Improved Modeling Techniques for Turbomachinery Flow Fields

B. Lakshminarayana (B1LAER@ENGR.PSU.EDU, (814) 865-5551)
The Pennsylvania State University
Department of Aerospace Engineering
153 Hammond Building
University Park, PA 16802

Edward Hall (ehall@nas.nasa.gov)
Allison Engine Company
2001 South Tibbs Avenue
PO Box 420   Speed Code T-14A
Indianapolis, IN 46206-0420

Abstract

Objectives and Method of Approach

The objective of the program is to develop improved methodology for modeling turbomachinery flow fields. Specifically, it will address the deficiencies of the stress tensor models in steady-state 3-D Navier-Stokes models used for the design of turbomachinery components. Since the derivation of the average-passage equations clearly shows that the deterministic features of the turbomachinery flow contribute to the mixing stress tensor and stress tensor modeling does not address these contributions, the approach is to directly measure the mixing stress tensor in a high-speed turbomachinery component. Advanced analysis tools will be used to resolve the random and the deterministic components of the mixing stress tensor and a model will be developed from the governing equations with an appropriate change in the frame of reference. These models will be tested in Navier-Stokes solvers available at Allison.

The overall objective is to provide models and tools for improved methodology for the design of high efficiency turbomachinery and drastically reduce the time required for the design and development cycle. This methodology will replace present day approach based on empiricism and extensive testing.

The proposed research consists of three tasks:

- Experimental investigation of three-dimensional steady and unsteady flow field in multi-stage turbomachinery, including analysis and processing the data required for modeling multi-stage turbomachinery flows. Statistical analysis of the data acquired will be carried out to identify flow events at various scales using conventional and wavelet technique. The wavelet analysis should lead to identification of sources not associated with blade or shaft

Research sponsored by the U.S. Department of Energy's Morgan Energy Technology Center, under contract DE-FC21-92MC29061 with South Carolina Energy R & D Center, Clemson University, Clemson, SC. This program was initiated in September 1994.

frequency and involves decomposition of “unresolved unsteadiness” to derive random fluctuations and other sources of unsteadiness.

- Modeling of multistage flow field using the data acquired. The modeling will involve order-of-magnitude analysis of various sources associated with unsteady flow and its importance in the performance and design of turbomachinery.

- Incorporation of the model in Navier-Stokes code to predict flow field in multistage and single stage turbomachinery, including aerodynamic losses. Allison personnel will incorporate this in their proprietary code and Penn State will incorporate this in their three-dimensional Navier-Stokes code. The background and the method of approach used in accomplishing these tasks are given below.

Results and Accomplishments

The computational and experimental studies performed during this study were based on the Pennsylvania State University Research Compressor (PSRC). The PSRC employs a 3-stage axial flow compressor consisting of an inlet guide vane row and three stages of rotor and cantilever-mounted stator blading with a rotating hub. An area traverse mechanisms is available for detailed area traverse of 1 ½ passages downstream of stator 2, downstream of rotor 3, and downstream of stator 3. Four different types of probes (five-hole probe, aspirating probe, single sensor slanted hot wire, and thermocouple probe) can be traversed using the mechanism. The PSRC facility is unique in that the blade loading (average blade section diffusion factor near 0.438) and the rotational speed (tip Mach number near 0.5) are roughly equivalent to an embedded portion of a modern, high speed gas turbine compressor. This makes the PSRC facility a unique vehicle through which realistic studies of multistage compressor aerodynamic mixing can be performed.

Slanted hot film measurements (4 rotations) at the exit of stator 2 indicate that the stator wakes, hub leakage flow region, hub boundary layer scraping region, and the casing endwall suction surface corner are regions of highly three-dimensional and unsteady flow. These “apparent” stresses were most significant in the stator wake and suction side casing endwall corner and increased significantly with compressor loading. The flow in the suction side casing endwall corner was identified as being the dominant source of flow unsteadiness to the downstream rotor. Measurements indicate that the unresolved flow unsteadiness was everywhere larger than that of the total periodic unsteadiness with the exception of the stator wake regions. Oscillations of the structure frequencies due to various flow interactions may act to average out unsteady periodic flow structures. Both the revolution and blade periodic components were seen to be larger than the revolution and blade aperiodic components and suggests that the aperiodic components of flow unsteadiness can be neglected relative to the periodic components in the modeling. “Apparent” deterministic stresses measured at the exit of the stator passage arose due to an ensemble averaging technique applied to the temporal variation of the upstream rotor flow. These “apparent” stresses were most significant in the stator wake regions. An attempt to derive a deterministic mixing coefficient relating the deterministic stresses to the mean flow was not feasible. The five-hole probe measurements carried out at the exit of the rotor 3 indicate that the stator 2 wakes still persist and the defect and the width of the stator wakes are appreciable. A new wake correlation for the decay of the stator wake through a rotor blade row has been developed.

Correlations are presented which accurately model the decay of the maximum defect in total velocity of the stator wake as it passes through the rotor passage.

A wavelet analysis of the unsteady pressure and temperature data at the exit of the stator 2 has been carried out using Morlet's wavelet. This analysis indicates that the flow at midspan consists mainly of high frequency content, while those near the casing and hub are composed of various frequency components. These frequencies are lower than blade passing frequency and show nonlinear interaction with different frequency components.

The Allison personnel have predicted the flow in the multistage compressor. The predicted results for the 3 ½ stage Penn State research compressor were obtained using two different inter-blade row coupling techniques. The first technique, referred to as a mixing plane, was employed to characterize the overall performance of the compressor and to evaluate the ability to predict detailed flow features such as blade wakes, endwall flows, clearance vortices, etc. The second technique, referred to as rotor/stator interaction, provides detailed evaluations of the time-dependent flow features resulting from the relative motion of adjacent blade rows in turbomachines. These time-dependent fluctuations form the basis for the deterministic mixing stresses which are believed to be of significant importance in multistage compressor flows. The deterministic stresses resulting from the time-dependent solution were computed and compared with experimental results. These calculations and the detailed time-dependent test data taken from the PSRC facility have led to the development of a preliminary computational model designed to incorporate the time-averaged effects of multistage turbomachinery deterministic unsteadiness into a rapid 3-D Navier-Stokes solution algorithm. Coding of this preliminary model is underway, and quite promising early results are now available.

Application and Benefits

The results of this program are of great interest to the Gas Turbine Industry and has potential benefits in several manners. If suitable modeling procedures for multistage compressor flows were available, then it is likely that significant improvements in multistage compressor (and turbine) performance and design cycle cost and time could be achieved. Given the ability to accurately account for these multistage mixing effects, an estimated 2 - 3% improvement in compressor adiabatic efficiency and a 5% or greater improvement in compressor surge margin over current compressor designs might be achieved. Perhaps of greater importance is that the ability to rapidly analyze and alter compressor design with confidence using multistage CFD tools would result in an estimated reduction of one year in compressor development time and a savings of over $1,000,000 in compressor development cost. Clearly then, on the basis of economics alone, there is a strong industry motivation to develop accurate multistage compressor flow modeling tools.

Future Activities

Future activities would include complete survey of the flow field at the exit of rotor, using high response hot film and aspirating probes. This data will be used to develop "apparent" and mixing stress models and tested in the analysis code developed by Allison Engine Company.

This research is sponsored by METC through SCERDC (through Sub Contract 95-01-SR036) with Dr. Daniel Fant as the contract monitor.

INTRODUCTION

- Complex, unsteady, 3D, viscous flow field with close coupling of blade rows
- Need to identify and quantify various features and flow mechanisms; spanwise mixing, various sources of unsteadiness, leakage and secondary flows, AWBL, wakes
- Most research limited to single stage facilities or multistage with steady state instrumentation
- PSU multistage compressor: Mid-range facility with temperature rise: Ideal vehicle for understanding the flow in multistage compressors

Benefits of Improved Flow Modeling for Multistage Turbomachinery

- ☆ Increased aerodynamic efficiency (2–3% gain expected)
- ☆ Enhanced stall margin for compressors(5% or more) resulting in a wider operating range
- ☆ Increased power output for turbines
- ☆ Significant reduction in design cycle time and cost (elimination of 1 compressor build valued at $1,000,000 and 3 months development time)
- ☆ Improved off–design performance

OBJECTIVES

- To develop Fluid Dynamic and Thermal models and tools for improved methodology for the design and analysis of high efficiency turbomachinery and drastically reduce the time required for design and development cycle

- To gain a basic understanding of rotor-rotor and rotor-stator interaction and the effects of the unsteadiness arising from various blade rows on the overall flow field

- Address deficiencies of stress tensor models for average passage equations

- Measure stress tensor in a multi-stage environment, use advanced analysis tools to resolve deterministic and random mixing stress tensor for momentum equations, temperature-velocity correlations for energy equation

- Provide models for these stress tensors & heat flux for incorporation in steady state Navier-Strokes codes for analysis & design

- Validate the model/code for design & analysis of high speed multi-stage turbomachinery

APPROACH AND PROGRAM ELEMENTS

Task 1 EXPERIMENTAL PROGRAM

Experimental investigation of three-dimensional steady and unsteady flow field in multistage turbomachinery, including analysis and processing the data required for modeling multi-stage turbomachinery flows. Statistical analysis of the data acquired will be carried out to identify flow events at various scales using conventional and wavelet technique.

Task 2 MODELING OF MULTISTAGE FLOWFIELD

Data acquired will be analyzed and synthesized; an order-of-magnitude analysis will be carried out to derive models for apparent or mixing stress, heat flux terms associated with various sources of unsteady flow and blade-to-blade flow variation. Its importance in the performance and design will be evaluated. This model will be publicly available and generally applicable to Navier-Stokes solvers.

Task 3 INCORPORATION OF MODEL IN NAVIER-STOKES ANALYSIS AND DESIGN CODES

The model will be incorporated into Navier-Stokes code to evaluate these and earlier models to demonstrate capabilities of the completed model, including the prediction of Aerodynamic losses and efficiencies. The code will also be evaluated for improvement in design and development cycle.

TEST COMPRESSOR SPECIFICATIONS

Number of Stages	3
Tip Diameter	0.6096 m
Hub Diameter (inlet)	0.5075 m
Hub Diameter (exit)	0.5232 m
Blade Count (rotor)	70, 72, 74
Blade Count (stator)	71, 73, 75
Design Corrected Rotor speed	5410 rpm
Design Corrected Mass Flow	8.609 kg/s
Design Overall Total Pressure Ratio	1.354
Mass Averaged Peak Efficiency at 100% Corrected Speed (Torque Based)	90.65%
Blade Tip Mach Number	0.5
Average Hub-Tip Ratio	0.843
Average Rotor Tip Clearance (static)	1.328 mm (2.84%)
Average Rotor Tip Clearance (dynamic)	0.667 mm (1.43%)
Average Stator Hub Clearance (static)	0.686 mm (1.5%)

ASPIRATING PROBE

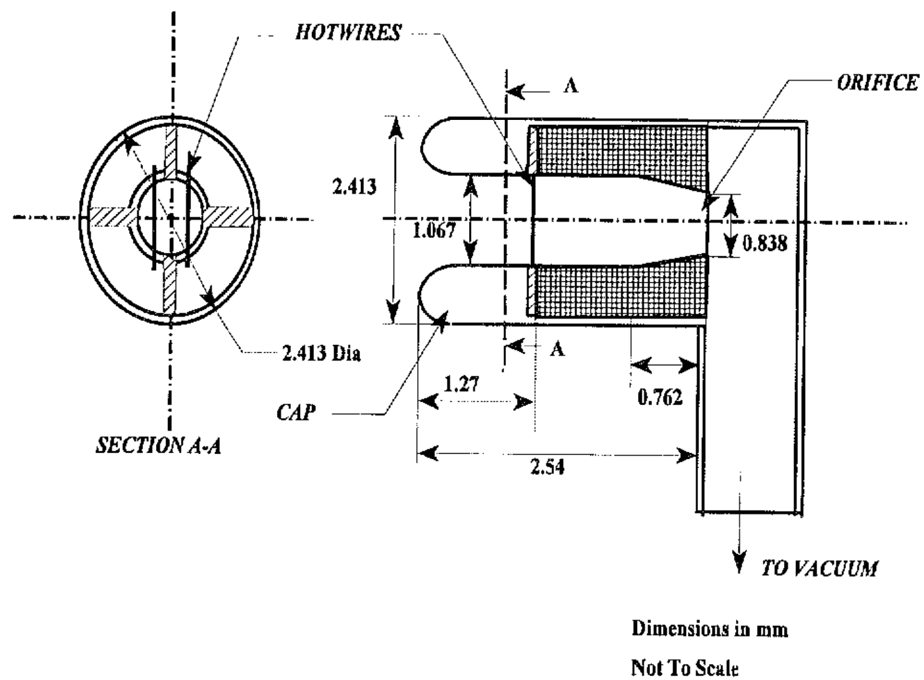
Governing Equation:

$$E_i^2 = C_i\left[\frac{P_o}{\sqrt{T_o}}\right]^{n_i}(T_{w_i} - rT_o)$$

2 Coplanar Hot-wires Operated at Different Overheat Ratios in a Channel in Front of a choked Orifice

Static Calibration, approx. 40 kHz Response in Compressor

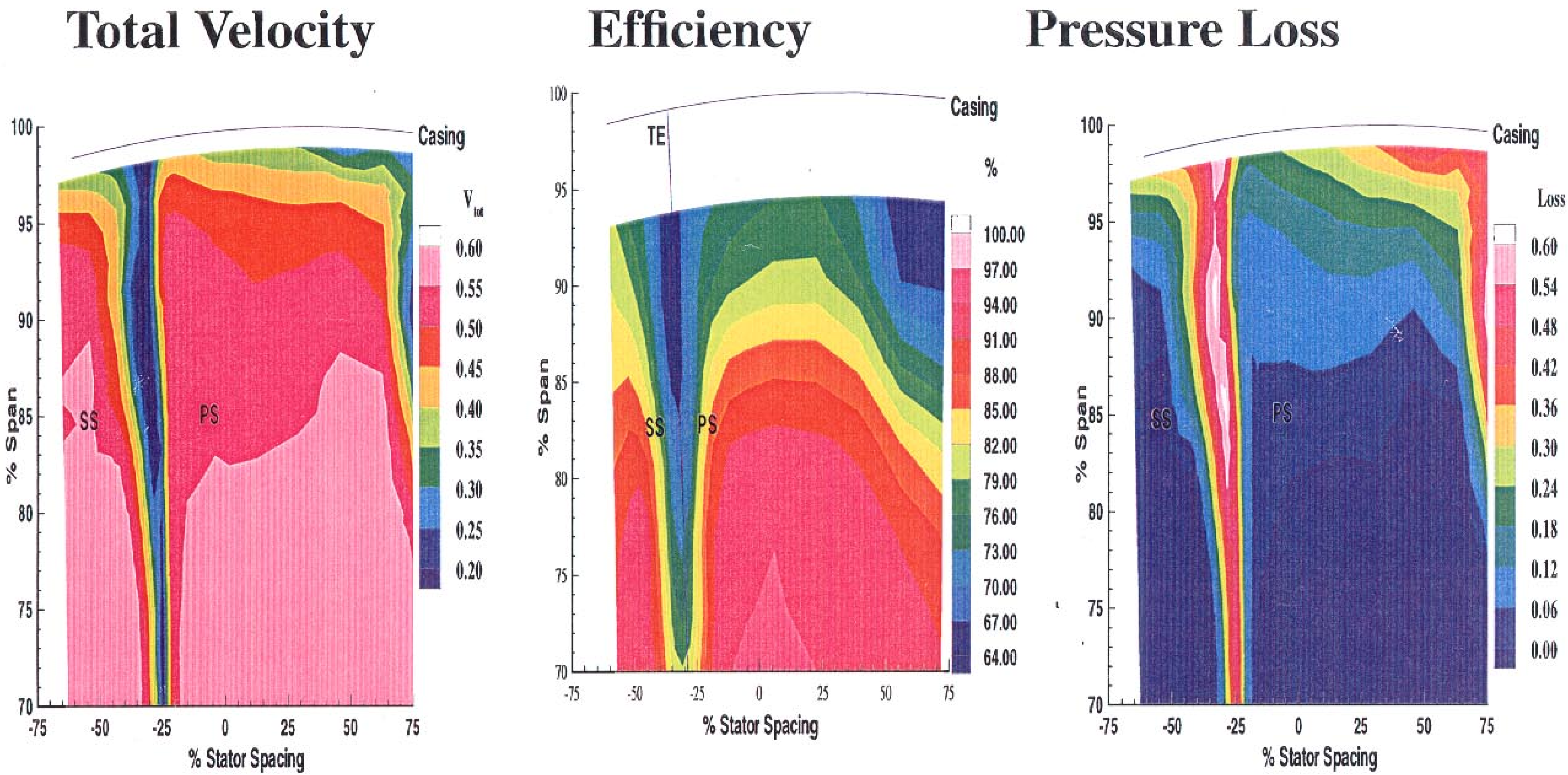
SCHEMATIC DRAWING



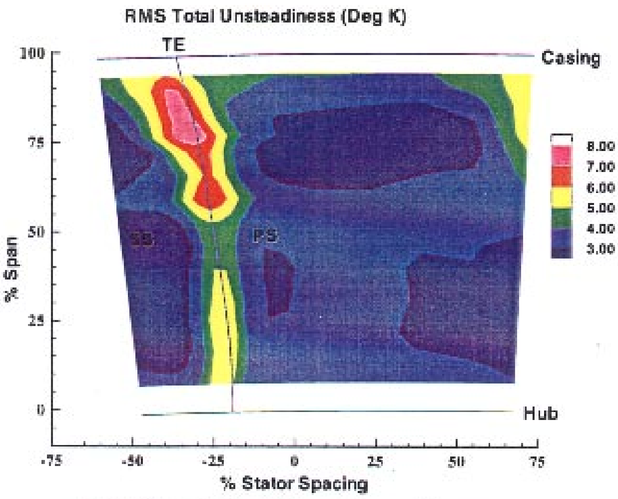
DECOMPOSITION OF INSTANTANEOUS SIGNAL

- *Ensemble average*: **Contributions from viscous and inviscid rotor-stator interaction effects**
- *Revolution periodic*: **The temporal fluctuations due to the relative motion between the blade rows**
- *Revolution aperiodic component*: **Arises from different blade count in successive stages (rotor or stator).**
- *Blade periodic*: **Denotes** *Average Passage*.
- **Based on the idealized assumption that all of the deterministic structure is synchronized to the shaft rotation.**
- **Limitations: Some deterministic physical phenomena, such as non-stationary vortices or wakes in the relative frame of reference, will appear in the unresolved component. Variations in the magnitude of the velocity deficit, width, and spatial positions of the rotor wakes between rotor revolutions contribute to the unresolved component.**

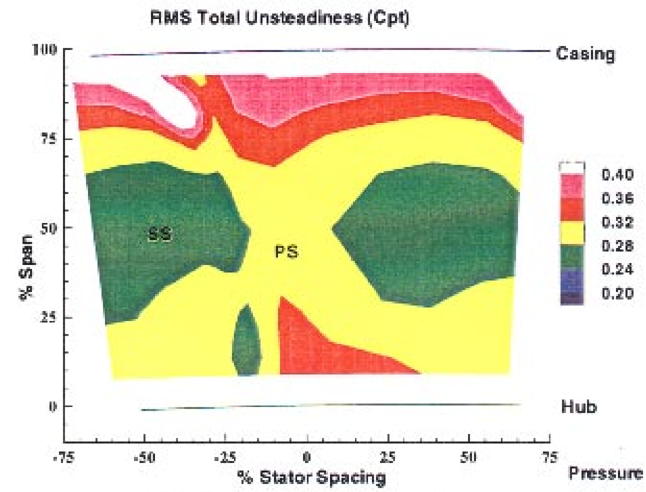
TIME AVERAGED FLOW NEAR TIP (Cont'd)



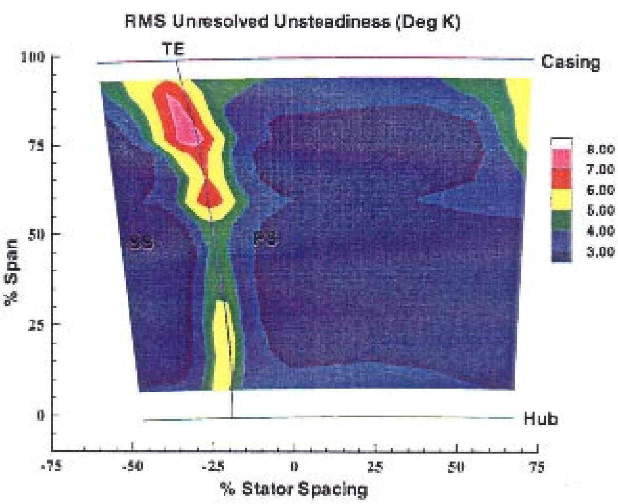
RMS UNSTEADINESS AFT STATOR 2



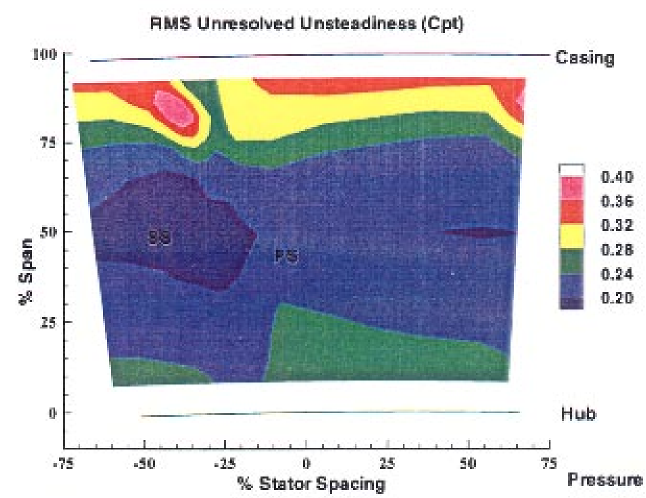
RMS Total Unsteadiness



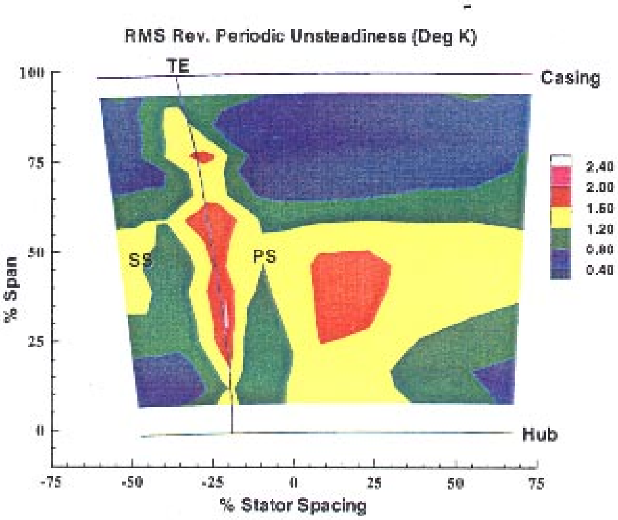
RMS Total Unsteadiness



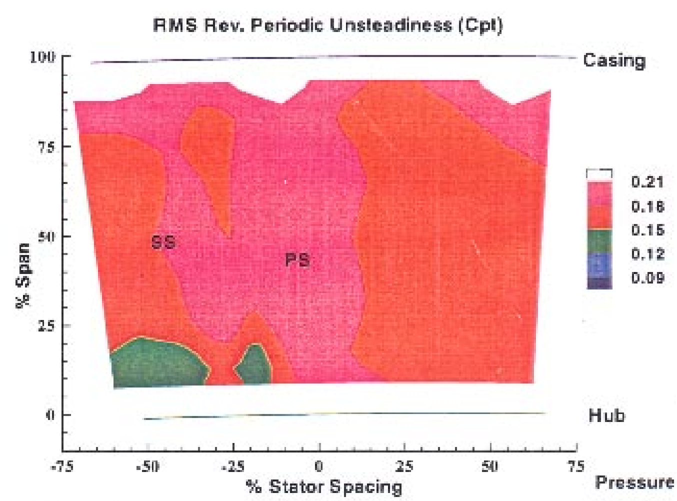
RMS Unresolved Unsteadiness



RMS Unresolved Unsteadiness



RMS Revolution Periodic Unsteadiness

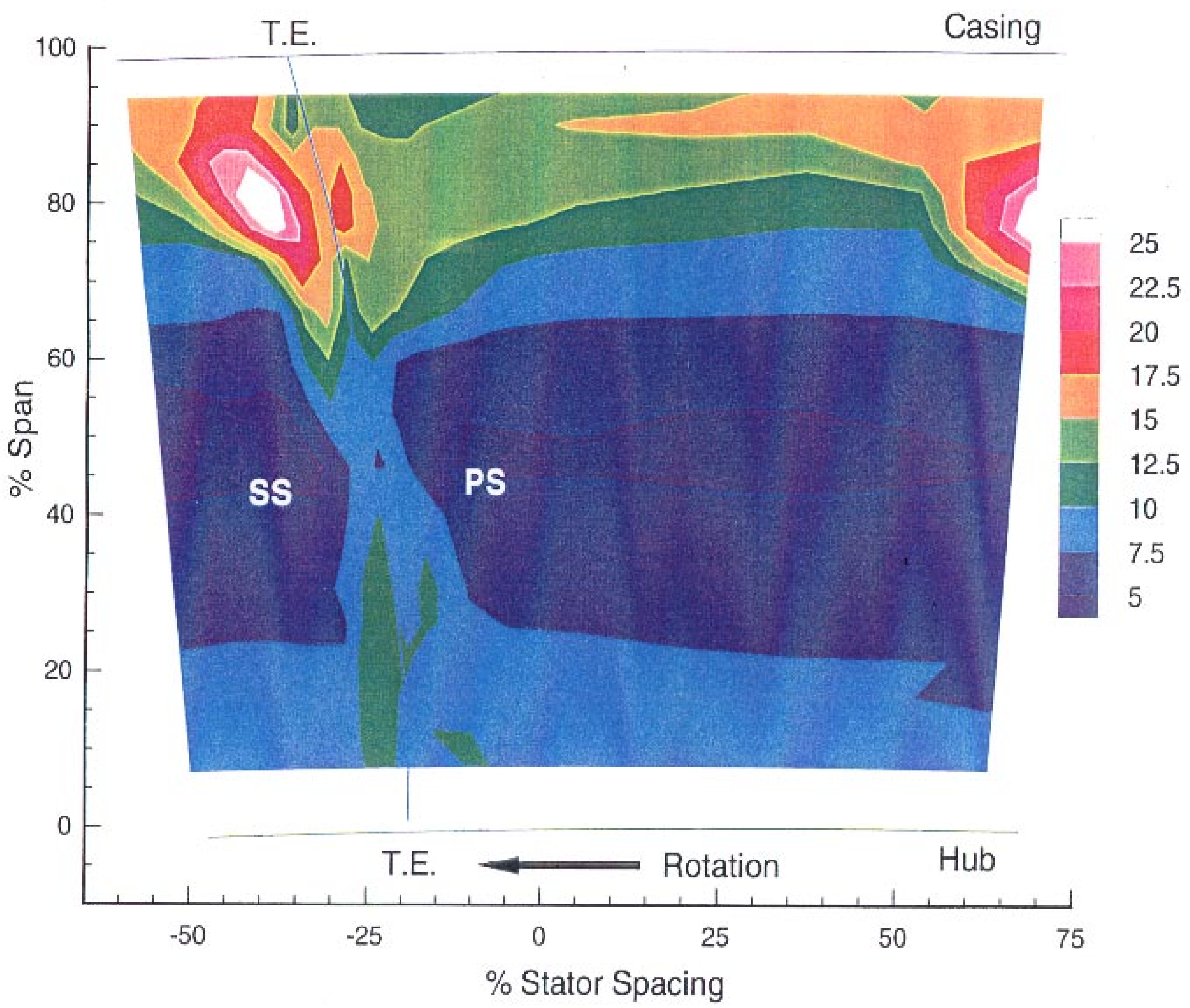


RMS Revolution Periodic Unsteadiness

TOTAL TEMPERATURE

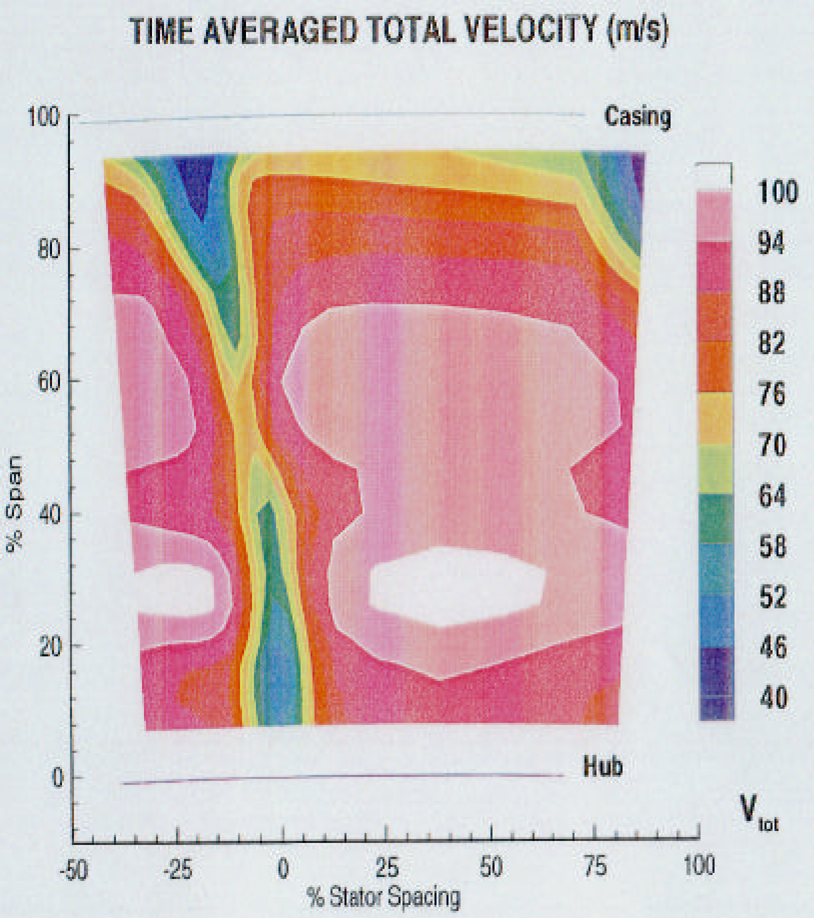
TOTAL PRESSURE

Unresolved Unsteadiness in $V_{eff1}/\overline{Vz}_{inlet}$ (%)

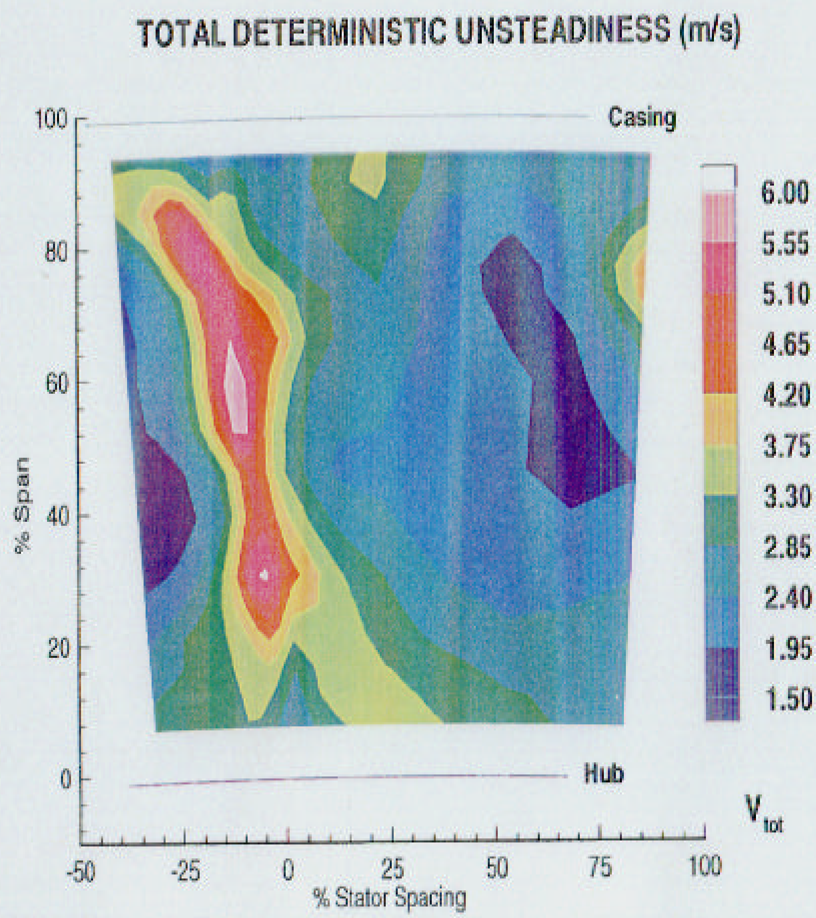


Unsteady Total Velocity Field, Aft Stator 2
Slanted Hot-Film

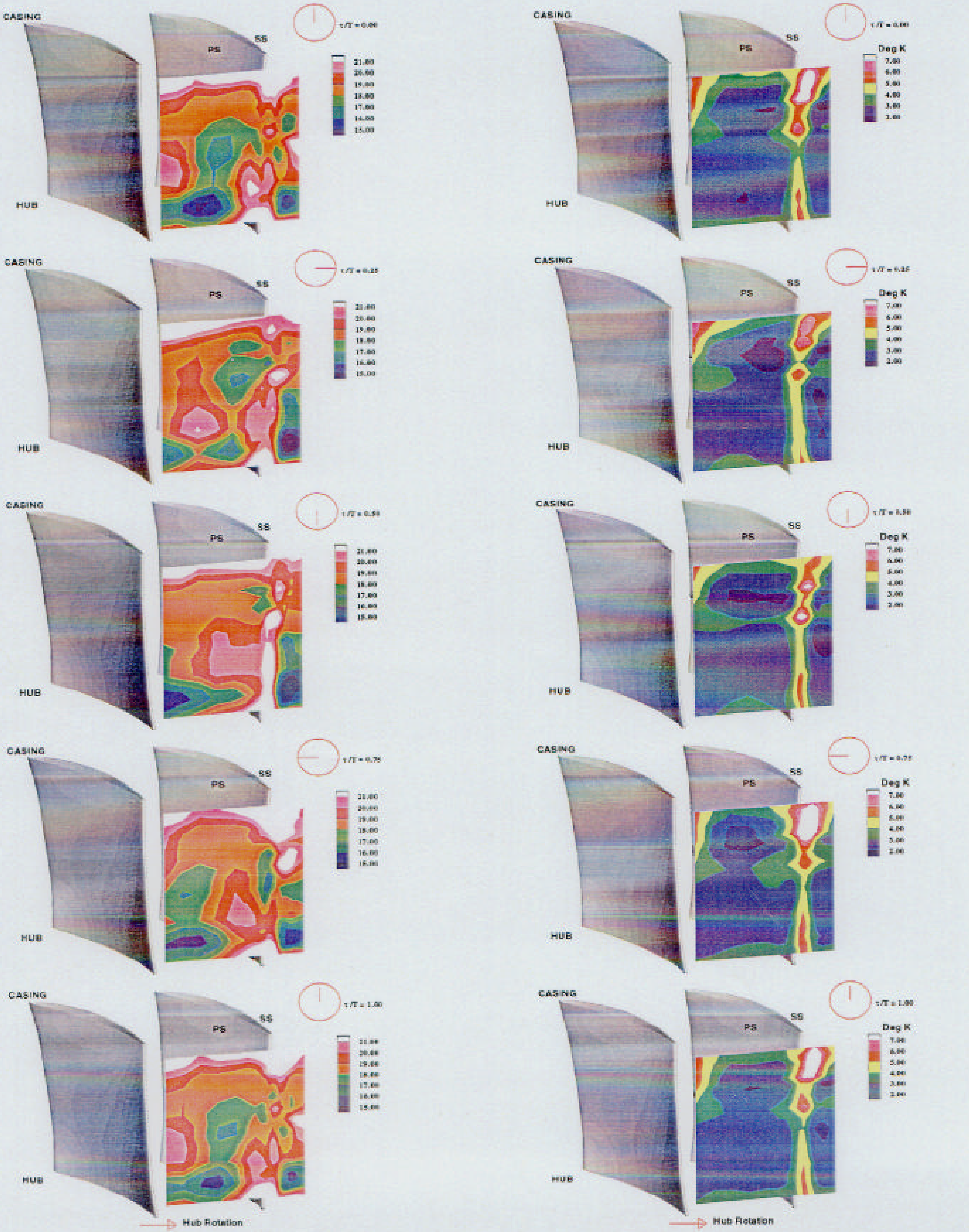
TIME AVERAGED TOTAL VELOCITY (m/s)



TOTAL DETERMINSTIC UNSTEADINESS



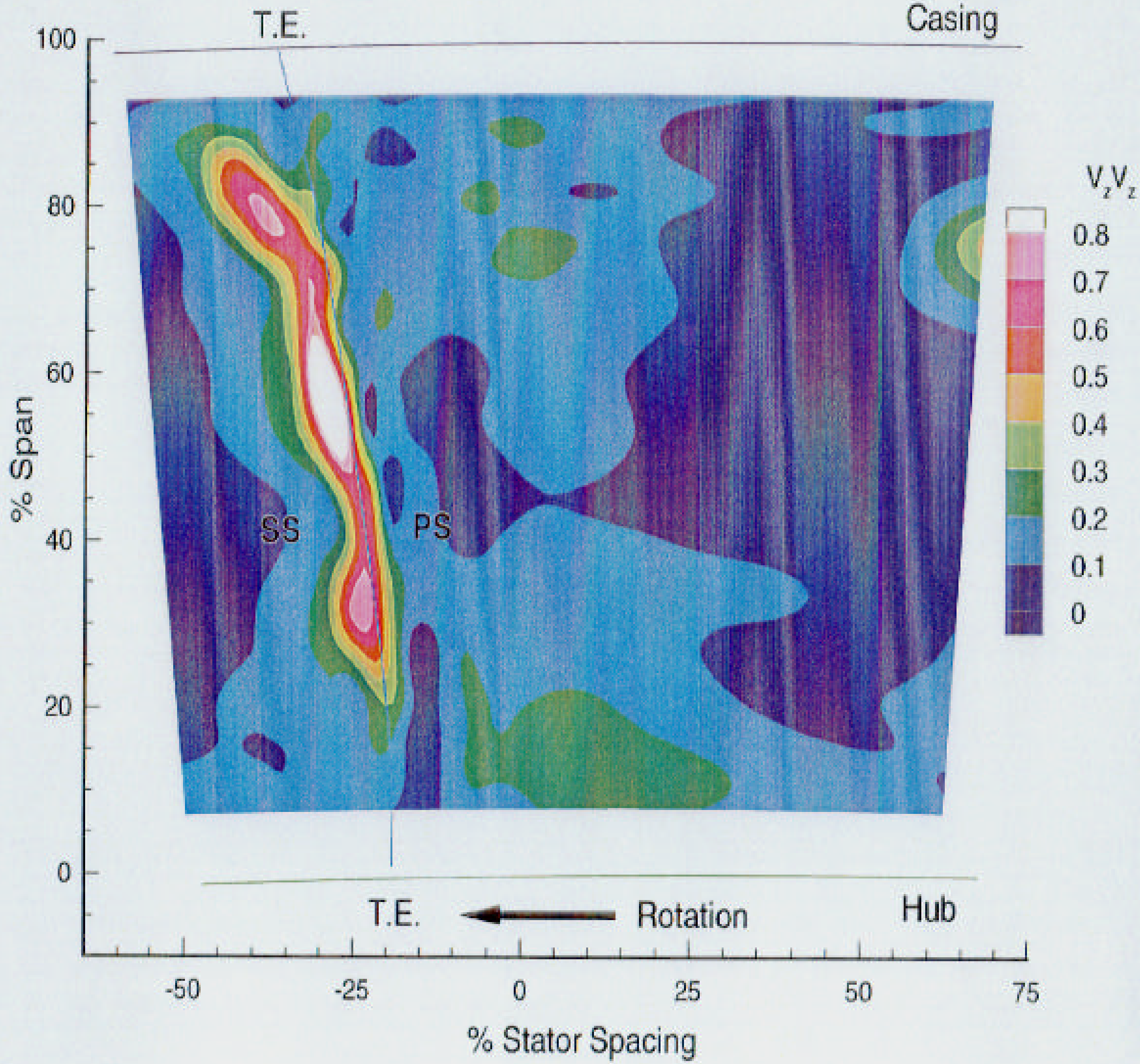
AFT STATOR 2: TEMPORAL VARIATION - To



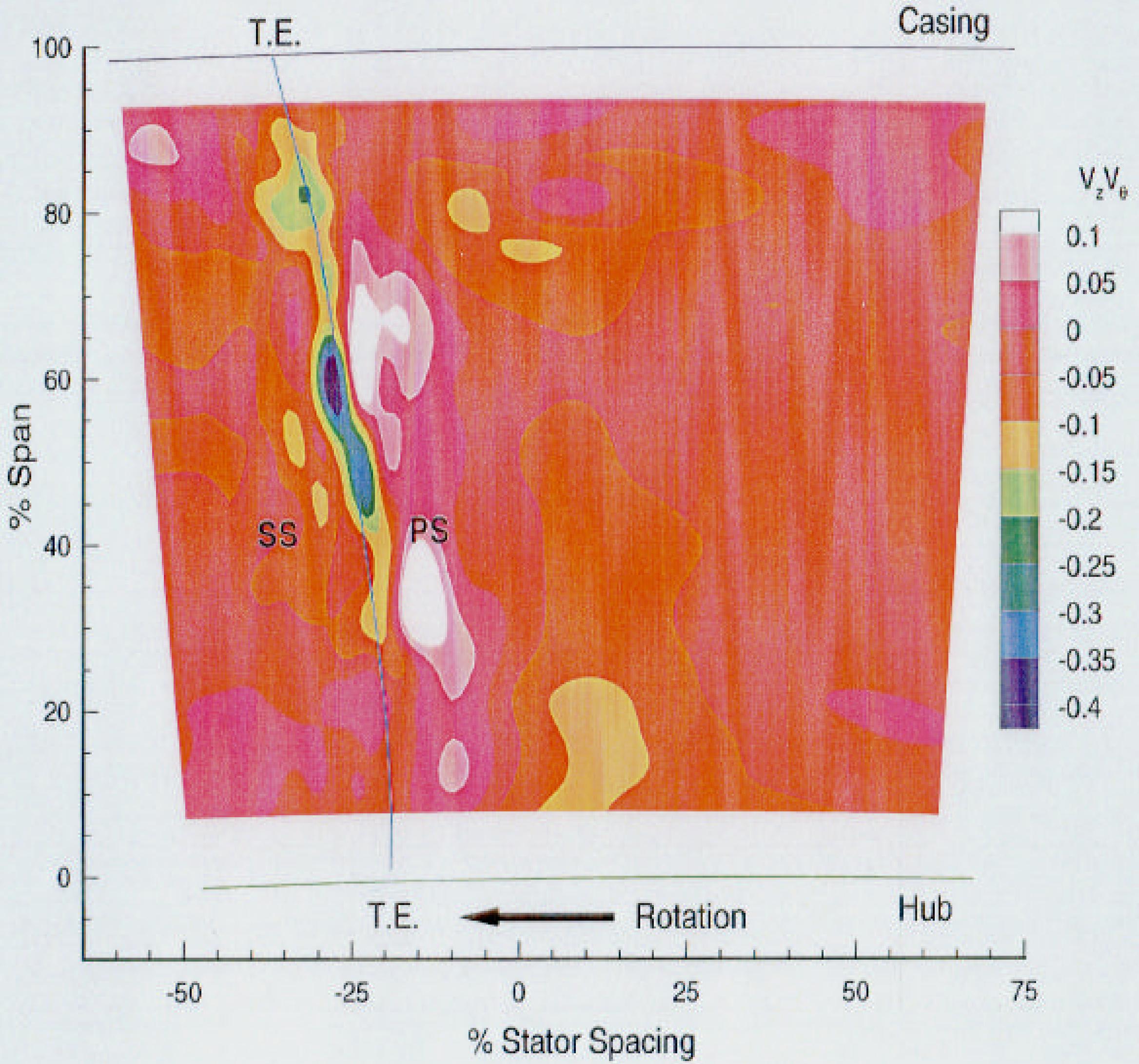
Ensemble average

RMS Unresolved Unsteadiness

Contour of $\overline{V_z V_z}/\overline{V_z}^2_{inlet}$ (%) Deterministic Normal Stress

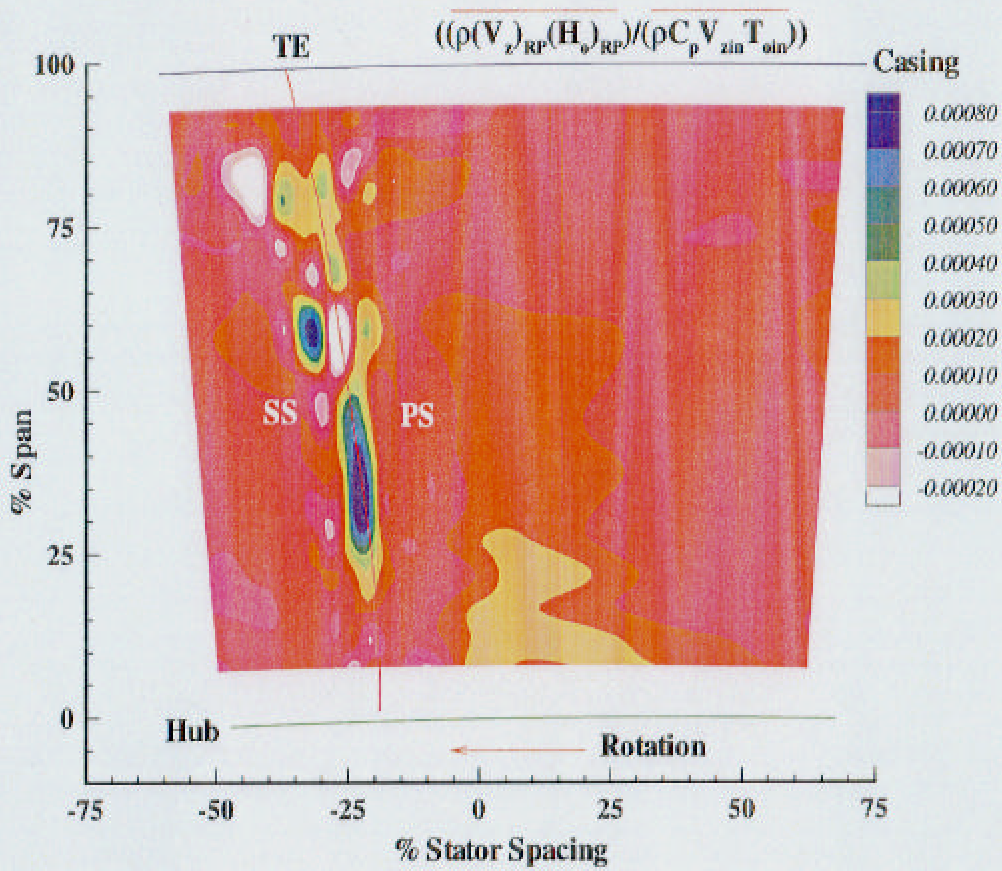


Contour of $\overline{V_z V_\theta}/\overline{V_z}^2_{inlet}$ (%) Deterministic Shear Stress



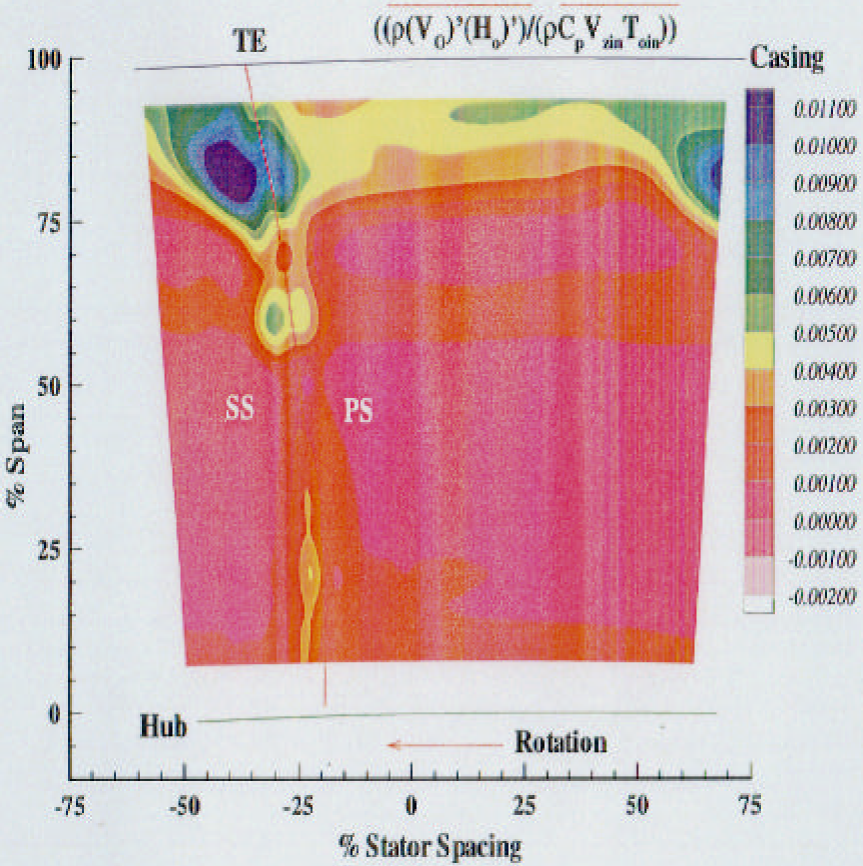
HEAT-FLUX DISTRIBUTION

DETERMINISTIC - AXIAL COMPONENT

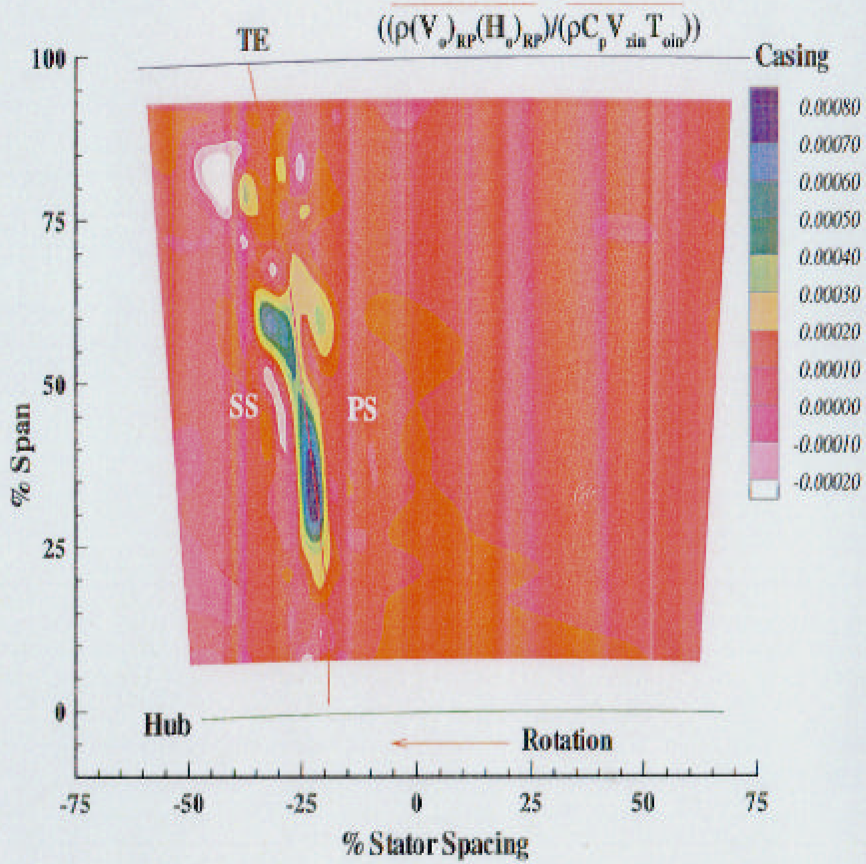


HEAT-FLUX DISTRIBUTION

UNRESOLVED

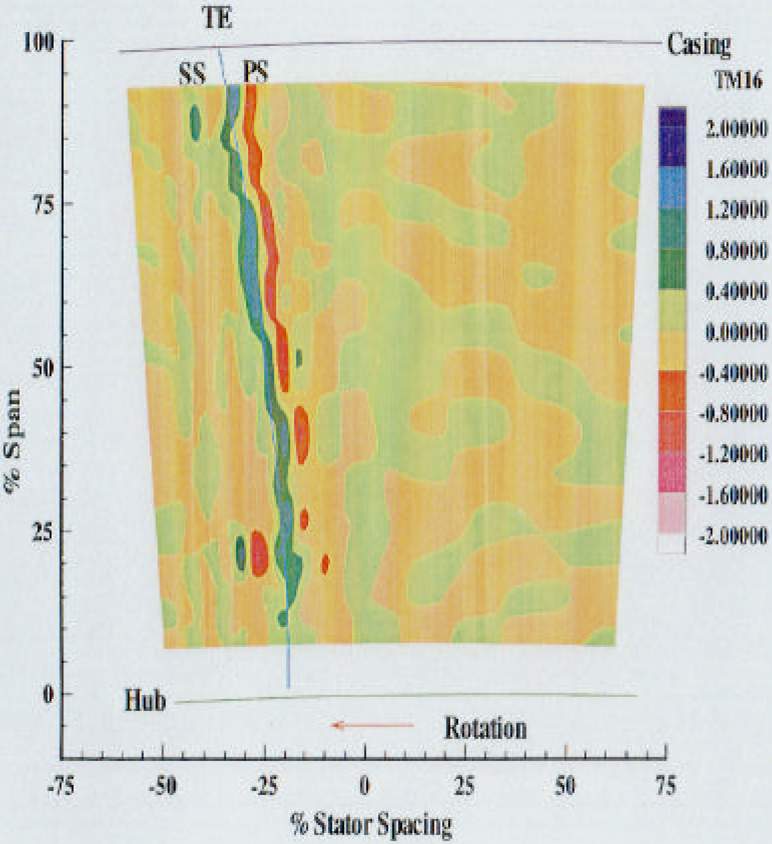


DETERMINISTIC



CIRCUMFERENTIAL MOMENTUM EQUATION (Cont'd)

$$\frac{\partial}{\partial\theta}\lambda_j\left(\underbrace{r\overline{\tau_{\theta\theta}}}_{TM16}\right) \qquad \frac{\partial}{\partial\theta}\lambda_j\left(\underbrace{\overline{\rho V_{\theta RP} V_{\theta RP}}}_{TM1819}\right)$$



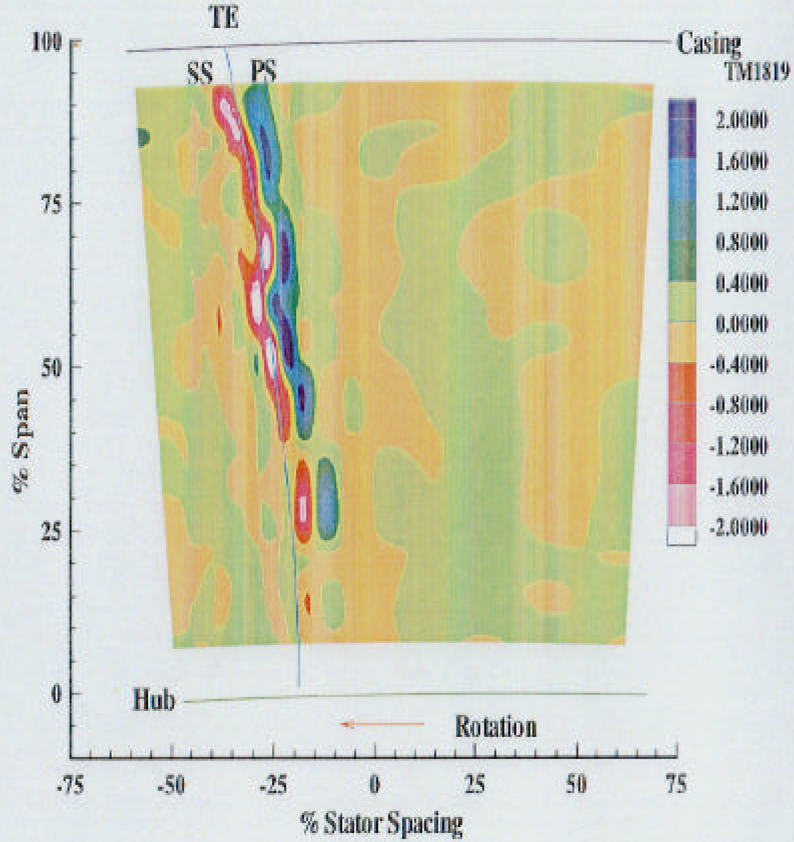
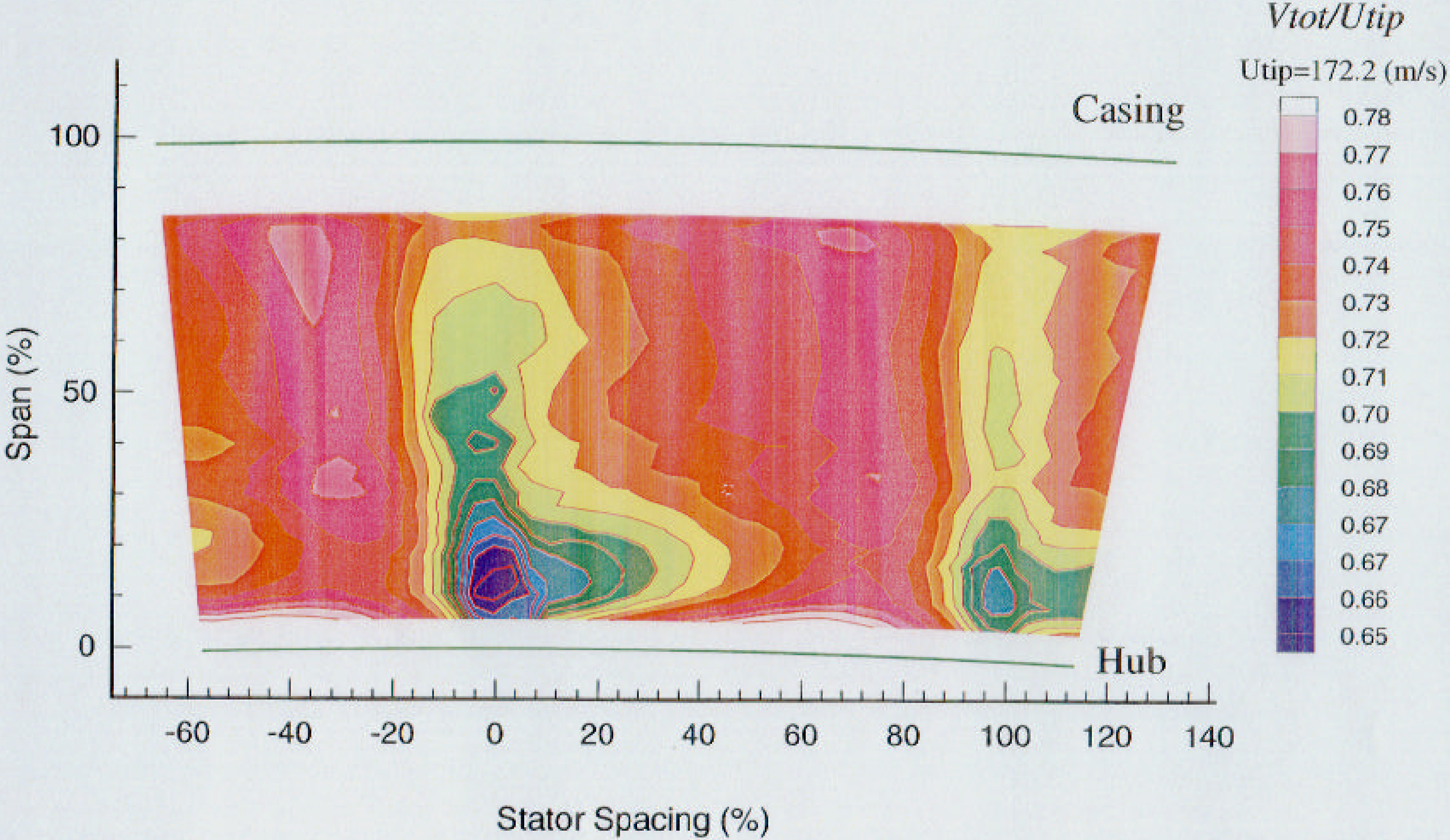


Fig. 9

PSU/MSCF Five Hole Probe Data: 14.37% Chord Downstream of Rotor 3

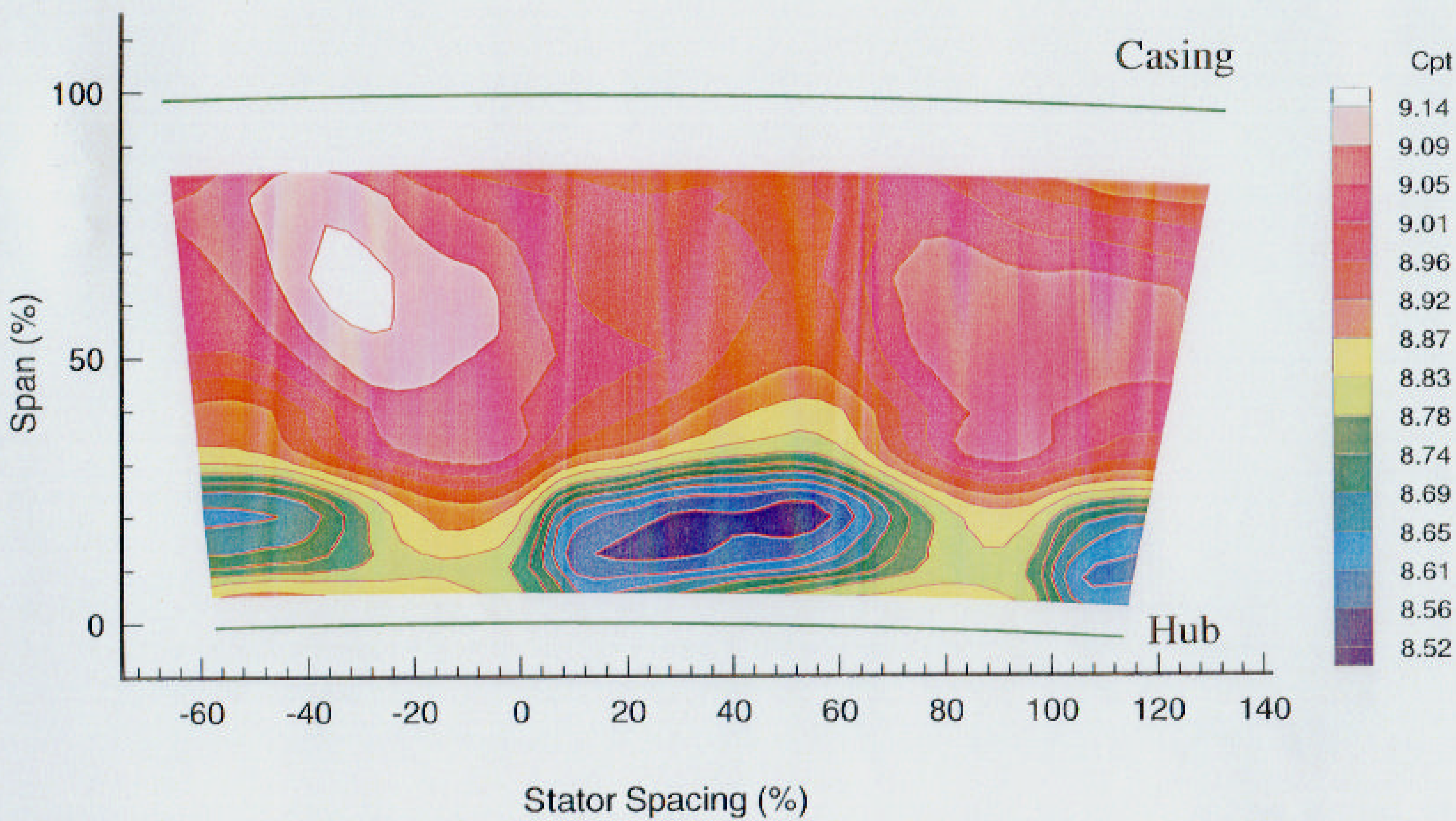
Time Averaged Normalized Total Velocity Distribution at Peak η and 100% Corrected Speed



E:/zhe/fhp/aera-t/contour

PSU/MSCF Five Hole Probe Data: 14.37% Chord Downstream of Rotor 3

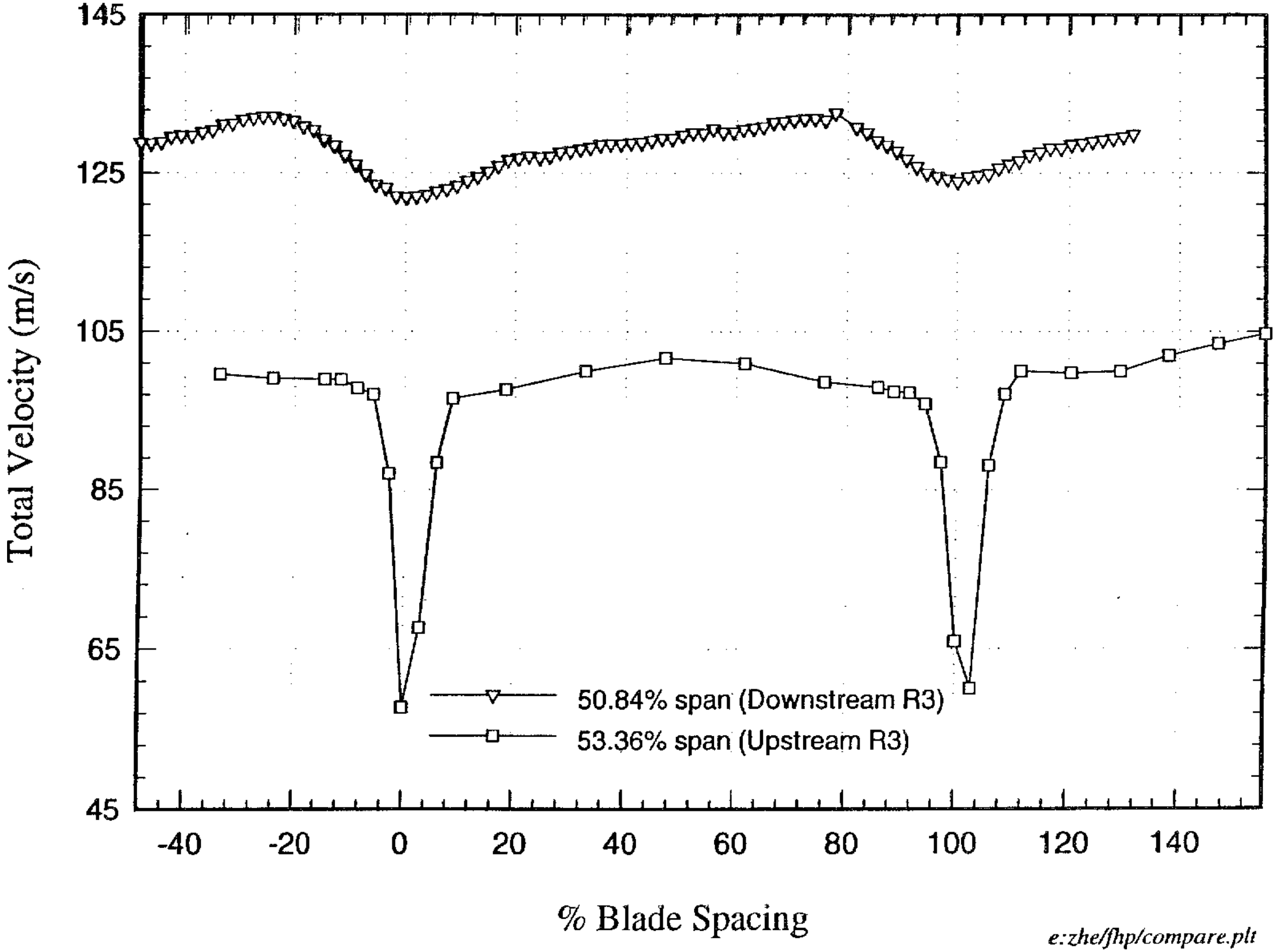
Time Averaged Total Pressure Coefficient Distribution at Peak η and 100% Corrected Speed



E:/zhe/fhp/aera-t/contour

PSU-MSCF FHP DATA: The Comparison Between Upstream and Downstream of Rotor 3

Tangential Variation of Time Averaged Total Velocity at Midspan (Peak Efficiency)



e:zhe/fhp/compare.plt

CONCLUSIONS

- **Transport of Rotor Wake Flow to the Pressure Side of the Stator - High Levels of Deterministic Unsteadiness and Higher Levels of Mixing**

- **Hub Endwall Region: Clearance Flow Vortex Region - High Levels of Deterministic and Unresolved Unsteadiness**

- **Casing Endwall Suction Surface Corner - Low Momentum, Low Efficiency, High Unresolved Unsteadiness, High Loss - Also High Vorticity Region**

- **Away From Endwalls - Significant Levels of Both Deterministic and Unresolved Unsteadiness**

Conclusions (cont.)

- The flow in the suction side casing corner endwall region was identified as the dominant source of unsteadiness to the downstream rotor.

- The unresolved flow unsteadiness was seen to be everywhere larger than the periodic unsteadiness.

- The deterministic (periodic, shaft related) flow unsteadiness was most significant in the stator wake regions and is very small in the endwall and core regions of the flow field.

- The aperiodic components of flow unsteadiness can be neglected compared to the periodic components.

Reduced Form of the Average–Passage Equation System

Tangential Momentum Equation

$$\frac{\partial}{\partial t}(\rho r v_\theta) + \frac{\partial}{\partial r}(\rho r v_r v_\theta) + \frac{\partial}{\partial \theta}(\rho v_\theta v_\theta) +$$

$$\frac{\partial}{\partial z}(\rho r v_z v_\theta) + \rho v_r v_\theta =$$

$$-\frac{\partial p}{\partial \theta} + \frac{\partial}{\partial r}(r\tau_{r\theta}) + \frac{\partial}{\partial \theta}(\tau_{\theta\theta}) + \frac{\partial}{\partial z}(r\tau_{z\theta}) + \tau_{r\theta}$$

Ensemble Average Operator

$$\tilde{f} = \lim_{N\to\infty} \frac{1}{\bar{\rho} N} \sum_{1}^{N} \rho_i f_i$$

$$v_r = \tilde{v}_r + v'_r$$

Reynolds Averaged Tangential Momentum Equation

$$\frac{\partial}{\partial t}(\bar{\rho} r \tilde{v}_\theta) + \frac{\partial}{\partial r}(\bar{\rho} r \tilde{v}_r \tilde{v}_\theta) + \frac{\partial}{\partial \theta}(\bar{\rho} \tilde{v}_\theta \tilde{v}_\theta) +$$

$$\frac{\partial}{\partial z}(\bar{\rho} r \tilde{v}_z \tilde{v}_\theta) + \bar{\rho} \tilde{v}_r \tilde{v}_\theta =$$

$$-\frac{\partial \bar{p}}{\partial \theta} + \frac{\partial}{\partial r}(r\bar{\tau}_{r\theta} - r\overline{\rho v'_r v'_\theta}) +$$

$$\frac{\partial}{\partial \theta}(\bar{\tau}_{\theta\theta} - \overline{\rho v'_\theta v'_\theta}) + \frac{\partial}{\partial z}(r\bar{\tau}_{z\theta}) + \bar{\tau}_{r\theta} - r\overline{\rho v'_z v'_\theta} - \overline{\rho v'_r v'_\theta}$$

Time–Average Operator

$$\bar{\bar{f}} = \frac{\Omega}{2\pi \bar{\bar{\rho}}} \int_{t_1}^{t_1 + \frac{2\pi}{\Omega}} \bar{\rho} \bar{f}(t) dt$$

$$\tilde{v}_r = \tilde{\tilde{v}}_r + \hat{\tilde{v}}_r$$

Outline of the Problem

Motivation:

Need to provide a rapid, easy to use multistage turbomachinery flow solver for *rapid* design assessment

Adamczyk average–passage equation system appears to be the best model for incorporating multistage effects in "steady" flow solvers

Computational efficiency and simplicity afforded by mixing plane modeling strategy difficult to ignore

Objective:

Develop a mixing–plane based multistage compressor modeling strategy which employs the average–passage equation system to permit rapid assessment of multisatage compressor aerodynamic performance

Approach:

Evaluate contributions to unsteady flow effects in multistage compressors
Develop flow structure–based models for flow perturbations
Explicitly construct correlation quantities in the average–passage equation system
Adapt existing mixing–plane based solver (ADPAC) to employ the modeled terms

ADPAC Code Description

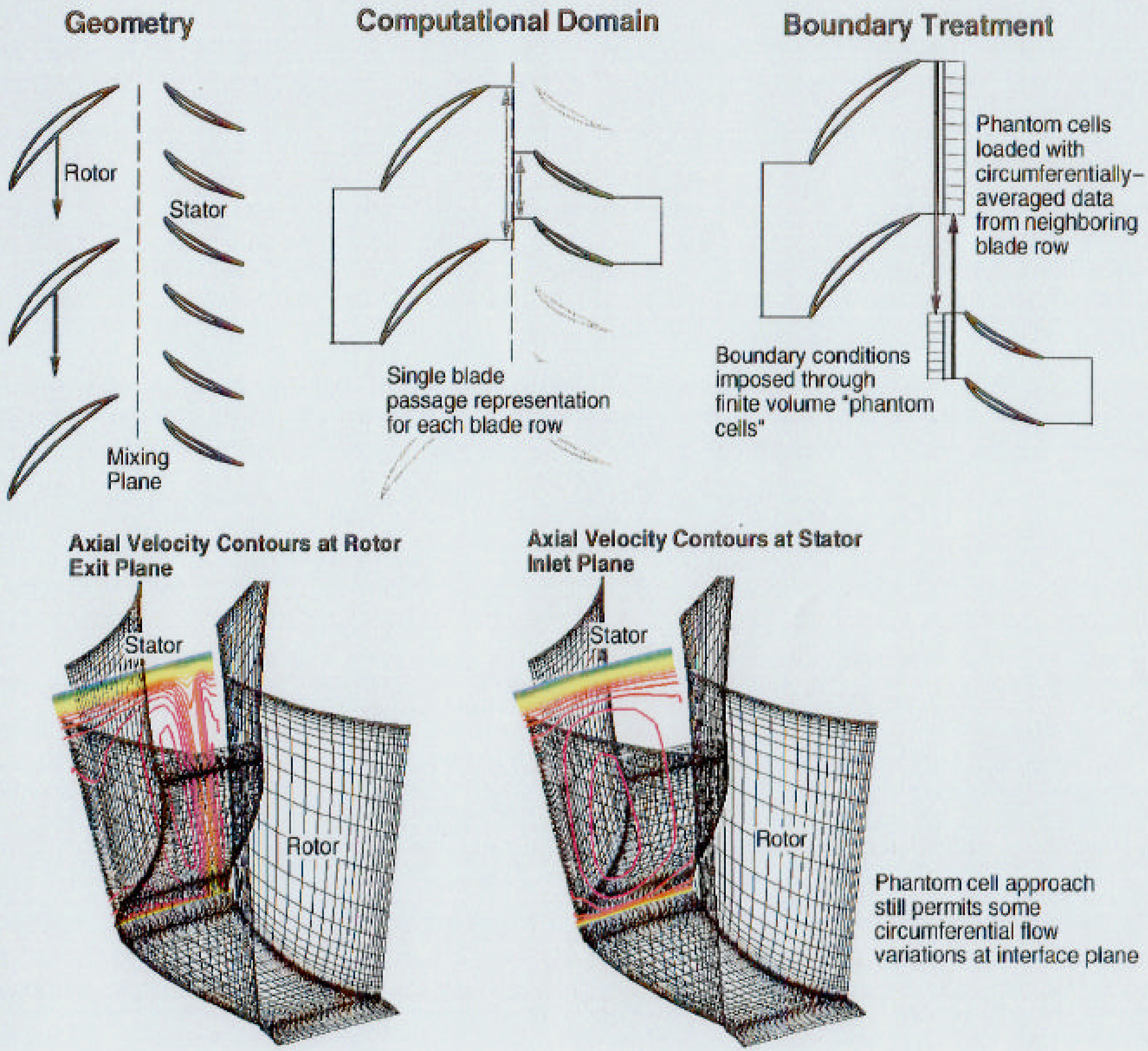
- 2–D and 3–D Navier Stokes aerodynamic analysis
- NASA–sponsored code development
- Developed and validated at Allison
- Unique capability to utilize separate computational domains for different components and numerically couple these domains to analyze complex geometries (provides a mechanism for aerodynamic interaction)

CFD Features

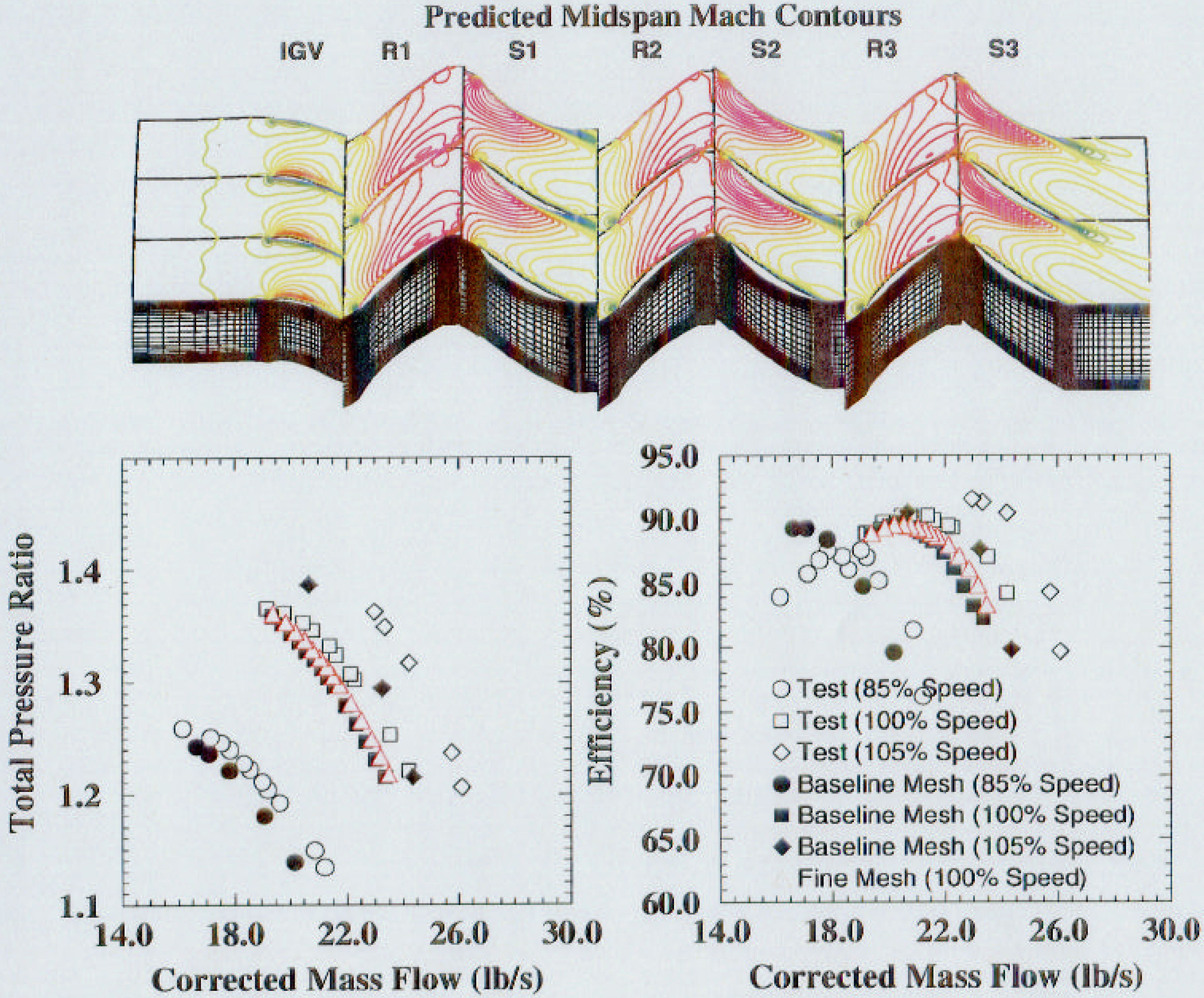
4/5 stage Runge–Kutta time–marching algorithm
Multiple block mesh discretization
Eigenvalue–scaled dissipation
Cartesian or cylindrical coordinate system
Eigenvalue–scaled implicit residual smoothing
Iterative implicit (dual time step) solution option
APPL/PVM/MPI interprocessor message passing

Finite volume formulation
Local time stepping
Multigrid convergence acceleration
Baldwin–Lomax turbulence model
k–R two–equation turbulence model
Wall functions
Flexible parallel computing options

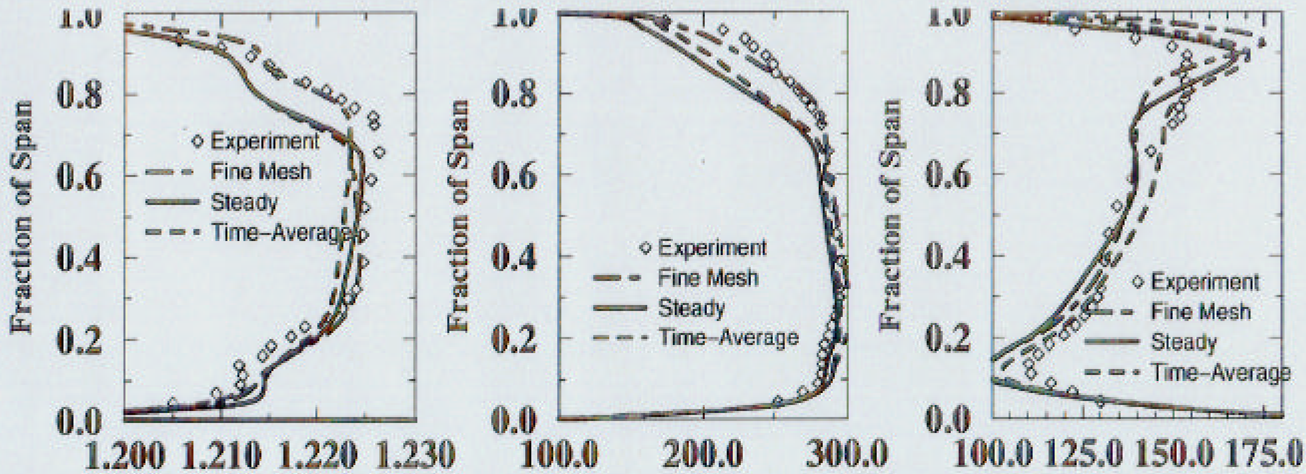
ADPAC Mixing Plane Boundary Formulation

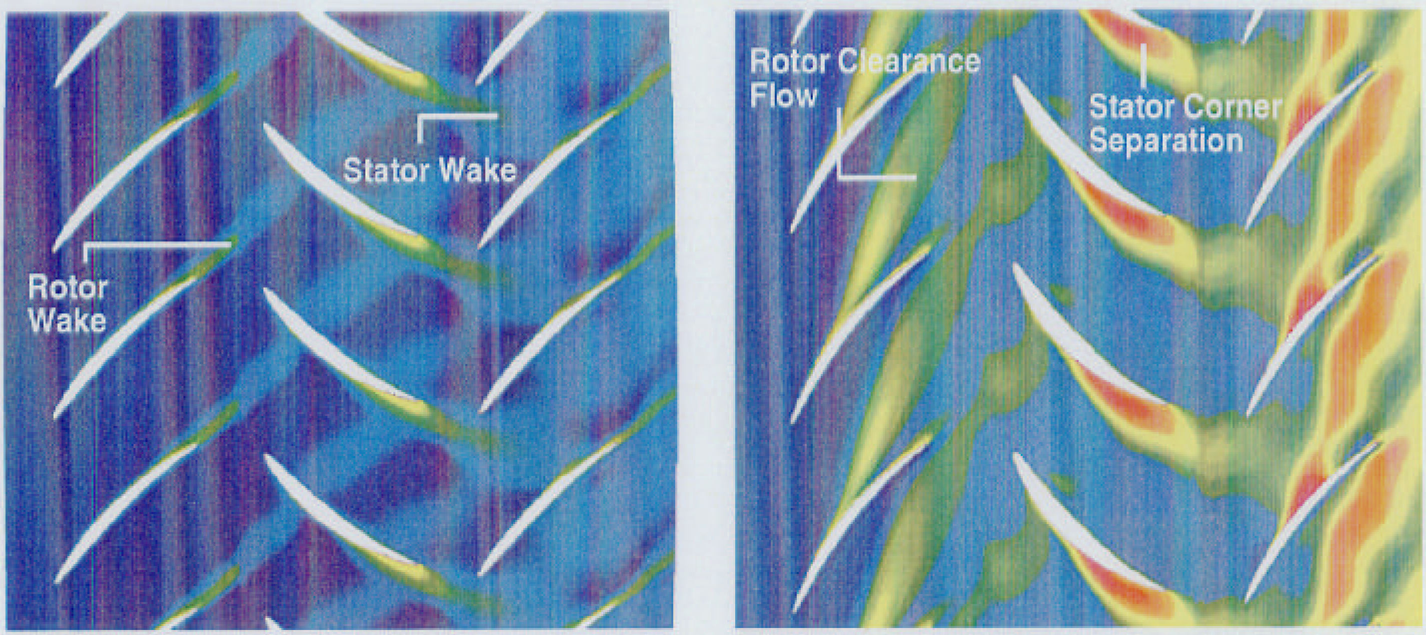


ADPAC Baseline Mixing Plane Analysis of Penn State Research Compressor



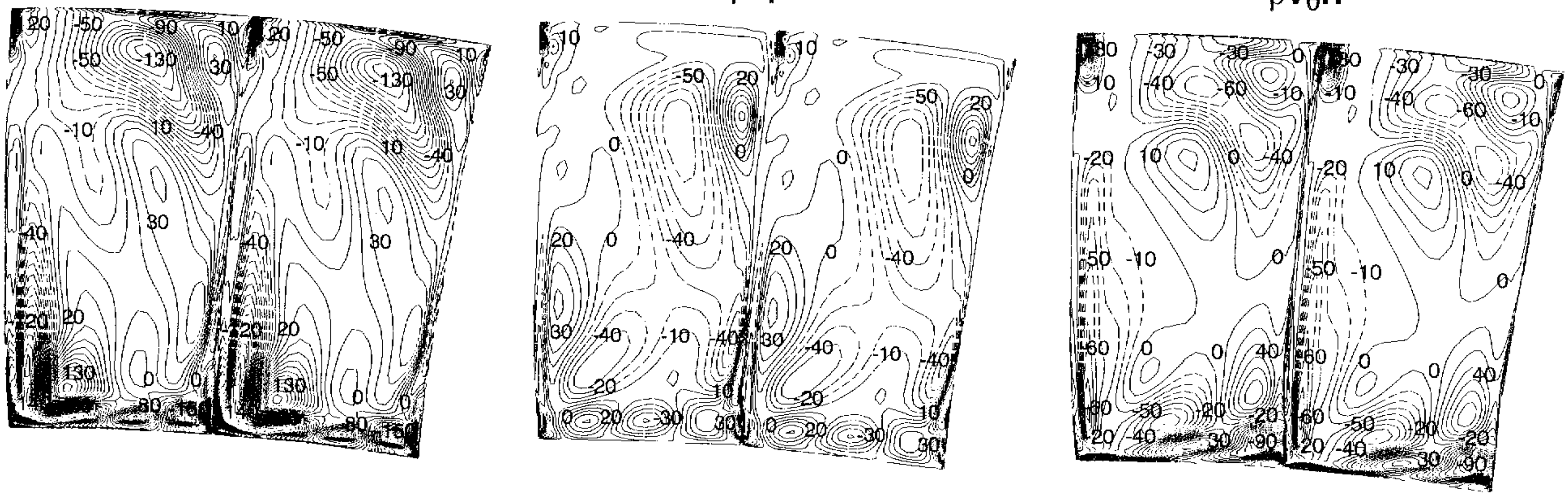
ADPAC Rotor/Stator Rotor Aerodynamic Interaction Model
Penn State Rotor 2/Stator 2/Rotor 3





Predicted Deterministic Stress Velocity/Enthalpy Correlation Terms for Penn State University Research Compressor Rotor 2/Stator 2/Rotor 3 Aerodynamic Interaction Simulation

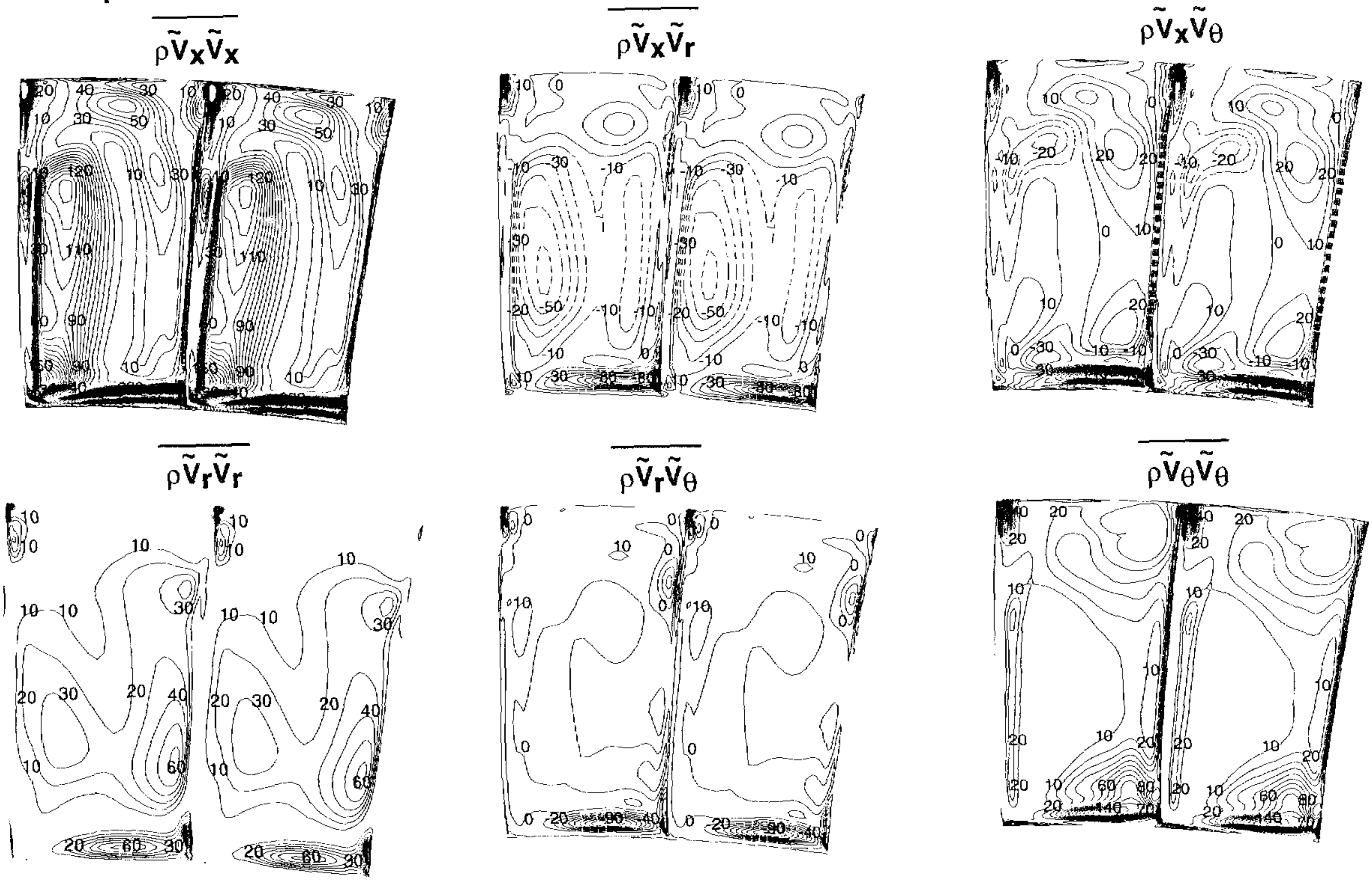
$\overline{\rho\tilde{V}_x\tilde{H}}$ $\overline{\rho\tilde{V}_r\tilde{H}}$ $\overline{\rho\tilde{V}_\theta\tilde{H}}$



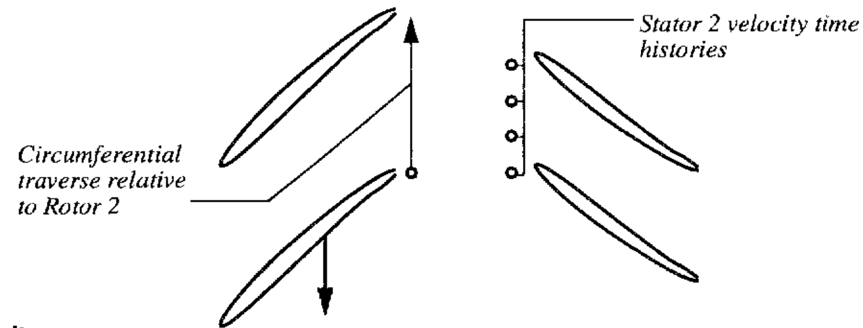
OBSERVATIONS:

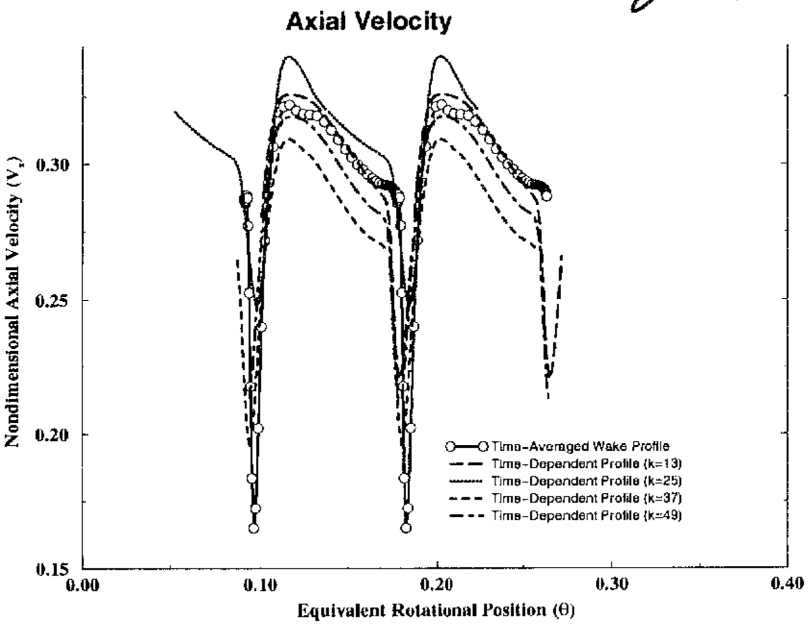
- High intensity region near case/suction surface corner
- Significant stress levels on hub endwall (related to stator clearance flow)
- Strong clustering near stator wake
  (remember – gradient of stress terms is important)

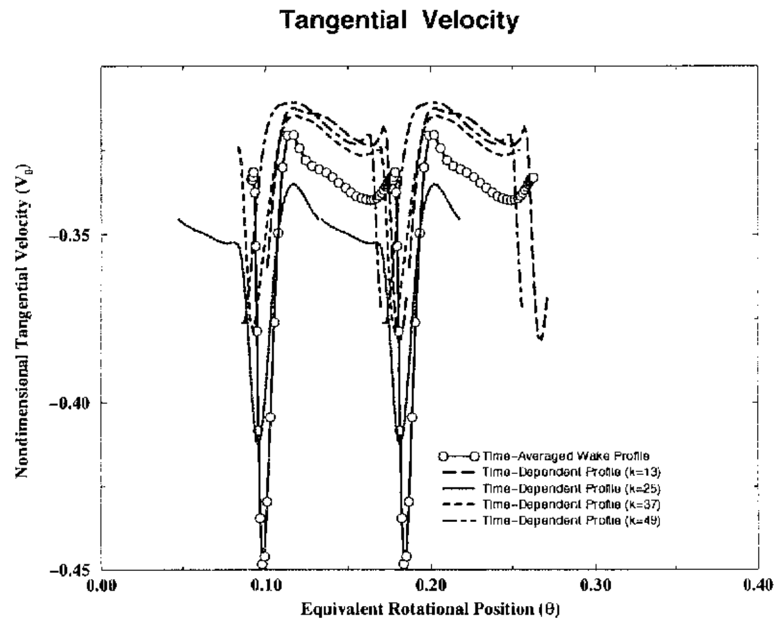
Predicted Deterministic Stress Velocity Correlation Terms for Penn State University Research Compressor Rotor 2/Stator 2/Rotor 3 Aerodynamic Interaction Simulation (5.6% Chord Aft of S2)



Comparison of Stator 2 Velocity Time Histories with Rotor 2 Exit Time–Averaged Circumferential Velocity Profiles for Penn State Research Compressor Rotor 2/Stator 2/Rotor 3 Aerodynamic Interaction Analysis



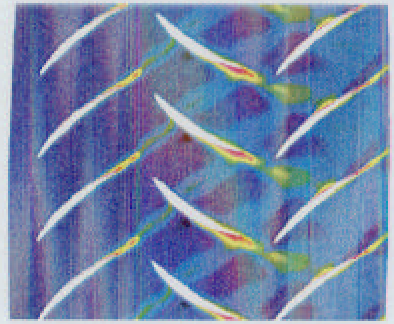


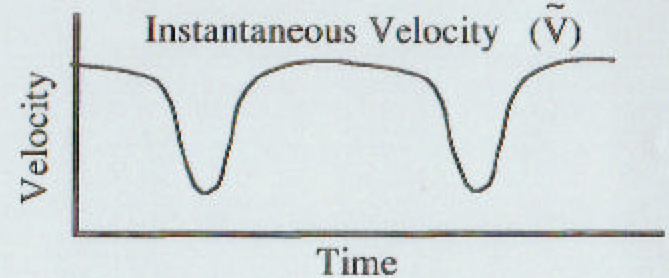


Time history of Stator 2 upstream velocity field correlates with Rotor 2 time–averaged wake

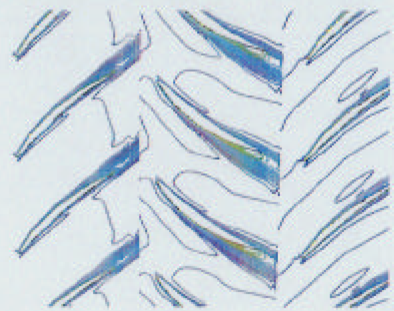
Computing Deterministic Stress Correlation Terms

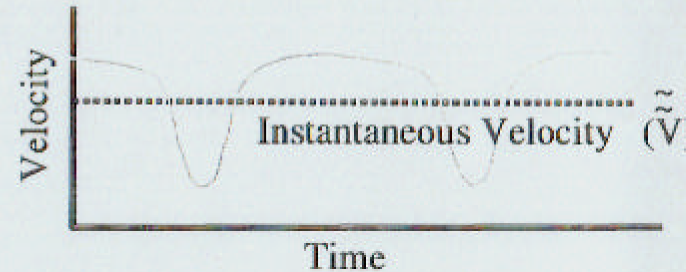
1. Perform 3–D Time–dependent aerodynamic analysis of rotor/stator/rotor interaction



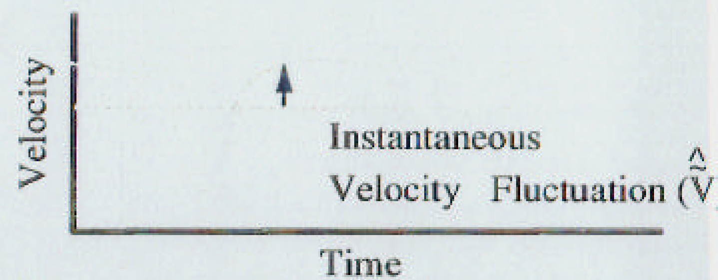


2. Extract time average of time–periodic flowfield





3. Derive instantaneous fluctuations

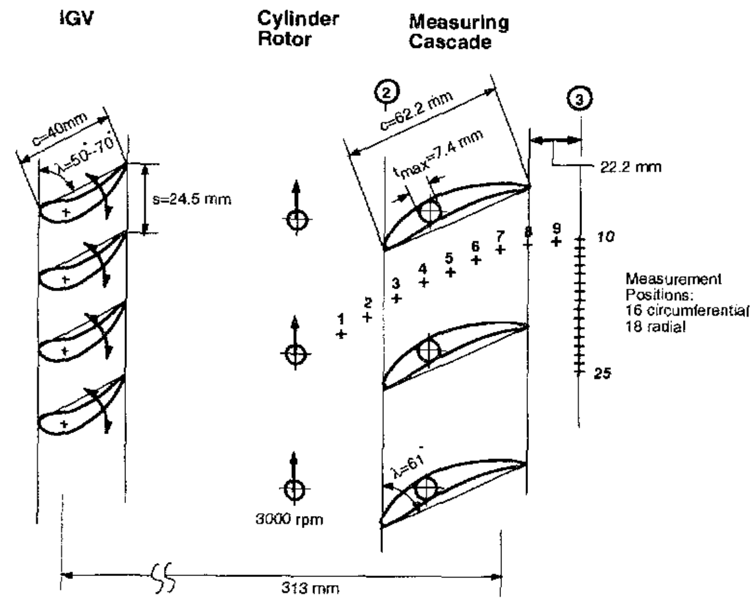


4. Integrate products of instantaneous fluctuations over time period to compute correlation magnitude

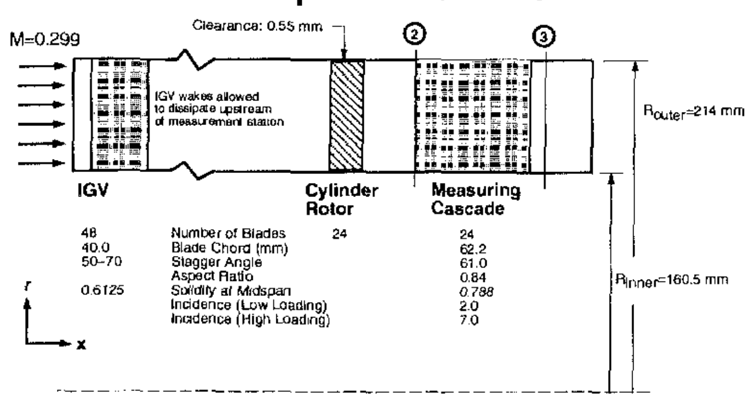
$$\overline{\bar{\rho}\hat{\tilde{V}}\hat{\tilde{V}}} = \int_t^{t+2\pi/\Omega} \bar{\rho}\hat{\tilde{V}}\hat{\tilde{V}}$$

Poensgen and Gallus Wake Decay Measurement

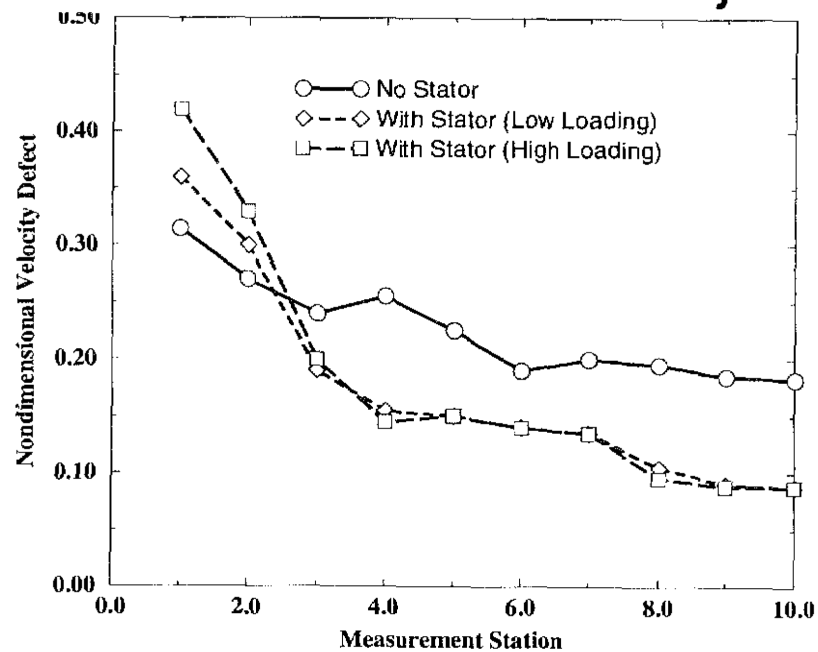
Blade Configuration



Flowpath Orientation

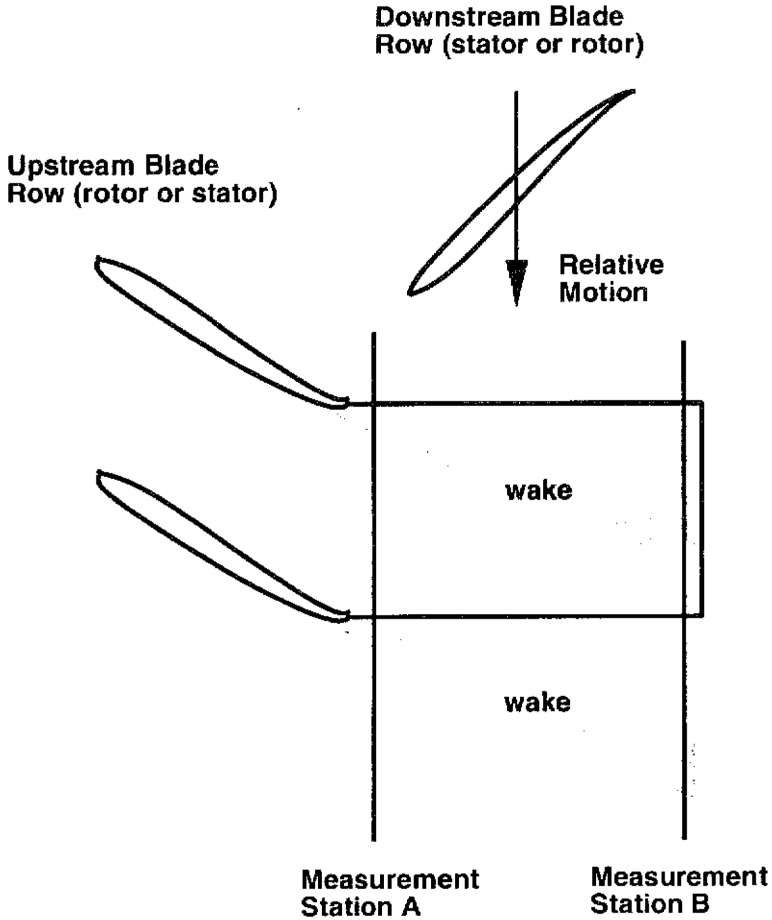


Measured Wake Centerline Velocity Decay



- *Wake decay acclerated through interaction with downstream airfoil row*
- *Downstream airfoil loading did not significantly alter the wake decay characteristics*

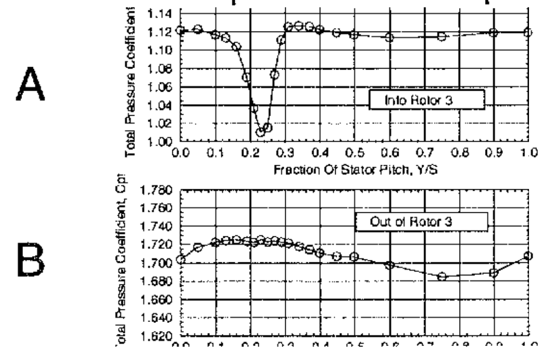
Illustration of Wake Decay Due to Interaction With Downstream Relatively Rotating Blade Row



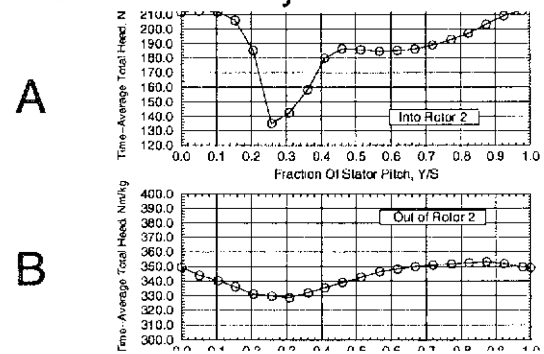
Commonly Observed Characteristics:

- Sharp, clearly defined wake deficit aft of upstream blade
- Distributed, smeared wake profile aft of downstream row

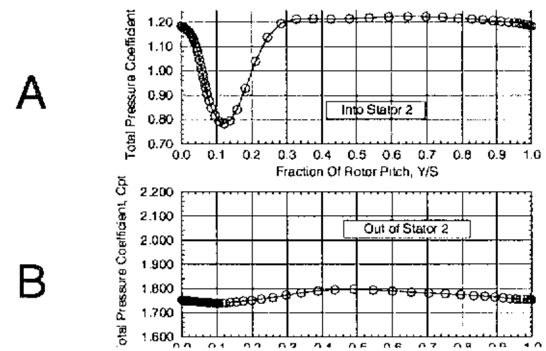
NASA Low Speed Axial Compressor



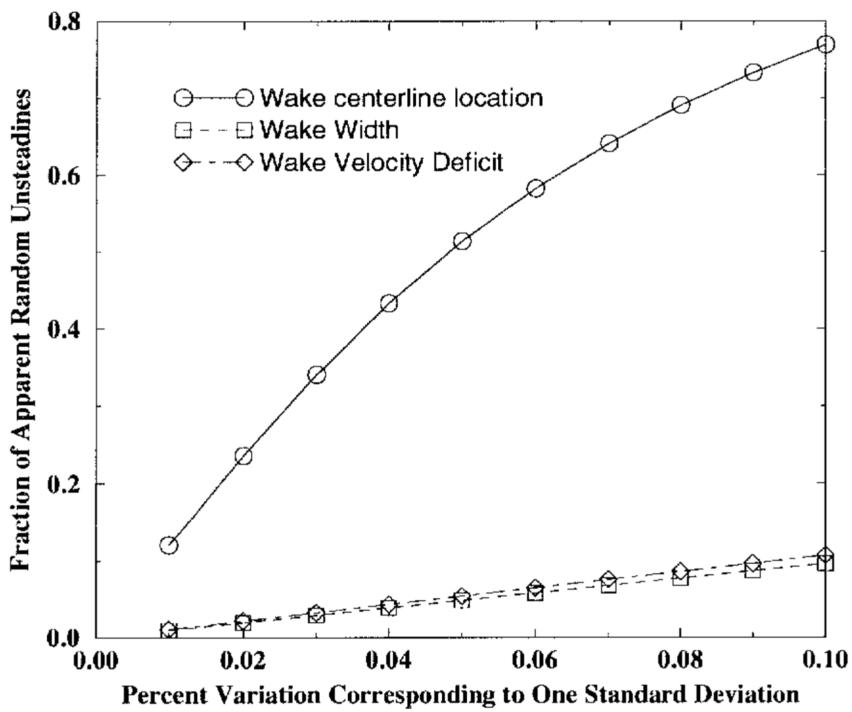
Iowa State University Research Compressor



Penn State University Research Compressor

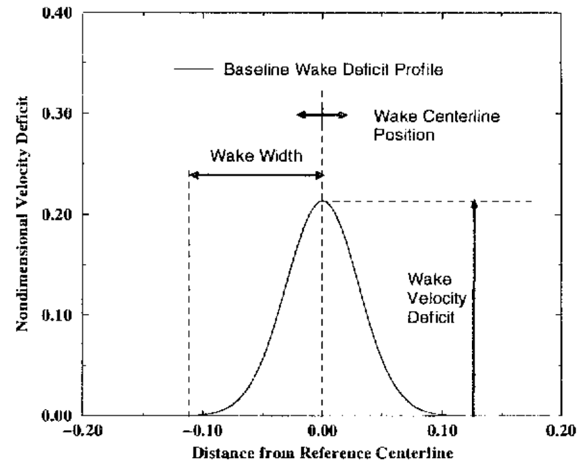


"Apparent" Random Energy Resulting from Minute Variations in an Otherwise Structured Wake

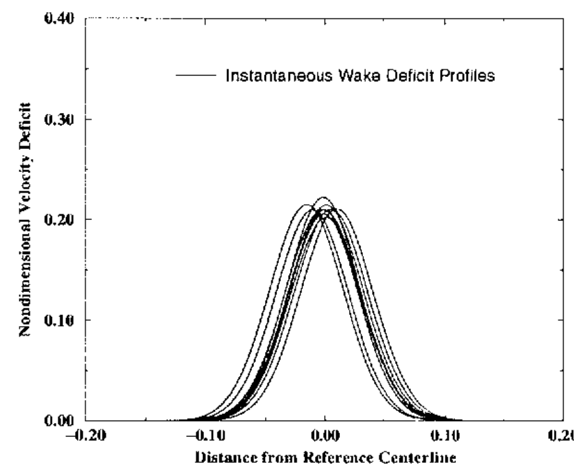


Steep gradients in wake profile result in large contributions to apparent random unsteadiness from variations in wake centerline location

Reference Wake Profile



Instantaneous Wake Variations



Summary

- Baseline performance of Penn State Research Compressor adequately modeled
- Significant improvement in predictions with mesh refinement – particularly in the radial direction (substantiates recent recommendations of 200,000 points per blade row)
- Detailed time–dependent simulations of rotor/stator/rotor aerodynamic interactions completed
- Additional time–dependent calculations completed to improve prediction of rotor clearance flow transport through downstream stator blade passage
- Preliminary deterministic stress modeling strategies proposed and coded – initial test runs very encouraging. Additional CPU, memory overhead is minimal
- Still need to address potential interactions –propose using linearized Euler terms to compute correlations
- Program on schedule and all required deliverables have been met

Concluding Remarks

- To a large extent, wake–based models can be used to represent the effects of deterministic unsteadiness in steady state turbomachinery flow solvers
- No significant CPU increase due to wake–based deterministic stress model
- Additional validation opportunities will be available as detailed test data is gathered
- Comparisons between steady–state wake–based deterministic stress solutions and time–average of unsteady flow solutions are favorable
- Enhancements to model potential interaction effects currently being developed