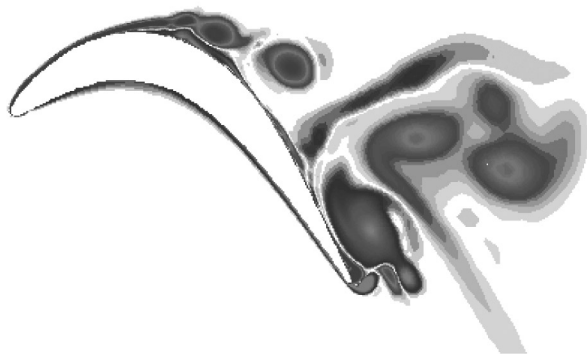# Minnowbrook IV
2003 Workshop on Transition and Unsteady Aspects of Turbomachinery Flows

John E. LaGraff
Syracuse University, Syracuse, New York

David E. Ashpis
Glenn Research Center, Cleveland, Ohio

August 2004

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Minnowbrook IV
2003 Workshop on Transition and Unsteady Aspects of Turbomachinery Flows

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Syracuse University, Syracuse, New York

David E. Ashpis
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National Aeronautics and
Space Administration

Glenn Research Center

August 2004

Acknowledgments

Preface

On August 17 to 20, 2003, over 40 attendees participated in a workshop entitled "Minnowbrook IV—2003 Workshop on Transition and Unsteady Aspects of Turbomachinery Flows."

Workshop co-chairs were
>   John E. LaGraff , Syracuse University, Syracuse, NY, U.S.A.
>   Terry V. Jones, Oxford University, Oxford, U.K.
>   J. Paul Gostelow, University of Leicester, Leicester, U.K.
>   Reza Abhari, ETH, Zurich, Switzerland

The sessions were held at the Syracuse University Minnowbrook Conference Center in Blue Mountain Lake, New York, and followed the theme, venue, and format of three earlier workshops in 1993,[1] 1997,[2] and 2000.[3] Earlier themes focused on improving the understanding of late stage (final breakdown) of boundary layer transition. The specific engineering application of improving design codes for turbomachinery was encouraged by the attendance of representatives from gas turbine manufacturers. The 2003 workshop had a particularly strong representation from industry.

The format of the workshop was intentionally kept informal, to encourage presentations which could include a wide range of material spanning a level of formality from previously published work to work-in-progress or even future/proposed work. We did not want to inhibit presentation of relevant material for artificial reasons of normal publication restrictions. Written papers were not requested. Abstracts and copies of figures were the only written record of the workshop aside from specifically commissioned transcriptions of a workshop summary and the extensive working group reports, discussions, and summary that followed on the final morning of the workshop. The format of the workshop was also unusual in that nearly as much time was allowed for discussions as was allowed for the presentations. Groupings of three or four papers were followed by a large block of discussion time.

This volume contains abstracts and copies of the viewgraphs presented, organized according to the workshop sessions. The hard copy contains the keynote lecture, abstracts, and the transcripts of the plenary and summary sessions. The presentation viewgraphs are included on the accompanying CD. The post-workshop summary and the plenary-discussion transcript clearly highlight the need for continued vigorous research in the technologically important area of transitional and unsteady flows in turbomachines.

John E. LaGraff, Syracuse University
David E. Ashpis, NASA Glenn Research Center

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[1] Syracuse University Report, J.E. LaGraff, editor
[2] NASA/CP—1998-206958, J.E. LaGraff and D.E. Ashpis, editors
[3] NASA/CP—2001-210888, J.E. LaGraff and D.E. Ashpis, editors

Table of Contents

Presenters' names in boldface

Session 4—Roughness and Receptivity

Session 5 – Working Group Meeting 1
Reported in Plenary Session 12

Session 6—Flow Control

Session 10 – Working Group Meeting 2
Reported in Plenary Session 12

Session 11 – Working Group Meeting 3
Reported in Plenary Session 12

Session 12—Workshop Plenary Session

Report of Breakout Sessions

Keynote Presentation

CURRENT ISSUES IN UNSTEADY TURBOMACHINERY FLOWS

Louis Povinelli
NASA Glenn Research Center
Cleveland, OH

Among the numerous causes for unsteadiness in turbo machinery flows are turbulence and flow environment, wakes from stationary and rotating vanes, boundary layer separation, boundary layer/shear layer instabilities, presence of shock waves and deliberate unsteadiness for flow control purposes. These unsteady phenomena may lead to flow-structure interactions such as flutter and forced vibration as well as system instabilities such as stall and surge.

A major issue of unsteadiness relates to the fact that a fundamental understanding of unsteady flow physics is lacking and requires continued attention. Accurate simulations and sufficient high fidelity experimental data are not available.

The Glenn Research Center plan for Engine Component Flow Physics Modeling is part of the NASA 21st Century Aircraft Program. The main components of the plan include Low Pressure Turbine experimental and computational databases and models for flow control, data for Reynolds Stress modeling and model development and combustor spectra measurement and an LES version of the National Combustor Code. The goals, technical output and benefits/impacts of each element are described in the presentation. The specific areas selected for discussion in this presentation are blade wake interactions, flow control, and combustor exit turbulence and modeling.

The results of the technical work lead us to the recognition that (1) it is critical to sort out the limitations of current models and determine the needed improvements for models of transition, separation and reattachment, (2) to understand both the surface properties as well as those within the boundary layer, (3) to understand the interaction of the force created by the control device on the boundary layer behavior and the excitation required, (4) an understanding of combustor exit flow field spectra and (5) an understanding of turbulent reacting flows. These phenomena hold the key to a more effective utilization of turbomachinery devices.

Keynote

Current Issues in Unsteady Turbomachinery Flows

Louis A. Povinelli

NASA Glenn Research Center

MINNOWBROOK IV
TRANSITION AND UNSTEADY ASPECTS OF
TURBOMACHINERY FLOWS
17-20 AUGUST 2003

HIGH BYPASS RATIO ENGINE
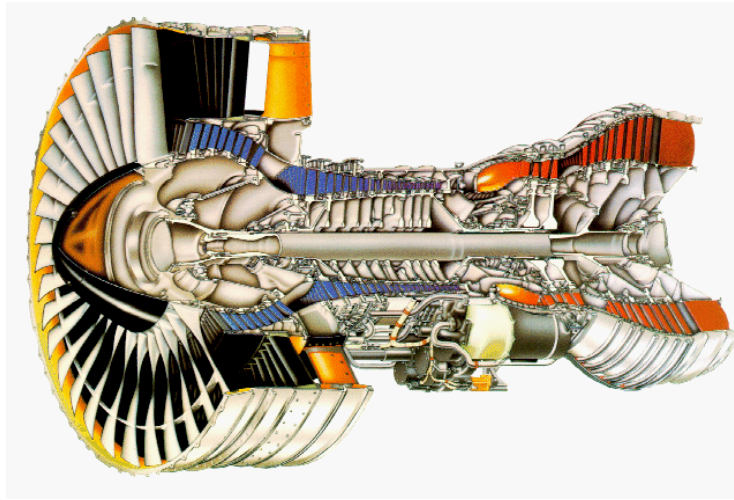
PW4000
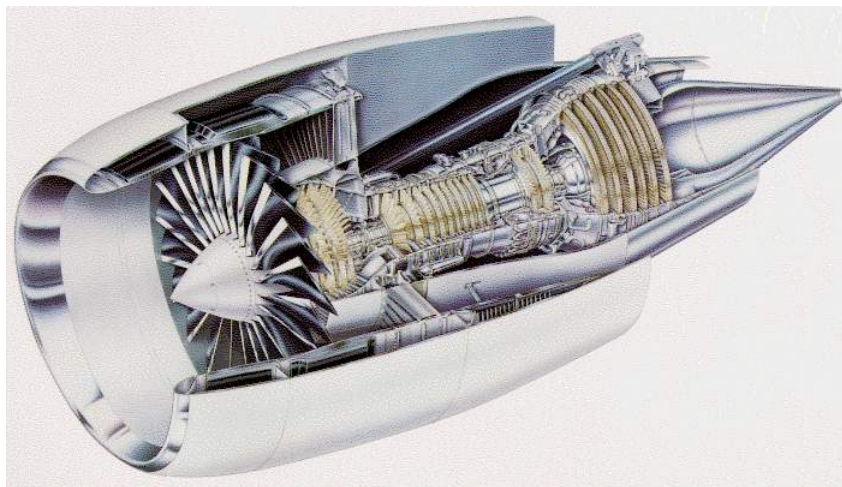
GE90

Hybrid PDE Concept
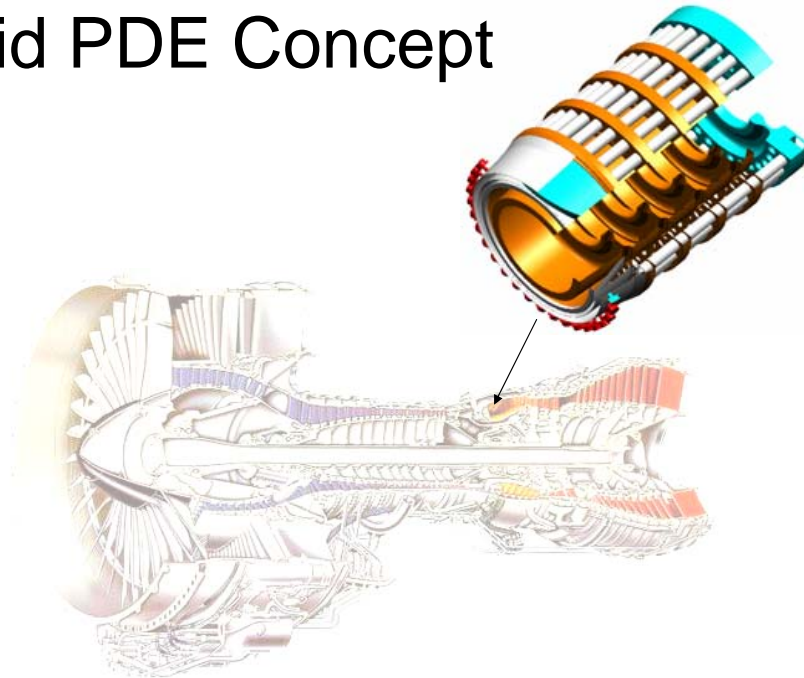
Sources of unsteadiness in turbomachinery flows

- Turbulence and flow environment
- Wakes - stationary & rotating vanes
- Boundary layer separation
- Boundary layer / shear layer instabilities
- Presence of shock waves
- Deliberate unsteadiness – flow control

- Flow-structure interactions-flutter & forced vibration
- System instabilities-stall, surge
- Turbofan hybrid cycle-PDE

Other Cause for Unsteadiness

FOD damage and the fix !
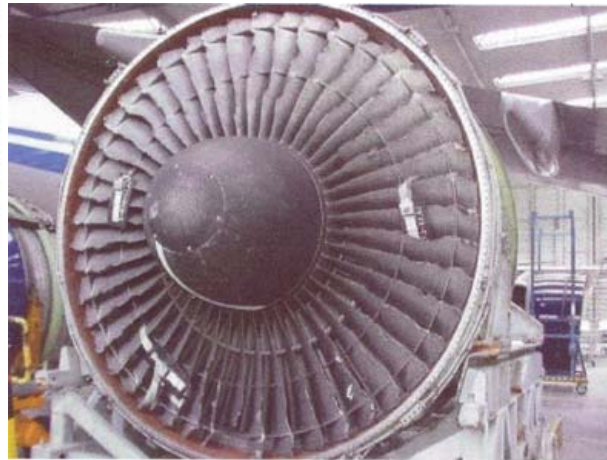
Another cause of unsteadiness

Major Issues

- Fundamental understanding of unsteady flow physics is lacking and requires continued attention.
- Accurate simulations and sufficient high fidelity experimental data are not available.

GRC PROGRAM

Engine Component Flow Physics Modeling

Low Pressure Turbine databases

Combustor Spectra Measurement

Models for Low Pressure Turbines & Flow control

LES version of NCC

Data for Reynolds Stress Modeling

Hybrid Computational (PANS) Scheme

Reynolds Stress Model Development
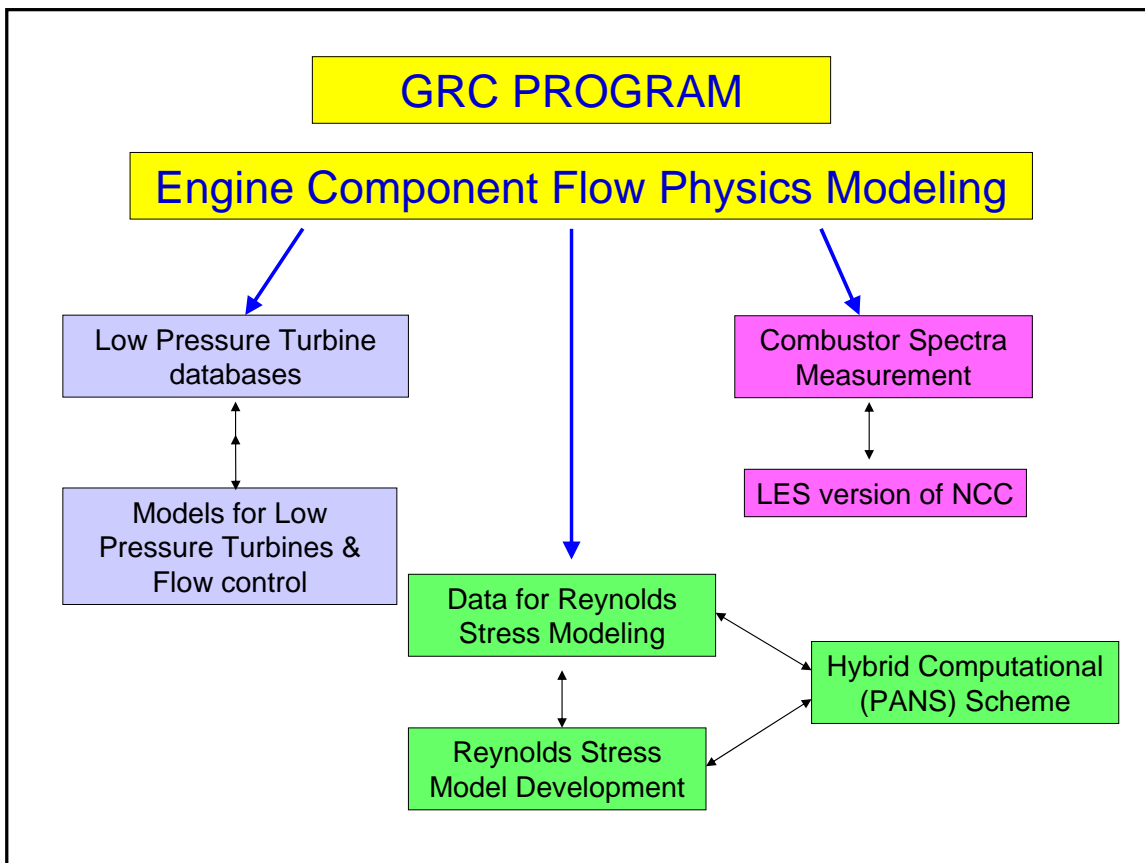
Engine Component Flow Physics Modeling

MS#	MS Lvl	EASI MILESTONE/DP (Short Phrase)	OUTPUT (Performance Metric/Exit Criteria)	OUTCOME (Benefits & Impact)
11-04-2-01	L3	Data for Reynolds Stress Modeling	Measurements for validation of Reynolds stress modeling.	Provide measured cross term correlations needed for validation of 2nd order modeling.
11-04-2-02	L3	Reynolds Stress Model Development	Improved turbulence modeling for unsteady turbulent flows in engine and airframe components.	Enables improved accuracy for flow field simulation, providing increased confidence in design and analysis of engine and airframe components
11-04-3-03	L3	Hybrid Computational (PANS) Scheme	Demonstrated scheme for Partially Averaged Navier Stokes (PANS) flow simulation and demonstration of test cases for steady and unsteady turbulent wall and jet flow fields.	Verified robust, reliable computational method that will compute turbulent flow fields with a higher level of accuracy
11-04-3-04	L3	Combustor Spectra Measurement	Measurements of combustor turbulence	Provides for accurate boundary conditions for turbine heat transfer requirements and reduced cooling flow reqts
11-04-3-05	L3	LES version of NCC	Large Eddy Simulation (LES) version of National Combustor Code (NCC)	Provides accurate numerical data sets for improved modeling for combustor CFD design tools.
11-04-3-06	L3	Low PressureTurbine databases	Experimental and numerical data sets of unsteady low pressure turbine flows.	Provides validation data and physical understanding for CFD and modelling for more fuel efficienr engine performance.
11-04-2-07	L3	Models for Low Pressure Turbines	Improved transition and turbulence modeling for unsteady separated low pressure turbine flows.	Provides accurate models for design tools for prediction of high lift low pressure turbine airfoils to increase loading and avoid flow separation..
11-04-3-08	L3	Low Pressure Turbine Flow Control	Demonstration and CFD development for active and passive flow control techniques for effective control of boundary layer separation.	Provides high efficiency, low weight, reduced part count, as well as increased loading over entire flight envelope.

Selected areas for discussion

1. Blade wake interactions
2. Flow control
3. Combustor exit turbulence & modeling
4. Pulse detonation hybrid cycles

1. Blade Wake Interactions

- This topic has been an active research area,.

- Major recent contributions by Hodson et al,

Halstead et al, Solomon et al, and others, mostly

originating in Europe

- Has been a major topic in prior Minnowbrook

workshops

- Research is particularly applicable for LPT flows

 Characteristics of flow in LPT airfoil passages:
- Flow in LPT is unique compared to gas turbine components
- Low Reynolds number 25,000 - 300,000, Exit M ~0.5
- High free stream turbulence 0.5 % to 10 %
- Complex flow : transition, wakes, separation
- Unsteadiness
- Additional complexity in 3D flow at endwalls
- Cause of efficiency loss due to laminar separation on airfoil suction surface

Design needs
- Increase airfoil loading – reduce part count, weight, cost
- Reduce takeoff-to-cruise efficiency degradation.

Wake interaction in LPT - Background

- Much of the experimental work was based on surface measurements.
- Effort at GRC focus on high fidelity measurements *inside* the boundary layer -essential for successful CFD and model development.
- The goal is accurate simulation and validation of BL transition, separation and reattachment locations
- Common blade geometry (P&W PAK B) used
- Cascade simulations have yielded excellent agreement with experiment data.
- Simulation of cascade experiments with unsteady wakes are underway.

Funding Programs:

TCAT

SEC

Funding Programs:

SEC

PDF

NASA GRC LPT PROGRAM

High lift LPT

Flow Control

Unsteady - wakes

Steady- no wakes

Active

Passive

Turbulence/Transition Modeling

Experiments

Plasma

Models & physical understanding and databases for improved designs of LPT

Baseline for LPT flow control

Theory - optimization

Promising initial results

In-house & universities team

Experiments: GRC/CW7, U. Minnesota, Texas A&M, USNA

Modeling/CFD: U. Kentucky

In-house & universities team

Experiments: GRC/CW7, USNA, Notre Dame

Theory: U.Arizona SBIR: Techsburg

PAK B Blade Cascade Experiments of Corke et al. (2002)

Re =100k — Computation / Experiment — C_p vs x/C_x (%)

Re = 75k — Computation / Experiment — C_p vs x/C_x (%)

Re = 50k — Computation / Experiment — C_p vs x/C_x (%)

Re = 25k — Computation / Experiment — C_p vs x/C_x (%)

Re = 10k — Computation / Experiment — C_p vs x/C_x (%)
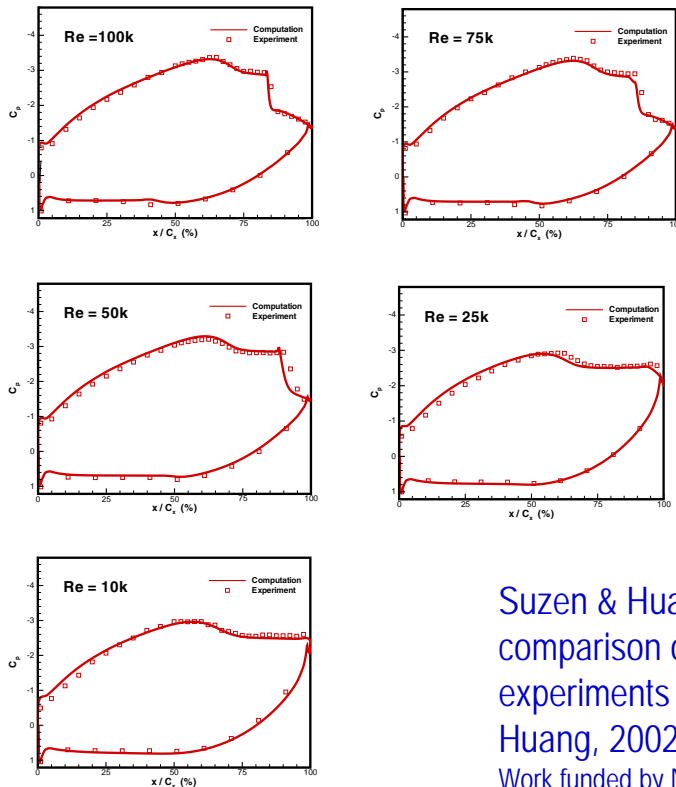
Suzen & Huang (U. Kentucky) 2003: comparison of CFD with PAK B cascade experiments at U. Notre Dame by Corke & Huang, 2002,
Work funded by NASA GRC

Unsteady LPT flows with wakes:

• Focus on experiments with low speed <u>simulated</u> wake generators

Advantages:

• Enables detailed hot wire anemometry providing details of boundary layer behavior; transition, separation, reattachment, vortex formation, etc

•There is some criticism on use of cylindrical bars – however they are good for model validation – models that work for the turbulent wakes generated by cylindrical bars will work for airfoil wake.

Recent Studies sponsored by GRC:

• U. Minnesota – Simon et al

• Texas A&M – Schobeiri et al

• Univ. Notre Dame – Corke et al development of a solid state wake generator.

Suzen & Huang Simulation of
the Experiments of Schobeiri and Pappu (1997) SSME Airfoil
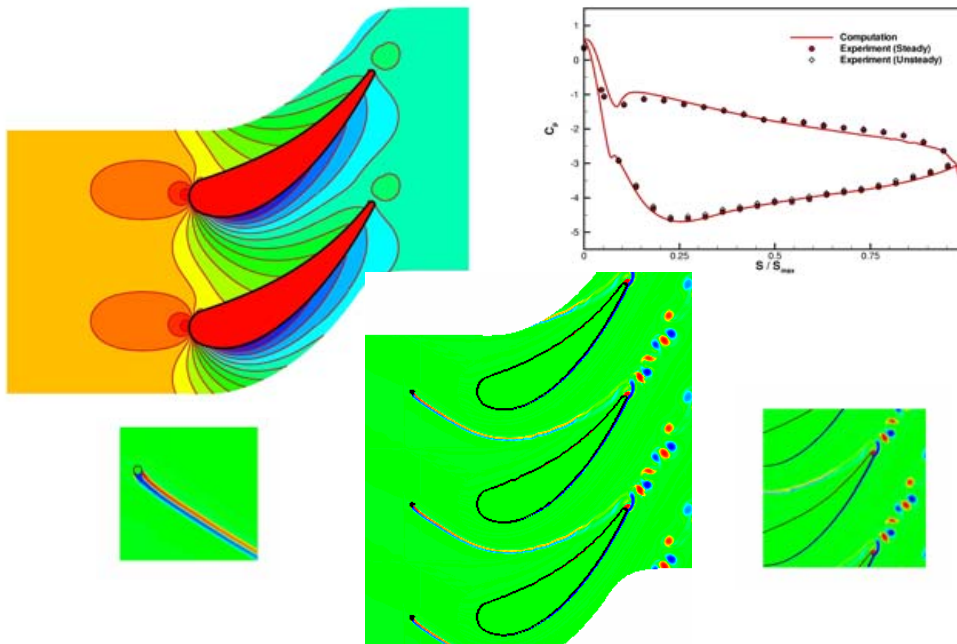
Suzen & Huang (U. Kentucky) 2003:
Comparison of CFD with experiments at U. Minnesota
by Simon & Kaszeta (2001)
Work funded by NASA GRC

• Re = 21,000
• FSTI = 2.5%
• PAK-B blade passage
• $U_{rod} / U_{axial} = 0.7$
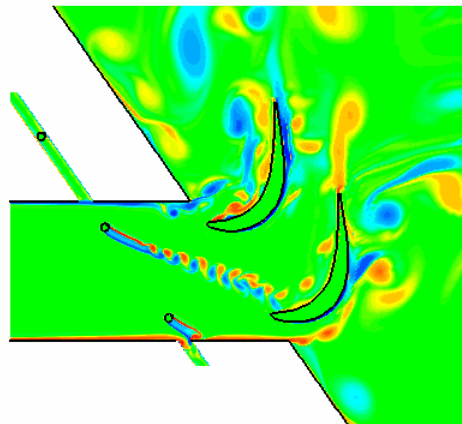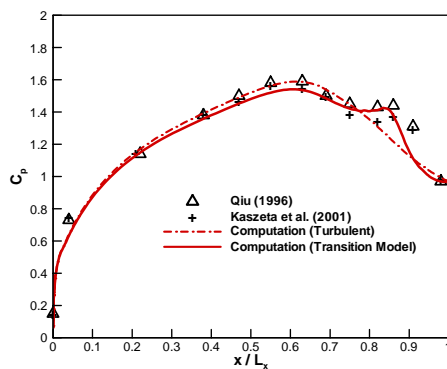
Future Work

- New blade configurations with higher loading to be used in common study
- Blade coordinates will be made available to researchers as done with PAK B
- Evaluation of current modeling to be carried out with new blade
- Extend work to 3D
- Design high lift LPT airfoil and test in new GRC dual spool rig (under construction)

2. Flow Control

Motivation
- There is limit to what can be accomplished with airfoil design and optimization
- Flow control provides a leap to new enabling technologies
- However; unsteadiness is challenge for experiments, simulation and physical understanding

Classification
- Passive Flow Control – trips, dimples, vortex generators, bumps
  - unsteadiness caused by shedding, transition
- Active Flow Control
  - Steady - aspiration – suction-blowing
    - Unsteadiness may be caused by separation (shedding, instabilities) or transition
  - Oscillatory/Pulsed – Synthetic jets, pulse jets, plasma actuators
    - unsteady by definition

NASA GRC

Hultgren & Ashpis (2001)

CW-7 TRANSITION WIND TUNNEL
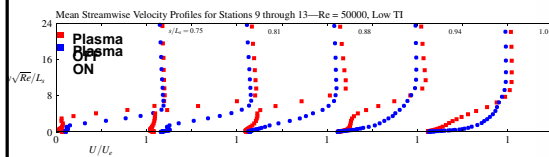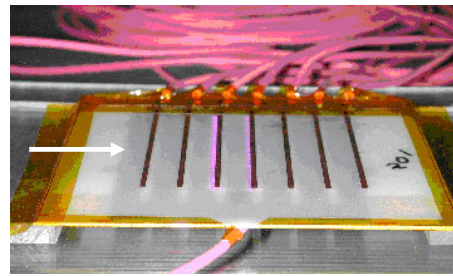
Phased Array - Oscillating wall jet configuration

Mean Streamwise Velocity Profiles for Stations 9 through 13—Re = 50000, Low TI

VELOCITY PROFILES
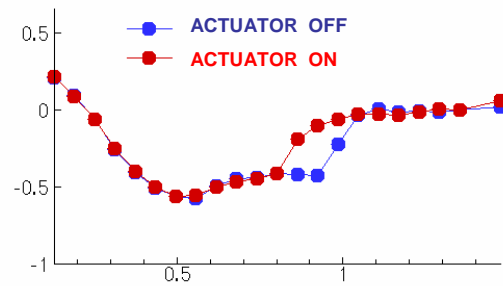
PRESSURE DISTRIBUTION ALONG THE SURFACE

Separation control via generation of streamwise vortices

DIMPLES -Passive

STREAMWISE ORIENTED GLOW
DISCHARGE PLASMA ACTUATORS

FLOW

ω_z
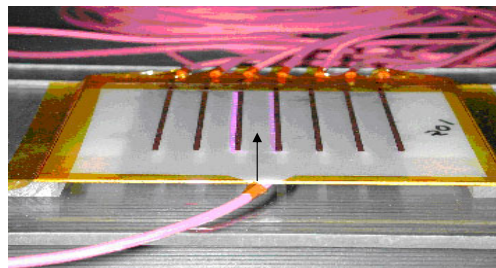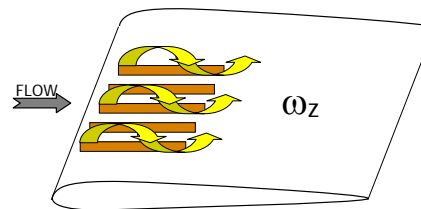
Lake et al , 2000

Corke et al 2002, Hultgren & Ashpis , 2002

Volino, USNA, 2002

2D tripping strip

Vortex generator jets

Flow
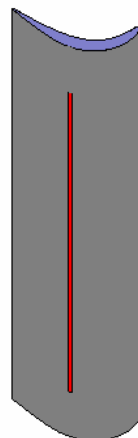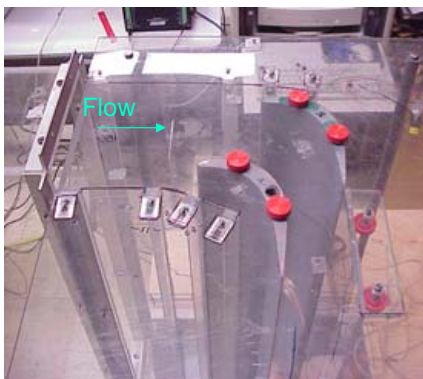
Ejector jet – SBIR – Technology in Blacksburg Inc.

LPT Blade

Incoming low Re flow

Separation bubble on
suction surface

Boundary Layer
Approaching Separation

Suction

High Pressure Air

Blowing

Energized
Boundary Layer
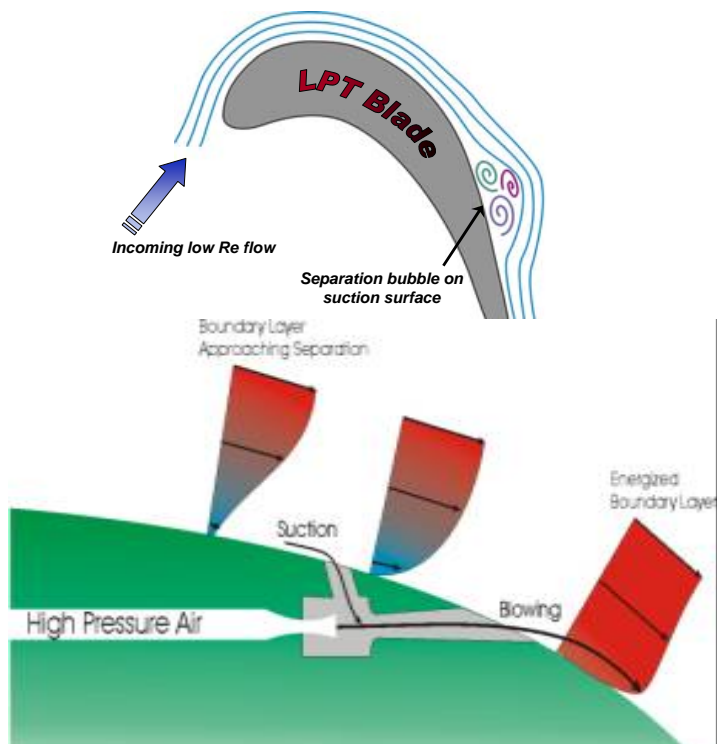
ZERO NET MASS DEVICE - SYNTHETIC JET

Laminar 2D simulation

Synthetic Jet
by
George Huang
Dept of Mech Eng
University of Kentucky
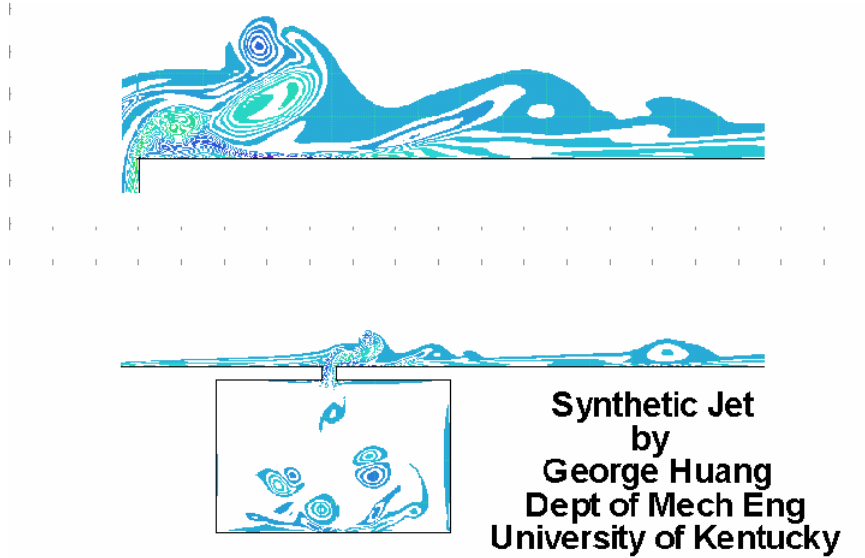
Synthetic Jet for CFD Validation and Modeling

Instantaneous Velocity Vector Plot of Synthetic Jet
with FUN2D Code at f=450 Hz
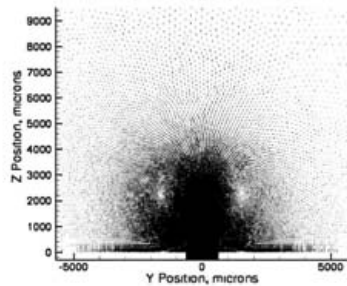
- Benchmark time-accurate codes, both unstructured and structured, against synthetic jet model
- Outcome will provide flow physics understanding of actuator interactions
- Calculations and experiments underway

· New actuator jointly designed by CFD modelers and experimentalists
  – Best performance not required
    · Single disk - easier B.C.
    · Wider 2D slot - better measurements
  – Redundant measurements
    · Hot-wire, LV, PIV, input signal, diaphragm displacement, cavity pressure

2.250"
[57.15mm]

.050"
[1.27mm]

.800"
[20.32mm]
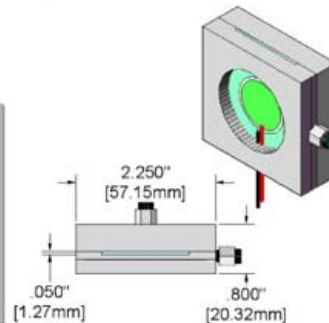
Benchmarks for Validating CFD

Isolated Synthetic Jet

Synthetic Jet in a Cross Flow

Flow

Modified Glauert-Glas II
Airfoil Section
t/c = 20%

x/c = .64   x/c = 1.32

2-D Hump Model

Hump Model - FUN2D

Mach = 0.25,   Rn = 16 million, Steady blowing, Cm = 1.68%

Flow

Modified Glauert-Glas II Airfoil Section

t/c = 20%

Separation Bubble
.65 < x/c < .655

Completely Attached

Synthetic Jet in Crossflow
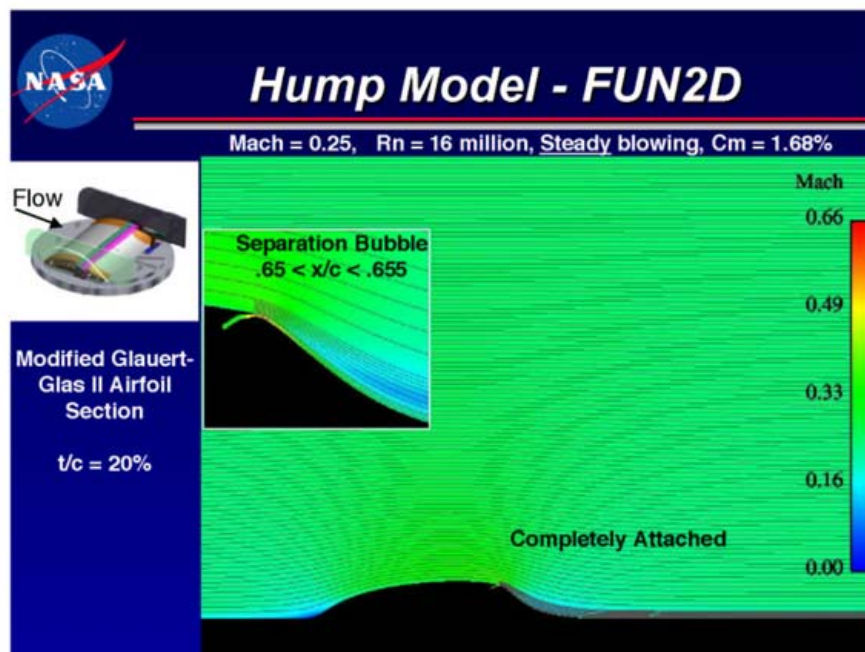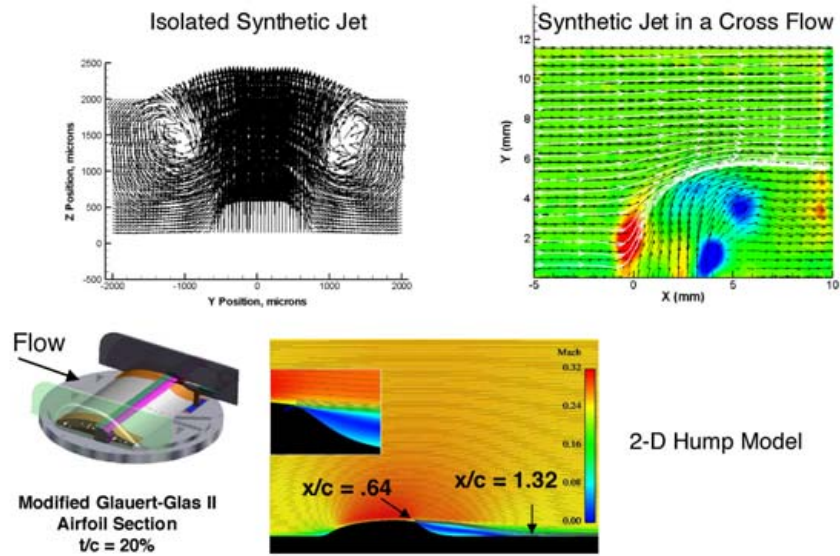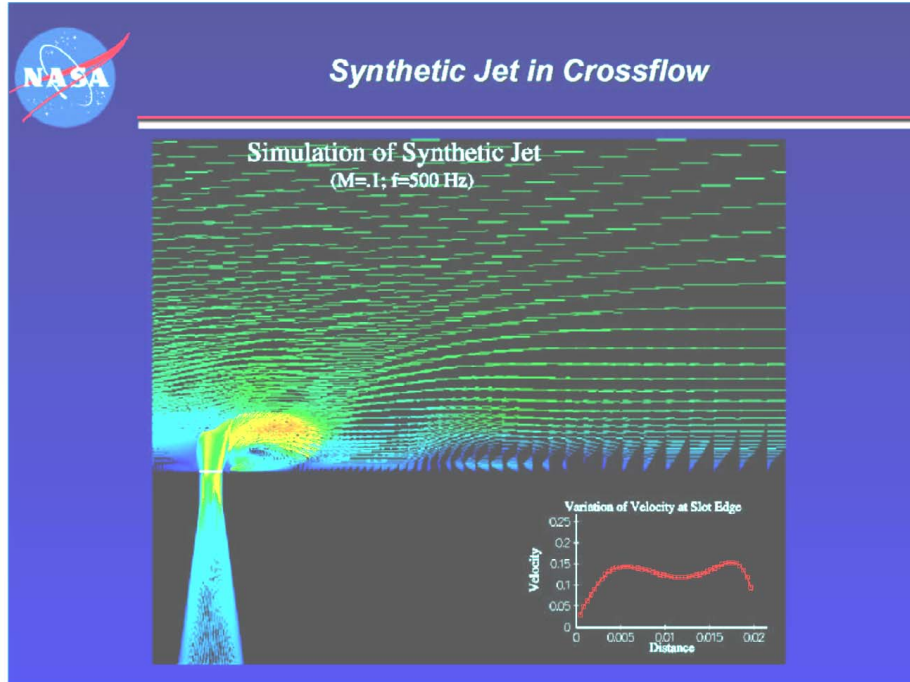
FLOW CONTROL - Summary (Inspired by Sellers, NASA Langley)

- **Active Flow Control has the potential to revolutionize the gas turbine**

However ….
- **The dynamic environment that empowers flow control is not well understood,**

nor…
- **Can that dynamic environment be readily predicted with today's computational tools,**

The challenge….
- **The engineering and integration needed to use and manufacture the necessary actuators, sensors and controls using advanced and smart materials needs to be demonstrated,**

3. Combustor exit turbulence and combustor modeling

- **Combustor Spectra Measurement**

  - *Attainment of turbulence intensity, scale and spectra at combustor exit plane in a full scale combustor facility*

- **LES version of NCC (National Combustor Code)**

  - *Shih, Ohio Aerospace Institute*
  - *Develop generalized wall function valid for adverse and favorable pressure gradient and validate with benchmark combustion datasets*
  - *Develop LES version of the National Combustor Code with suitable modeling for turbulent, swirling, reacting flow*

Injection Mechanism
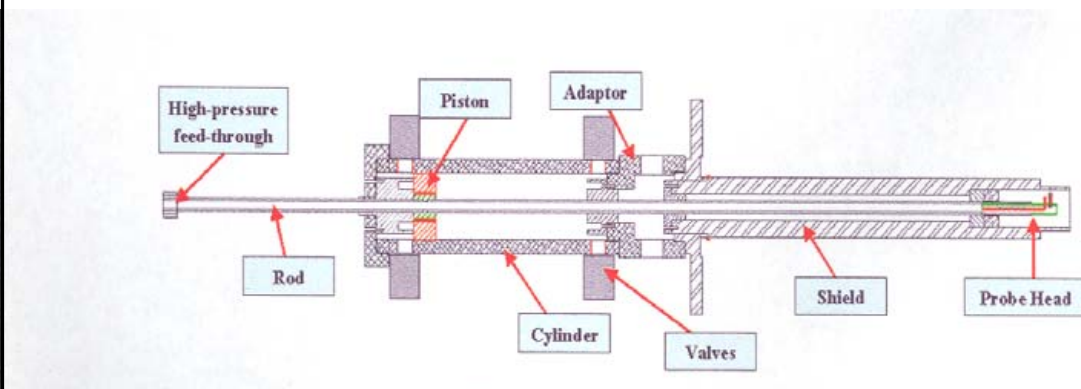
COMBUSTOR SPECTRA MEASUREMENTS
PROBE MECHANISM
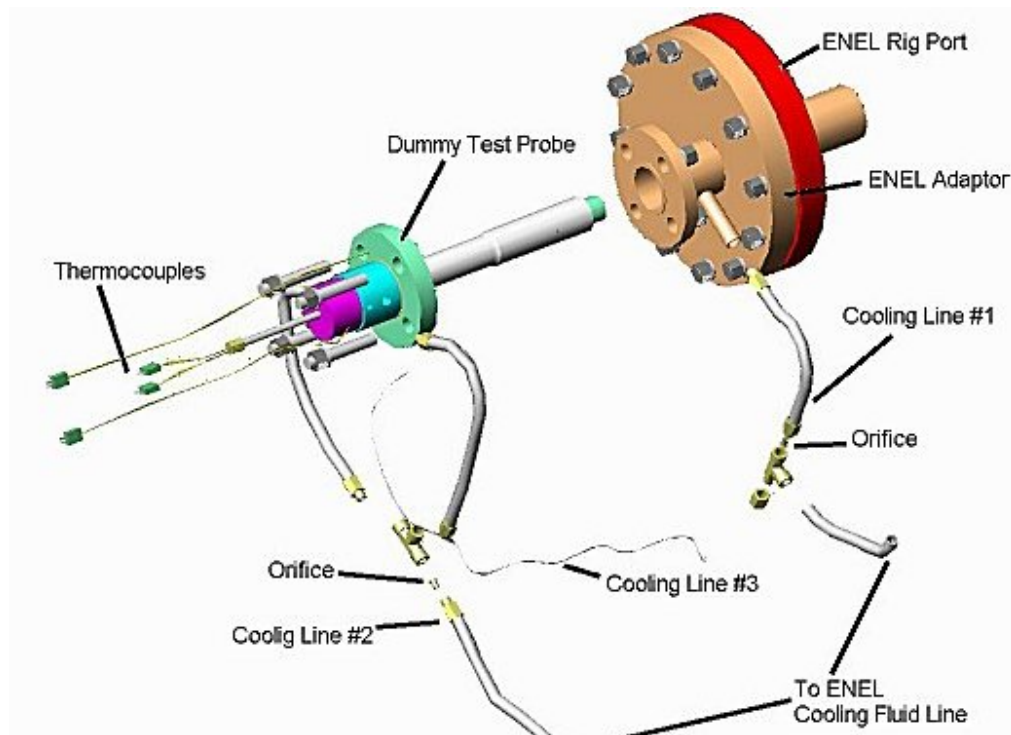
Combustor Spectra Measurement

MEASUREMENT OF TURBULENT PRESSURE AND TEMPERATURE FLUCTUATIONS IN A GAS TURBINE
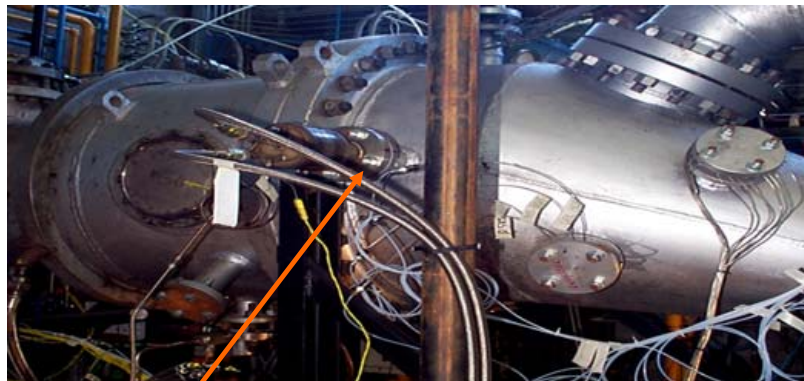
Injection Mechanism in ENEL Rig

Power Spectral Density
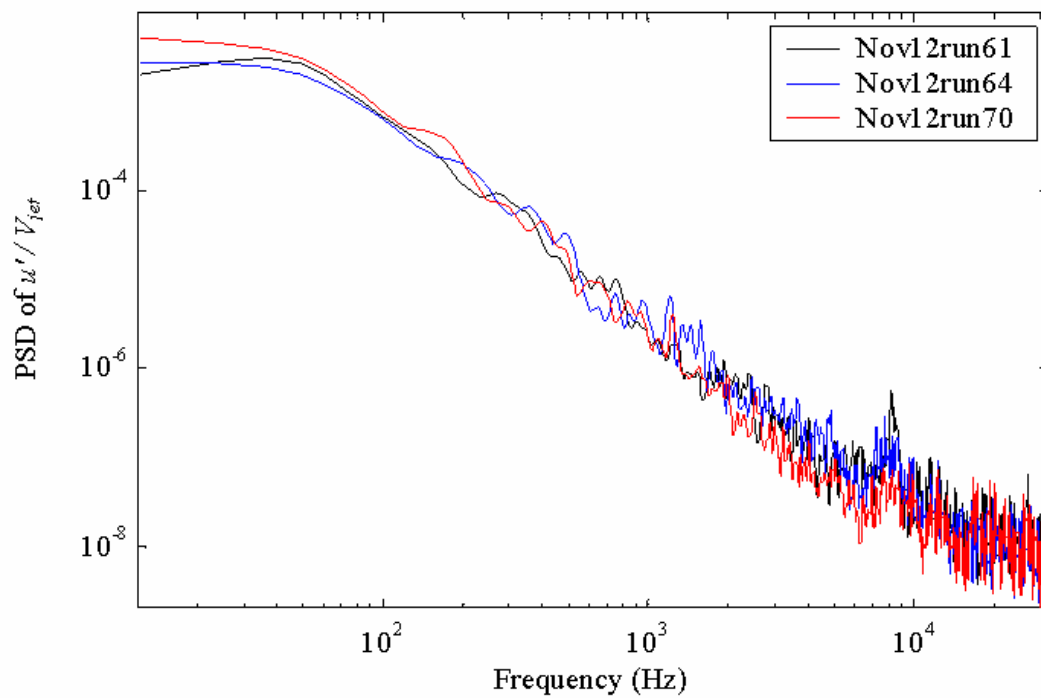
4. Pulse detonation hybrid cycles
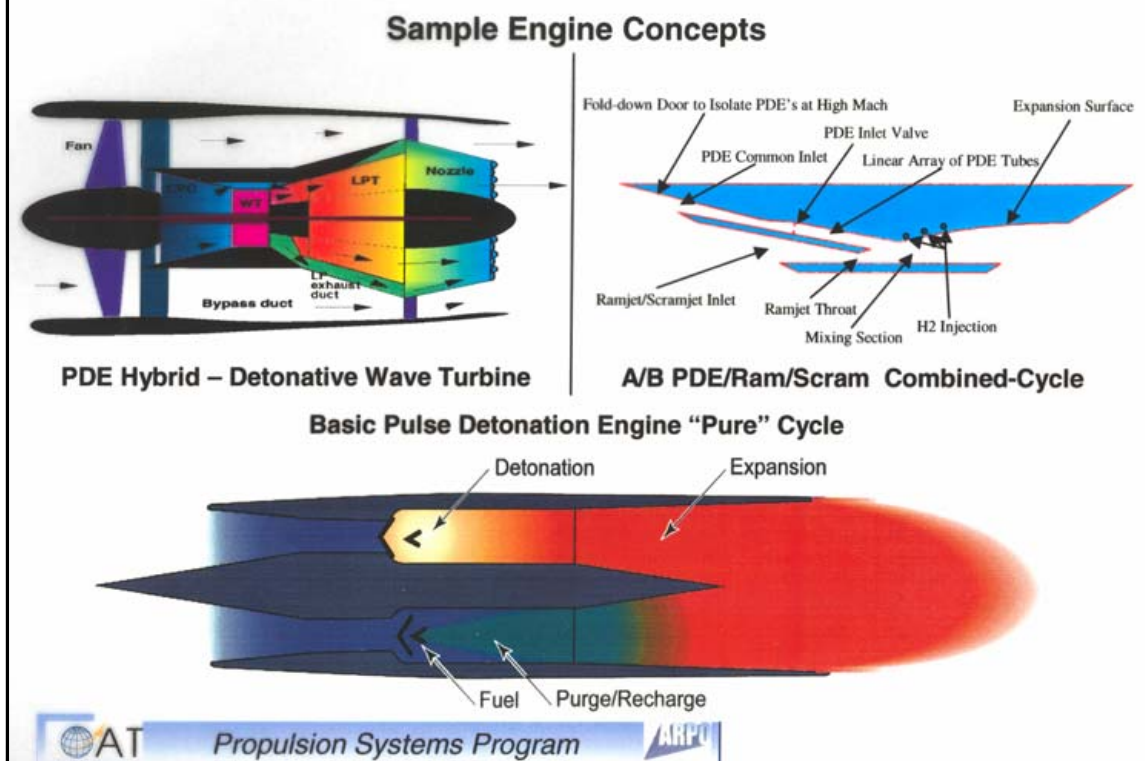
THERMO CYCLE ANALYSIS
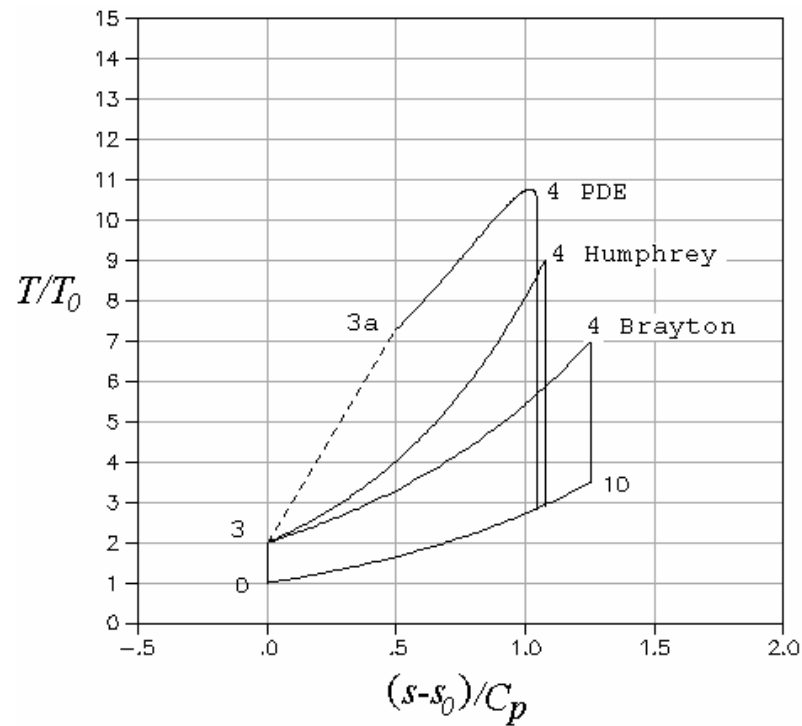
PDE & Brayton Thermal efficiencies
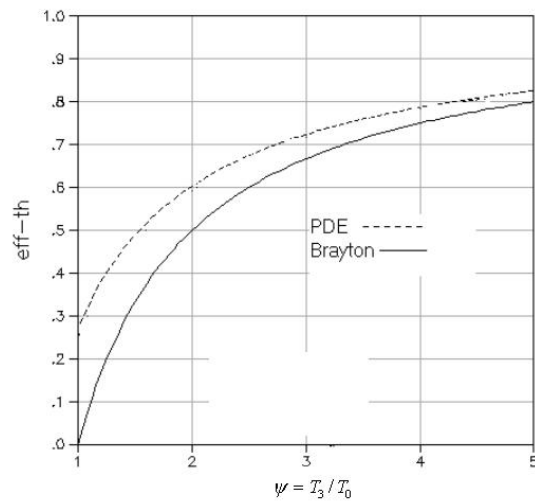
Specific thrust for the PDE and Brayton Cycles versus temperature ratio, stoichiometric propane-air
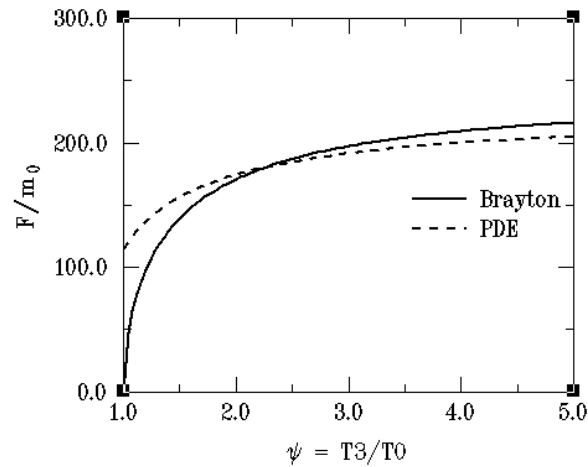
Specific Thrust and Impulse for the PDE and Brayton Cycles
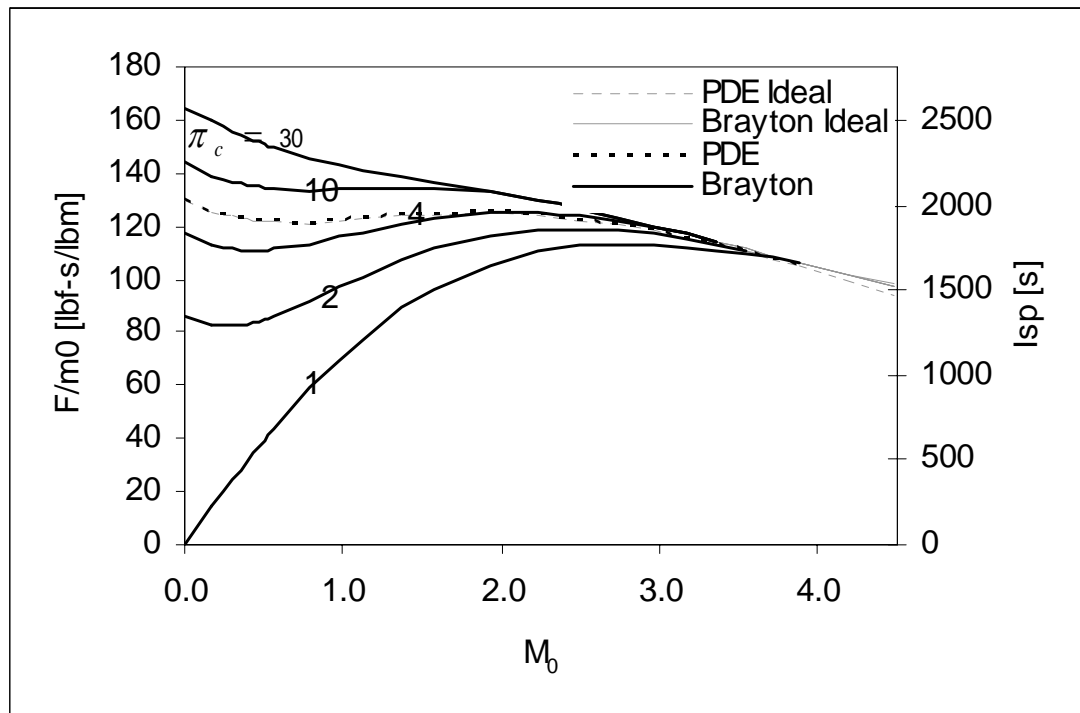
PDE Testing at Glenn

PDET Project – Hybrid PDE Application

Advanced Hybrid PDE Concept

- Pulse detonation combustor replaces conventional core in commercial turbine engine

- Conceptual studies by NASA GRC, P&W, and APRI were completed

- **10-15% TSFC improvement potential**
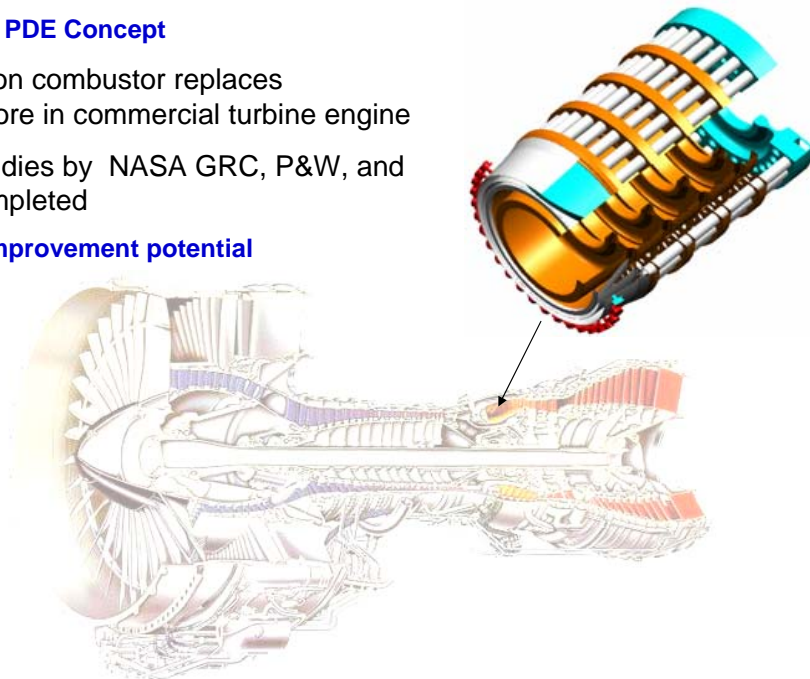
PDET Project - Summary

• Pulse detonation (PD)-based engine concept studies indicate significant performance improvements possible but----
- **Significant technology challenges remain**

• Future efforts will focus on **PDE-hybrid** systems

• Continue fundamental research in support of engine concept development

- Initiate proof-of-concept demonstrations (NASA/Industry)

- Hybrid engine single tube combustor test in process

- Combustor operability

- Combustor integration

- Develop a multi-PD tube - nozzle test rig

• Develop robust system analysis capability

- Requires accurate component loss models

Closing remarks

- Critical to sort out the limitations of current models and determine the needed improvements
- Necessary to understand both the surface properties as well as those within the boundary layer
- Knowledge of the interaction of the force created by the control device on the boundary layer behavior and excitation is needed
- BL transition, separation and reattachment remain as key issues for gas turbine flows
- Combustor exit flow field spectra need further resolution
- Turbulent reacting flow understanding has improved, but continues to be challenging

Closing remarks

- As scientists, researchers and engineers, we recognize the need to pursue improved understanding of the flow physics inherent in propulsion devices

- There is a recognized path (or scientific approach) to achieving this knowledge

- There is a need to sustain the activities started by this group some 8 –10 years ago

- Therefore, we must remain committed to our research activities in order to achieve significant improvements in propulsion systems

Closing remarks

- There is an increasing impatience with the "art of science"
- NASA is emphasizing a broader technology readiness level for IH research; Levels 1 through 6.
- NASA also emphasizing earlier application of S&T efforts
- NASA's turbine engine research is focusing on emissions (fuel efficiency), noise and high speed accelerators.
- Commercial aircraft business undergoing severe reductions world-wide with some consequence on S & T funding.
- A persistent effort is needed on our part to accomplish our objectives.

Abstracts of
Session Presentations

Full presentations are available on the accompanying CD

GLOBAL INSTABILITY AND CONTROL OF LOW-PRESSURE TURBINE FLOWS

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The potential of a laminar separation bubble to become self-excited through BiGlobal linear instability, besides being susceptible to the well-known (Kelvin-Helmholz/Tollmien-Schlichting) mechanism of linear amplification of incoming disturbances, has been recognized in the last decade. Hammond and Redekopp [2] considered a model separation bubble and, assuming quasi-parallel flow, applied linear local analysis based on numerical solutions of one-dimensional eigenvalue problems (EVP) of the Orr-Sommerfeld class in order to determine the conditions for absolute instability of the separation bubble. By contrast, Theofilis et al. [4] performed 2D direct numerical simulations to recover the separated bubble flows described by Briley [1] and used such (essentially nonparallel) 2D steady flows as basic states in 3D BiGlobal linear instability analyses. The appropriate 2D (partial-derivative) EVP was solved numerically and the potential of separated flow to support global instability, without having to resort to restrictive assumptions on the basic flow, was demonstrated for the first time. Theofilis and Sherwin [5] extended this work to detect stable BiGlobal eigenmodes in the trailing-edge separation region of a NACA 0012 airfoil at an angle of attack $\alpha = 5^o$; the basic flow, including a magnification of the trailing-edge separation region is shown in the left part of figure 1, while the spanwise component of the disturbance velocity of the BiGlobal eigenmode pertaining to the trailing-edge separation region is shown in the middle of the same figure. Recently, Theofilis et al. [6] performed BiGlobal instability analysis of the entire NACA 0012 flow-field, considering an integration domain extending well into the free-stream, upstream and downstream of the airfoil; it was demonstrated that the most unstable eigenmode of the flow in question (at the same parameters as in [5]) is that in the related wake-flow, shown in the right part of figure 1.
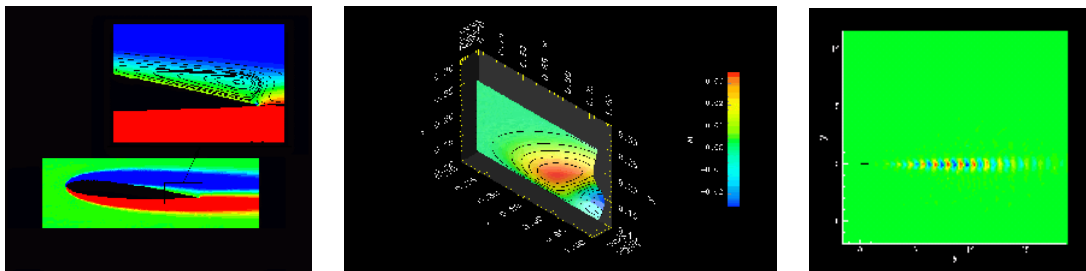
Fig 1. *Left*: Basic flow on a NACA0012 airfoil at chord $Re = 1000$ and angle of attack $\alpha = 5^o$. *Middle*: The structure of the spanwise velocity component of the (stable) BiGlobal eigenmode in the separated trailing-edge region [5]. *Right*: The most unstable eigenmode of the flow, in the wake [6].

The present work is concerned with instabilities of flow in a Low Pressure Turbine passage. The well-documented T-106 blade model is considered and two steps are taken. First, steady or time-periodic basic states are computed numerically, to be analyzed subsequently using BiGlobal theory. A high-order spectral/*hp* element scheme (Karniadakis and Sherwin [3]) is used for both the basic flow and the instability calculations. Appropriate space tessellations have been designed, which use classical *h* - refinement to resolve the boundary layers and then apply a high order polynomial expansion within each subdomain. In the cases studied a *p* = 8 polynomial order expansion has been applied within each elemental domain. This type of technique is also possible with unstructured domains [3] and has the advantage that the surface geometry is also represented by high order polynomial expansions. An example of the grid utilized is shown in the upper part of figure 2, while basic state results obtained are shown in terms of flow vorticity in the lower part of this figure. The boundary for amplification of the first 2D BiGlobal eigenmode has been identified in the region 500 < *Re* < 1000, where *Re* is the chord Reynolds number, while currently attention is focused on 3D BiGlobal eigenmodes at *Re* = 750. Further details of the basic flow and instability computations will be provided at the meeting.

Re = 500	*Re* = 750	*Re* = 1000
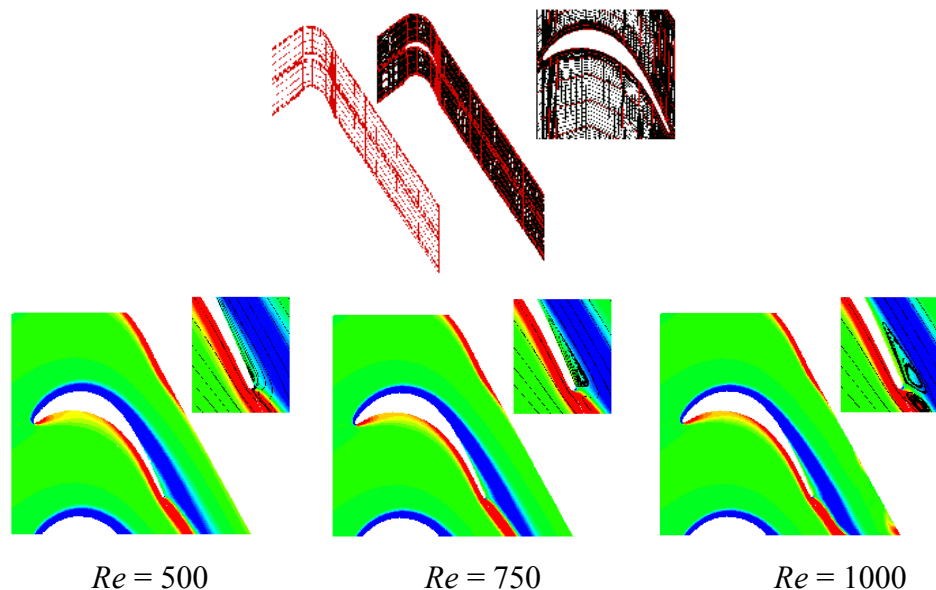
Fig 2. *Upper*: Details of the structured spectral/*hp* element mesh. *Lower*: Snapshots of the basic flow vorticity and magnification of the respective trailing-edge separation regions at *Re* = 500, 750 and 1000.

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INFLUENCE OF END WALL LEAKAGE ON SECONDARY FLOW DEVELOPMENT IN AXIAL TURBINES

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This paper presents steady and unsteady measurements of the 3 dimensional flow structure in a multistage axial turbine. The experiments were performed in a two stage axial research turbine facility, with the first stage being used to generate a realistic unsteady flow field at the inlet of the second stage. In this multistage environment, extensive measurements are taken in the second stage using Fast Response Aerodynamic Probes (FRAP). The influence of the strength of the leakage jet on the formation of secondary flow structure within the blade passage is studied.

The results indicate that the labyrinth leakage flow strongly influences, and in many cases dominates the formation of the passage secondary flow vortex. A direct link between the strength of the passage vorticity and the related total pressure losses downstream of the passage is demonstrated. It is observed that for the cases studied, the classical linear cascade secondary flow structures does not provide the correct flow structure as measured. This result also suggests that when considering rotating multi-stage turbines with significant end-wall leakage flow, the unsteady interaction of the leakage re-entry would be an important design consideration for improved aerodynamic efficiency.

ACTIVE AND PASSIVE FLOW CONTROL ON LOW PRESSURE TURBINE AIRFOILS

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Modern low-pressure turbine airfoils are subject to increasingly stronger pressure gradients as designers impose higher loading to improve efficiency and lower cost by reducing the number of airfoils in an engine. If the adverse pressure gradient on the suction side becomes strong enough, the boundary layer will separate. Separation bubbles, particularly those which fail to reattach, can result in a significant degradation of engine efficiency. The problem is particularly relevant in aircraft engines. Airfoils optimized to produce maximum power under takeoff conditions may still experience separation at cruise conditions, due to the thinner air and lower Reynolds numbers at altitude. An efficiency drop of 2% may occur between takeoff and cruise in large commercial transport engines, and the difference could be larger in smaller engines operating at higher altitudes. Needed is a means of controlling separation at low Re, without sacrificing the gains achieved at high Re.

In the present study, passive and active flow control are applied to the suction surface boundary layer on an LP turbine airfoil. Experiments are conducted in a single passage cascade simulator. Reynolds numbers (based on exit velocity and suction surface length) from 25,000 to 300,000 are considered under both high (8% inlet) and low (0.5%) free-stream turbulence (FSTI) conditions. In the passive control experiments, thin rectangular bars are applied to the airfoil near the suction surface velocity peak. Bars that are sufficiently large immediately trip the boundary layer to turbulent and prevent separation. Smaller bars initially appear to have little or no effect, and the boundary layer separates. Some distance downstream, however, small disturbances induced by the bars induce transition in the shear layer over the separation bubble, causing reattachment to move upstream relative to its location in the unmodified flow. The cases with the shortened separation bubbles appear to have lower losses than those with the larger trips. Bars which produce optimal results at low Re, however, invariably cause higher losses at the highest Re, suggesting the possible benefit of active flow control.

Active control is achieved using synthetic (oscillating, i.e. no net mass flow) vortex generator jets. An airfoil was constructed with a central cavity and a spanwise row of small holes extending from the cavity to the suction surface. The cavity is pulsed with a loudspeaker, causing jets to enter the boundary layer at a compound angle relative to the blade surface and the main flow. A single case has been documented to date with Re=25,000 and low FSTI. The separation bubble is completely eliminated, as shown through smoke visualization and animations of phase locked quantitative data. Ensemble averaged data (relative to the jet pulsing) show a turbulent patch moving down the blade after each outward jet pulse, followed by an extended "calmed" period characterized by a thin, attached laminar boundary layer. Losses appear substantially lower than with passive control.

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF TRANSITIONAL FLOWS AS AFFECTED BY PASSING WAKES

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A new transport equation for the intermittency factor is employed to predict the transitional flows in low-pressure turbine applications. The intermittent behavior of the transitional flows is taken into account and incorporated into computations by modifying the eddy viscosity, μ_t, with the intermittency factor, γ. Turbulent quantities are predicted by using Menter's two-equation turbulence model (SST). The intermittency factor is obtained from a recently developed transport equation model. The new transport equation model not only can reproduce the experimentally observed streamwise variation of the intermittency in the transition zone, but also provides a realistic cross-stream variation of the intermittency profile.

The new model is first applied to predictions of a number of steady LPT cases and compared to several recent experiment with separated and transitional boundary layers under low-pressure turbine airfoil conditions. Detailed comparisons of the computational results with the experimental data are provided. The new model has been shown to have the capability of predicting the low-pressure turbine flow transition under a variety of Reynolds number and freestream turbulence conditions. The model is then applied to experiments on LPT blade passage with bar-generated wakes performed at University of Minnesota. Detailed experimental results and comparisons to computations are presented. The results show good qualitative agreement and the unsteady features of the boundary layer as affected by the wakes are captured. Further work is needed to improve the accuracy of the prediction.

EFFECTS OF FREESTREAM TURBULENCE ON TURBINE BLADE HEAT TRANSFER

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Experiments have shown that moderate turbulence levels can nearly double turbine blade stagnation region heat transfer. Data have also shown that turbine blade heat transfer is strongly affected by the scale of turbulence as well as its level. In addition to the stagnation region, turbulence is often seen to increase pressure surface heat transfer. This is especially evident at low to moderate Reynolds numbers. Vane and rotor stagnation region, and vane pressure surface heat transfer augmentation is often seen in a pre-transition environment. Rotor pressure surface augmentation is often seen in a relaminarized post-transition environment. Accurate predictions of transition and relaminarization are critical to accurately predicting blade surface heat transfer. An approach is described which incorporates the effects of both turbulence level and scale into a CFD analysis. The model for the effects of turbulence intensity and scale is derived from experimental data for cylindrical and elliptical leading edges. Results using this model are compared with experimental data for both vane and rotor geometries. There is a twofold purpose to these comparisons. One is to illustrate that using a model which includes the effects of turbulence length scale improves agreement with data. The second is to illustrate where improvements in the modeling are needed.

BYPASS TRANSITION VIA CONTINUOUS MODES AND UNSTEADY EFFECTS ON FILM COOLING

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In the informal spirit of this workshop, I will present research that is currently in progress in two areas. The first is bypass transition. We have pursued the idea that aspects of this phenomenon can be characterized by the continuous modes of the Orr-Sommerfeld equation. At low frequency, these eigenfunctions penetrate into the boundary layer; at higher frequency they are expelled by the mean shear. We characterize the degree of penetration by computing a coupling coefficient between Orr-Sommerfeld and Squires modes. Penetrating modes produce wall streaks, but do not transition; non-penetrating modes are innocuous by themselves. Transition occurs when these modes interact. DNS has been used to study these processes. The modal content is set at the inlet and non-linear evolution is simulated. When only penetrating modes are included, wall streaks form, but no not transition within the flow domain. Penetrating and non-penetrating modes seem to be needed for transition to occur. Pressure gradient effects on transition are also being studied by DNS.

The second topic is the effects of natural and forced unsteadiness on trailing edge film cooling. Experiments show that film effectiveness is far less than that predicted by steady CFD. Natural unsteadiness (vortex shedding) accounts for only a small part of the discrepancy. Periodic forcing reproduces the levels of effectiveness seen experimentally. This might correspond to incident wakes, or other ambient disturbances, in the engine environment. At present, this work is in the vein of a conceptual study: it is not entirely clear how our computations bear on practical prediction methods. An exploration of flow patterns and frequency spectra provides an understanding of how unsteady perturbations ultimately influence surface heat transfer. Various blowing ratios, in the vicinity of unity, are considered. These computational observations will be described in my presentation.

HIGH FREQUENCY SURFACE HEAT FLUX IMAGING OF BYPASS TRANSITION

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A high-frequency surface heat flux imaging technique was employed in an investigation of bypass transition induced by freestream turbulence. Fundamental experiments were carried out at Oxford using high-density thin film arrays on a flat plate model. Bypass transition was induced by grid-generated turbulence with varying intensities of 2.3%, 3.6%, and 17% with a fixed integral length scale of approximately 12mm.

Results show, under moderate freestream turbulence (Tu>0.7%), enhanced heat flux streaks first appear elongated in the streamwise direction and originating near the leading edge. These are followed by a breakdown into streaky, subcritical turbulent spots at low Reynolds number. Under high freestream turbulence (Tu>17%), temporal heat flux images show structures traveling within the boundary layer at a fraction of the freestream velocity with unsteady spanwise motion. Evidence suggests strong spanwise fluctuations in the freestream may force local, unsteady crossflow effects within the boundary layer.

The temporal imaging technique allows us to study unsteady surface heat transfer in detail, and help elucidate the complex nature of transition in the high-disturbance environment of turbomachinery.
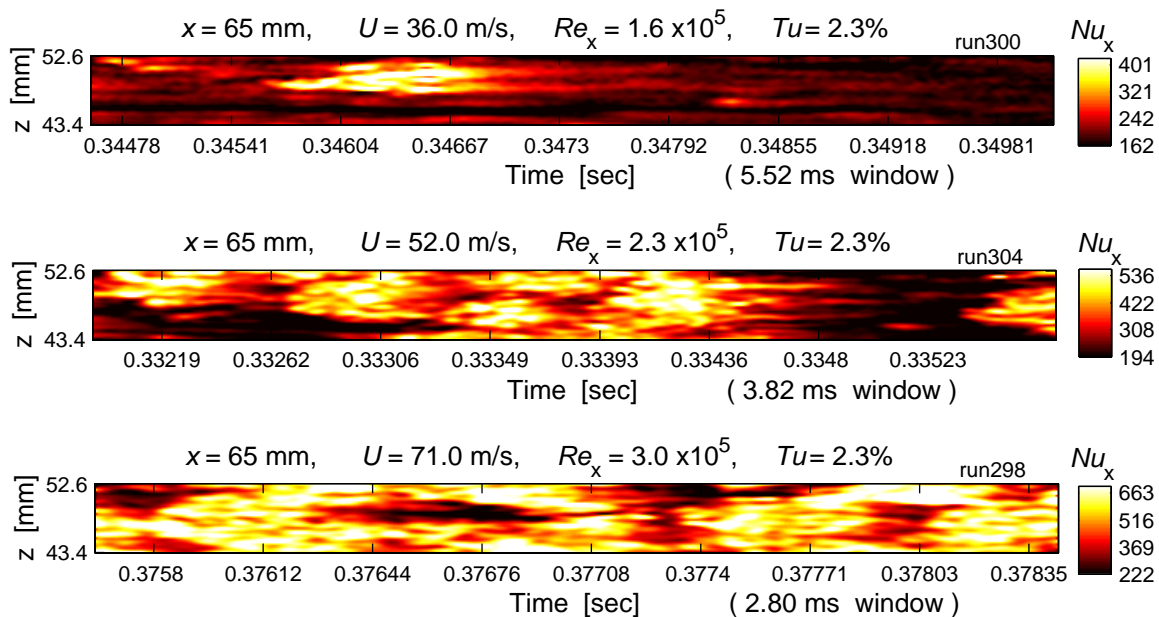
SKIN FRICTION AND HEAT FLUX OSCILLATIONS IN UPSTREAM MOVING WAVE PACKETS

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Recent theoretical studies suggest that the wave / vortex eigenmodes' coupling occurs in the linear stage of disturbance development under the influence of centrifugal forces. Subsonic boundary layers of two different types provide pertinent examples typical of turbomachinery environments. The first one relates to a three-dimensional motion with crossflow on a plate. The curvature of stream surfaces naturally warping in the crossflow direction maintains centrifugal forces. The second example corresponds to the two-dimensional boundary layer on a concave cylindrical surface. In this case centrifugal forces are supported by the fixed curvature of a solid surface bending in the streamwise direction. In both cases centrifugal forces are balanced out by the normal-to-wall pressure gradient. The inclusion of the vortex eigenmodes brought about by centrifugal forces makes an asymptotic approach self-consistent at large Reynolds numbers.

In the range of the wave / vortex eigenmode interactions the higher-order effects build up to magnitudes comparable to the leading-order contributions. Accordingly, the asymptotic approach gives rise to an extended version of the triple-deck theory with the main higher-order terms included in the system of governing equations. An essential broadening of the pulsation spectrum derives from the eigenmode coupling and results in two side bands emerging in the Tollmien-Schlichting interval of the eigen-frequencies and wavenumbers. Similarity laws show for each side band the dependence on different physical quantities such as wall shear, free-stream and wall temperatures among others. An inference of conceptual importance from the asymptotic model is that the boundary layer with crossflow much like the one on the concave surface suffers absolute instability in the streamwise direction which may result in earlier transition.

Mechanical oscillations in the upstream propagating wave packets are capable of inducing temperature disturbances affecting the heat transfer across the turbine-blade surface. An asymptotic theory is advanced to embrace temperature pulsations in the range of the wave / vortex eigenmode interactions. The basic equation of the theory bears certain resemblance to that controlling the Squire eigenmode of three-dimensional disturbances. With a Mach number increasing, the impact of vortical eigenmodes on the skin friction and temperature pulsations becomes larger in high Reynolds number flows.

TRANSITION MECHANISMS AND USE OF SURFACE ROUGHNESS TO ENHANCE THE BENEFITS OF WAKE PASSING IN LP TURBINES

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This paper is concerned with the interaction of upstream wakes with the low Reynolds number boundary layer on the suction side of LPT airfoils. It is this interaction that has led to the design of LPT airfoils with increased levels of lift. The main aim of the paper is to describe, in detail, the transition mechanisms that result from the interaction of the wakes with the separation bubble that exists on the suction side of modern airfoils. This transition results in a profile loss that is lower than would otherwise be the case for high lift and ultra high lift airfoils. Comparisons are made between the results from high speed and low speed moving bar cascades to confirm the validity of the mechanisms described. Finally, it is shown that by using surface roughness, it is possible to further reduce the profile loss of these airfoils.

The first part of the paper justifies the use of large-scale low speed research rigs. A comparison is made between equivalent low speed and a high speed cascades to demonstrate the validity of low speed testing. A detailed experimental investigation into the interaction of a wake and a separation bubble on the rear suction surface of a highly loaded low-pressure turbine blade is then described. A two-dimensional Laser Doppler Anemometer has been used to measure the convection of representative wakes through a large scale, low speed turbine cascade fitted with the T106A profile. These measurements confirm that the wake convection is kinematic and reveal that the results of wake stretching and bowing result, respectively, in a decrease and an increase in the turbulence energy of the flow. Thus, while the mean level of turbulence energy is largely unchanged, significant variations exist within the unsteady wakes. Boundary layer measurements, also made with 2D LDA and using PIV, reveal the transition mechanism. Prior to the arrival of the wake, the boundary layer profiles in the separation region are inflexional. The perturbation of the separated shear layer caused by the convecting wake causes an inviscid Kelvin-Helmholtz rollup of the shear layer. This results in the breakdown of the laminar shear layer and a rapid wake-induced transition in the separated shear layer. The vortices also produce a series of high frequency large amplitude pressure perturbations. These are also found to exist in the high speed moving bar cascade.

Ultra High Lift profiles have large separation bubbles that result from the very high levels of deceleration on the rear of the suction surface. It is shown that LP turbine blade lift has now reached a level of loading and diffusion where profile losses can no longer be controlled by wake unsteadiness alone. A parametric study of the effects of roughness elements including roughness height, type and location in steady and unsteady flow conditions is described. In steady flow, the perturbations after the roughness element trigged the separated flow transition earlier and the bubble size was reduced in both length and height. In unsteady flow, the boundary layer under the wake became turbulent sooner, but not immediately after the roughness element and the separation bubble between the wakes is much smaller than that on the smooth surface. The losses are reduced providing that the balance between the extra losses produced by the earlier transition of the flow under the wakes and the lower losses produced by flow in between is favourable.

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TRANSIENT GROWTH APPROACH TO ROUGHNESS-INDUCED TRANSITION

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Surface roughness can have a profound effect on boundary layer transition. However, the mechanisms responsible for transition with three-dimensional distributed roughness have been elusive. Various T-S based mechanisms have been investigated in the past but have been shown not to be applicable.[1] More recently the applicability of *transient growth theory* to roughness induced transition has been studied. Transient growth arises through the coupling between slightly damped, nearly streamwise Orr-Sommerfeld and Squire modes leading to algebraic growth followed by exponential decay outside the T-S neutral curve. A weak transient growth can also occur for two-dimensional or axisymmetric modes since the Orr-Sommerfeld operator (also its compressible counterpart) is not self-adjoint, therefore its eigenfunctions are not strictly orthogonal. A model for roughness-induced transition is developed that makes use of computational results based on the spatial transient growth theory.[2,3] In all cases, $Re_{\theta,tr} \sim (k/\theta)^{-1}$

For a flat plate in incompressible flow, the result reduces to $U_e k/\nu = $ const. The data of Feindt[4] suggest that the constant is 120. For a compressible flat plate with $T_w/T_{aw} > 0.75$, the constant is a function of surface temperature level but essentially independent of Mach number. For cold walls, the constant is sensitive to both Mach number and surface temperature level.

Nosetip transition is the early transition that takes place on spherical nosetips of entry vehicles. It occurs in the subsonic region behind the bow shock wave, a region of highly favorable pressure gradient that is T-S stable, but amenable to transient growth. For nosetip transition, the resulting transition relations reproduce the trends of the Reda[5,6] and PANT[7–9] data and account for the separate roles of roughness and surface temperature level on the transition behavior. A correlating relation for both the PANT and the Reda data is

$$Re_{\theta,tr} = 180 \, (k/\theta)^{-1} (T_e/2T_w)^{-1.27}$$

or alternatively

$$U_e k/\nu_e = 180 \, (2T_w/T_e)^{1.27}$$

From these examples, it is evident that transient growth is a very promising explanation for roughness-induced transition.

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ROUGHNESS- AND FREESTREAM-TURBULENCE-INDUCED TRANSIENT GROWTH AS A BYPASS TRANSITION MECHANISM

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Laminar-to-turbulent transition of attached turbomachinery boundary layers has been categorized as being either "natural" or "bypass" transition. Natural transition refers to the exponential growth of low-amplitude Tollmien–Schlichting (TS) waves leading to three dimensionality and breakdown under low-disturbance conditions; bypass transition is the process that occurs under high-disturbance conditions. While this is an acceptable phenomenological distinction, use of the term "bypass" hinders transition prediction efforts because it does not refer to a specific disturbance growth mechanism whose behavior can be explained using the physics of that mechanism. A more useful approach to transition scenarios that do not follow the TS path is to identify the physical mechanism leading to receptivity, growth, and breakdown because understanding these features is essential to accurate transition prediction.

One example of progress in this area is the development of transient-growth theory. Transient growth is a nonmodal growth mechanism through which certain disturbances undergo a brief but significant period of algebraic growth and then exponential decay. Unlike modal instabilities such as TS waves, the behavior (e.g., growth rates) and not just the amplitude of transient disturbances is a strong function of the initial disturbances conditions and this makes the receptivity problem for transient growth especially important. Theoretical work over the past decade has not addressed receptivity and has instead worked with so-called "optimal" initial disturbances that lead to the largest transient growth over a defined length or time. The finding is that optimal disturbances are stationary streamwise vortices that produce streamwise streaks downstream. Despite the fact that optimal disturbance theories do not address receptivity, these results are quite promising as a means of explaining some cases of bypass transition because the optimal streaks bear a striking resemblance to Klebanoff modes produced by freestream turbulence or distributed surface roughness. In the context of turbomachinery transition it is significant that these results have been obtained using linearized equations and that non-TS bypass may not be restricted to high-amplitude disturbances; the frequencies and wavenumbers of the initial disturbances may play a more important role than amplitudes alone.

The present experimental work provides data that quantifies the effects of roughness-induced transient growth in zero-pressure-gradient boundary layers and continuing work will address freestream turbulence, pressure gradients, and surface curvature. The data obtained to date shows that transient growth exists but that there are significant differences between optimal-disturbance predictions and disturbances that can be realized experimentally. The findings also give a preliminary indication of how transient disturbances scale with roughness amplitude but these results do not agree with some recent receptivity calculations. Overall, the results highlight that although computational tools are already capable of modeling the transient growth of particular small-amplitude disturbances, additional effort will be needed to understand how roughness and freestream-turbulence lead to transient growth in realistic situations and how transition will be affected in those cases.

RECEPTIVITY CALCULATIONS AS A MEANS TO PREDICTING TRANSITION

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Previous experimental work at Liverpool has shown how bypass transition is preceded by the growth of near wall velocity fluctuations in the pre-transitional boundary layer. When these fluctuations reach a critical amplitude turbulent spots are initiated through transient local 3-d flow separations of the boundary later. At Minnowbrook IV recent work on the numerical prediction of these laminar fluctuations will be presented.

The magnitude of the near wall velocity fluctuations depends on the local receptivity of the boundary layer to the freestream turbulence. In the work to be presented, the fluctuations are assumed to be fully 3-d viscid, but linear, perturbations to the steady flow. Fourier expansions are used to represent the fluctuating velocities and pressure in the spanwise and streamwise directions, which reduces the numerical problem to the solution of a family of ordinary differential equations. Fourth order finite differences are used for the discretisation and solutions are obtained using standard numerical techniques on a PC. The freestream turbulence is considered as a superposition of vortices of varying frequency and 3-d orientation.

Results show that the boundary layer is most receptive to freestream vortices with axis orientations close to the streamwise direction. These vortices interact with the outer part of the boundary layer to produce fluctuating pressures within it. These pressure fluctuations induce streamwise velocity fluctuations within the boundary layer, which are observed as streamwise velocity streaks near the wall in flow visualization experiments and DNS calculations. The high receptivity of boundary layers to these approximately streamwise vortices, which possess a low streamwise frequency (the frequency most commonly measured with a hot wire), is also responsible for the experimental observation that the boundary layer is most receptive to low frequencies. The current numerical results indicate that receptivities are highest for spanwise wavelengths between 1.2 and 1.6 boundary layer thicknesses, which concurs with experimental observation.

The overall receptivity of boundary layers to freestream turbulence simulated through the full spectra of vortex frequencies and orientations is also considered. The numerical results reproduce the experimental observations reasonably well, although at the lowest frequencies (wavelengths of 100's of boundary layer thicknesses) the numerical calculations over predict the receptivity. The reasons for this discrepancy will be discussed in the presentation. The overall receptivity results are used to derive a predictive method for start of transition, which contains no empirical information. The predicted start of transition locations are similar to the Abu-Ghannam and Shaw correlation values, but the present method extends the adverse pressure gradient range beyond separation.

Work currently in progress at Liverpool is extending the current numerical procedure to consider the receptivity of 3-d boundary layers and also of boundary layers on compliant surfaces. The primary objective of the work is to understand the underlying physics of transition in order to improve methods for its prediction.

ON STREAMWISE VORTICES IN A CURVED WALL JET AND THEIR EFFECT
ON THE MEAN FLOW

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Wall jets are often used to enhance the heat and mass transfer from a surface, to provide super-circulation and to delay boundary-layer separation from lifting surfaces. A wall jet, flowing over the outer surface of a circular cylinder has the unique ability to wrap itself around the surface detaching itself at a direction that is opposite to the nozzle from which the jet emanated. In the example shown below, a jet of momentum **J**, emanating to the right from a slot located on top of the cylinder turns around it before separating to the left at the bottom of this cylinder. The turning of the flow generates a low pressure region on the right hand surface creating a side force that is almost equal to twice the value of **J.** This force is currently used to prevent the autorotation on a NOTAR type of a single rotor helicopter eliminating the need for a "tail-rotor".
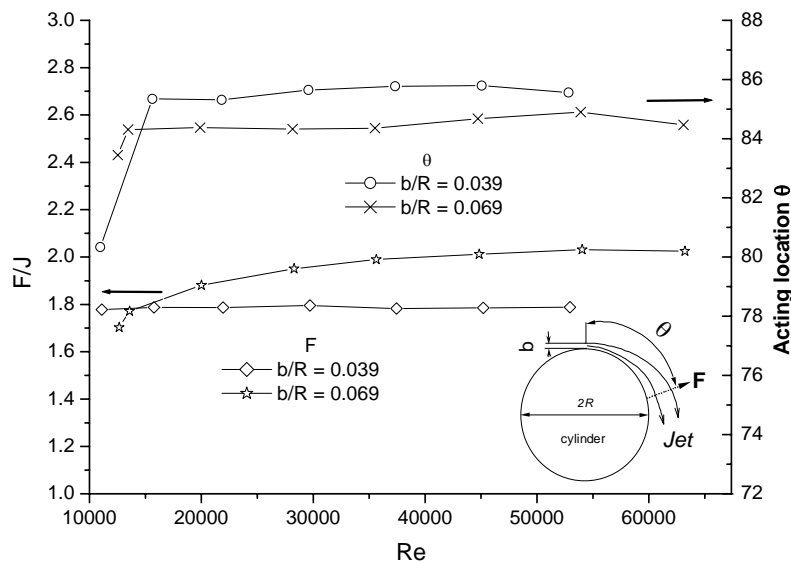
The side force F generated by a wall jet emanating from a circular cylinder. $Re=(JR/v^2)^{1/2}$

The existence of longitudinal vortices in a turbulent wall jet that flows over a convex surface was shown earlier by Neuendorf et al. The spanwise wavelength of these vortices corresponds to the local width of the wall suggesting that they are a product of a centrifugal instability. The growth of these vortices in the direction of streaming is attributed mainly to vortex amalgamation, but they also individually, though weakly amplify. This amplification is attributed in part to a secondary instability resulting from distortions in the mean velocity field. Therefore there is a great disparity in the turbulence level and its structure between the curved and straight wall jets.

Since the longitudinal vortices meander in span, the mean flow is two dimensional. In order that the streamwise vortices will be initiated at preferred spanwise locations without hindering their natural meander and instabilities, a row of micro vortex generators (µVGs) was placed on the outer lip of the nozzle. The µVGs are no more than wires (needles) having a diameter of 0.6 *mm* that protruded into the nozzle flow a distance of 0.4 mm only. The size of the micro VG was so selected as not to impede the growth of the streamwise vortices in the direction of streaming. It was an arduous "cut and try" process that eventually bore fruit.
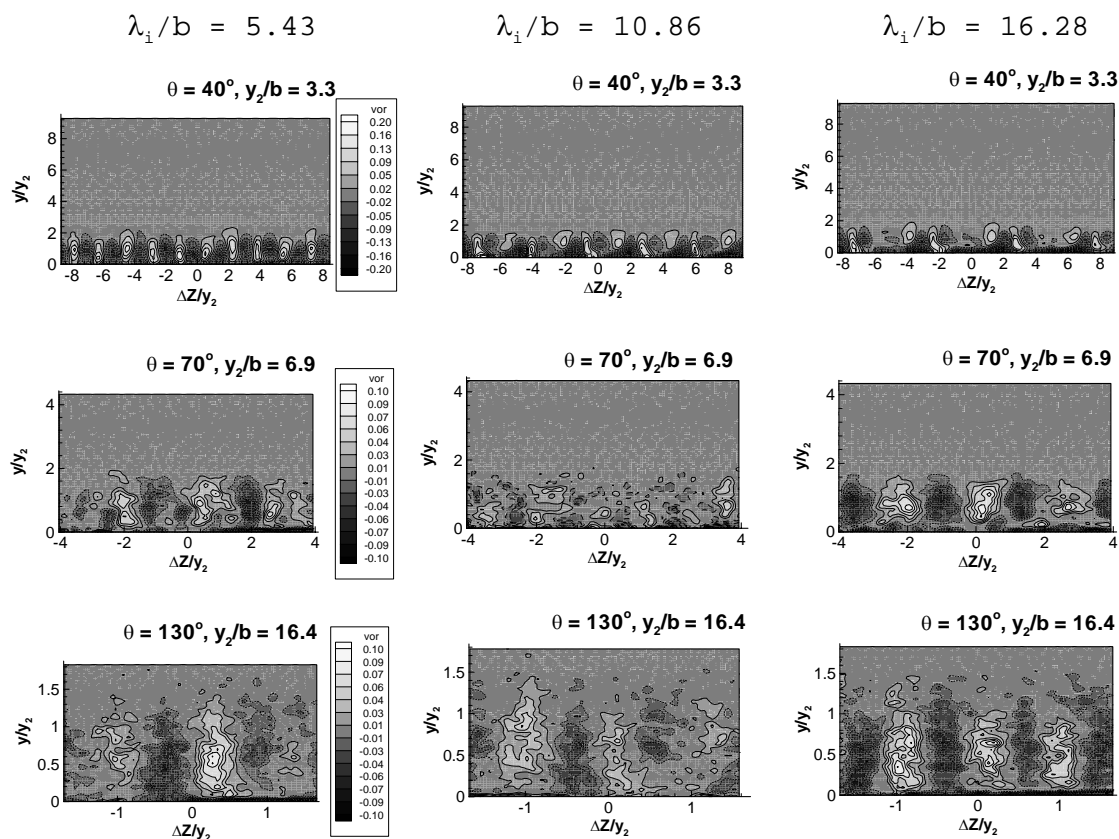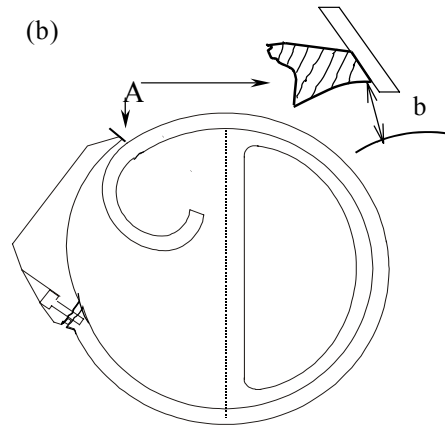
The figure above indicates that the flow structures triggered by differently spaced µVGs (λ_i/b varied by a factor of 3) evolve into the approximately the same spanwise wavelength far downstream. The process of amalgamation and its effects on the flow will be discussed.

PLASMA ACTUATORS FOR SEPARATION CONTROL OF LOW PRESSURE TURBINE BLADES

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This work involves the documentation and control of flow separation that occurs over turbine blades in the low-pressure turbine (LPT) stage at the low Reynolds numbers typical of high altitude cruise. We utilize a specially constructed linear cascade that is designed to study the flow field over a generic LPT cascade consisting of Pratt & Whitney "Pak B" shaped blades. The center blade in the cascade is instrumented to measure the surface pressure coefficient distribution. Optical access allows LDV measurements for boundary layer profiles. Experimental conditions were chosen to give a range of chord Reynolds numbers from 10K to 100K, and a range of free-stream turbulence levels from $u'/U_\infty =0.08\%$ to 2.85%. The surface pressure measurements were used to define a region of separation and re-attachment that depend on the free-stream conditions. The location of separation was found to be relatively insensitive to the experimental conditions. However, the re-attachment location was very sensitive to the turbulence level and Reynolds number. Excellent agreement was found between the measured pressure distributions and predictions from Euler simulations. Separation control was performed using a single plasma actuator that is placed at different chord locations, upstream of the separation line. The actuator is designed to produce a steady 2-D jet which is locally parallel to the blade surface. This is intended to add momentum to the near-wall boundary layer. Re-attachment occurred in all cases. The amplitude level of the actuator was varied to determine its effect on the re-attachment location.

BOUNDARY-LAYER SEPARATION CONTROL UNDER LOW-PRESSURE-TURBINE CONDITIONS USING GLOW-DISCHARGE PLASMA ACTUATORS

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Modern low-pressure turbines, in general, utilize highly loaded airfoils in an effort to improve efficiency and to lower the number of airfoils needed. Typically, the airfoil boundary layers are turbulent and fully attached at takeoff conditions, whereas a substantial fraction of the boundary layers on the airfoils may be transitional at cruise conditions due to the change of density with altitude.[1] The strong adverse pressure gradients on the suction side of these airfoils can lead to boundary-layer separation at the latter low Reynolds number conditions. Large separation bubbles, particularly those which fail to reattach, cause a significant degradation of engine efficiency.[1-3] A component efficiency drop of the order 2% may occur between takeoff and cruise conditions for large commercial transport engines and could be as large as 7% for smaller engines at higher altitude. An efficient means of of separation elimination/reduction is, therefore, crucial to improved turbine design. Because the large change in the Reynolds number from takeoff to cruise leads to a distinct change in the airfoil flow physics, a separation control strategy intended for cruise conditions will need to be carefully constructed so as to incur minimum impact/penalty at takeoff.

A complicating factor, but also a potential advantage in the quest for an efficient strategy, is the intricate interplay between separation and transition for the situation at hand. Volino[5] gives a comprehensive discussion of several recent studies on transition and separation under low-pressure-turbine conditions, among them one in the present facility.[6] Transition may begin before or after separation, depending on the Reynolds number and other flow conditions. If the transition occurs early in the boundary layer then separation may be reduced or completely eliminated. Transition in the shear layer of a separation bubble can lead to rapid reattachment. This suggests using control mechanisms to trigger and enhance early transition.

Gad-el-Hak[4] provides a review of various techniques for flow control in general and Volino[7] discusses recent studies on separation control under low-pressure-turbine conditions utilizing passive as well as active devices. As pointed out by Volino[7], passive devices optimized for separation control at low Reynolds numbers tend to increase losses at high Reynolds numbers. Active devices have the attractive feature that they can be utilized only in operational regimes where they are needed and when turned off would not affect the flow. The focus in the present paper is an experimental study[8,9] of active separation control using glow discharge plasma actuators.

Separation is induced on a flat plate installed in a closed-circuit wind tunnel by a shaped insert on the opposite wall. The flow conditions represent flow over the suction surface of a modern low-pressure-turbine airfoil ('Pak-B'). The Reynolds number, based on wetted plate length and nominal exit velocity, is varied from $50,000$ to $300,000$, covering cruise to takeoff conditions. Low (0.2%) and high (2.5%) free-stream turbulence intensities are set using passive grids. A spanwise-oriented phased-plasma-array actuator,[10] fabricated on a printed circuit board, is surface-flush-mounted upstream of the separation point and can provide forcing in a wide frequency range. Static surface pressure measurements and hot-wire anemometry of the base and controlled flows are performed and indicate that the glow-discharge plasma actuator is an effective device for separation control.

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CONTROL OF SEPARATION FOR LOW PRESSURE TURBINE BLADES: NUMERICAL SIMULATION

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Boundary layers on the suction surface of low pressure turbine (LPT) blades are known to be susceptible to laminar separation. This is mainly due to the fact that, during high-altitude cruise, Reynolds numbers in LPTs can drop to very low values, on the order of 25,000. The resulting laminar boundary layer separation is associated with dramatic losses in turbine performance. Numerous experimental studies of separation on LPT blades clearly suggest that flow control might be beneficial for preventing or delaying separation. Lake et al. (1999) reported investigations involving modified blade surfaces (dimples) and concluded that boundary layer separation was significantly reduced. Such passive techniques, however, are ultimately limited by the fact that increased viscous losses may incur penalties at higher Reynolds numbers where unmodified (uncontrolled) blades yield satisfactory turbine performance. More recently, the influence of active control devices (pulsed vortex generator jets (VGJs)) on the separation behavior has been studied extensively by Bons et al. (1999, 2001a, 2001b). These experiments have shown that so-called pulsed VGJs have a dramatic effect on low Reynolds number separation in LPTs. A reduction in wake losses of up to 60% was measured. However, many of the underlying physical mechanisms responsible for these striking experimental results are not understood.

In our investigations, Direct Numerical Simulations (DNS) are employed to aid in the understanding of the physical mechanisms that are relevant for controlling flow separation from LPT blades. Toward this end, we are performing both two- and three-dimensional simulations of the entire turbine cascade as well as of model geometries, utilizing various Navier-Stokes codes that have been developed in our research group.

Results obtained for example from a 2-D simulation of the entire turbine cascade are presented in Figure 1. For these simulations, body-fitted, structured grids are used. The Reynolds number
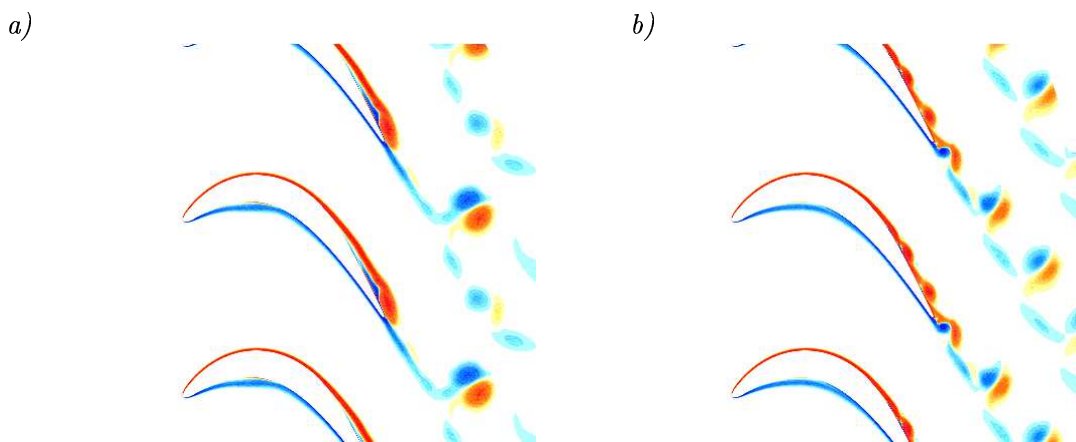
Figure 1: Simulation of the entire turbine cascade. Contours of spanwise vorticity. *a)* Natural, unforced case. *b)* Pulsed blowing upstream of separation.

based on inlet velocity and chord length (Re=25,000) was chosen to match that of the experiments by Bons et al. The (unforced) laminar boundary layer separates at the aft portion of the suction side of the blade (s. Fig. 1a). Using period forcing (pulsed blowing through a slot at approximately 60% chord) the mean flow separation is significantly reduced (s. Fig. 1b).

For the purpose of gaining better insight into the mechanisms of the pulsed forcing and for exploring the large parameter space associated with the control device (jet blowing ratios, forcing frequencies, duty-cycles, pitch and skew angles, etc.), flat-plate simulations of generic laminar separation bubbles are performed using an incompressible Navier-Stokes code originally developed by Meitz and Fasel (2000). Figure 2 shows some of the results obtained from the simulations of a prototypical separating boundary layer ($Re_{x,separation} \approx 25,000$). Instantaneous pictures of contours
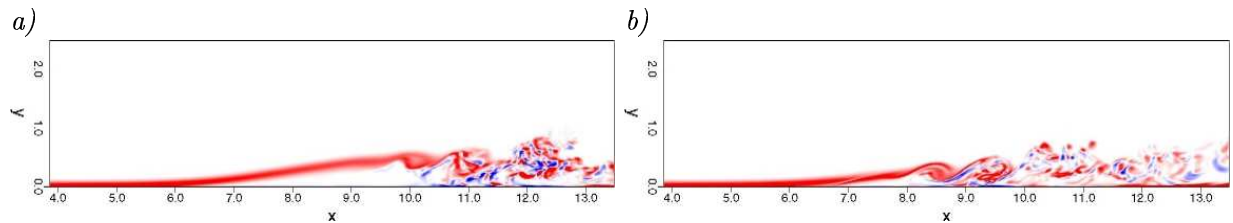
Figure 2: 3-D simulations of separating boundary layers on the flat plate. Contours of spanwise vorticity. $a)$ Unforced. $b)$ Forced with pulsed jets at pitch angles of 30° and skew angles of 90°.

of spanwise vorticity for an unforced and a forced case (3-D simulations) are given in Figure 2. For the forced case (Fig. 2b), the jet blowing ratio (ratio of maximum jet velocity and freestream velocity) was 1 and the duty-cycle was 10%. The effect of the forcing is significant. The separation region is considerably reduced and is in fact almost completely eliminated.

Acknowledgement

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EFFECTS OF ELEVATED FREE-STREAM TURBULENCE ON ACTIVE CONTROL OF A SEPARATION BUBBLE

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The Effects of elevated free-stream turbulence (FST) on the natural and periodically excited separation bubbles were studied experimentally, due to the relevance of this flow to low-pressure turbine blades at low Reynolds numbers.

A bubble was formed at the leading edge of a flat plate and the FST level was altered by placing a grid across the flow at different locations upstream of the plate. The mixing across the separated shear-layer, forming the free boundary of the bubble, increased due to the elevated FST and due to nominally two-dimensional periodic excitation, both flattening and shortening the bubble. Periodic excitation at frequencies that were at least an order of magnitude lower than those associated with the initial shear-layer instability, were very effective at low FST, because the amplitudes of the excitation frequency and its harmonic were amplified over the bubble.

High frequency excitation ($F^+ \approx 3$, based on the length of the baseline low FST bubble) had a major effect close to the separation location, while farther downstream the excited fluctuations rapidly decayed in the reattachment region. Low frequency excitation, that generated waves comparable to the length of the unperturbed bubble ($F^+ \approx 1$) were less effective and their magnitude decayed at a slower rate downstream of reattachment.

An increase in the level of the FST reduced the net effect of the periodic excitation on the mixing enhancement and subsequent reattachment process, probably due to a destructive interference between the nominally 2D excitation and the random (in space and time) FST, reducing the spanwise coherence and therefore the effectiveness of the current control strategy. However, even at the reduced effectiveness of 2D periodic excitation at elevated FST, it accelerated the reattachment process and the recovery rate of the reattached boundary layer, enhancing the boundary layer resistance to repeat separation and reducing its momentum loss further downstream.

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[1] Also AME Dep. Uni. of Arizona, Tucson AZ.

WAKES, CALMING AND TRANSITION UNDER STRONG ADVERSE PRESSURE GRADIENTS

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A flat plate under a strong adverse pressure gradient was subjected to wakes generated by rods moving transversely upstream of the leading edge. The results highlight the interaction between incoming wakes and the undisturbed boundary layer, which features a long and thin laminar separation bubble. Wakes have been presented individually and in pairs at different wake spacing intervals; in this way it is proposed to investigate wake interaction effects in more detail.

Each wake provoked a vigorous turbulent patch, resulting in the instantaneous collapse of the separation bubble. This was followed by a very strong and stable calmed region. In the undisturbed flow the bubble exhibited a natural growth of Tollmien-Schlichting waves. The bubble was closed by a short, but conventional, transition region that could be characterized by the universal intermittency distribution. The data gathered extend our transition length prediction capability well into the laminar separation region.

TRANSITIONAL BUBBLE IN PERIODIC FLOW PHASE SHIFT

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One particular characteristic observed in unsteady shear layers is the phase shift relative to the main flow. In attached boundary layers this will have an effect both on the instantaneous skin friction and heat transfer. In separation bubbles the contribution to the drag is dominated by the pressure distribution. However, the most significant effect appears to be the phase shift on the transition process. Unsteady transition behaviour may determine the bursting of the bubble resulting in an unrecoverable full separation.

An early analysis of the phase shift was performed by Stokes for the incompressible boundary layer of an oscillating wall and an oscillating main flow. An amplitude overshoot within the shear layer as well as a phase shift were observed that can be attributed to the realtively slow diffusion of viscous stresses compared to the fast change of pressure.

Experiments in a low speed facility with the boundary layer of a flat plate were evaluated in respect to phase shift. A pressure distribution similar to that on the suction surface of a turbomachinery aerofoil was superimposed generating a typical transitional separation bubble. A periodically unsteady mainflow in the suction type wind tunnel was introduced via a rotating flap downstream of the test section. The experiments covered a range of the three similarity parameters of momentum-loss-thickness Reynolds-number of 92 to 226 and Strouhal-number (reduced frequency) of 0.0001 to 0.0004 at the separation point, and an amplitude range up to 19 %. The free stream turbulence level was less than 1%

Upstream of the separation point the phase shift in the laminar boundary layer does not appear to be affected significantly bei either of the three parameters. The trend perpendicular to the wall is similar to the Stokes analysis. The problem scales well with the wave velocity introduced by Stokes, however, the lag of the main flow near the wall is less than indicated analytically. The separation point comes closest to the Stokes analysis but the phase is still 20 degrees lower at the wall.

The behaviour in the bubble is somewhat different. For comparison purposes with the Stokes data the origin of the y-coordinate was shifted to the point of zero velocity at the reversing flow. Far from the wall and close to the wall the phase appears to follow the general trend of the Stokes-model. In between, however, a phase lag in the shear layer is observed which is increasing with the growth of the bubble and the displacement thickness downstream. Within the separation, in the deadwater zone, the phase lags by about 180 degrees.

The most pronounced phase shift is observed at the transtion and reattachment regions. The phase lag upstream, half way through the laminar shear layer (x/L = 0.43), being only about 45 degrees, a dramatic change to about 280 degrees can be seen in the transitional region. After reattachment, in the full developed turbulent boundary layer downstream, the phase shift is very low. This phenomenon is caused by the initiation of transition which is not only affected by the the diffusion of shear stresses but predominantly by the stability characteristics. Stability response to unsteadiness is obviously very much stronger than that of the viscous effects. Accordingly the behaviour of the flow will depend considerably on the Strouhal-number and the amplitude of the free stream.

Summerizing the phase shift characteristics, it is observed that:
- transition is very sensitive to main flow unsteadiness;
- the phase shift upstream of the separation point is very similar to the analytical results for the oscillating Stokes-flow;
- there is a very pronounced time lag of the transitional region resulting in an out of phase oscillation of reattachement and the dead water zone,
- generating positive shear stress at the wall over large portions of the cycle.

Another phenomemon was observed for low Reynolds numbers. The instability of the separated shear layer generates large vortical structures which are released downstream at the end of the separation bubble. They are very similar to those observed in laminar steady flow experiments and CFD calculations, however, in the unsteady case they are locked to the frequency of the external flow. This vortex shedding occured well within the lower range of turbomachinery Reynolds numbers, but with the low turbulence levels of the experiment.

MODELLING SPOTS: THE CALMED REGION, PRESSURE GRADIENT EFFECTS AND BACKGROUND

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This ongoing work is aimed at the understanding and modelling/analysis of spots from a first-principles basis within either a laminar or a turbulent layer. This continues previous studies by the author's group and addresses in particular attempts at theoretical modelling of (i) the calmed region, (ii) the effects of pressure gradient , and (iii) a spot within a turbulent layer. The development of spots initially localised and at low or high amplitudes is to be described.

In (i), an inviscid model of the laminar 'calmed region' following a 3D turbulent spot within a transitioning 2D layer is formulated. Products of small fluctuations force a perturbation to the mean flow, especially to the surface streamlines. Available experimental evidence shows a fuller more stable streamwise profile in a considerable region trailing the spot, with cross-flow inwash towards the line of symmetry. Present results are in qualitative agreement with this evidence.

(ii) is on the evolution of a spot within a simplified boundary layer form which models pressure gradient effects. A favourable gradient makes the spot split into two parts, overlapping at first but then moving along in tandem. An adverse gradient instead splits the spot into two non-overlapping regions between which a strong sub-spot develops, full of exponentially growing fluctuations. Comparisons with experiments are made, of the spot spread angle under various pressure gradients, and these prove to be fairly close.

(iii). The above theory and computation is for laminar incompressible flow but is extendable to turbulent and compressible spots also. Some progress on the latter has been reported previously. On the former, the turbulent case is attempted by means of a mixing length model for unsteady flow. Nonlinear three-dimensional spots are tracked with a view to understanding their long-term behaviour.

The influences of disturbance size and Reynolds number are among the other main features. Allied recent work is on the effects of vortical wake passing as an initiator, followed by nonlinear evolution, nonparallel flow evolution and related three-dimensional responses. Wakes with an in-parallel arrangement, modelling the wakes from a row of quasi-rotor blades upstream which are vertically periodic but moving downward, could also be discussed.

MODELING OF UNSTEADY TRANSITIONAL FLOW ON AXIAL COMPRESSOR BLADES

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Engineering predictions of unsteady transitional flow on C4-section axial compressor blades are obtained with linked UNSFLO and PUIM (Prescribed Unsteady Intermittency Method) calculations. The aim is to provide simplified models of wake-disturbed flow suitable for implementation in iterative design calculations for axial turbomachine blades.

The UNSFLO code of Giles solves the unsteady thin-layer Navier-Stokes equations for the viscous flow near a blade surface and treats the rest of the flow domain as inviscid. The effects of upstream wakes are modelled by imposing inviscid wake profiles that approximate the real wake profiles on the inflow boundary. Viscous diffusion and dissipation due to turbulence within the wakes is ignored.

Previous work by Coupland, using the PUIM model of Hodson, employed a steady flow solution from UNSFLO together with a time-varying free-stream turbulence level approximating that imposed by passing upstream wakes to estimate the unsteady intermittency distribution, $\gamma(x,t)$, produced by fluctuations of the laminar-turbulent interface within the blade boundary layer in the wake-disturbed flow. Effects of fluctuating boundary layer thickness and local pressure gradient parameter on stability and transition were ignored in computing this approximate distribution. An unsteady UNSFLO calculation with $\gamma(x,t)$ prescribed from this model was then used to predict the unsteady viscous flow behavior around the blade.

The present paper reports on current attempts to extend this approach by using an unsteady UNSFLO calculation to include first-order estimates for the effect of potential flow (pressure field) interactions on boundary layer stability in determining $\gamma(x,t)$. Results of the linked UNSFLO and PUIM calculations are compared with experimental data of Hughes for the unsteady intermittency distribution obtained from surface hot film measurements for a range of blade loading and Reynolds number. Additional comparisons are made with hot-wire observations of downstream blade wake thickness fluctuations produced by the passage of upstream blade wakes. The effect of using different transition onset and transition length prediction methods is examined and outstanding problems are discussed.

CHALLENGES IN PREDICTING COMPONENT EFFICIENCIES IN TURBOMACHINES WITH LOW REYNOLDS NUMBER BLADING

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The ability to predict boundary layer transition locations accurately on turbomachinery airfoils is critical to determine both thermal loads and aerodynamic performance. Here we report on an effort to include an empirically based transition modeling capability in a RANS solver. Testing of well known empirical models from literature against cascade data revealed that the models do not provided enough fidelity for implementation in an airfoil design system. Consequently, a program was launched to develop a new modeling capability that would provide sufficient accuracy for use in the design system. The results of the effort were two empirical models for the prediction of transition onset locations: the first is for attached flow, and the second is for separated flow. To validate the new models, a two-dimensional design optimization of a Low-Pressure Turbine (LPT) airfoil was performed with the objective of increasing airfoil loading by 25%. Subsequent testing of the new airfoil confirmed pre-test predictions of both high and low Reynolds number loss levels. In addition, the accuracy of the new models was benchmarked with a number of legacy cascade and LPT rig data sets. Excellent agreement between measured and predicted profile losses was found in both cascade and rig environments. However, use of the transition modeling capability has elucidated deficiencies in typical RANS simulations that are conducted to predict component performance. Efficiency-versus-span comparisons between data and simulations for multi-stage LPTs indicate that endwall loss levels are significantly under-predicted. Possible causes for the under-predicted endwall losses are discussed as well as suggestions for future improvements that would make RANS-based transitional simulations more robust and accurate.

OBSERVATIONS ON THE CAUSAL RELATIONSHIP BETWEEN BLADE COUNT AND DEVELOPING ROTATING STALL IN A FOUR STAGE AXIAL COMPRESSOR

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The frequency spectra of signals from pressure transducers mounted in axial and circumferential locations in the casing wall of a compressor, as well as a dynamic flow probe were analysed throughout stable operation, incipient and fully developed rotating stall. From the properties of the Auto Power Spectral Densities (APSD) and the relative phase and coherence of two signals, the stall frequency and its higher harmonics were estimated. The conclusions are: The stochastic estimators APSD and coherence are useful for precursor identification and for detection, if the compressor approaches the stability limit slowly (e.g. during cruise operation or base load in power plants). An acoustic resonance in the rotor tip region precedes rotating stall when increasing aerodynamic loading. The precursor and rotating stall frequencies are related to blading passage blockage. They can be estimated from integer fractions of the rotor/stator - the ratio of the stall frequency and the frequency of rotation is a function of the common divisors of the blade numbers in the rotor and stator blade count.

EXPERIMENTAL AND NUMERICAL STUDY OF NON-LINEAR INTERACTIONS IN TRANSONIC NOZZLE FLOW

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Transonic flows about streamlined bodies are strongly affected, particularly near the shock location, by unsteady excitations. Experimental and computational studies have shown that the unsteady pressure distribution along the surface of an airfoil or a cascade blade in unsteady transonic flow exhibits a significant unsteady pressure bulge near the shock location whose phase variation results from non-linear interaction between the mean and unsteady flows. The shock motion, and thus the pressure distribution along the surface, can be critical regarding to the self-exciting oscillations of the airfoil. The sharp rise in the unsteady pressure distribution was due to near-sonic velocity that acts as an acoustic blockage barrier preventing acoustic disturbances from propagating upstream. The present investigation focuses the analysis on the shock features. Experiments have been carried out in a simple 2D convergent divergent nozzle, using multichannel transient pressure measurements, surface oil flow and Schlieren. Comparisons were made with numerical simulations utilizing a three-dimensional unsteady, compressible, Reynolds Averaged, Navier-Stokes solver.

CLOCKING EFFECTS ON A MODERN STAGE AND ONE-HALF TRANSONIC TURBINE

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This paper describes pressure measurements obtained for a modern one and one-half stage turbine. As part of the experimental effort, the position of the HPT vane was clocked relative to the downstream LPT vane to determine the influence of vane clocking on both the steady and unsteady pressure loadings on the LPT vane and the HPT blade.

In addition, the axial location of the HPT vane relative to the HPT blade was changed to investigate the combined influence of vane/blade spacing and clocking on the unsteady pressure loading.

Time-averaged and time-accurate surface-pressure results are presented for several spanwise locations on the vanes and blade. Results were obtained at four different HPT vane-clocking positions and at two different vane/blade axial spacings for three (of the four) clocking positions. For time-averaged results, the effect of clocking is small on the HPT blade and vane. The influence of clocking on the transition ducts and the LPT vane is slightly greater (on the order of ±1%). Reduced HPT vane/blade spacing has a larger effect than clocking on the HPT vanes and blades (±3%) depending upon the particular surface. Examining the data at blade passing and the first fundamental frequency, the effect of spacing does not produce a dramatic influence on the relative changes that occur between clocking positions. The results demonstrate that clocking and spacing effects on the surface pressure loading are very complex and may introduce problems if the results of measurements or analysis made at one span or location in the machine are extrapolated to other sections.

DNS AND LES OF TRANSITION ON TURBINE BLADES

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On turbine blades, a rich variety of transition mechanisms can be found. In the absence of disturbances of the oncoming flow, natural transition via Λ- vortices was observed. In the presence of oncoming wakes, usually by-pass transition occurs with the location of transition moving back and forth on the blade surface. Under some conditions, especially at lower Reynolds numbers, transition occurs in a laminar separation bubble which can be suppressed by the periodically passing wakes. In low pressure turbines (LPT) the Reynolds numbers are relatively low so that, with the much increased computer resources available today, Direct Numerical Simulations (DNS) of the flow at operating conditions are possible, at least for the lower Re-range of interest, and also well-resolved Large-Eddy Simulations (LES) for the higher Re-range. In such simulations, the transition mechanisms can be studied in detail and the results can be used as basis for developing and testing less expensive RANS engineering calculation methods. In a German Research Foundation (DFG) project "Unsteady periodic flow in turbomachinery" such simulations are performed for unsteady transitional flow in turbine-related geometries, and an overview is given in the present contribution. Altogether three geometries are considered, two different LPT cascades with oncoming wakes generated by moving cylinders, and an idealized situation of a boundary layer in a converging-diverging channel with oscillating flow. In the latter case, the oscillating pressure gradient causes the boundary layer to alternately separate and re-attach; in the laminar separation bubble transition occurs and at some phases there is self-sustained turbulence. These complex processes were studied by DNS. For the T106 LPT cascade, DNS was carried out for a Reynolds number based on the approach flow velocity and the axial chord length of $Re = 5.18 \times 10^4$ with passing wakes generated upstream by moving cylinders. Also in this case, in the adverse pressure gradient region on the suction side, alternately laminar separation with transition and re-attachment (when the wakes pass) occurs. This flow was also simulated by LES on a coarser grid and similar results were obtained. For the same cascade the situation of the higher Reynolds number of $Re = 1.48 \times 10^5$ with passing wakes was calculated by LES. In this case there is no separation on the suction side and by-pass transition occurs which is induced by the passing wakes. For this flow the LES results are compared with the previous DNS results obtained by Wu and Durbin (J. Fluid Mech., 446, 2001). Preliminary LES were also carried for a different cascade at $Re = 7.2 \times 10^4$, again with oncoming wakes. These calculations will be extended to study the influence of passing wakes on the heat transfer to the blades, also by DNS. In the presentation, the transition mechanisms are discussed with aid of these simulation results and they are illustrated by animations.

* presently with GE Nuovo Pignone, Firenze, Italy

THE USE OF CELLULAR AUTOMATA IN MODELING THE TRANSITION

Roddam Narasimha
Indian Institute of Science
Bangalore, India

The lecture will describe recent developments in the author's group at Bangalore in research on the transition zone. It will in particular concentrate on two of these developments.

1. Asymptotic theories for analyzing the stability of nonparallel shear flows in compressible and three-dimensional flows.

2. A computer simulation of the transition zone using cellular automaton ideas, with emphasis on subtransitions.

The implications of these developments for transition zone research will be discussed in the lecture.

The work has been carried out with Rama Govindarajan and S Sanjeeva Rao.

PREDICTING UNSTEADY BUFFET ONSET USING RANS SOLUTION

J.D. Crouch
Boeing Commercial Airplanes
Seattle, WA

A. Garbaruk, M. Shur, and M. Strelets
Federal Scientific Center
Russia

The onset of unsteady flow is modeled by a linear perturbation to a steady solution of the Reynolds Averaged Navier-Stokes (RANS) equations. The current formulation is based on a compressible two-dimensional mean flow with a one-equation turbulence model (Crouch, Garbaruk, Shur & Strelets 2002, *Bull. Am. Phys. Soc.* Vol. 47). The mean flow is calculated using a third-order upwind scheme on a structured grid. The unsteady perturbations are represented by normal modes in time, leading to an eigenvalue problem for the complex frequency. The eigenmodes are two-dimensional functions, which are calculated numerically. The basic formulation follows the earlier works of Zebib (1987, *J. Engr. Math.* Vol. 21) and Jackson (1987, *J. Fluid Mech.* Vol. 182), who considered bluff-body shedding at low speeds. More recently, this type of approach has been used to study global instabilities for a wide range of low-speed flows (Theofilis 2000, *Aerosp. Sci. Technol.* Vol. 4).

The current formulation is aimed at capturing buffet onset, including transonic buffet. The eigenmodes are calculated using a third-order upwind scheme with a 13-point stencil applied to the mean-flow grid. A fourth-order central difference scheme is also used for low-speed applications, for comparison. This leads to a large sparse matrix, $O(10^5)$, governing the eigenmodes. A Krylov method is used to calculate a small set of eigenvalues in the neighborhood of a prescribed (complex) frequency. The eigenvalue indicates whether the flow wants to go unsteady, and if so, what the dominant frequency will be. This approach provides critical information about the unsteadiness at a fraction of the cost of a full unsteady RANS solution.

Results are presented for the onset of shedding for a low-Reynolds-number circular cylinder, as considered by Zebib (1987) and Jackson (1987). This problem is characterized by an incompressible laminar basic flow. The current results predict a critical Reynolds number for shedding of $Re_C = 46.6$. This is in good agreement with the computational results of Barkley & Henderson (1996, *J. Fluid Mech.* Vol. 322), given as $Re_C = 46 \pm 1$. Zebib (1987) predicted $Re_C = 39 - 43$, and Jackson (1987) predicted $Re_C = 46.2$. The frequency at the onset of shedding is also well predicted.

Results are also presented for transonic buffet on airfoils at high Reynolds numbers. A supersonic bubble, ending in a shock, followed by trailing-edge separation, characterizes these flows. As the shock becomes stronger, the separation point moves forward, and at some point, the flow goes unsteady. For an 18% thick bi-convex airfoil, the critical Mach number and frequency for buffeting are in good agreement with experiments of McDevitt, Levy & Deiwert (1976, *AIAA J* Vol. 14), and with unsteady computations of Rumsey, Sanetrik, Biedron, Melson, & Parlette (1996, *Comp. & Fluids* Vol. 25).

TRANSITION MODELLING WITH THE SST TURBULENCE MODEL AND AN INTERMITTENCY TRANSPORT EQUATION

K. Lodefier, B. Merci, C. De Langhe, and E. Dick
Ghent University
Ghent, Belgium

A transition model for describing bypass transition is presented based on the SST-model by Menter, with the k-ω part in low-Reynolds form according to Wilcox, and a dynamic equation for intermittency factor. This intermittency factor multiplies the turbulent viscosity computed by the turbulence model. Following a suggestion by Menter et al. [2002], the start of transition is computed based on local variables.

For development of the model and testing, bypass transitional flows on adiabatic flat plates with sharp leading edges proposed by Clemson University (CU case) and by ERCOFTAC (T3 cases) have been used. Three zero pressure gradient test cases were considered (CU, T3A and T3B), and three with pressure distribution (T3C1, T3C2 and T3C5). After development, the model has been applied to two cascade test cases with a turbine profile of the Von Karman Institute (VKI), measured at the University of Genova. Reynolds number based on the chord for VKI1 is $Re_{2c} = 1600000$ and for VKI2 $Re_{2c} = 590000$. For the cascade test cases, a turbulent time scale bound has been applied according to Medic and Durbin [2002], in order to suppress excessive generation of turbulent kinetic energy at the leading edge.

The intermittency equation is the one earlier used by Steelant and Dick [2001], but where the source term is multiplied with a starting function inspired by the one suggested by Menter et al. [2002]. This function is dependent on a local sensor for Re_θ. The Mayle-correlation giving Re_θ as function of the turbulence level Tu is used to estimate the transition value. The function is zero before start of transition and goes rapidly to 1 after transition. For flat plate experiments, Tu is the leading edge turbulence intensity. For cascades, the turbulence intensity at the boundary layer edge, just before the start of transition has been used.

For the flat plate test cases, the correspondence with the experiments is very good except for the T3C2 case. The T3C cases all have an acceleration phase followed by a deceleration phase. For the T3C1 and T3C5 cases, transition occurs during the acceleration. For the T3C2 case, the acceleration is very long and transition occurs at the beginning of the deceleration phase. The Mayle-criterion predicts the transition too early for such a flow.

For the cascade test cases, the correspondence with the experiments is good. There is some underestimation of the skin friction prior to transition due to the neglect of pre-transitional fluctuations in the model.

The results obtained so far for cascades are encouraging. In the presentation at the workshop, also heat transfer results will be shown. Tests on transition caused by wake passing in turbine cascades are done now. Results for these unsteady flow cases will be shown at the workshop. The final goal of the research is to have a model for unsteady transitional flows.

Plenary Sessions

Transcripts

INDUSTRY GROUP—FINAL REPORT

Brent Gregory
Alstom Power
Baden, Switzerland

Industrial Panel Feedback

- Historical review
- Review of last two days
- Proposals for future directions
- Summary

Historical review

- The last ten years has seen a tremendous improvement in our understanding of transition and this has been utilised in our products. This has been a tremendous achievement and it is you guys who have achieved it.

Review of last two days

- Industry appreciates that the scope of the work has mushroomed and the understanding with it.
- Wide scope of work presented, illuminating and impressive material!
- Academics appear to be communicating and growing together
- Gap widens between immediate translation of today's work (relative to the past ten years) and the benefit to industry
- An observation is that the size of the problem continuously outpaces the capacity to computer

Proposals for future directions

- Perhaps it is now time to consider how the considerable talents in this room can be further utilised
- The industrial panel wants to support you
- We have tried to match our difficulties with your strengths
- Recommendation is to meet in two years
- Panel should make available a modern compressor aerofoil

- Heat loads in turbines (Brent)
  - we know that this might be difficult (proprietary info) but we should try.
- Instabilities (Om)
  - acoustics, aero.
- LPT closure (Jochen)
  - summary of all that has been learnt and a proposal for some future work (i.e. Focused effort from today's level)

Proposals for future work

- Flow control (Aspi)
  - needs more emphasis on the system
- CFD modelling (Simon)
  - BC, - flows, tip flows, modelling
- Unsteady interaction (Greg)
  - Compressors and turbines. Shocks etc.

Summary

- Excellent progress has been made through this format and focus. Industry has been benefited greatly. Thank you!
- We would like to use the expertise of the group on some different problems that are hurting us. We are confident that the LPT success will be repeated.

CFD AND TRANSITION

Wolfgang Rodi
Karlsruhe Universitat
Karlsruhe, Germany

3 levels of sophistication:
- i.   DNS
- ii.   LES
- iii.   RANS based calculations

DNS

- Very important tool for studying transition mechanisms/providing data for developing and testing transition models.
- Calculations of 2D blade geometry/single cascade channels soon possible up to $Re_{exit\,u}$ 500,000.
- Calculations of 3D geometries also possible in a few years (at lower R_e) – should be done.
- Heat transfer can be and should be studied by DNS
- So far only 2 groups doing DNS of cascade flows – encourage more groups to join.
- Standard set of test problems to be calculated should be established – ask industry where greatest needs are.
- Codes should be tested with linear problems.

LES

- Not very promising for transition
- SGS models do not seem to work well for intermittent regions
- Best for flows away from walls
- Useful for precursor calculations for DNS

RANS Calculations

- Using RANS turbulence models without any special transition models (e.g. transition calculations) not a reliable approach.
- Some transition model needed in combination with RANS turbulence model
  - entirely empirical correlations not satisfactory
  - physics based transition methods need to be developed – could be correlations, but also based on equations
  - here stability theory, transient growth methods, etc. could enter
  - extensive testing of those methods/correlations necessary for unsteady flows

- Good experimental/ DNS data needed for this – should be generated
- Transition correlations usually involve boundary layer parameters – difficult to use in 3D situation. Should be extended to more generally applicable methods.
- RANS models to be used:
  - purely algebraic models not general enough
  - Reynolds stress models not accepted by industry

- 1- equation models possible (e.g. SA)
- but 2-equation level seems most suitable (e.g. k-w)
- RANS approach can not handle turbulence/transition control.

- Pre-transition models need to be developed – calculate growth of fluctuations before transition
  - Can lead to prediction of start of transition
  - important for heat transfer in laminar boundary layers affected by turbulence from outside

- Hybrid RANS/LES does not make sense for transition.

FLOW CONTROL GROUP

Thomas Corke
University of Notre Dame
Notre Dame, IN

•Beutner	• Seifert
•Car	•Van Treuren
•Corke	•Volino
•Fasel	•White
•Hultgren	•Wygnanski

Flow Control Designed Engine
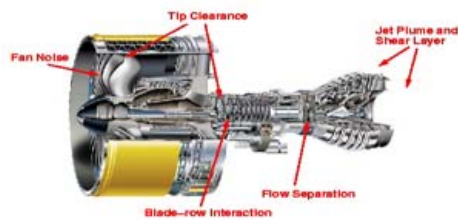
The "Flow–Control Designed Engine"

"Flow Modules*": Identifiable simple flow elements that make up a more complicated flow field.

* Morkovin (1982)

• Stresses flow physics that provide scaling, Academic ⟷ Real Applications.

• Addresses sensitivities.

Minnowbrook IV (Flow Control)

Flow Control Designed Engine

Importance	Ability	"Flow Modules": <u>Ranking</u>
1	3	• Tip/gap flow
1	1	• LPT separation
1	1	• IGV and stator flows
1.5	1	• Fan tip & separation
2	1	• Stator/rotor interaction
2	2	• Compressor rotor separation
1	1	• Inlet distortion
2	1	• Augmenter (afterburner)
1.5	1	• Vectored jet
1	3	• Film cooling

Minnowbrook IV (Flow Control)

Flow Control Designed Engine

<u>Focus flow modules:</u>
1. LPT – Separation Control*
2. Fan – Tip & separation flow
3. Augmenter – thrust/vectoring

* Critical mass of experiments and computations.

<u>Request to Industry:</u> LPT operating conditions (Max. and Cruise rated) of:

<u>Issues:</u> Actuator
Operation &
Durability

1. Internal blade temperature
2. Pressure
3. Wake frequency (unsteadiness)
4. Tip speed
5. Flow Mach No.
6. Other conditions deemed important

Minnowbrook IV (Flow Control)

Flow Control Designed Engine

LPT – Separation Control

Dialogue with Industry:

1. Metric of merit (quantity and level) for LPT separation control? (e.g. diffusion factor rise, pressure recovery, % bleed flow, shaft power …)

2. Ability for hollow blades in LPT?

3. Access to engine-condition test facilities?

Minnowbrook IV (Flow Control)

UNSTEADY FLOWS

Howard Hodson
University of Cambridge
Cambridge, U.K.

Challenges
Two Main Themes

- Unsteady Effects in Heat Transfer and Cooling
    - CFD with sufficient resolution/ fidelity of film cooling/ tips/ platforms/ leakage
    - Experiment with sufficient fidelity, e.g. PIV, conditional sampling
    - Characterization of combustor exit flow

- Unsteady flow effects in multistage compressors
    - Reference geometry
    - Spike stall inception
    - High fidelity experiments
    - Bladerow interaction (clocking/ blade count/ spacing)
    - Shock-BL interaction (transition/separation)
    - Flutter (transition/ separated flow/ shock)
    - Improvement of design capability
    - Acoustic waves

- Noise
    - Broadband/ tone
    - EXCLUDED?

- Long-term CFD/Exp effort in systematic database

Paul Gostelow
University of Leicester
Leicester, U.K.

Reports and Discussions of Breakout Sessions

Okiishi: We had three working groups and Howard Hodson is going to do the honors first.

Unsteady Flows

Hodson: We spent about two and a half hours discussing this. We came up with a very long list of problems. By focusing on areas where we felt this community could make a serious contribution, we managed to narrow it down to just two topics.

The most important problem had to be unsteady effects in heat transfer and cooling in HP turbines.

We felt there was a real need for CFD with sufficient resolution, fidelity, quality; something better than a bit of RANS with a few turbulence model tweaks. Something on the subject of heat transfer, film cooling, blade tips, platforms, shrouds, leakage flow, because all of those things are related in some way, firstly to the heat transfer problem and the cooling problem, but also to the unsteady flow in a high pressure turbine system. We felt that we needed not only CFD but also experiments that go with that CFD; and again the problem with many experiments is that they tend to be RANS-type experiments. I am not trying to pre-judge the recommendations here, because I am not permitted to do that.   But we need high quality experiments as well. The sort of situation where you might bring in PIV; where you are no longer looking just at the statistics of the flow, but at the quality and the quantity of the flow simultaneously. You will not only need things like PIV but also LDA, hot wires, Kulites, at the same time. Because we want to put the whole flow structure together. We want to understand what the key principles are that govern these unsteady flow problems. Why for example, the pressure side of the HP turbine rotor blade is still too hot, relative to what we would expect it to be. That's a key thing that was really driving this group. You'll need techniques like conditional sampling. It's no good just phase lock averaging the data, you'll just come up with periodic statistics. We need to take it further than that. Possibly – we don't know, therefore we need to go there to find out. There is also the strong feeling, and this goes back to Minnowbrook 1, 2, 3, and it is now here in Minnowbrook 4, that we need to understand more of what is really going into the turbomachinery components. I think last time we ended up with a recommendation that said we need to map out the full unsteady flow field in entire turbine HP, IP, LP system. I think we have watered that down a bit now, so that we do need to understand what goes into the HP system. Then coupled with high fidelity CFD, or whatever, we can begin to at least evolve through the machine in terms of understanding the process further downstream. So that's heat transfer and unsteady effects.

The other heading we really thought was ripe for picking is multi-stage compressors. We had a large debate about what this included. We felt the strong need for a reference geometry. Something like the T106 or the Pak B philosophy, which has done us proud in terms of the advances that have been made in low pressure turbines, for example, where a number of groups over a large number of years have made excellent progress.   That actually comes back to the point that a long term computational and experimental effort aimed at producing systematic-style experiments that feed into not just a data base but a library of knowledge and understanding, that we can grow on the basis of what we see. Now a

compression system is a bit different from Pak B or T106 so clearly there is a funding issue there; that needs to be addressed. If you don't ask you don't get. So we need a reference geometry.

And we have a whole list of problems.

We really weren't that concerned about modal stall. It is a relatively periodic phenomenon, you might argue.

Spike stall inception – what actually causes spike stall inception? Is it an excursion from the periodic mean, is it the periodic fluctuations? Is it something else? We don't know.

We need high fidelity experiments, as I've said, with the heat transfer and we also need high fidelity CFD. It is imperative that we go beyond where we are today. It is no good just going into the compressor again and making the same sort of measurements that we have already made. There are fewer of those measurements around. Let's face it, the L.P turbine has been worked on for at least ten years in this way. The compression system has had some attention over that period of time but nothing like as much. Again we need to go beyond that.

In terms of real unsteady problems in a periodic sense we've got blade row interactions, which could include clocking. Blade-count effects. Clocking is where you have equal numbers; what about the issue that Ted Okiishi raised, about good and bad blades, which we've all seen when we traverse behind a rotor. Is that a clocking issue, is it a manufacturing issue? We don't know necessarily.

Blade row spacings – axial gaps. Again, an issue that comes up quite often in discussions about compressor design these days.

Shock – boundary layer interactions. In terms of not only things like transition and separation, but simply running shock wave systems through upstream and downstream blade rows. What happens, for example, in flutter, where again you see separated flows and transition being listed. We need to improve the design capability, we need to understand more what is going on if we are going to use these things. We need to understand how these things will feed into that process.

Acoustic waves. As a possible agent for exciting instability waves – of all types. We saw some examples of that yesterday.

We had a very active, even noisy, debate about noise. It was definitely broadband, probably unfocused. We came to the conclusion that as a group we shouldn't say that we are going to solve the noise problem. But we also came to the conclusion that, when addressing these issues, perhaps the compression system and the HP turbine are not the places to address the noise problem. That perhaps it is the LP compression system and the LP turbine where we should be looking at noise. But nonetheless when we look at these things we should have in mind the noise community.

At the end of the day when we are addressing these issues we do need to attack it in this systematic way. We need this reference geometry; reference geometries – given that we have the Atlantic Ocean dividing the funding agencies. We need experimental and CFD to work in concert, and it needs to be high fidelity, not more of the same.

Okiishi: Good job, Howard. So now are there some questions?

Reshotko: Just a simple comment. I find it interesting that at this meeting the LPT does not appear explicitly in your chart.

Hodson: Well, we were given a five to ten year horizon for the question. And we felt that in five years the LP turbine won't be solved, it won't be a complete design system in the companies, but we are a long way toward that. Most of the understanding is almost there. The modeling is coming. This is not the next problem.

Durbin: When you talk about unsteadiness are you talking about blade row interaction unsteadiness or vortex shedding unsteadiness?

Hodson: The answer is all of the above. We have a broad church – we don't wish to exclude any particular religions or faiths.

Fasel: Regarding acoustic waves, the comment was that they are causing instability waves and that means causing transition.   Is there any evidence that acoustic waves, or noise, does cause transition in compressors?

Walker: Well not directly in my low speed experience.

Hodson: There has been work done on the acoustic excitation of transition, but whether that is actually a mechanism in the turbomachine, I've no idea.

Fasel: Or free stream turbulence.

Praisner: Really a comment about the long term. As an unfortunate user of CFD in industry we find that the majority of the experimental data-base, low speed and high speed cascade data, much of it is executed with turbulence generated from grids that provide length scales that are not even remotely engine specific. That puts us in more of a data-matching mode for our two equation models. Data needs to be matching not just the level but the length scale.

Hodson: If you are looking at heat transfer you can see where that is important. We were thinking of compressors in the first instance – yes there will be maybe cascades or flat plates or whatever that comes out of that. But the main driver here was the multistage compressor and in that context I don't think that issue arises. I'm being told it does but I think we would really like to know what the combustor is doing before we do much else is that respect. And Lou, you mentioned on Sunday evening that there is some work going on in NASA so hopefully by next Minnowbrook we shall have some answers.

Walker: Going back to the acoustic waves, you can get acoustic resonances excited by instability waves as a major noise source.

Okiishi: O.K. We had better move on. Thanks Howard, you've done a good job. Tom Corke – if you could come up and present the results from your group on control.

Flow Control

Corke: As with the unsteady flow group we had some interesting and lively conversations the first night. Lou Povinelli had to come in and knock on our door and have us break up. There was a fear that we were going to go on all night. We did and he led us to the bar.

Our vision in the flow control group is what we would call flow control designed engines. The approach to this is one that was coined by Mark Morkovin in the early eighties which is called flow modules and the idea there is to break down a complicated flow situation into a number, a list, of simple flow elements,

which are the flow modules, which then you can study in the lab. You can understand the physics behind these and in particular with flow control the physics leads you to how to control it in a favorable way and then you apply that to the design. The rationale of the flow modules approach is that it stresses flow physics, that provides the scaling. There have been discussions at this meeting about 'are we matching the flow conditions of the real engine?' If we understand the scaling we don't need to match those conditions in the beginning to understand the physics but always in our mind we are looking to ultimately apply to the real situation. So this is the mantra of flow control designed engines. Given that we then went to ranking flow modules, the core elements where flow control can have an impact. This is a list that we came up with. It is a fairly long bit, I'm sure not exhaustive. In fact in looking at the unsteady flow group's list some of theirs would go into here and I'm sure there is also overlap with what they considered. What we then did was rank these in terms of what we called 'importance'. Importance means importance in controlling these to the performance of the engine. This column represents our assessment of the ability to control these. I want to note here that originally I suggested that we rank these from 1 to 3 and everyone insisted that we rank them from 1 to 2 with 1.5, which is still the same, just a compressed scale. Interestingly we thought that tip gap flow was important. For some reason we said that it was difficult to do. Not quite sure why, since we had about four talks that discussed it, although when we talk about ability we are talking about ability in the engine environment. Tip gap is probably difficult in the engine environment. Nevertheless all of us could discuss this ranking but we then further refined this list into what we call focus flow modules and these are ranked in order with the very top one being LPT separation control. The reason for ranking this high is that we feel that right now there is a critical mass of experiments and computations and so we are ready to really focus on this in an engine application. Based on this, and taking advantage of the industry participation in this meeting, we voiced a request to industry, which is that we be given information on the LPT operating conditions, at both max and cruise-rated engine conditions. This is a list that we believe is a minimum set but we open this other condition as deemed important. The issue here is the actuator operation and durability. It's not that we don't understand the physics of controlling this flow but in order to go to the next step we want to be certain that the actuator will perform under these conditions. We are not making any statement on which actuator this is because we know there is more than one way to do this; and possibly this issue of durability might be the ultimate decider of which actuator type would be the one that makes it.

Lastly using LPT separation control as the top contender we open what we hope will be a dialog with industry. Dialog means 'back and forth' and the first issue of the dialog is a metric of merit. What quantity and level should we consider as a flow control group, with industry's guidance on what would be the metric of merit that decides whether a particular approach will be successful and of interest to industry. One question in this dialog was the ability for hollow blades in the LPT and again this was brought up because of possible ways of controlling this flow in the engine. And then finally, 'access to engine conditions'. Test facilities in order to do these durability tests, to do these ultimate tests at engine conditions and apply the flow physics that we can glean from the flow module approach.

Okiishi: O.K. Tom, good. Let's take some questions here.

Narasimha: Isn't there a fair bit of work done on film cooling?

Corke: Well, you know, one of our crew members was Professor Wygnanski and I immediately thought of him because he has done a lot of work on tangential jets, which seems to be the same physics, and he indicated that it was not pertinent.

Reshotko: There is a difference between tangential jets and film cooling. You don't want a jet in film cooling. You want a layer.

Corke: That's true. It's a jet at one point. Something that I didn't know about came out in these discussions – the 'shower head' at the leading edge.

Durbin: You had the ejector in a cross flow down as 'difficult'?

Corke: The fact is that this is the way the committee was ranking these, and it is totally debatable. This was at the end and I think you would get different opinions.

Hodson: Clarification. What do you mean by controlling stator-rotor interactions and inlet distortion?

Corke: Inlet distortion was looking at these S-shaped inlet ducts which is separation bubble flows. Stator-rotor interaction would be issues of stator control in terms of wakes, possibly vectoring in terms of reducing incidence of high cycle fatigue.
That was the motivation.

Reshotko: I've a question for the compressor crowd. We recently had a thesis where a person was working on characterizing inlet distortion and I asked the question 'What do you do about swirl at the compressor face?' He said we really don't have any criteria for dealing with that. Is there any experience with what happens when you have swirl at the compressor face?

Hourmouziadis: We have a sigma the engine manufacturers introduced for dealing with ground operations. They introduced this for test beds and testing compressors. I'm not sure they have something like the DC60.

Reshotko: No. There is no criterion for limiting swirl on engine performance.

Hourmouziadis: I cannot tell you how they define swirl.

Povinelli: Could you say more on augmenters? I am wondering why it is on there and why ability, for example, is rated as one, when we know all the messy reacting flows associated with afterburner stability. Is it a matter of looking over the fence and thinking the grass is greener over there or is there something that goes beyond that here?

Wygnanski: No because you can pulse the fuel that you inject into the afterburner and this makes quite a difference in the length of mixing required. The feeling is that you can then reduce the length of the tube that you carry behind and that can be relatively easily done.

Hodson: Isn't the point that you can control re-combustion. Therefore you can actually get more thrust. That is simple active control of the fuel supply and that has been demonstrated.

Okiishi: O.K. I can see that this discussion is getting lively and could go on. We'd better quit. The last group is represented by Wolfgang Rodi.

Transition and CFD

Rodi: I am talking about the CFD and transition group. I am sorry about this non hi-tech presentation. I didn't have a laptop and I hope you can read my writing and this was written after I drank quite a bit of this prize wine since I was sitting next to Lou. Anyway, we talked about the three levels of sophistication in CFD which came up already in the first session. There is Direct Numerical Simulation at

one level. Next level is Large Eddy Simulation and then Reynolds Averaged Navier Stokes equations based calculations. For each level we discussed 'where are we now, what can these methods do on transition, and where is research needed?'

So first, Direct Numerical Simulation: We found that this was a very important tool for studying transition mechanisms and finding out the physics, but then also for providing data for developing and testing simpler transition models. I think it was shown during this meeting that with such methods you can find out everything about transition that you really need to know, so it is a very important tool and we are lucky that we can do such calculations. They are very expensive but they can be done. To give you an idea, for calculations of 2D blade geometries similar to what I have presented yesterday on single cascade channels, it will soon be possible to calculate for Re_{exit} up to about 500,000. That can be done within the next two or three years with the machines that we shall have then, just to give you an idea.

Calculations of 3D geometries. It was found important that one should go out to the end walls to get the effects there. Of course this will also be possible in a few years but then you will have to lower the Reynolds number so that you can afford the grid points in the spanwise direction. This should certainly be done.

We agreed that heat transfer can and should also be studied by DNS so here DNS has a very important role in finding out how heat transfer happens especially when you have turbulence and wakes coming on and how this influences the heat transfer. So far we found that there are actually only two groups doing DNS of cascade flows, the group at Stanford around Paul Durbin and ourselves (Hermann Fasel are you doing some?)

Fasel: We are doing a cascade.

Rodi: Anyway it is not enough since we found that DNS is actually an important tool and we would encourage more groups to join and also do DNS when they have the computer facilities available.

It was suggested that a standard set of test problems to be calculated should be established. One cannot have too many because these calculations are so expensive. Turnaround is slow and since there have to be only a few we have to find the most important ones and here we should ask industry where the greatest needs are. They should give us some idea on what test problems should be studied by DNS. Perhaps more an aside remark that came up is that we have to ask how these codes will be validated. It would perhaps help to validate them with linear problems. So much on DNS.

The next discussion was on Large Eddy Simulation. Here we concluded that LES is not a very promising tool for transition. I gave you a little taste yesterday. It seems that the sub-grid scale models which you have to use in LES do not seem to work well for intermittent regions which you have in a transition problem.

These methods are really best for flows more away from walls; I think they are important for combustor calculations but not for transition on turbine blades. They are, however, quite useful as precursor calculations for DNS. When we want to set up DNS calculations what we usually do is to do first an LES, to get an idea about the flow, and the kind of grid one may need. For that purpose LES is useful but we found that LES is not all that promising to actually solve transition problems.

Then the third category, if you don't resolve the three-dimensional turbulence, whether it is fully turbulent or in a transitional state, either by DNS or LES, then you have to average out turbulence, and that is what is called RANS.

There have been attempts to simply use the RANS turbulence models that have been developed for turbulent flows, i.e. to apply them without any special transition models to transition. We have found that that is not a reliable approach. Actually it doesn't work at all if you have natural transition; a RANS model cannot give you natural transition. You can get bypass transition because turbulence from outside diffuses through the model and into the boundary layer and then turbulence is generated but it is certainly not a reliable approach. You have to be lucky to get transition at the right place and in the right way.

So some transition model is needed in combination with RANS turbulence models. We have heard about various approaches at this meeting, for example using highly empirical correlations but they are not really satisfactory since they are entirely empirical.

So the suggestion was made that physics-based transition methods need to be developed – they could be either correlations, I suppose that is what industry wants – some good physics-based correlations, but they could also be based on equations, not just correlations. Here stability theory, transient growth methods, etc. could enter and help to develop such methods. Now some correlations are around and new ones have to be developed but what is important is an extensive testing of these methods for unsteady flows. Here we are really lacking something; we do not know how well the methods that are available, and that are to be developed, work for unsteady flows.

So here a lot of work is necessary and for that of course you need good experimental and DNS data for this testing and they should be generated. So here also DNS is important but also we need additional good and detailed experiments.

Transition correlations usually involve boundary layer parameters, momentum thickness - things like that, and that is causing trouble when you have 3D situations. In the end we want to go to 3D end wall effects, tips and so on. So these methods for transition should really be extended to more generally applicable methods. That is an important point if you want to finally calculate these problems that are important in an engine.

Then we discussed which RANS models to actually use in such calculations. We found that purely algebraic models (like mixing length, Cebeci-Smith and so on) are not general enough. So that is probably not a good approach. At the other end Reynolds stress models have been developed but have not been accepted by industry, they are just too complicated, so that is also not a way to go for practical flow calculations. One-equation models are possible (Spalart-Allmaras has had some success) but also perhaps they are not general enough, so we suggested that models at the two-equation level (k-ε, k-ω, nowadays one uses more k-ω), are perhaps most suitable and that should be used together with any transition modeling.

A point that was made was that the RANS approach really cannot handle turbulence and transition control. Such problems really have to go to DNS or LES (which doesn't do so well) but RANS really cannot contribute anything in this area.

Then came up the problem of pre-transition - what is actually happening before you have transition. That is also an important phenomenon. So such models need to be developed that calculate the growth of fluctuations before transition happens and that can lead to a prediction of the start of transition. But it is also important, for example, for heat transfer in laminar boundary layers. Before you actually have transition you have a strong influence of turbulence from outside on the heat transfer and here there really is a need to develop good models.

Finally a hot topic these days is hybrid RANS/LES models where some areas are calculated by LES and some by RANS; an example is the Detached Eddy Simulation method. But since we found that LES is not very good for transition this approach does not make sense for transition calculations.

That's what we discussed and I have given a number of suggestions where research should be done.

Okiishi: Great. What questions do you have?

Hourmouziadis: Would LES be appropriate for studying the initiation of stall in compressors?

Rodi: I've been talking about its suitability for transition. It's not so suitable for transition but, for example, if you have an airfoil at a large angle of attack, with a massive separation zone, that's actually where this method would be suitable.

Hourmouziadis: I have another question. Howard said that one of the tasks was prediction of stall in compressors that enter surge. Is LES appropriate for such a study?

Rodi: I think it would be but is transition important for this?

Hourmouziadis: No.

Rodi: Well, if transition is not important then it would be suitable.

Gostelow: I think transition is important for that question and therefore for that reason I doubt whether LES is a valid tool for that purpose.

Rodi: Well, if transition is very important it would not give an accurate answer but if transition is not so important then it would certainly be very suitable.

Hourmouziadis: My second question is: We have shear layers in turbomachines which are not close to the wall – free shear layers, secondary flows, tip leakages. Originally these are also laminar and go through a transition process. Do you think that the turbulence models we have been discussing here will cope also with that?

Rodi: Transition also occurs in a separated shear layer, so in a sense it is similar.

Hourmouziadis: Would you expect that these models would also cope with that?

Rodi: Well, o.k. There I think LES could perhaps do better, if it is not close to the wall.

Narasimha: I've asked this question before but I'd like to get a feeling for it, because you are the people who have said, at various times during this meeting, how DNS is very expensive. Can you give me a feel for numbers now? Suppose you were thinking of doing this calculation.

Rodi: Well I can give you numbers about how long our calculations took, of course. Yes.

Narasimha: No. I would like to compare the numbers for the cost of making a DNS calculation against the cost of making experiments. We know there are problems with experiments but there are problems with DNS as well.

Rodi: For us it doesn't cost anything. You have to pay the researcher but the computers, in our case, are provided by the government. If I want to do experiments I have to buy equipment and so on. Also, the cost of computing is going down all the time.

Hourmouziadis: You can give the cost of the CPU time?

Rodi: Yes. But I cannot tell you how much a CPU hour costs. He wants to have it in dollars to compare with his experiments.

Okiishi: Let's go to one more question.

Fasel: Did you spend any time in your discussions on how you define DNS? It is not academic, that's why I am asking that question.

Rodi: No. I have to say not really. My understanding is that DNS has to resolve all scales and it has to be numerically accurate. Only then is it a DNS.

Fasel: Many calculations are not really DNS. They call it DNS but it isn't.

Rodi: That's true.

Hodson: Are your conclusions equally valid for attached flow transition as for separated flow transition?

Rodi: Yes. We need correlations or some transition methods both for attached and separated flow transition.

Hodson: And the relative ranking of DNS, LES, RANS, is that the same?

Rodi: Yes. But LES, I think, would not work for either one.

Okiishi: O.K. We have to move on. I think the three groups did an excellent job in bringing some high priority issues to the fore, so let's give them all a hand.

Gostelow: We now have the industrial panel part and Simon's going to do that for us and I hope we will have time for discussion after.

Industry Panel Feedback

Gallimore: Om was fully involved in this. Although he had to leave yesterday afternoon, we met yesterday lunchtime. We structured this in four areas. First we will give some historical perspective on where we have got to in the last ten years. Then we will have some review of last two days and our perspective on what we've been hearing. Then we will have some proposals for how things might go in the future. And then we'll summarize.

Historical review
From our perspective the last ten years has seen a tremendous improvement in our understanding of transition and this has been utilized in the industry's products. This has been a tremendous achievement and it is you guys who have achieved it. So we look at Minnowbrook and certainly while I've been here I've been impressed by the wide variety of effort that has gone on that has actually delivered at the end of

the day. From the industrial point of view we are here to make money, that's what it is all about, and I can see that the work of this group has actually helped the companies to make better products. So that is excellent and I think we were all very impressed, weren't we guys?

Review of the last two days
We appreciate that the scope of the work has mushroomed since it started but also so has the understanding. We are impressed by the wide scope of work presented, it was illuminating and very impressive. The community seems to be communicating, which is excellent, and growing together. There seems to be a lot of cross-fertilization and exchange of ideas, which is good.

What we did notice was that some of the stuff we were seeing was getting a bit distant from our needs in a way. In the last ten years the work has found its way into LP turbines, in particular, fairly readily. But we started wondering about some of the stuff we were hearing and thinking 'Well, how do we see that finding its way into our products'? And we thought some of the areas were getting a bit distant. And that will come out when we get onto the next foil about some of our proposals to you guys as to what might happen next. And then there was an observation, and I guess this will carry on forever, that the computers are never big enough.

Proposals for future directions
Perhaps it is now time to consider how the considerable talents here can be further utilized on the back of the successes so far. The industrial panel is keen to support you in the proposals that we are going to make just now.

We have gone through the difficulties that we have got and tried to match it to the skills that we have in this room. So hopefully we have done that. We are asking for a bit of a change in direction so we thought that if we leave it three or four years and then we find out that nothing has changed that might be too long. So we are suggesting that maybe in a couple of years it would be appropriate to have some kind of check to see whether any of the suggestions have been taken on board. And the other thing, which has actually been mentioned before by the unsteady group, the industrial panel should make available a modern compressor airfoil. We have been discussing amongst ourselves what we might do to help move along the compressor side of the business, which the unsteady flow group said was one of their requirements. There are a few possibilities there, the new airfoils that Greg is going to test, perhaps

Proposals for future work
And now for the list: what we have done is to assign one of the industrial panel members to each of these. We did have some thoughts about who in the academic community might be associated with these but we decided not to volunteer people but to ask for volunteers. There are six suggestions up here. There is an industrial panel contact and we would like people to think about getting involved.

Heat loads in turbines (Gregory)
Brent is going to lead this off, at least initially. Now we know that this might be difficult, because everyone keeps their heat transfer and cooling data close. But it came out top of the list of the unsteady flow guys and we should try. So that was our number one. You guys are into boundary layers and transition, let's look at the heat transfer associated with all of that. Brent never gets his turbines to live for as long as he wants, we are all in the same boat, so that is a major problem.

Instabilities (Sharma)
The general topic of instabilities, acoustics, aerodynamic instabilities. We actually had combustion down here and we took it off because we felt there was a large community working in combustion. The point of what does a combustion chamber give a turbine is part of that. Again this all goes back to what was said in the unsteady group.

LPT closure (Gier)

We feel that now is the time to review everything that has been done over the last ten years, with great success. We have taken advantage of it and we feel that now is the time to perhaps move on. We are not saying stop everything on LP turbines, but our feeling would be if Minnowbrook 5 came along and there were an awful lot of people doing the Pak B cascade and there wasn't much else then that would be disappointing. So our proposal would be that somebody from the community tries to draw together everything that has been learned up until now and come up with a proposal for some very focused work to move us forward. But, as an industrial panel, we were feeling that we would like to see the amount of work on LP turbines, as a net amount, go down to leave room for some of these other things. We have got to the stage now where the returns, from our perspective, are getting fewer and fewer and the amount of effort to get them is getting higher and higher and there are some bigger fish out there in the pond to catch. So, in terms of bang for your buck, it is probably better to move to another topic. Clearly there are some issues in LP turbines left but we don't want everybody working on them. That would be our view.

Flow control (Wadia)

We feel we need to understand more about where this is going, at the end of the day. Can we see how it is actually going to be implemented in a useful way in a gas turbine. We assume that you can do all the actuators and everything else and that is done. But we still feel a gap. Let's assume you can all do everything that you are talking about but how are you going to use it? We think we need that question to be answered. I'm still not clear how it is going to be used. Then coming one step back from what we do need to look at the system, and this was mentioned before. If you are going to use extra air, or something else, you have to look at the whole system. That is tricky and it would need industry support because industry are the people who know the system.

CFD modeling (Gallimore)

This is a broad church because it is talking about boundary conditions, tip flows, leakage flows, all that sort of stuff. The stuff that Reza was showing and all that. And in there would come in what is an appropriate turbulence model. I don't think that is particularly controversial. But CFD modeling of course will spread across all of these topics.

Unsteady interaction (Headland)

Our last one was unsteady interaction for compressors and turbines and particularly for shocks and stuff and this is where we would be looking to think about compressor profiles. People doing experiments on them, and whatever. We can develop that as it goes along. So we think there is an awful lot to cover from there as we go to these highly loaded turbines and compressors with short axial gaps and shocks everywhere. So those were our proposals.

Summary

So, in summary, excellent progress has been made through this format and with its focus. We have benefited greatly so thank you very much. It has been really good and we appreciate it.

What we would like to do now is use the expertise of this group which is now formed and focus it on some of the difficult problems that are actually hurting us. If we can do that we are confident that the success that has occurred on the LP turbine will be repeated in these other areas. It is quite pleasing that I don't think there is too much difference between what I have just said and actually what most of the academic groups have said. We were a little worried about how this might go but after the first presentation or two we thought, yes, it is going to be o.k., because we are basically saying the same thing. So that is good. With that I will stop. Questions and comments?

Povinelli: It is remarkable how closely this matches with what you had in the unsteady group. It leads me to ask whether you and Howard got together on this last night?

Gallimore: No. We did not talk about that. We talked about lots of other things.

Hodson: What is even more remarkable is the things that Simon said that we also didn't say. There is a lot that we took out, like combustion and so on, for exactly the same reasons you gave. So that is good.

Povinelli: Heat transfer etc. It's remarkable. It shows how compliant a small stable we are all working in.

Hodson: Or that we have no imagination.

Gallimore: One of the things I did have down was a note to myself to say that it should be for industry to say just what we want but we are always looking out for someone to come up with a whacky idea that changes things dramatically.   There is a balance here, it is a two way street. You guys should be telling us, this is what you should be doing, to a certain extent, and we should be saying 'this is what our problems are'. If you can come up with something that is really interesting and different, that brings a solution to a problem, that is worthwhile.

Abhari: In a way it is not that surprising; with the diffusion of knowledge in meetings and papers we have an idea of your problems, you know what we are doing. My question is, you identified heat transfer ranked number one.   There were six topics. I assumed that's because there were six of you on the committee.

Gallimore: Well we didn't want anyone to get off scot-free. That's correct.

Abhari: For the heat transfer, where there was an overlap, at least with unsteady flow, did you talk in more detail. This is too vague. Frankly, this is like saying 'Let's go to the moon' but not how to get there. So did you talk about specifics, because we did talk about that.

Gallimore: Brent – you were driving this.

Gregory: The big gains that have been made in LP turbines have realized a certain percentage in performance improvement there, that large companies in aircraft engines have already benefited from. Those margins   where you created the opportunity for benefit realized themselves in fuel burn and the ability to reduce the amount of fuel consumed and open up margins for profitability. What we are looking for now in LP turbines is that those margins have, to a large extent disappeared. The amount of dollars you have to spend is exponential with the amount of gains on the x axis, becoming increasingly small. We think that is the time to bring this to an end. But the next opportunity for gains, perhaps even bigger than the LP ones, is that the amount of cooling air that is used in a turbine, which consumes cycle benefits, let's say in a highly cooled turbine, 15-20% of the air that is compressed in the compressor is used to cool the cooled parts of the turbine. You put a lot of expense into compressing it and then it is essentially thrown away in terms of cycle benefits in cooling the metal. That's for the complete cycle. That cooling air, if it could be reduced, goes back into the cycle and you get fuel burn benefits throughout the cycle. These numbers are much more impressive, perhaps, than where you are with the LP turbine gains. 1% reduction in cooling air is 1% reduction in specific fuel consumption, more or less. That translates to huge numbers in terms of benefits. So, is there a way that you can use instability and unsteadiness to better improve the heat transfer area and the cooling area in saving cooling air. That's the push. The gas turbine community puts a lot of cooling air into the turbine. Far more than it needs to cool

the turbine. Because we don't know where the hot gas goes within the turbine and we don't know what the effects of instabilities are. We just swamp the cooled turbines. There is a picture where you can see a typical HP turbine.

Gallimore: In terms of the details. The heat load on the pressure surface of the airfoil. We can't get that right. That clearly is an issue about boundary conditions, but also the details of what is happening very close to the boundaries as well there. That really, Reza, is a broad topic but then I think there is a lot to go at. We didn't really focus it down as much as you would like to consider this particular aspect.

Beutner: Two comments. One programmatic, the other a challenge to the industry panel. You recommended revisiting this conference in two years; I think the question needs to be asked 'What would be different in two years versus three years?' For many academics in the U.S. at least the funding cycle is such that none of the new ideas spawned from this workshop is likely to be initiated in a research project for at least a year, because of the way the fiscal years line up.

Gallimore: We appreciate that. We thought it might be useful to monitor it to see if things had started to change, rather than wait for three or four.

Beutner: But what is quickly done in three years is something from industry. And what I would suggest, and the challenge to industry, is if you take it upon yourselves to pick apart pieces of the engine where flow control, for example, may be of benefit. This is one where you said it needs a systems overview. That point was made a couple of times over the past couple of days and has been made in the broader community repeatedly. But that systems overview is something that only the engine companies can bring to the table. What we are lacking for some of the flow control applications in the engine is a clear understanding of what the cost benefit is. And so it would be nice if the industry panel members went for specific applications to come off this list, the tip flow issues, LPT separation, combustion-mixing enhancement, film cooling, whatever you choose. Each company do one system trade study on that and tell us what the cost of either shaft work or compressor bleed is and what kind of a benefit you would need to see. You can count this in whatever terms you like, durability, performance, ultimately it is a cost issue though and you are going to put it down. And you are also going to tell us what we have to show in return for 1% bleed or shaft power.

Gallimore: But there is something the academics can do. Assuming all the gizmos are working, what is it actually going to do for the machine on a technical aerodynamic level. And that is one of the problems I had yesterday, maybe because I am stupid; I couldn't understand how active control of separation was going to be combined with wakes. I need someone to tell me that that will actually work. Then I can tell them whether there is an advantage or not by looking at the whole system. A bit of both is needed.

Beutner: Part of the prioritization has to come from the cost benefit analysis, and this is something industry is uniquely able to do.

Gallimore: I agree. No problem with that.

Beutner: And if, over the next two or three years, before we meet again, there were a systematic series of trade studies done, it would be of great benefit to this community in helping to focus or identify rich target areas.

Gostelow: One more question?

Narasimha: It is actually a personal question to you Simon, because you had said on Monday that you would like to see us move away from modeling towards more direct calculations, and I just wondered what you meant by that and I didn't see it in the report today, so have you changed your view or what?

Gallimore: I was just reflecting the views of my colleagues and that was really focused on turbulence modeling.

Just before I finish, since Brent has put in all this effort to put this turbine up. All these streaks here are the streaks of the cooling flow which is protecting the surface of the airfoil from the high temperatures and you can see that is nothing like an LP turbine and you can just imagine the volume of air that is used to keep these things cool. As Brent says, 12% of the air that is coming out of the back of the turbine didn't actually go in at the front. It came in through other areas.

Wadia: Right now we have a lot of conservatism in what we do. To give you an example, we set up experiments and tried to plot out the heat transfer coefficients just by calculation. We did calculations with Star CD, CFX. There was a difference of 200%. So, when you see that you don't know what is right any more, so you start depending on experiments. This is where the community can help us, in getting accurate external heat transfer coefficients, film effectiveness, we always go and run an experiment. So if those things can be done where people have a little more confidence it saves a lot of fuss because we don't have to do the experiments and it also takes out the conservatism that we put in. So that's a few things that are specific. I can add more.

Gostelow: O.K. I'd like you all to thank Simon and the Industry Panel. I think they've done a great job.

We now have Roddam to do his usual job of really summing up and drawing all the threads together. It's a great honor to have Roddam come and do this for us. To fly for forty hours to get here and then give us his best. A few weeks ago Greg and I had the pleasure of attending Roddam's, believe it or not 70th birthday meeting. Isn't that hard to believe? This young guy here. He did propose intermittency in 1957 but it is still difficult to believe he is 70. Now Roddam has a great set-up there in India. He's told you about the IUTAM symposium in December of next year. He has a beautiful Indian Minnowbrook there in the Nehru Centre. A beautiful outfit that he runs there. I would strongly recommend it to all of you. It can be a kind of interim Minnowbrook there – a step towards the next two or three years. Roddam, it's a great honor to have you come and do this, so we look forward to hearing what you have to tell us about the meeting.

WORKSHOP SUMMARY TRANSCRIPT

Roddam Narasimha
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Thank you for those kind words, thank you also for the advertisement for the Bangalore meeting. We would be delighted to see many of you there, just over a year from now.

Well, I see that many things that I wanted to say have in fact been said here by other people, so to some extent my comments will echo what has already been said. But some of the comments I'm going to make have not had the benefit of the presentations that were made this morning, so maybe in some cases the perspective will be slightly different. It's in any case a very personal reaction to this splendid meeting we have had. I was very happy to hear Simon's tribute to these meetings this morning, because I think that the uniqueness, the spirit of the meeting, is that academics, research scientists and people from industry – people like Frank Smith as well as Simon – all sit together around the same table trying to figure out these problems.

At the start of this meeting we had an industry panel. What struck me during their presentations, and in fact in many of the things that were said later on, was how often people from industry used the word 'understanding'. And in some sense, for those who are in academia or are doing research, providing 'understanding' is their trade, so it was very nice to hear that, in fact, understanding is what is required from them. I think it was Om Sharma who said, 'You do all these calculations but in the end it is people who make designs'. And that again I think is true. What it really means to me is that we need knowledge at many different levels. There has been some discussion here, and I think sometimes rather warm, about correlations, about codes, about what RANS can do, about what RANS cannot do, about DNS, about LES and so on. But I think, to borrow a phrase that Lou used in his inaugural talk, we are here talking about the art of science. Not everything in turbomachinery can yet be completely reduced to numbers, so you need knowledge of different kinds. If people are in difficulty with a design they need hunches about what to do, and eventually that may boil down to 'understanding', to knowing how much to trust correlations, codes, tests etc.

On <u>CFD</u> we had a whole spectrum of views here. Some people have said CFD is no good. But others have said, 'No, models can do a lot, and in fact we should spend a lot more time on them.' I think that's the basic question that was handled by Rodi's group, and they listed what DNS can do, what LES can do, what RANS can do, and so on. So I am going to make a sweeping suggestion, because we heard different things about RANS from different people – some had good experience and some bad. Sabnis made a very interesting comment about a discussion he had with one of his colleagues about methods; he had to conclude it by saying, 'Well, maybe these work for the design philosophy that we have.' That may be the key. The data base that one has and the kind of systems that one tests may decide how to fix correlations and codes to work best. Undoubtedly there are fundamental problems with RANS codes; they work well some times, not so well at other times, so maybe users should develop their own codes if they have confidence in the design philosophy that they have. Maybe the time has come when RANS codes will be generated and 'fixed' in-house, rather than be formulated as 'universal' models.

Finally, do we actually need all of them – RANS, LES, DNS etc.? I believe we have to find a method of doing more DNS. This thought is something which goes back a couple of meetings: six years ago we started asking 'Why is there not more DNS?' – turbomachinery-related of course. (The basic argument for turbomachinery DNS has always been that the Reynolds numbers are generally manageable, but the flows are too complex for RANS, even LES.) And at the next meeting we did have one. And I am happy to see

that at the present meeting there is more of it and, if there is a Minnowbrook 5, perhaps two years from now, maybe there will be even more. But some new methods may have to be devised to see how to do more DNS, because people keep saying that it is expensive. I shall return to this question.

Now, one thing that came up in this meeting was about all these problems that people normally brush under the carpet: leakage flows, cavities, blade tip flows etc., which academics tend to look upon as 'dirty' fluid mechanics. Our industry friends have pointed out that these are not something we can ignore. If you are trying to understand something you want to make the situation as simple as possible, but when you actually make an engine there are all these 'little' things which you can't avoid but which add up to a considerable effect on the performance of the system. These problems will have to be looked at in greater detail.

The other thing that came out, and it was emphasized by several people this morning as well, was that heat transfer needs a great deal more attention, unsteady, instantaneous heat fluxes in particular. Little hot spots can have an enormous impact on the operation of an engine, in particular its life. Some very interesting studies in heat transfer were indeed presented by experimenters at this meeting, and there were also some computer simulations, so it appears that many people have come to the same conclusion. Many more experiments and computational studies will be needed before some understanding develops for the problem.

The industry group also emphasized, especially on the first day, that their major concerns now are with product life, cost, performance, part count, noise, reliability and so on. What industry would like to know is what are those fluid dynamical parameters which will affect the parameters of great interest to industry. This morning we have gone through part of that exercise, and I see that we are already beginning to identify those fluid dynamical problems where there are strong implications for these parameters. Once more it looks as if heat transfer will figure at the top of the list.

Control. There were some very interesting ideas and papers presented at this meeting on flow control, both passive and active. Obviously these need to be assessed and tested now in a different way. We talked about roughness, dimples, bars, vortex generator jets, plasma actuators and so on, and have some rough idea of their scientific feasibility. We talked about creating what I like to think of as a bazaar of technologies that, for example, academic or basic research scientists might offer, from which industry will be able to pick what seems most interesting or worthwhile to them. I am once again glad that Simon made the point that industry was always open to whacky ideas from academia. As someone who likes to think of himself as an academic (although perhaps not a very innocent one), I think academics must reserve some time for pursuing their own idea, even if industry says they don't see how they are going to use it in the immediate future, because some of those weird ideas do in fact find application.

What should be done next in control, apart from more of the interesting experiments reported here? There is also DNS, of the kind that Hermann Fasel described – more of that kind of work is something which should be pursued with vigor. I was glad to hear from Tom Corke's group suggestions about 'flow-controlled engines'. The time may have come to try out some of these ideas, particularly on control of separation and heat transfer, at system or sub-system levels, because once again they seem to be major problems where new control technology can help.

What are the things that might be interesting to do now in transition? I think that there is a continuing need to do basic experiments, but in terms of goals that are related to transition modeling, especially for low pressure turbines, we now seem to have considerable basic understanding of the broad features of unsteady transition, with the effect of wakes from an upstream rotor, for example. But I still wonder how much we know about what happens in a real turbine where you have multiple stages upstream, rotors, stators and so on. It would be interesting to make experiments to gain insights in multi-stage flows, of the

kind we have from the simpler experiments – with one highly idealized upstream 'rotor' – that have already been carried out so successfully.

3D transition is the other problem. We actually talked about 3D at Minnowbrook 2 but on the whole the total effort on the problem still tends to be small. There are cases where, as Paul Gostelow and others described, we might be able to see different transition behavior in different parts of a 3D flow system. Some strange behavior may be discovered if a complete computation or experiment can be carried out.

Another thing that seems worth doing is study of 'flow modules' (going back to Mark Monrovian's phrase, also mentioned by Tom Corke this morning) connected with leakage flows, cavities and all those other things that affect secondary flows and so on. Can we define, for these flow situations, reference flow modules which can then be studied in considerable detail, both experimentally and computationally – just as we have a standard Pak B, T106 or whatever? Can we start looking at what the flow structure is in these situations – flow characteristics that affect so many other parameters of interest in turbines? It should be interesting to do experiments as well as DNS on such modules. The major problem in doing them may be defining the appropriate boundary conditions, at the non-solid boundaries of the flow domain.

Returning to DNS, after hearing the presentations made at this meeting, and also Professor Rodi's report earlier this morning, one gets the impression that the major limiting factor here now is cost; but computers are getting cheaper, and the cost of making a calculation is still going down rapidly. Of course our ambitions have also grown, and we now want to do more difficult things than we did before – complex 3D geometry and unsteadiness are major problems. My personal reaction has been that, given the need for what everyone has been calling high fidelity simulation – whether one is doing experiments or computations – and given the particularly difficult situation that prevails with models and with LES, how can there be argument about the value of doing DNS? Turbomachines are one area where the Reynolds numbers are awkward (transition, separation, relaminarization, unsteady, 3D etc.) but computationally just manageable – ideal from the point of view of doing DNS. And the alternatives are not terribly attractive. If modeling should really become the preserve of industry – maybe with some inputs from academics – and LES has the kind of limitations that were described yesterday and today, then it seems to me the question is not whether we should be doing DNS but rather how best to do it. There are some innovative possibilities here. If it is largely a question of computer time, the facilities being already there, as Wolfgang said (although of course *someone* is paying for the computers), perhaps some international initiative is required. One thing you can do with computing easily is to share the task – it is unlike working on an experimental rig. I am reminded of the project that the climate change people have been running, where thousands of people run a code on their own machines: the work is distributed among such a large number of people that the total expense comes down. (See Langenberg H 2003 'Global effort to plot climate change' *Nature* 425:112.) Well, turbines might not have the same appeal that climate change does, but I think a lot of people would be very interested if the project became international. So it may be something worth looking at, taking a major international initiative on DNS, on both the big problems and the little modules. The purpose would be gaining insight and 'understanding' – as from a good experiment – rather than providing design tools immediately. After all, DNS is more likely to provide insight on real technological problems in the turbomachinery industry than in any other industry one can think of.

A few words about spots. In the earlier Minnowbrook meetings we talked a great deal about them and their peculiar behavior in different situations. There has been a fair bit of work done and slowly feeling for spot behavior is improving – this is another area where the Minnowbrooks have made a significant contribution. It is important that work like what Frank Smith is doing must continue, because I don't know of any other theory about spots at all. There is still work to be done with transition scenarios in

complex unsteady situations. As we get closer to handling messy 3D flows these issues will become important.

One last suggestion. After attending these and other transition meetings for some decades now, I see that some issues keep cropping up again and again. It is time to look for a scapegoat who will write a book, or at least a comprehensive review, so that what was done ten or twenty years ago is not forgotten, and there is one place where you can find roughly what is known at any given point in time. Mark Morkovin was trying to do such a book but I don't think he got very far. I was asking Eli whether he would do it and he said 'No'. Writing that book maybe one of the most useful things that can be done now in the field of transition. The problem is not solved, but it would be good to set out what is known and what is not.

So, let me stop there. There is only one other thing that I have to do, and that is to thank the people who have organized these meetings all these years, John LaGraff, Paul Gostelow, the absent Terry Jones and their friends and colleagues who, I think, have discovered the unique format these meetings work to. Having been at all the four meetings in the series I must say that they are among the most unusual and enjoyable meetings I have ever attended. Part of the reason is that we are locked up here for a few days in idyllic surroundings, and can talk about the subject morning, noon and night, around the bar, next to the lake or wherever. There is also the composition of the group, which includes people doing high theory, computing, experiments, and control, and people designing and building engines: all can get together and talk about their problems with intensity. So when Simon said 'Thank you' this morning to all assembled here, I think we should pass on the thanks to the people who organize these meetings. So on behalf of all of you and on behalf of myself I would like to thank them for their splendid effort.

Thank you very much for giving me the opportunity to be here.

Gostelow: That's pretty rare isn't it? Come and meet in two years time. We'll see about that. It will be two or three years anyway, that's for sure. We'll be here and you will, I hope. Thank you Roddam, the usual excellent summary of the meeting. I think you've drawn everything together. I will resist any temptation to invite questions or discussion because I think Roddam has really brought it all together. So I think it is a good idea now to bring things to a close, so thank you very much Roddam and over to John for wrapping things up.

LaGraff: O.K. Thank you Paul. Thank you Roddam for your kind words and for your contribution to this workshop. A lot of people have helped me with this and I'd like to thank again my co-chairs, Paul, Reza and Terry Jones, who is not here but still put a lot of work into helping me with planning this. And also it's very important to thank our sponsors that make it possible to get together, to get all these people here. Without that help we wouldn't be here. So I would like to thank them once again. And also to acknowledge a lot of very busy people who take time out to come here and to put in a lot of time these three days. I was feeling guilty last night looking at the beauty of the lake and the sun setting and all these groups were hard at work in breakout sessions at nine o'clock in the evening.

Narasimha: It's a wonderful prison.

LaGraff: Please may I ask you, when you get back home and think about it, to send one of the co-chairs or myself any suggestions for how we can improve the format, the scheduling, the times of presentations, the question period format. Please let us know how we can continue to improve it.

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13. ABSTRACT (Maximum 200 words)

This volume and its accompanying CD–ROM contain materials presented at the Minnowbrook IV—2003 Workshop on Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows held at the Syracuse University Minnowbrook Conference Center, Blue Mountain Lake, New York, August 17–20, 2003. Workshop organizers were John E. LaGraff (Syracuse University), Terry V. Jones (Oxford University), J. Paul Gostelow (University of Leicester), and Reza Abhari (ETH, Zurich). The workshop followed the theme, venue, and informal format of three earlier workshops: Minnowbrook I (1993), Minnowbrook II (1997), and Minnowbrook III (2000). The workshop was focused on physical understanding the late stage (final breakdown) boundary layer transition, separation, and effects of unsteady wakes with the specific goal of contributing to engineering application of improving design codes for turbomachinery. The workshop participants included academic researchers and representatives from the gas-turbine industry from the United States and abroad and from U.S. Government laboratories. The physical mechanisms discussed included flow instabilities, bypass and natural transition, turbulent spots and calmed regions, wake interactions with attached and separated boundary layers, turbulence and transition modeling and CFD, DNS, and active and passive flow control in turbomachinery. This volume contains abstracts and copies of the viewgraphs presented, organized according to the workshop sessions. The viewgraphs are included on the CD–ROM only. The workshop summary and the plenary and discussion transcripts clearly highlight the need for continued vigorous research in the technologically important area of transition, separated and unsteady flows in turbomachines.

14. SUBJECT TERMS

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