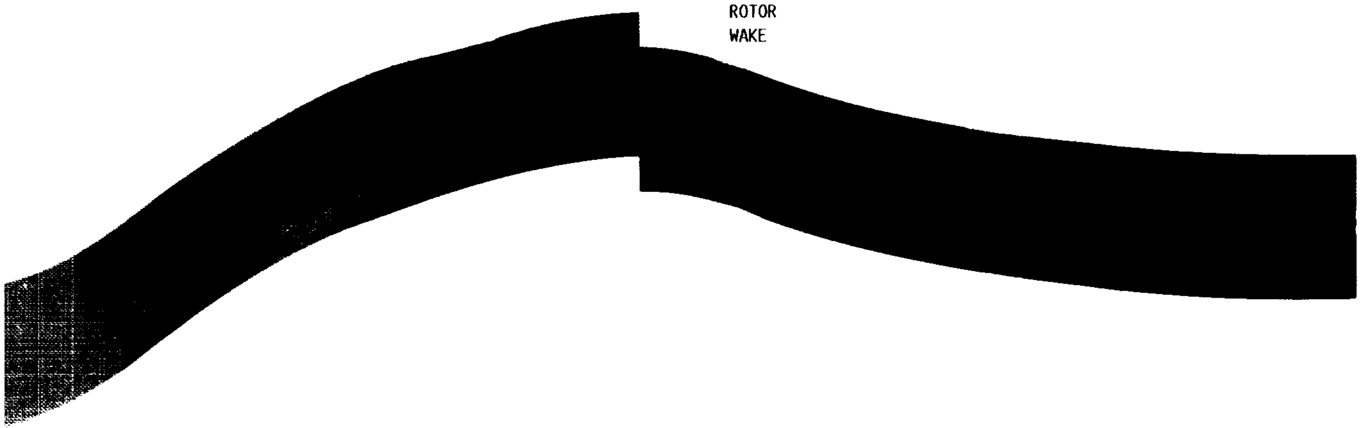


Figure 10.—Supersonic throughflow fan absolute Mach number contours at 25-percent cycle fraction from the Rai code.

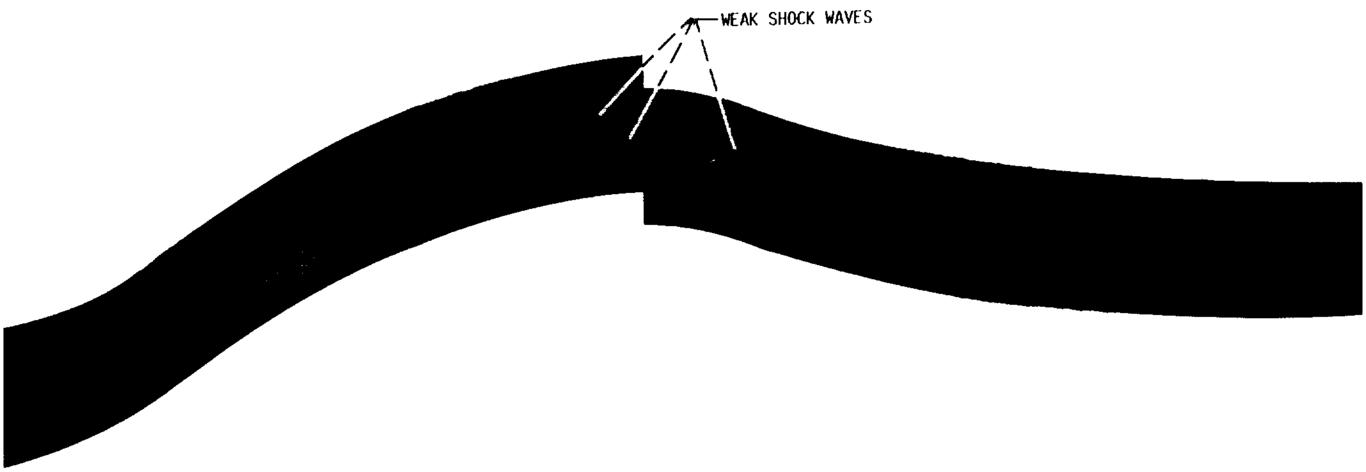


Figure 11.—Supersonic throughflow fan pressure coefficient contours at 25-percent cycle fraction from the Rai code.

Comparison of Rai Code to Chima Code Results

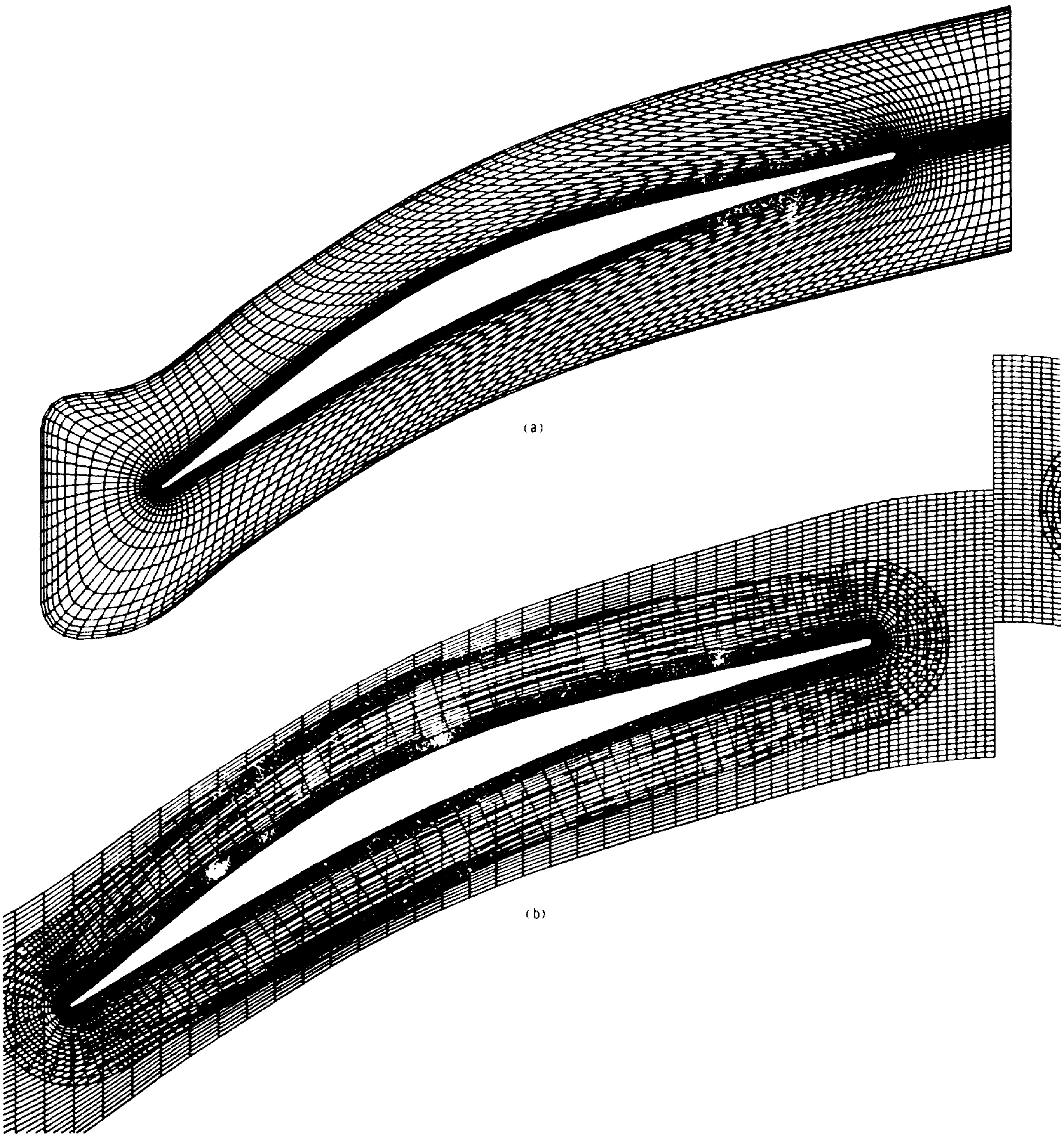
Because the SSTF axial Mach numbers are supersonic (except within the wake regions) the Rai code results for the rotor are nearly independent of stator position and can be compared with the steady-flow Chima RVC code results for the rotor.

The Sorenson GRAPE code was used to generate a 161-by-33 C-grid for the Chima RVC code. Figure 12 compares the Chima code grid with the Rai code grid for the SSTF rotor. The Chima C-grid has greater grid density variation in the region downstream of the rotor where the Rai H-grid density is uniform. Otherwise, the two grids are comparable in density.

Figure 13 shows the computed pressure ratio contours for the two codes. They appear to match well. A shock wave is indicated by the closely spaced contours that extend from the rotor leading edge to the rotor suction surface at about 60-percent chord. This 60-percent chord location is where the rotor-suction-surface entropy contours (figure 7) indicate the onset of a disturbance. Computed overall pressure ratios are 2.388 for the Chima code and 2.376 for the Rai code.

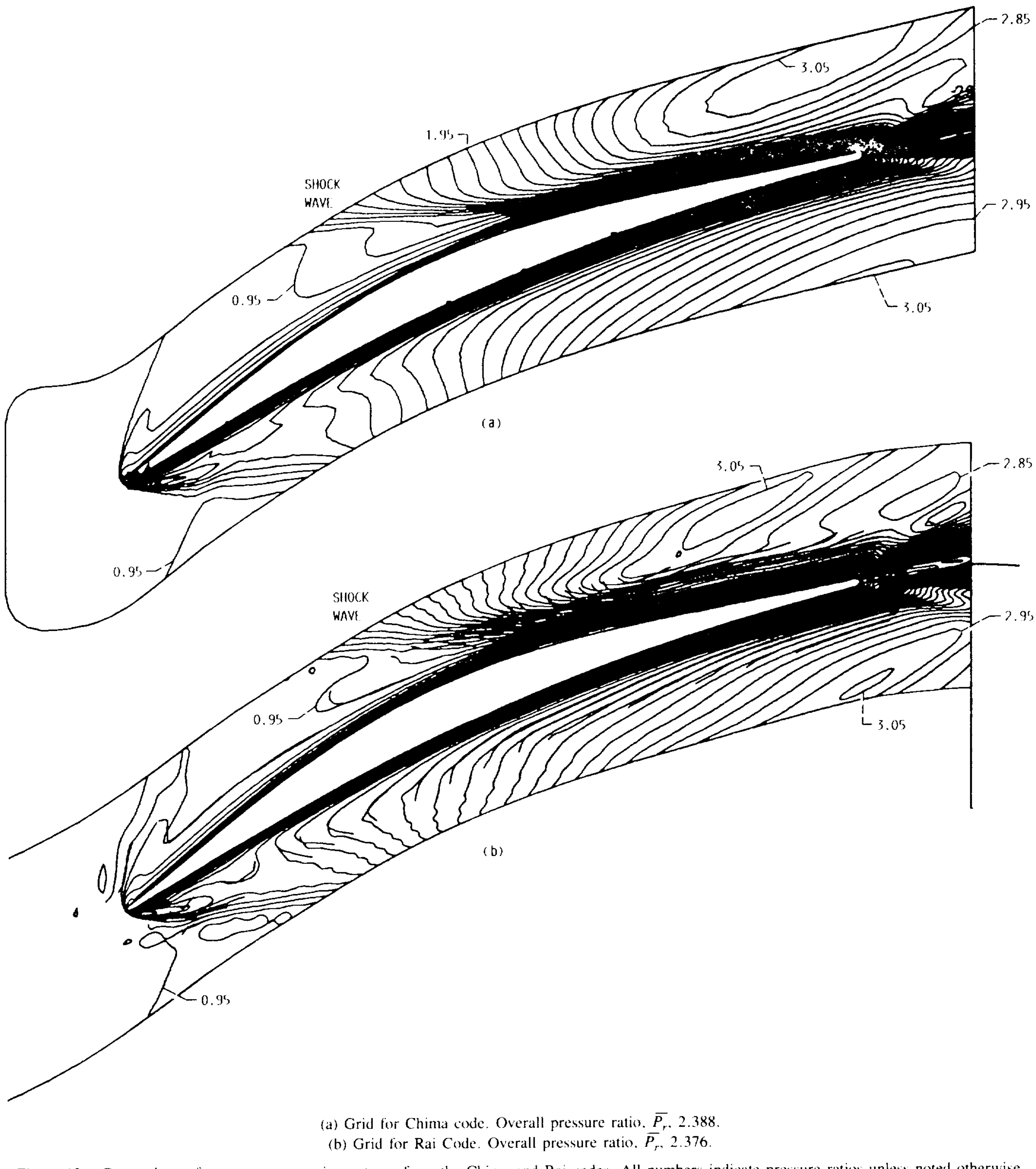
Figure 14 compares the efficiency distributions at the rotor exit for the two codes. They are very similar. The Chima distribution contains more points in the rotor wake and defines a sharper wake. Both codes show efficiencies near 1.0 outside of the rotor wake region, thus indicating weak rotor blade shocks. Rotor overall efficiencies are 0.774 and 0.768 for the Chima and Rai codes, respectively.

Experience with the Chima RVC code in investigating the effects of various controls on predicted performance indicates that the efficiency may be 0.050 higher than indicated herein. Specifically, a denser 321-by-65 C-grid resulted in a 0.045 increase in efficiency. A reduced artificial viscosity, from 0.40 (used herein) to 0.35 (the numerical stability limit), resulted in a 0.005 increase in efficiency. Reductions of grid spacing below 0.0004 in. (0.00102 cm) at the blade surface had very little effect on efficiency.



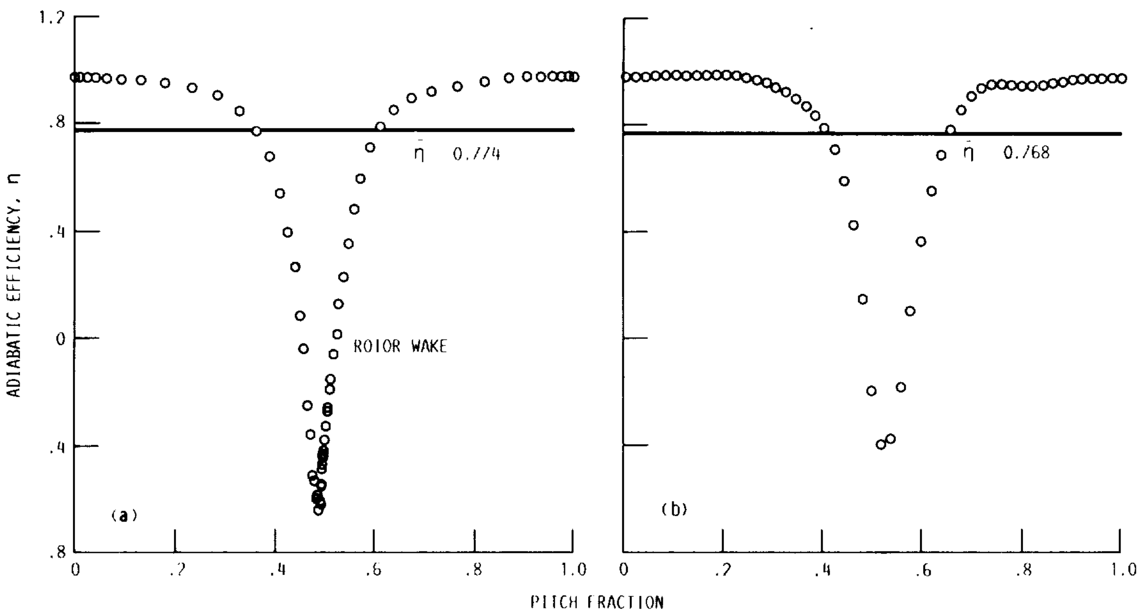
(a) Grid for Chima code: 161-by-33 C-grid.
(b) Grid for Rai code: 151-by-31 O-grid; 71-by-51 H-grid.

Figure 12.—Comparison of the rotor grid for the Chima code with the rotor region grid for the Rai code.



(a) Grid for Chima code. Overall pressure ratio, $\overline{P_r}$, 2.388.
(b) Grid for Rai Code. Overall pressure ratio, $\overline{P_r}$, 2.376.

Figure 13.—Comparison of rotor pressure ratio contours from the Chima and Rai codes. All numbers indicate pressure ratios unless noted otherwise.



(a) Chima RVC code.
(b) Rai code; 0-percent cycle fraction.

Figure 14.—Comparison of rotor adiabatic efficiency distributions from the Chima and Rai codes.

Concluding Remarks

Results from an analysis of a model of the Lewis supersonic throughflow fan design (SSTF) have been presented. The model was analyzed by using the Rai ROTOR1 two-dimensional, unsteady viscous code, and some comparisons were made with results from the Chima RVC code. The following remarks and conclusions can be made at this time.

1. The Rai code O- and H-grids permit uniform grid packing throughout the rotor-stator interface region.
2. The Rai ROTOR1 code provides detailed insight into the unsteady flow field of the Lewis SSTF design.
3. The SSTF design goal of low blade-generated shock losses is consistent with Rai code results.
4. The computed overall SSTF efficiency is low because of high rotor and stator viscous losses.
5. For rotor grids of similar density, Rai code rotor results compare very well with Chima RVC code results.
6. Experience with the Chima RVC code indicates that a 0.05 computed efficiency increase is possible with a grid that is four times denser than used herein.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 13, 1989

Appendix – Averaging Method for Overall Performance Parameters

This appendix defines some performance parameters and the method of averaging used to obtain the overall performance parameters, such as adiabatic efficiency. Adiabatic efficiency η is calculated from

$$\eta = \frac{(P_r)^{(\gamma-1)/\gamma} - 1.0}{T_r - 1.0} \tag{1}$$

where P_r is the total pressure ratio, T_r is the total temperature ratio, and γ is the specific heat ratio.

Overall rotor and stage performance parameters are calculated from q-data (density, momentum, and energy) files averaged over one blade pitch. First mass flow $\dot{m}$ for one pitch is obtained from

$$\dot{m} = \int \rho u (dy)$$

where ρ is the density, u is the axial velocity, and y is the tangential distance. Trapezoidal integration is performed over one pitch. Then average density $\bar{\rho}$ is calculated from

$$\bar{\rho} = \frac{\dot{m}}{\int u (dy)}$$

Average axial and tangential velocity components $\bar{u}$ and $\bar{v}$ are calculated from

$$\bar{u} = \frac{\int u(\rho u)dy}{\dot{m}}$$

and

$$\bar{v} = \frac{\int v(\rho u)dy}{\dot{m}}$$

where ρu is the axial momentum. Finally, average energy $\bar{e}$ is calculated from

$$\bar{e} = \overline{\left(\frac{e}{\rho}\right)}\bar{\rho}$$

where

$$\overline{\left(\frac{e}{\rho}\right)} = \frac{\int \frac{e}{\rho}(\rho u)dy}{\dot{m}}$$

Average static pressure $\bar{p}$ and Mach number $\bar{M}$ are next obtained from

$$\bar{p} = (\gamma - 1.0)[\bar{e} - 0.5\bar{\rho}(\bar{u}^2 + \bar{v}^2)]$$

and

$$\bar{M} = \left[\frac{\bar{\rho}(\bar{u}^2 + \bar{v}^2)}{\gamma\bar{p}}\right]^{0.5}$$

where the specific heat ratio γ is assumed constant at 1.40. Average total pressure $\bar{P}$ and total temperature $\bar{T}$ are calculated from

$$\bar{P} = \bar{p}\left(1.0 + \frac{\bar{M}}{5.0}\right)^{3.5}$$

and

$$\bar{T} = \frac{\bar{p}}{\bar{\rho}}\left(1.0 + \frac{\bar{M}}{5.0}\right)$$

where $\gamma = 1.40$ is assumed.

The average $\bar{P}$ and $\bar{T}$ are divided by the fan inlet total pressure and temperature to obtain the overall average pressure and temperature ratios $\bar{P_r}$ and $\bar{T_r}$. The overall average adiabatic efficiency $\bar{\eta}$ is then obtained from equation (1).

The pressure coefficient c_p is calculated from

$$c_p = \frac{p - p_i}{2.0\rho_i(V_i^2)}$$

where p is the static pressure, V is the velocity, and i refers to the fan inlet.

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15. Supplementary Notes

16. Abstract

The Rai ROTOR1 code for two-dimensional, unsteady viscous flow analysis was applied to a supersonic throughflow fan stage design. The axial Mach number for this fan design increases from 2.0 at the inlet to 2.9 at the outlet. The Rai code uses overlapped O- and H-grids that are appropriately packed. The Rai code was run on a Cray XMP computer; then data postprocessing and graphics were performed to obtain detailed insight into the stage flow. The large rotor wakes uniformly traversed the rotor-stator interface and dispersed as they passed through the stator passage. Only weak blade shock losses were computed, which supports the design goals. High viscous effects caused large blade wakes and a low fan efficiency. Rai code flow predictions were essentially steady for the rotor, and they compared well with Chima rotor viscous code predictions based on a C-grid of similar density.

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