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This report covers research performed under Grant AFOSR-91-0052. The work consisted of four separate projects: 1) Reduction of Fan Noise Through Boundary Layer and Wake Suction; 2) Effect of Rotor-Strator Interaction on Turbomachinery Stall Behavior; 3) Turbomachinery Tip Clearance Vortical Flows; 4) Effects of Compressibility on Streamwise Vorticity Enhanced Mixing.

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PERIOD OF INVESTIGATION: September 1, 1994- August 31, 1995

January 1996

Introduction

This is a final report on the Air Force Research in Aero Propulsion Technology (AFRAPT) Program at MIT. The report describes the work carried out during the period September 1, 1994 to August 31, 1995 (consisting of short descriptions of the research of each student during this period) and gives a brief summary perspective on the overall program.

During the above period, the students supported under this program, the advisors, and the research projects are as follows:

Trainee: John Brookfield (1/2 supported by AFRAPT)
Advisor: Professor I. A. Waitz/Professor I. U. Ingard
Project: Reduction of Fan Noise Through Boundary Layer and Wake Suction

Trainee: Martin Graf
Advisor: Professor E. M. Greitzer
Project: Effect of Rotor-Stator Interaction on Turbomachinery Stall Behavior

Trainee: Amrit Khalsa (1/2 supported by AFRAPT)
Advisor: Professor I. A. Waitz
Project: Turbomachinery Tip Clearance Vortical Flows

Trainee: David Tew
Advisor: Professor I. A. Waitz
Project: Effects of Compressibility on Streamwise Vorticity Enhanced Mixing

Description of the Research

Brief descriptions of the different research projects are given below; detailed descriptions will be given in the Ph. D. theses of the graduate student trainees.

Reduction of Fan Noise Through Boundary Layer and Wake Suction, J. Brookfield

Although consideration of engine noise in the engine design process is now standard, the classical methods of noise abatement are reaching their limits and new measures are required to obtain increased levels of noise attenuation. There are a number of methods of noise reduction aimed at tonal noise. However, since tonal and broadband noise contribute roughly equal levels of noise in the engine, even the complete removal of one of these will only generate a total noise reduction of approximately 3dB.

The approach taken at MIT for the reduction of rotor-stator interaction noise is the direct elimination of the noise source, not noise reduction after it has already been produced. If the wake shed by the upstream rotor blades can be smoothed before reaching the downstream stationary stator blades, there will be no unsteady velocity field to generate noise. Using trailing edge blowing on the rotor blades (see Figure 1), the momentum deficit and most of the mass deficit can be injected at the trailing edge leaving a momentumless wake. This technique yields a much smaller velocity deficit at the stator position and a much lower level of turbulent fluctuations in the wake. Provided the spatial harmonic content of the wake remains the same, these two reductions reduce both tonal and broadband noise. Figure 2 shows the pressure level of the injected flow required for wake management.

Tests will be carried out in the MIT Blowdown Compressor to examine this concept. The main data in the tests will be unsteady pressure measurements on the downstream stator row. A stator blade has been instrumented at one spanwise position with Kulite pressure transducers distributed along the chord on both the suction and pressure surfaces. This blade will be translated radially during the test to obtain the complete chord and spanwise unsteady pressure distribution. The data can serve as input to a noise radiation code which couples the unsteady blade pressures to the propagating duct modes and calculates the radiated noise. In addition, microphones will be installed in the tunnel walls to obtain qualitative measurements of the noise levels.

At present, preliminary tests with a solid (no blowing) rotor blade set are nearly ready to begin. All main parts for the test section are complete and their assembly and miscellaneous parts manufacturing is currently underway. Within the next several months, tests with the rotor alone and then with the stator row, will be conducted. This set of tests will provide the baseline for the noise generated from the fan rotor- stator interaction as originally designed.

The baseline tests, plus results from previous two-dimensional experiments and calculations, quasi-three dimensional computations, and noise radiation predictions give a method for designing the blades with trailing edge blowing. The estimates to date imply that both tonal and broadband noise associated with the rotor wake/stator interaction can be reduced by more than 6 dB.

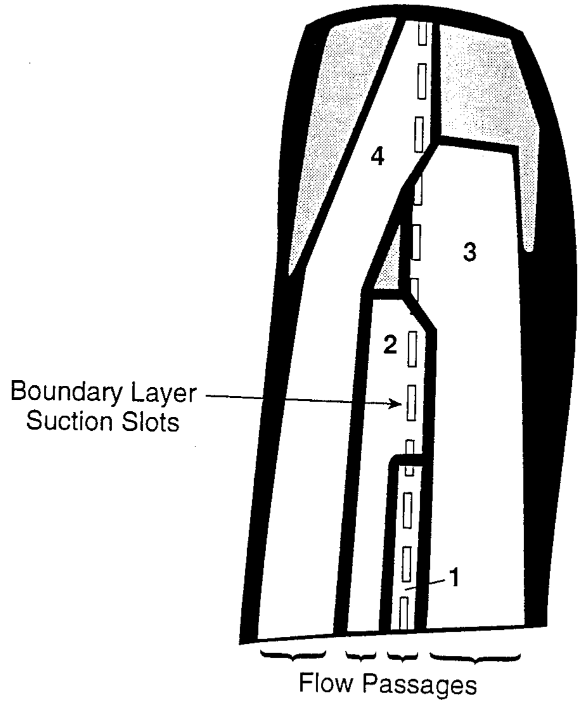


Figure 1: Fan blade design for boundary layer suction.

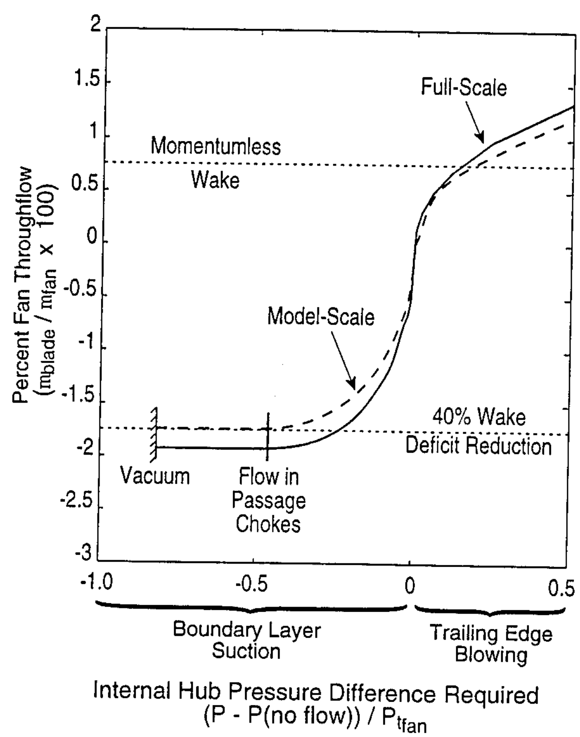


Figure 2: Suction and blowing performance for sample blade design.

Effect of Rotor-Stator Interaction on Turbomachinery Stall Behavior, M. B. Graf

During the past year work has progressed in the area of tip clearance flow effects on multi-stage axial compressor performance and stability. The two problems addressed during the doctoral research program are:

(1) Effects of Asymmetric Tip Clearance on Compressor Stability

(2) Downstream Stator Potential Effects on Upstream Rotor Performance.

Both of these projects are computational, but comparisons with experimental data are also planned. Research on the first topic was completed during the 1993-94 academic year [1].

The second topic involves a computational fluid dynamic (CFD) study of the effect of unsteady blade row interaction on rotor aerodynamic performance. This problem demands the use of state-of-the-art CFD codes and intensive computational resources. Because of mutual interest in the results, the Pratt & Whitney Division of United Technologies Corporation has supported use of their computational facilities for this investigation. The CFD code utilized in this study is a three-dimensional Reynolds-Averaged Navier-Stokes version of the solver developed by Ni [1]. The objectives can be summarized in the following questions:

(a) How does the rotor tip clearance flow and tip vortex respond to the unsteady (time-varying) pressure field being imposed by the downstream blade row? Is the response significantly different than that obtained assuming steady flow in the rotor relative frame?

(b) How is rotor performance (aerodynamic efficiency and pressure rise) affected by the unsteady rotor-stator interaction?

The study concentrates on examining these questions as they apply to a parametrically representative stage of a modern high pressure compressor. Figure 3 conceptually illustrates the problem being addressed.

[1] Interest in this work has lead to a series of experiments on the effect of asymmetric tip clearance on compressor performance. These experiments were designed using the model developed in part (1), and are being conducted by another student at General Electric Co. Aerodynamic Research Laboratory in Cincinnati, Ohio.

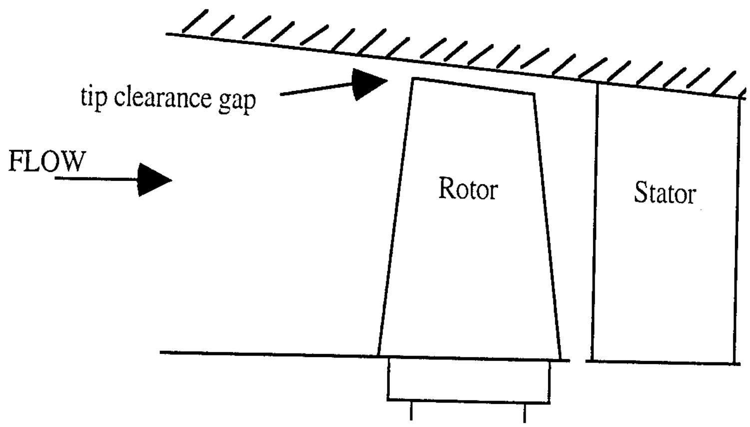
Three-dimensional steady flow calculations were initially carried out to give an overall determination of the stage performance. Based on this, the highest point on the constant speed pressure rise characteristic, as well as a point at lower loading, were run using the CFD code which includes full unsteady interaction of the blade rows. Comparisons of the steady and unsteady simulations illustrate the effects of stator potential interaction on the rotor aerodynamic performance. Conclusions to date include the following:

- Radial and tangential tip vortex motion exists in all unsteady simulations. The period of motion is always longer than blade passing time.
- Time averaging of flow must be done over the tip vortex flow time scale to correctly capture the time averaged endwall flow.
- Unsteady blade row interaction was found to impact rotor performance as follows:
  - little effect on time averaged rotor pressure rise or flow capacity
  - rotor losses in the tip region (~ outer 20% span) are decreased
  - rotor loss away from tip region is increased
  - large oscillations in rotor endwall blockage due to vortex-wake interaction occur, but the time averaged endwall blockage is lower than that found in steady flow

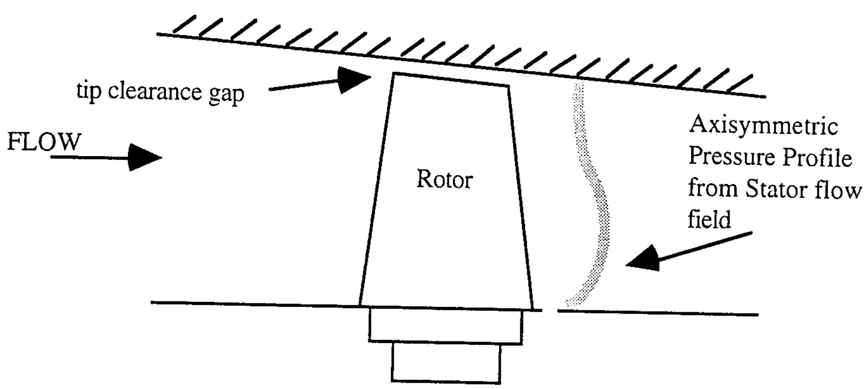
At the present time, work is underway to understand the fluid dynamic mechanisms responsible for the behavior summarized above. To aid this, a parametric study has been conducted to determine how stator radial loading distribution, rotor-stator axial spacing, and blade count ratio impact the results. These cases are currently being interrogated to establish the causal links responsible for the changes in performance associated with the unsteady flow environment.

Reference

[1] Ni, R. H., Bogoian, J. C., "Prediction of 3D multi-stage turbine flow field using a multiple-grid euler solver," AIAA Paper 89-0203.



(a) UNSTEADY FLOW: Rotor-Stator interaction



(b) STEADY FLOW: Rotor with axisymmetric exit pressure profile

Figure 3: Schematic of problem. Rotor subjected to two different exit boundary conditions.

Turbomachinery Tip Clearance Vortical Flows, A. Khalsa

An objective of this work is the development of physically based guidelines for compressor casing treatment design. Towards this goal, experiments and analysis have been done this past year to quantify the essential fluid dynamic features which impact axial compressor endwall blockage, and hence compressor pressure rise. Specific progress includes the development of analytic models which identify the key uncertainties in the prediction of endwall blockage, the measurement of endwall blockage in a low speed research compressor, an analysis of computational solutions of compressor flow fields to establish the mechanisms underlying the parametric dependence of endwall blockage, the beginning of a computational investigation of casing treatment, and additional data collection in a wind tunnel test section designed to simulate a compressor tip clearance flow.

The modeling effort accomplished this year used the behavior of a wake in an adverse pressure gradient to give a physical basis for the functional dependence of blockage. The model also aided in identifying the critical flow elements for soundly-based endwall blockage predictions. A key uncertainty is the mixing of the clearance jet with the free stream; this determines both the total pressure in the endwall region and the amount of free stream fluid entrained by the leakage jet.

Detailed measurements were made in a low speed compressor rig at the Whittle Laboratory at Cambridge University to confirm the blockage trends observed in computational simulations. A plot of the data taken on the rotating rig is shown in Figure 4, along with some of the computational results. The figure gives endwall blockage, A_b, normalized by the clearance area, τc, versus the static pressure coefficient minus the total pressure coefficient. Both pressure coefficients are endwall values at the trailing edge plane of the rotor, normalized by upstream free stream dynamic pressure. The gray area in the figure shows the asymptotic trend of the experimental data. The last computational points on the right mark the last conditions at which a converged solution was obtained.

An in-depth examination of a body of computational solutions was performed to identify the high leverage parameters in creation of endwall blockage. Clearance height and the blade row pressure rise were found to be the two dominant factors affecting blockage levels.

Computations were performed and experiments are underway to study the effect of a high total pressure jet on endwall blockage. This simulates one of the mechanisms of casing treatment operation. Quantitative understanding of the processes that occur between the injection of the high total pressure jet and the reduction in blockage will allow suggestions to be made for the more efficient design of casing treatments. A wind tunnel simulation of tip leakage flow (described in detail in a previous AFRAPT report) will be used. These experiments have recently begun.

In the coming year the investigation into the casing treatment blockage reduction mechanisms will be completed and emphasis will be on development of a methodology for estimating the mixing between the leakage jet and the main passage flow for the efficient alleviation of endwall blockage.

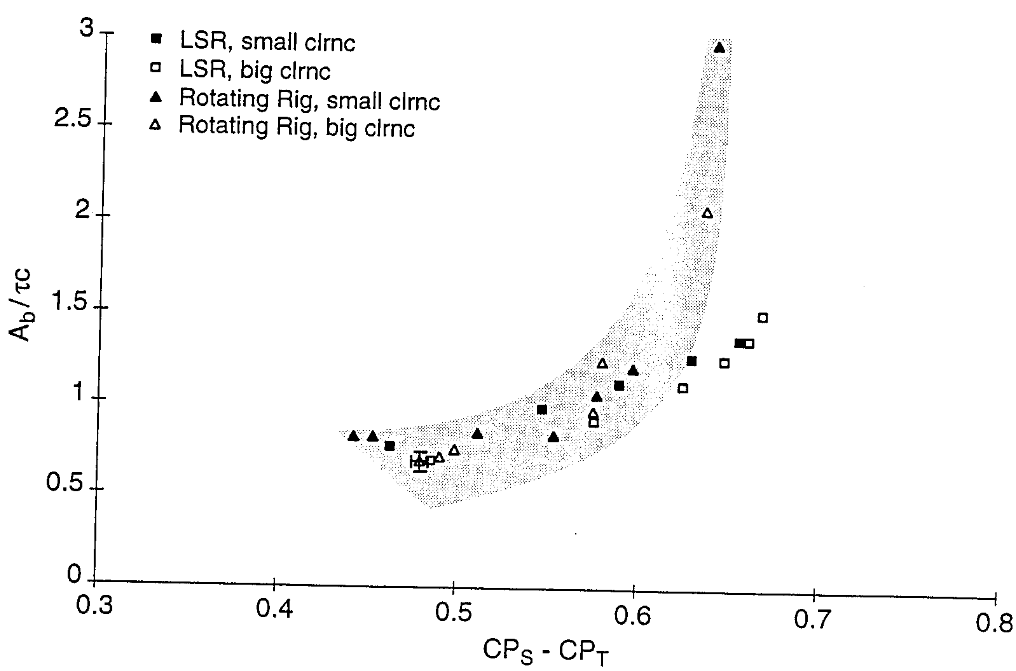


Figure 4: Comparison CFD-experiment.

Effects of Compressibility on Streamwise Vorticity Enhanced Mixing, D. Tew

A series of experiments have been conducted with lobed mixers in compressible shear layers to quantify the mixing augmentation associated with shed streamwise vorticity and to quantify the impact of the convective Mach number(M_C) on the streamwise vorticity enhanced mixing.

The overall streamwise circulation shed from the mixers was controlled via mixer geometry. Four mixers were designed--a flat plate, convoluted plate, 15° forced mixer, and 25° forced mixer. The streamwise circulations shed from the convoluted plate and two forced mixers non-dimensionalized by the mean inflow velocity and the lobe height were 0.08, 0.5, 0.9. All three lobed mixers have the same trailing edge shape, and a comparison between the mixing performance of these mixers has been used to delineate the impact of the streamwise vorticity on the mixing process. The convective Mach number was controlled by the varying the two inflow Mach numbers. The four mixers were tested at convective Mach numbers of 0.43 and 0.58.

The mixing rates downstream of the mixers were measured from wall static pressure measurements, Pitot/static pressure surveys, and Mie imaging of condensed methanol droplets. Three normalized mixing measures were utilized: the scalar mixedness, the momentum mixing parameter, and the normalized mass averaged total pressure(Ψ). These normalized mixing parameters vary from 0 at the completely unmixed trailing edge to 1 at fully mixed conditions.

In Figure 5, the normalized mass averaged total pressures, at 20 wavelengths downstream of three of the mixers, are plotted at convective Mach numbers of 0.43 and 0.58. As may be seen in the Figure, the overall mixing rate downstream of the 15° forced mixer was nearly double that of the flat plate with roughly half of this mixing augmentation associated with streamwise vorticity and half due to the increased initial interface length. Additionally, in streamwise vorticity enhanced compressible mixing layers a decrease in the mixing rate with increasing convective Mach number was identified. The mixing rate was reduced by 10 percent as the convective Mach number was increased from 0.43 to 0.58.

In the next year, additional experiments are to be conducted to extend the range of convective Mach numbers investigated, and numerical computations are to be performed to assess the ability of forced mixers to generate streamwise circulation in compressible($M_c > 0.3$) mixing environments.

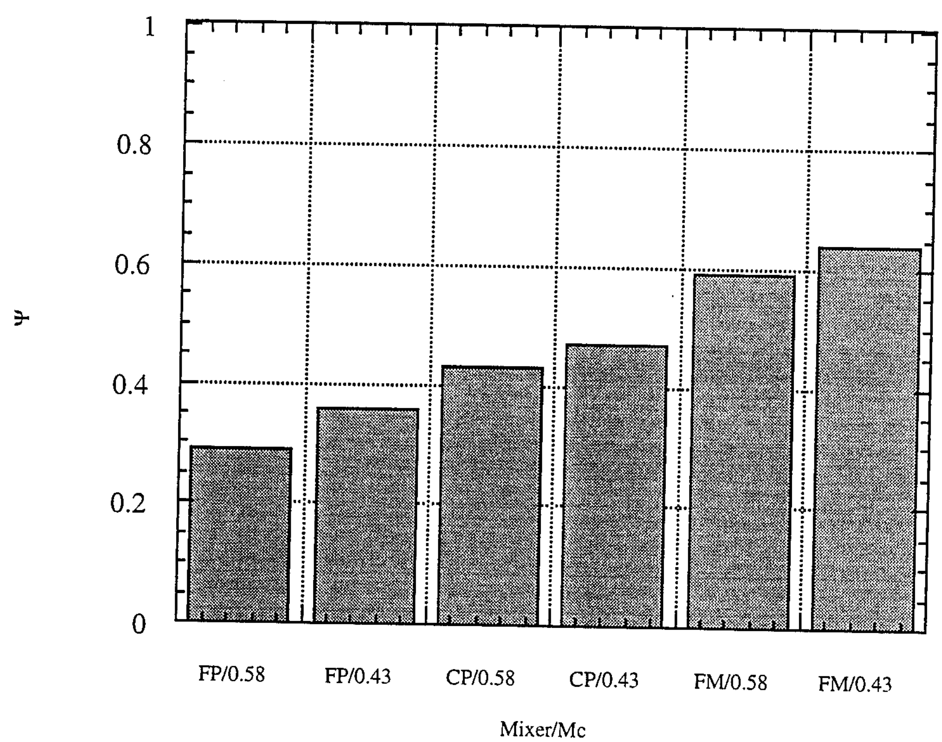


Figure 5: Normalized mass averaged total pressure(Ψ) 20 wavelengths downstream of the flat plate(FP), convoluted plate(CP), and 15° forced mixer(FM) at convective Mach numbers(M_c) of 0.43 and 0.58.

An Overall Perspective on the AFRAPT Program

The AFRAPT Program was set up with the objective of training graduate students for the U. S. Aeropropulsion industry. The research carried out by the students was supported separately, under grants or contracts from government and industry. From our perspective the program has been a success. There have been a number of students who heard about the program, investigated and became interested in the topic, and entered the field of aeropropulsion, who would not have done so otherwise.

The program was structured with the requirement that the student spend at least a Summer at a company. In some instances the period of time spent was longer, and in at least two cases, the work done during the stay at the company provided the nucleus for a thesis topics. A current example is Martin Graf who worked on effects of stator flow field non-uniformities (static pressure nonuniformities) on compressor rotor performance at Pratt and Whitney. After finishing his M. S. Thesis (on heat transfer in turbines) Mr. Graf decided to purse the topic he started at P&W and this became a major part of his Ph. D. research. It is a problem that not only is of scientific interest, but also of considerable technological interest, as evinced by he fact that P&W has encouraged Mr. Graf to carry out his computations using their computer system.

The interaction with the company was not only one way. Industry also appreciated the program because not only were the students useful during the time spent at the company, but the companies were able to get a close look at bright young individuals who could be candidates for future permanent employment. Indeed at the several overall AFRAPT program meetings, a strong support for the program was expressed by the industry participants.

In summary, the program worked, yielding not only useful scientific results, but also a number of well-trained engineers for the U. S. Aeropropulsion industry.