P21 Impact and Endwall Flow and Wakes on Multistage Compressor Performance and Design

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Abstract

This abstract describes a research program on the aerodynamics of unsteady blade-row interactions in multistage compressors. The research addresses the impact of multi-blade-row interactions, from endwall flows and blade wakes, on performance and design. In our view, it is the former that is far more critical; development of the ability to control endwall flow behavior in a multistage environment through design or otherwise would have the larger impact on performance improvement.

There are three main objectives of the proposed program: (1) definition of the key links between compressor design parameters and the mechanisms of multistage rotor-stator interactions which impact time-averaged performance; (2) use of understanding gained in (1) to develop design guidelines and effective methodologies for improving multistage compressor performance through management of endwall flow and blade wakes; and (3) use of these design guidelines for suggesting multistage configurations that yield radial and axial (stage) loading distributions which influence endwall flow and wake-blade interactions in a beneficial way.

The proposed program presents a new and comprehensive approach to a longstanding problem. In this we make use of increases in computing power as well as advances in the coupling of analysis, computations, and modeling to take advantage of the best features of each. Our industrial partner will be Solar Turbines who has designed and developed a multistage axial compressor under the AGTSR program. We propose to use this multistage axial compressor as a configuration to focus the research so the results are not only representative of modern compressors used in power generation but can also be assessed against measurements at Solar Turbines. The design guidelines developed during the course of the research will be used to suggest changes to the compressor for obtaining performance improvement. While the research is targeted at a specific compressor, the results and design guidelines developed will be generic and applicable to other industrial multistage axial compressors

IMPACT OF COMPRESSOR ENDWALL FLOW AND WAKES ON MULTISTAGE TURBOMACHINERY PERFORMANCE AND DESIGN

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PARTICULARS

- Research area: Multistage turbomachinery aerodynamics
- Principal investigators: C.S. Tan, E.M. Greitzer (on leave at UTRC)
- Doctoral graduate student: Y. Tzeng
- Organization: MIT Gas Turbine Laboratory
- Industrial collaborator: Jerry Stringham, Solar Turbines
- National laboratory collaborator: J. Adamczyk, NASA Lewis

BACKGROUND AND MOTIVATION (I)

- Strong impact of compressor endwall flow on
  - Pressure rise capability
  - Peak efficiency
  - Off-design performance
- Effects of endwall flow on performance
  - Accounted for on empirical/correlative basis
  - Hence configuration-specific
- Need to establish causal link between compressor endwall flows and performance on
  - Physically-sound basis
  - Quantitative basis

BACKGROUND AND MOTIVATION (II)

- A key feature of compressor endwall flows
  - Rotor tip leakage flow and subsequent interaction with stator/downstream blade row
- Effects of unsteady interaction on multi-stage compressor flow development and overall performance
  - Not known

THE EFFECT OF UPSTREAM ROTOR VORTICAL DISTURBANCES ON THE TIME-AVERAGE PERFORMANCE OF AXIAL COMPRESSOR STATORS

Theodore V. Valkov

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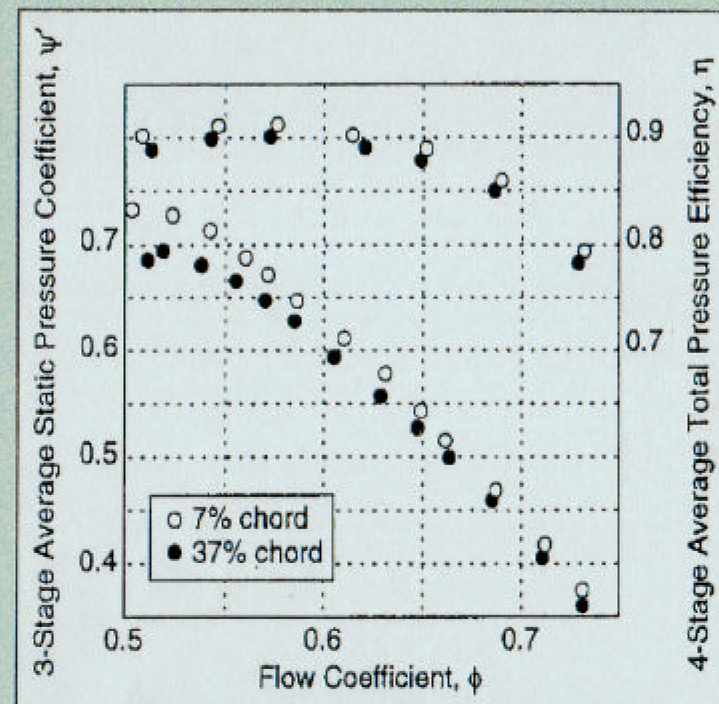
This work ia supported by NASA Leiws, Dr. J. Adamczyk as Technical Monitor

Motivation

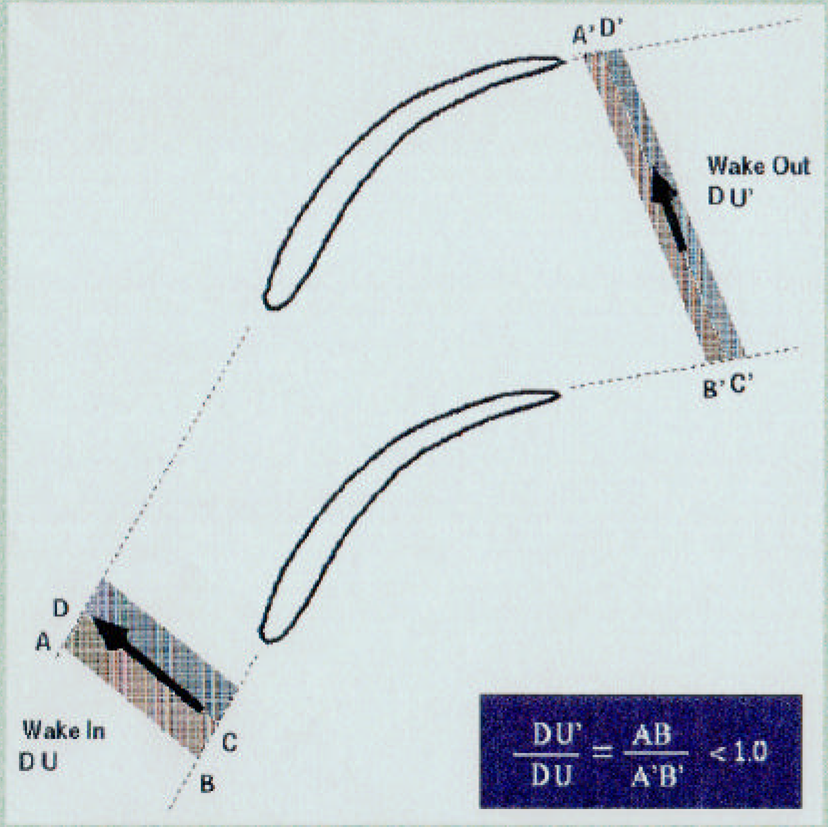
- Performance depends on axial spacing
- Dependence due to blade row interaction
- Engineering issues :
  - effect is important
  - cannot be quantified
  - unknown usefulness
  - uncertainty for design



Smith (1970) 4-stage LS compressor
h/c=2.1, c/s=1.2, tip clr=0.03c.

Background (2)

- Smith (1966) wake recovery
  - wake stretched
  - non-uniformity decreases
  - kinetic energy recovered without entropy increase
- However
  - accounts for only 25-50% of the measured one-point efficiency gain (Smith, 1996)

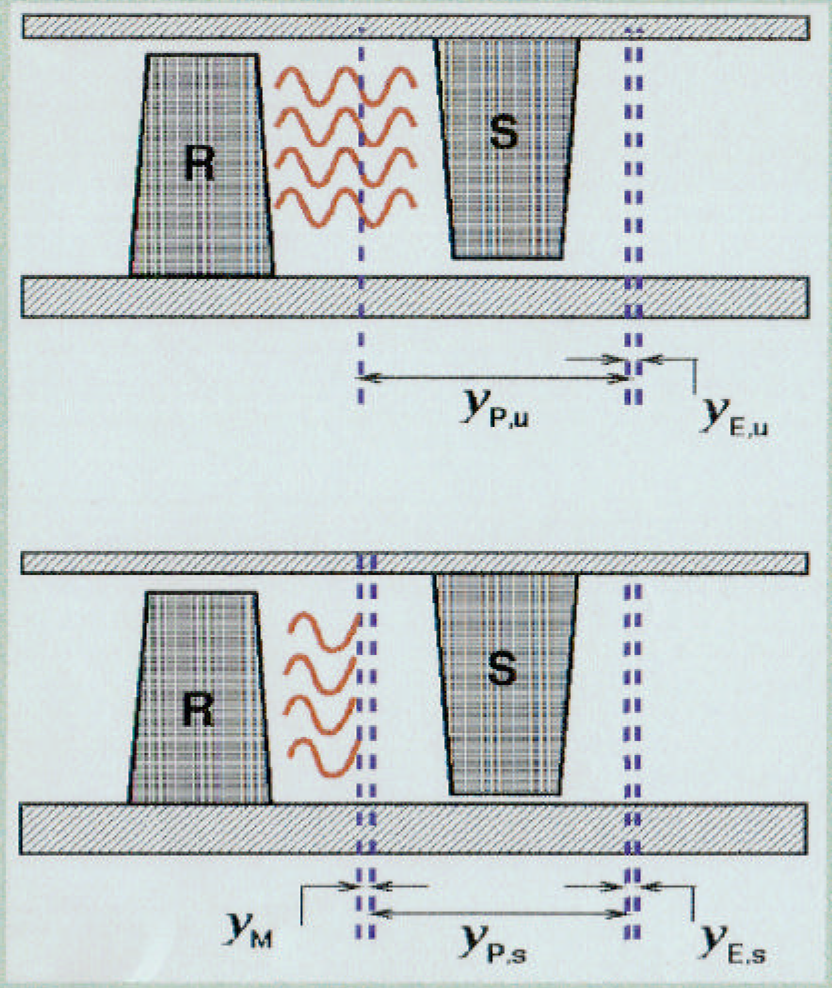


Background (3)

Rotor flow response to backpressure fluctuations	Graf (96)	known
Bypass transition	Halstead et al. (94)	?
Non-transitional BL response	not investigated	?
Transport of upstream wakes	Smith (66)	known
Transport of upstream vortices	not investigated	?
Unsteady vortex shedding	Frisch (92)	nil
Unsteady secondary flow	not investigated	?
Corner flow response	Schultz (90)	- 40 %?

Method of Investigation (1)

- Figure of merit: time/mass averaged Pt loss coefficient
- Steady flow obtained by mixing out disturbances at mid-gap plane
- Unsteady/Steady comparison
  1) Passage loss change
  2) Mixing loss balance
  3) Net effect = (1)+(2)

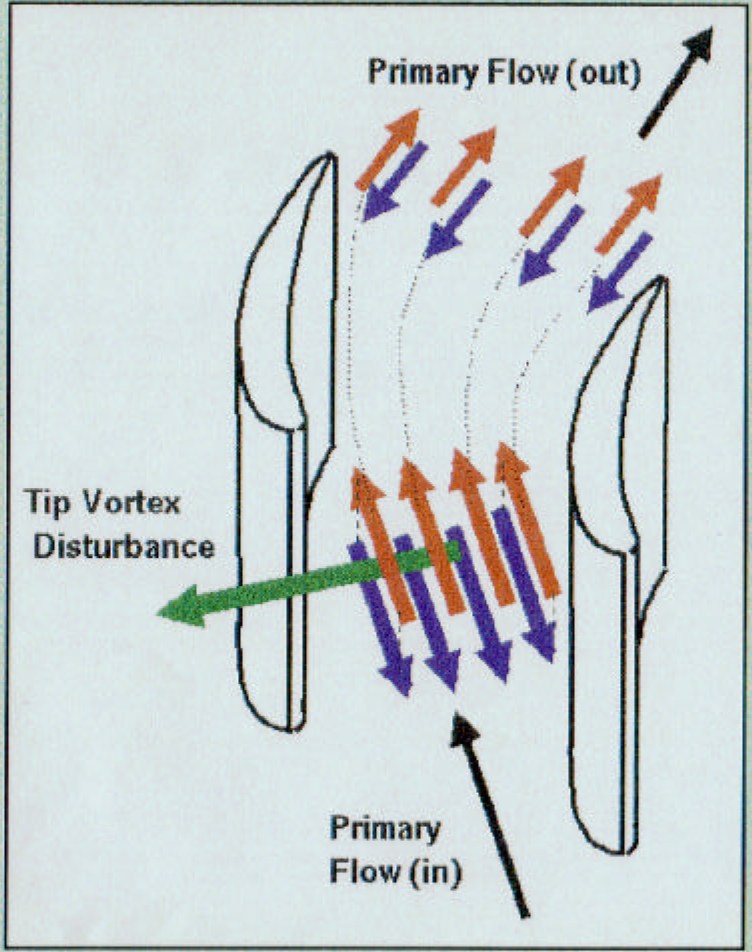


Conclusions from Baseline Study

- Two mechanisms
- Reversible recovery
  - Of rotor wake +0.2 pts
  - Of rotor tip vortex +0.3 pts
  - Details of recovery different, but effect scales in the same manner
- Normal distortion of the boundary layer
  - From rotor wake - 0.1 pts
  - From rotor tip vortex - 0.2 pts
  - Mechanism the same
- Net stage efficiency 0.2-0.3 pts higher

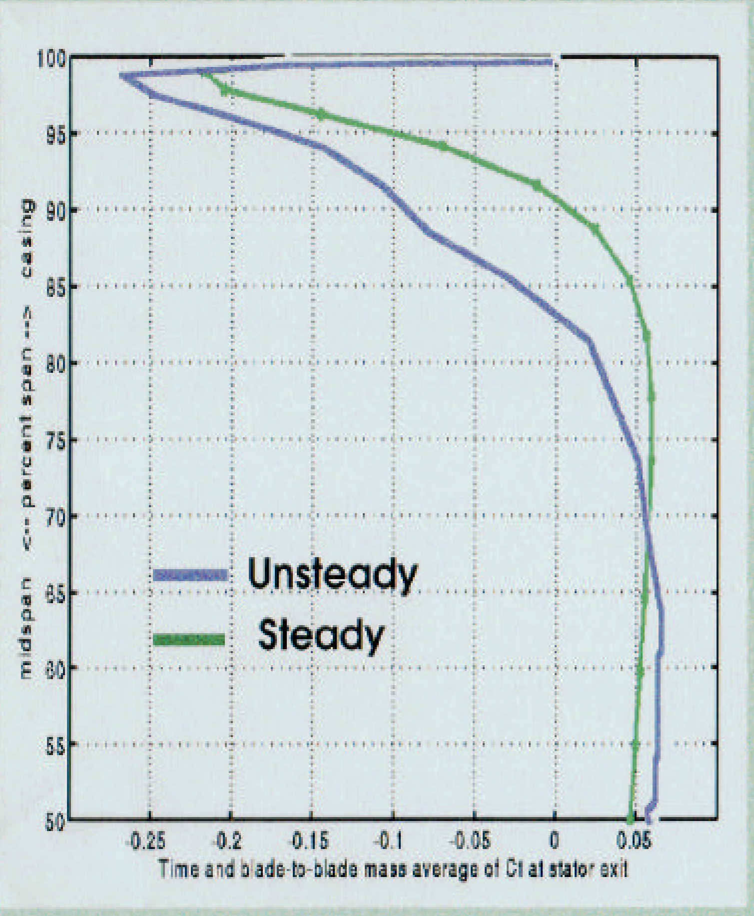
Proposed Tip Vortex Recovery Mechanism

- In stator frame, tip vortex appears as a jet
- Jet vortical filaments aligned with primary flow
- Streamwise vortex/Diffuser analogy : attenuation w/o increase in entropy
- Loss benefit scales in same manner as that of 2D wakes
- Benefit $\sim 1 - (L_i/L_e)^2$



Fully Viscous Tip Vortex Interaction

- Passage loss increases in tip region (75-95% span)
  - Inviscid $\Delta Yp = 0.06$ pts
  - Viscous $\Delta Yp = 0.25$ pts
- Due to boundary layer response
- In accord with Howard et al. (1993) data



Sensitivity Study

- Axial spacing (d=0.07)
- Wake defect fluctuation period ($0.14 < T_f/T_p < 2.00$)
- Stator loading (ϕ=0.38)
- Stator inlet profile (high shear)
- Tip leakage crossflow (set to zero)

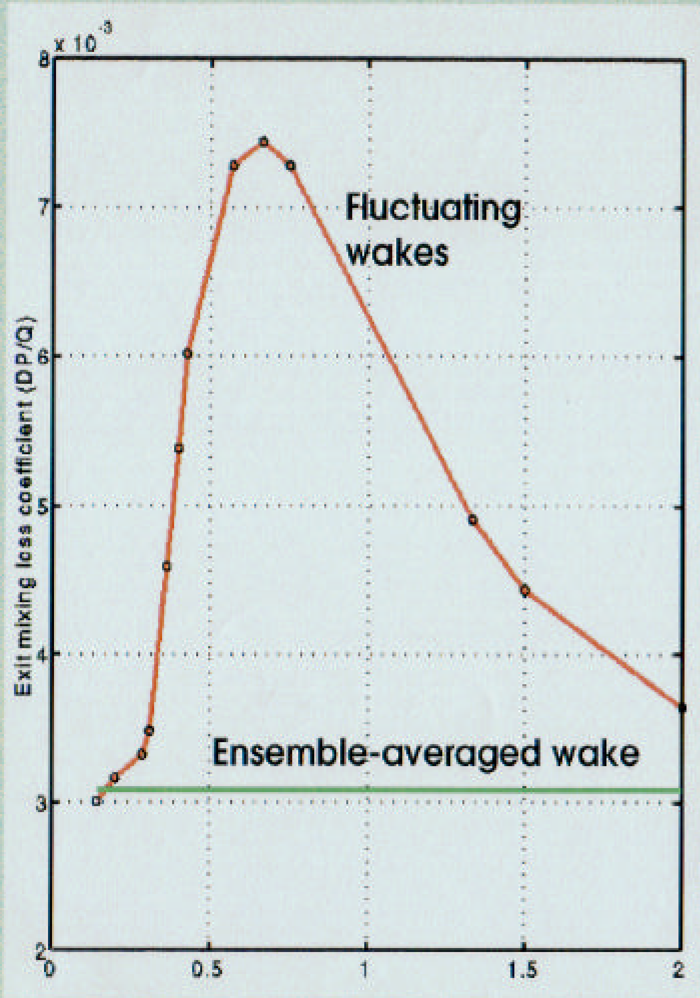
Sensitivity to Axial Spacing

	Recovery	BL response	Net effect
Wake	+0.6 pts	-0.3 pts	0.3 pts
Tip vortex	+0.7 pts	-0.4 pts	0.3 pts

- Reduced spacing increases net benefit
- At nominal spacing (d=0.37) net effect is 0.2 pts
- At decreased spacing (d=0.07) net effect is 0.6 pts

Sensitivity to Period of Fluctuations

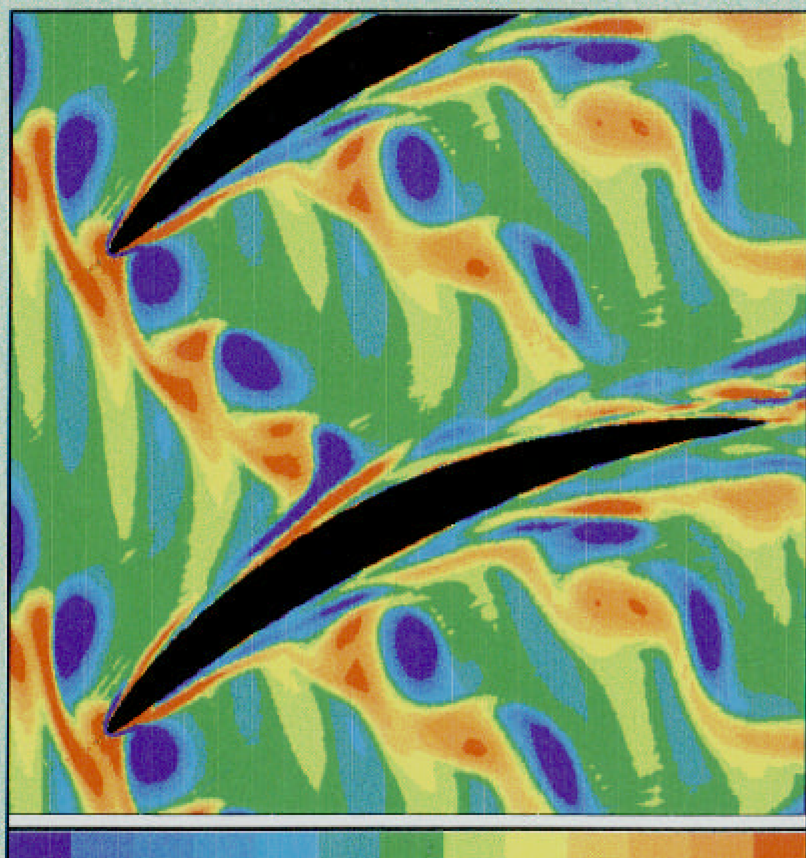
- Done for wakes
  - defect oscillated sinusoidally
  - same ensemble-average
  - wide frequency range
- Boundary layer response effect is quasi-steady
- No recovery for certain range of frequencies
- Using ensemble-averaged wakes is not always correct



Fluctuation period/Blade passing period

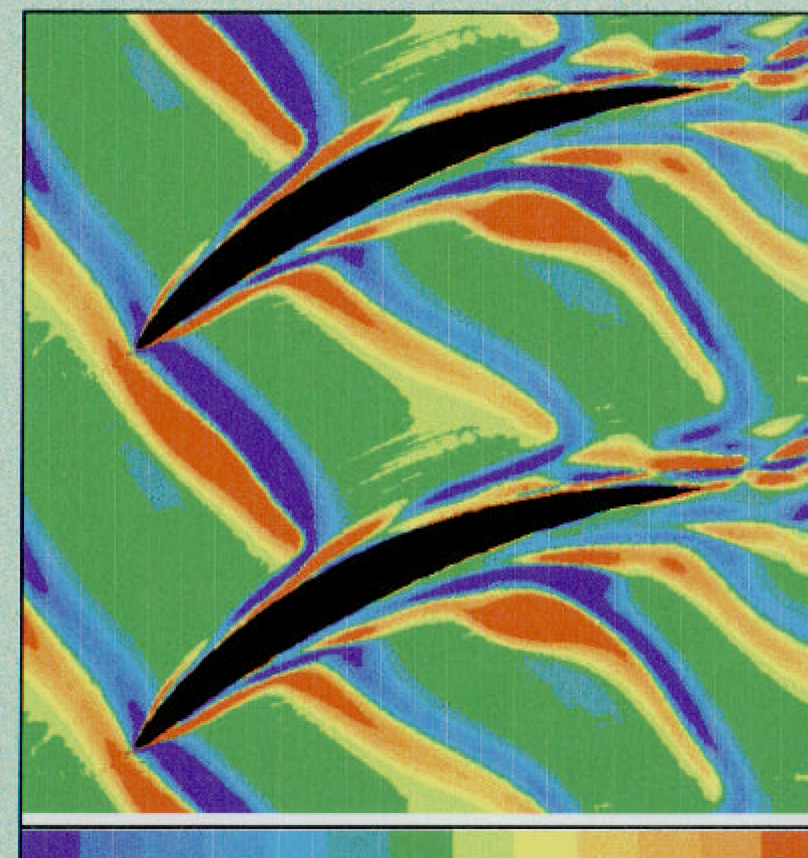
Flow Features with 2D Fluctuating Wakes

Disturbance vorticity, $T_f/T_p=0.4$



-6 U/c   0.0   +6 U/c

Disturbance vorticity, $T_f/T_p=2.0$



-6 U/c   0.0   +6 U/c

Sensitivity Study : Conclusions

- Mechanisms are generic
- Important parameters:
  - Axial spacing
  - Loading
  - Presence of fluctuations with certain frequency
  - Velocity defect in upstream wakes and vortices

Conclusions

- Steady-state approximation not always correct
  - Effect of wakes and tip vortices between 0.3-0.9 efficiency points
- Two generic mechanisms
  - Recovery (beneficial)
  - Boundary layer distortion (detrimental)
  - Quasi-steady 2D description
- Important parameters
  - Axial spacing
  - Blade shape and loading
  - Period of fluctuations within the upstream disturbances
- Design options available
  - Two sub-regions of design space
  - Boundary layer distortion effects can be mitigated

TECHNICAL OBJECTIVES

- Development of framework for assessment of unsteady interaction on multistage compressor flow development and overall performance

- Definition of key links between compressor design parameters and fluid dynamic mechanisms controlling multistage rotor-stator interactions

- Use of above understanding to develop design guidelines and effective methodologies for improving multistage compressor performance through management of endwall flow and blade wakes

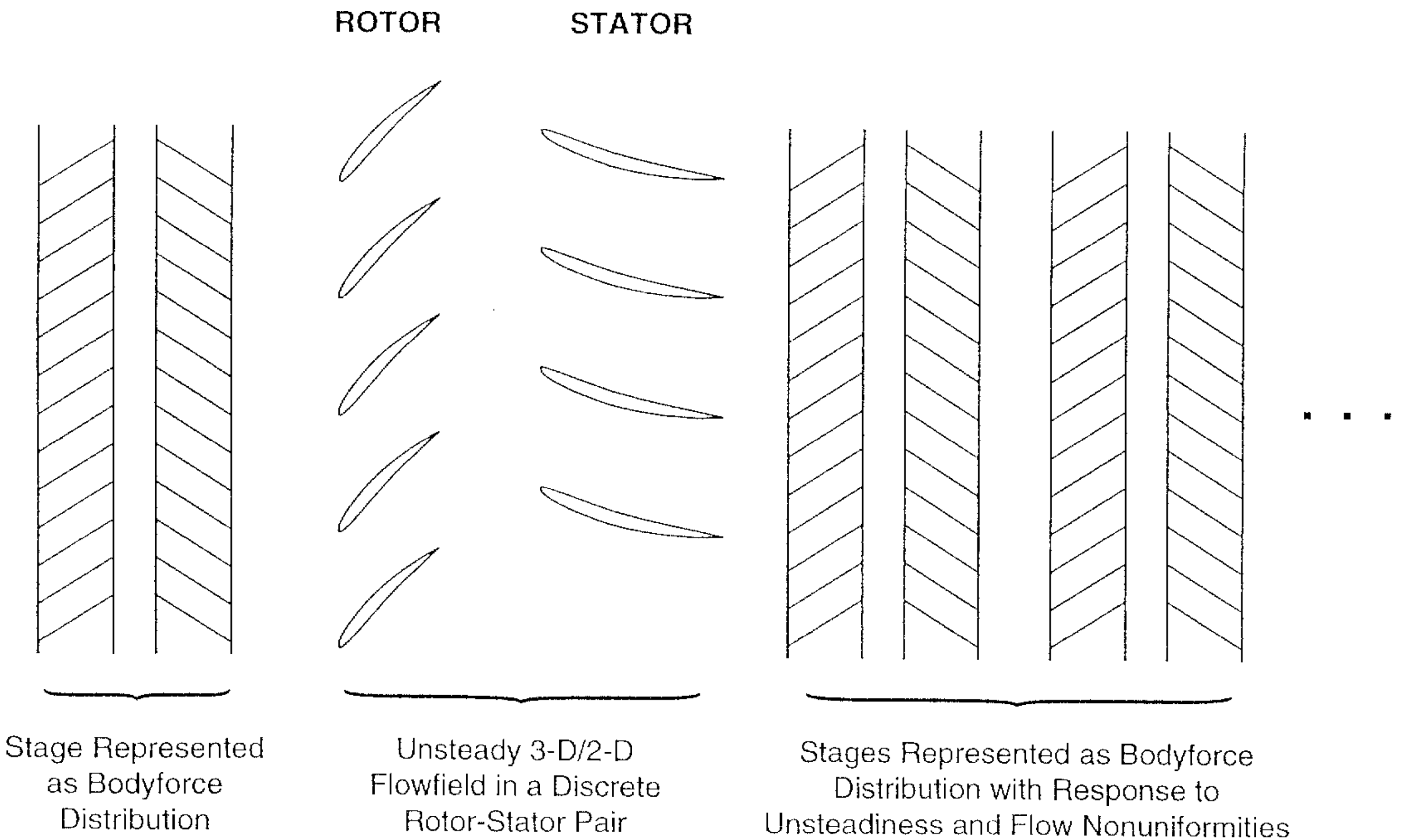
RESEARCH ISSUES

- Generation of tip leakage flows in multi-blade row environment
- Evolution of tip leakage flows through subsequent blade rows
- Controlling parametric trends of endwall flow on pressure rise capability, loss and blockage distribution
- Implications on overall performance and design
  - e.g., Aerodynamic matching of stages

TECHNICAL APPROACH

- Development of a bodyforce model which can replace one or several blade rows in a multistage compressor
  - Analytical approach
  - Development and validation of a steady bodyforce model for a blade row
  - Development and validation of an unsteady bodyforce model for a blade row
- Implementation of this bodyforce model to unsteady computations of a multistage compressor to address the research issues mentioned above

PHYSICAL MODEL OF MULTISTAGE COMPRESSOR FOR INVESTIGATION OF ENDWALL FLOW



MODEL REQUIREMENTS

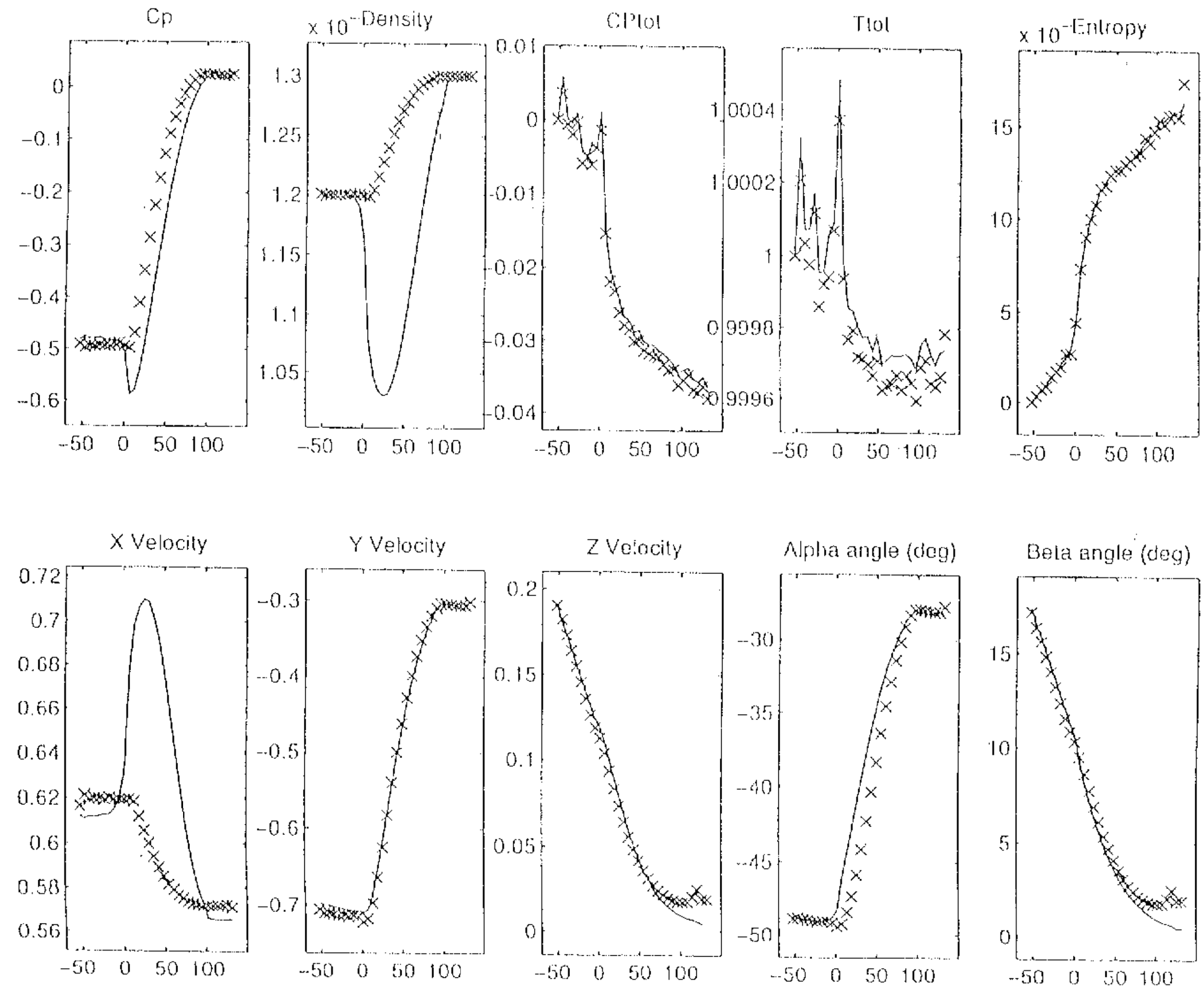
- Two levels of modeling
  - Steady Flow : single blade row
    - Match all aerodynamic and thermodynamic flow variables
  - Unsteady Flow : single stage
    - Match time-average pressure rise and loss across the stage
    - Reproduce physical phenomena which affect unsteady interaction

STEADY MODEL IMPROVEMENT (1)

- Inclusion of blockage in model - not implemented
- Iteration on body forces and heat sources to better match thermodynamics variables

* Results in this viewgraph and next viewgraph obtained by Mr. A. Wisnia on support provided by US Marshall Fellowship and MHI with Dr. S. Aoki as Technical Monitor

STEADY MODEL IMPROVEMENT (2)



NEAR TERM TASKS

- Identify a multistage axial compressor representation of current design as focus of research activities
  - Establish its operating chi'c
  - Determine a stage of relatively lower performance
- Use framework developed here to analyse flow in selected rotor-stator pair with focus on role of endwall & wake within multistage environment on performance

LONG TERM TASKS

- Develop design guidelines and suggest reconfiguration of multistage compressor to mitigate impact of endwall flow (I.e. desensitization of performance to tip leakage flow)
- Propose experimental investigations to complement present effort

ENVISIONED BENEFITS

- Transition of basic ideas/concepts on multi-stage compressor endwall flows to applications in industrial design environment
  - e.g., To achieve better aero-matching of stages
  - Hence compressor performance improvement
- Procedure for rational accounting of endwall flow effects in multi-stage compressor