NASA/CP—2020-220327

Proceedings of the 2010 NASA-Industry Low Pressure Turbine and Power Turbine (LPT/PT) Efficiency Improvement Workshop

David E. Ashpis, Editor
Glenn Research Center, Cleveland, Ohio

March 2020

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Proceedings of a workshop held at and sponsored by
NASA Glenn Research Center
Cleveland, Ohio
August 10–11, 2010

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

March 2020

Acknowledgments

Thanks to workshop note takers: Ashlie Flegel, Viki Alexander, Paul Giel, and Jerry Welch.

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Abstract

This report includes materials from the NASA-Industry Low Pressure Turbine and Power Turbine (LPT/PT) Efficiency Improvement Workshop that took place on August 10 and 11, 2010, at the NASA Glenn Research Center. The materials include all the presentation slides and a workshop summary article that provides background information, describes the workshop motivation, and provides a summary of the open discussions that took place. Participation included specialists from academia, government laboratories, and industry, from the United States and abroad. The workshop was motivated by underperformance of large commercial engines related to lower-than-expected efficiency of the LPT. It focused on addressing the relevant flow physics. Recommendations were made for continued research. The main recommendation was to conduct rotating rig tests accompanied by the study of fundamental mechanism using computational fluid dynamics (CFD) and turbulence and transition model development.

Contents

Workshop presentation slides

Note: The order is as presented at the workshop. Presenters' names in boldface.

Session 1—Opening

Session 2—Industry Reviews

Session 3—Invited Presentations

Session 4—Power Turbine

Session 5—Research Laboratories Views

Session 6—Brief Overviews of Experimental Facilities

Session 7—Keynote Presentations

Session 8—Invited Overviews

Workshop Summary

NASA-Industry LPT/PT Efficiency Improvements Workshop, August 10-11, 2010
AGENDA

Day 1 - Tuesday, August 10, 2010		
8:00 AM	Registration & Refreshments	
8:30 AM	Opening	NASA/GRC/RT Directorate Welcome NASA/FAP/SFW/Ruben Del Rosario NASA/FAP/SRW/Isaac Lopez
8:45 AM	Introduction -- Workshop Motivation	UTRC/Om Sharma
9:15 AM	Past LPT program	GRC/Lou Povinelli GRC/David Ashpis
9:30 AM	Industry Reviews	Rolls-Royce
		ITP
10:10 AM	Break	
10:20 AM	Industry Reviews - Cont.	General Electric
		Honeywell
		Pratt & Whitney
11:20 AM	NASA System Analysis - Benefits of LPT improvements	GRC/Chris Snyder
11:40 AM	MDAO at GRC	GRC/Meng-Sing Liou
12:00 PM	Lunch	
1:00 PM	Variable Speed Power turbine	GRC/Jerry Welch
1:30 PM	AFRL View	AFRL/John Clark
1:50 PM	CNRC View	CNRC/Mike Benner
2:00 PM	Topical Discussions: LPT/PT Design & Flow Physics Issues	
3:00 PM	Break	
3:15 PM	Topical Discussions (Cont.)	
4:15 PM	**Overview of experimental facilities:**	
4:15 PM	Notre Dame LPT Rig	U. Notre Dame/Joshua Cameron
4:30 PM	NASA New Turbine Rig	GRC/Paul Giel
4:40 PM	USNA LPT facilities	USNA/Ralph Volino
4:45 PM	OSU LPT facilities	OSU/Jeffrey Bons & Kyle Gumperz
4:50 PM	Summary Day 1	
5:00 PM	**Adjourn Day 1**	
6:00 PM	No-Host Dinner - 100th Bomb Group Restaurant	

Day 2 - Wednesday, August 11, 2010		
7:45 AM	Checkin & Refreshments	
8:00 AM	Keynote 1: LP Turbine Research Issues: Physical Phenomena & Performance Modelling	U. Cambridge/Howard Hodson & John Coull
9:00 AM	Keynote 2: Review of CFD for LPT flows	UC Davis/Roger Davis
9:45 AM	Break	
10:00 AM	Keynote 3: Transition & Turbulence Modeling for LPT Flows	ANSYS/Florian Menter
11:00 AM	Insights into LPT flow physics	U. Leicester/Paul Gostelow
11:20 AM	Intermittencey based transiton model validation	North Dakota State U/Bora Suzen
11:40 AM	DNS of LPT flows at U. Arizona	U. Arizona/Wolfgang Balzer & Hermann Fasel
12:00 PM	Lunch	
1:00 PM	Turbulence Modeling Working Group Overview	Wright State U./George Huang
1:30 PM	Open Discussion: Formulation of Action Items for Future Research Projects	
3:00 PM	Break	
3:15 PM	Workshop Summary	
3:30 PM	**Adjourn**	
3:45 PM	Optional facility tours (tentative)	Main Gate or Shuttle Transportation
	Optional one-one meetings	Pre-Arrange

Contact: David Ashpis ashpis@nasa.gov 216-433-8317 Mobile: 216-410-7485

9-Aug-10

NASA-Industry LPT/PT Workshop Aug 10-11, 2010 - List of Participants

Title	First Name	Last Name	E-mail	Company/Organization	Job Title
Dr.	Ali	Ameri	ameri@grc.nasa.gov	Ohio State University/NASA Glenn	Research Scientist
Dr.	David	Ashpis	ashpis@nasa.gov	NASA GRC/Turbomachinery	Aerospace Engineer
Dr.	Ravikanth	Avancha	avancha@research.ge.com	GE Global Research	Mechanical Engineer
Mr.	Wolfgang	Balzer	wbalzer@email.arizona.edu	The University of Arizona	Research Assistant
Mr.	Brian	Barr	barr@research.ge.com	GE Global Research	Mechanical Engineer
Dr.	Michael	Benner	michael.benner@nrc-cnrc.gc.ca	**National Research Council of Canada**	Group Leader, Internal Aerodynamics
Dr.	Jeffrey	Bons	bons.2@osu.edu	Ohio State University	Professor
Dr.	Dario	Bruna	dariobruna@oai.org	NASA/O.R.A.U	NPP Fellow
Dr.	Joshua	Cameron	j.cameron@nd.edu	University of Notre Dame	Professor
Dr.	Mark	Celestina	mark.l.celestina@nasa.gov	NASA GRC/Turbomachinery	Aerospace Engineer
Dr.	John	Clark	john.clark3@wpafb.af.mil	AFRL	Lead, Turbine Component Research
Mr.	Eugene	Clemens	eugene.f.clemens@rolls-royce.com	Rolls Royce	Senior Mechanical Engineer
Dr.	John	Coull	jdc38@cam.ac.uk	**University of Cambridge, UK**	Research Associate
Dr.	Lyle	Dailey	lyle.dailey@ge.com	GE Aviation	Senior Staff Engineer
Dr.	Roger	Davis	davisrl@ucdavis.edu	University of California, Davis	Professor
Dr.	Jim	DeBonis	james.r.debonis@nasa.gov	NASA/GRC/Inlets-Nozzles	Aerospace Engineer
Dr.	Ruben	Del Rosario	ruben.delrosario@nasa.gov	NASA	Principal Investigator, Subsonic Fixed Wing
Mr.	Kenneth	Durbin	kenneth.s.durbin@us.army.mil	Aviation Applied Technology Directorate	Aerospace Engineer
Ms.	Barbara	Esker	barbara.m.esker@nasa.gov	NASA	Deputy Chief, Fundamental Aeronautics
Mr.	John	Fabian	john.c.fabian@nasa.gov	NASA GRC/Turbomachinery	Aerospace Engineer
Dr.	Nick	Georgiadis	georgiadis@nasa.gov	NASA/GRC/Inlets-Nozzles	Aerospace Engineer
Dr.	Paul	Giel	paul.w.giel@nasa.gov	ASRC / NASA GRC	Sr. Research Engineer
Mr.	Kyle	Gompertz	gompertz.2@buckeyemail.osu.edu	The Ohio State University	Graduate Research Associate
Dr.	J. Paul	Gostelow	paul.gostelow@nrc.ca	**National Research Council of Canada**	Principal Research Officer
Dr.	Chunill	Hah	chunill.hah-1@nasa.gov	NASA GRC/Turbomachinery	Aerospace Engineer
Mr.	Tom	Hajek	thajek@rolfgroup.net	Rolf Group International	President & CEO
Dr.	David	Halstead	david.halstead@ge.com	GE Aviation	Manager, Turbomachinery Aerodynamics
Dr.	Frank	Haselbach	frank.haselbach@rolls-royce.com	**Rolls-Royce plc (UK)**	Chief of Function, Turbines
Dr.	Michael	Hathaway	michael.d.hathaway@nasa.gov	NASA GRC/Turbomachinery	Aerospace Research Engineer
Dr.	James	Heidmann	heidmann@nasa.gov	NASA GRC/Turbomachinery	Chief, Turbomachinery and Heat Transfer Branch
Dr.	Howard	Hodson	hph1000@cam.ac.uk	**University of Cambridge (UK)**	Professor
Dr.	George	Huang	george.huang@wright.edu	Wright State University	Professor and Chair
Mr.	Dennis	Huff	dennis.l.huff@nasa.gov	NASA/GRC	Deputy Chief, Aeropropulsion Division
Dr.	Lennart S	Hultgren	hultgren@nasa.gov	NASA GRC/Acoustics	Aerospace Engineer
Dr.	Brad	Hutchinson	brad.hutchinson@ansys.com	**ANSYS Canada Ltd.**	VP Industry Marketing, Aerospace & Turbomachinery
Dr.	Mounir	Ibrahim	m.ibrahim@csuohio.edu	Cleveland State University	Professor
Dr.	Meng-Sing	Liou	meng-sing.liou@nasa.gov	NASA GRC	Senior Technologist
Mr.	Isaac	Lopez	isaac.lopez@nasa.gov	NASA	Project Scientist
Lt.	Eric	Lyall	Michael.Lyall@afit.edu	Air Force Institute of Technology	PhD Student
Dr.	Nateri	Madavan	nateri.k.madavan@nasa.gov	NASA	API, Aerothermodynamics, FA-SFW Project
Mr.	Shankar	Magge	shankar.magge@pw.utc.com	Pratt and Whitney	Senior Fellow
Dr.	Malak	Malak	malak.malak@honeywell.com	Honeywell	Program Manager - Advanced Technology
Mr.	Craig	McKeever	craig.mckeever@honeywell.com	Honeywell	Turbine Aerodynamics
Ms.	Ashlie	McVetta	ashlie.b.mcvetta@nasa.gov	NASA GRC/Turbomachinery	Research Aerospace Engineer
Dr.	Florian	Menter	florian.menter@ansys.com	**ANSYS (Germany)**	R&D Fellow
Dr.	Louis	Povinelli	louis.a.povinelli@nasa.gov	NASA GRC	Senior Technologist
Dr.	Thomas	Praisner	thomas.praisner@pw.utc.com	Pratt and Whitney	Princicpal Engineer
Dr.	D. R.	Reddy	dreddy@grc.nasa.gov	NASA GRC	Chief, Aeropropulsion Division
Dr.	Lonnie	Reid	lonnie.reid@ap-solutions.com	AP-Solutions	President
Dr.	Aamir	Shabbir	aamir.shabbir@utrc.utc.com	United Technologies Research Center	Staff ResesEngineer
Dr.	Om	Sharma	om.sharma@utrc.utc.com	United Technologies Research Center	Senior Fellow
Dr.	Vikram	Shyam	vikram.shyam-1@nasa.gov	NASA GRC/Turbomachinery	Research Aerospace Engineer
Mr.	Gary	Skoch	gary.j.skoch@nasa.gov	Army	Aerospace Engineer
Dr.	Anthony	Strazisar	anthony.j.strazisar@nasa.gov	NASA	GRC Chief Scientist & FAP Senior Technical Advisor
Dr.	Y. Bora	Suzen	bora.suzen@ndsu.edu	North Dakota State University	Assistant Professor
Dr.	Wai-Ming	To	waiming.to@nasa.gov	University of Toledo/NASA GRC	Senior Research Associate
Mr.	Fu-Lin	Tsung	fu-lin.tsung@ge.com	General Electric	Senior Engineer
Mr.	Raul	Vazquez Diaz	raul.vazquez@itp.es	**Industria De Turbo Propulsores, S.A. (Spain)**	Head of Aerodynamics & Systems Department
Dr.	Ralph	Volino	volino@usna.edu	U.S. naval Academy	Professor
Dr.	Aspi	Wadia	aspi.wadia@ge.com	GE Aviation	Chief Consulting Engineer - Aerodynamics
Dr.	Gerard	Welch	gerard.e.welch@nasa.gov	NASA GRC/Turbomachinery	Aerospace Engineer
Dr.	Jixian	Yao	yaoj@ge.com	GE Global Research	Sr. Mech. Engr.

Session 1
Opening

National Aeronautics and Space Administration

Welcome to the NASA-Industry Low Pressure Turbine / Power Turbine (LPT/PT) Efficiency Improvement Workshop

August 10-11, 2010

NASA Glenn Research Center

Supported by

the Fundamental Aeronautics Program

Subsonic Fixed Wing Project

Subsonic Rotary Wing Project

Workshop Objectives

- *Discuss, on a pre-competitive basis, efficiency improvements of modern LPT/PT for reduced engine fuel burn and weight*
- *The expected outcomes of the workshop are*
  - *Comprehensive understanding of flow and losses in modern LPT & PTs,*
  - *Understanding of the barriers to efficiency improvements*
  - *Develop an outline of future research needs*

National Aeronautics and Space Administration

Overview of NASA Aeronautics Programs

Dr. Rubén Del Rosario, Principal Investigator
Subsonic Fixed Wing Project
Fundamental Aeronautics Program

Presented At LPT/PT Efficiency Improvement Workshop
Ohio Aerospace Institute
Cleveland, OH, USA
August 10-11, 2010

The National and NASA context

- National Aeronautics R&D Policy (2006) and Plan (2010 update)
  - "Mobility through the air is vital…"
  - "Assuring energy availability and efficiency …" and "The environment must be protected…"
  - "Aviation is vital to national security and homeland defense"

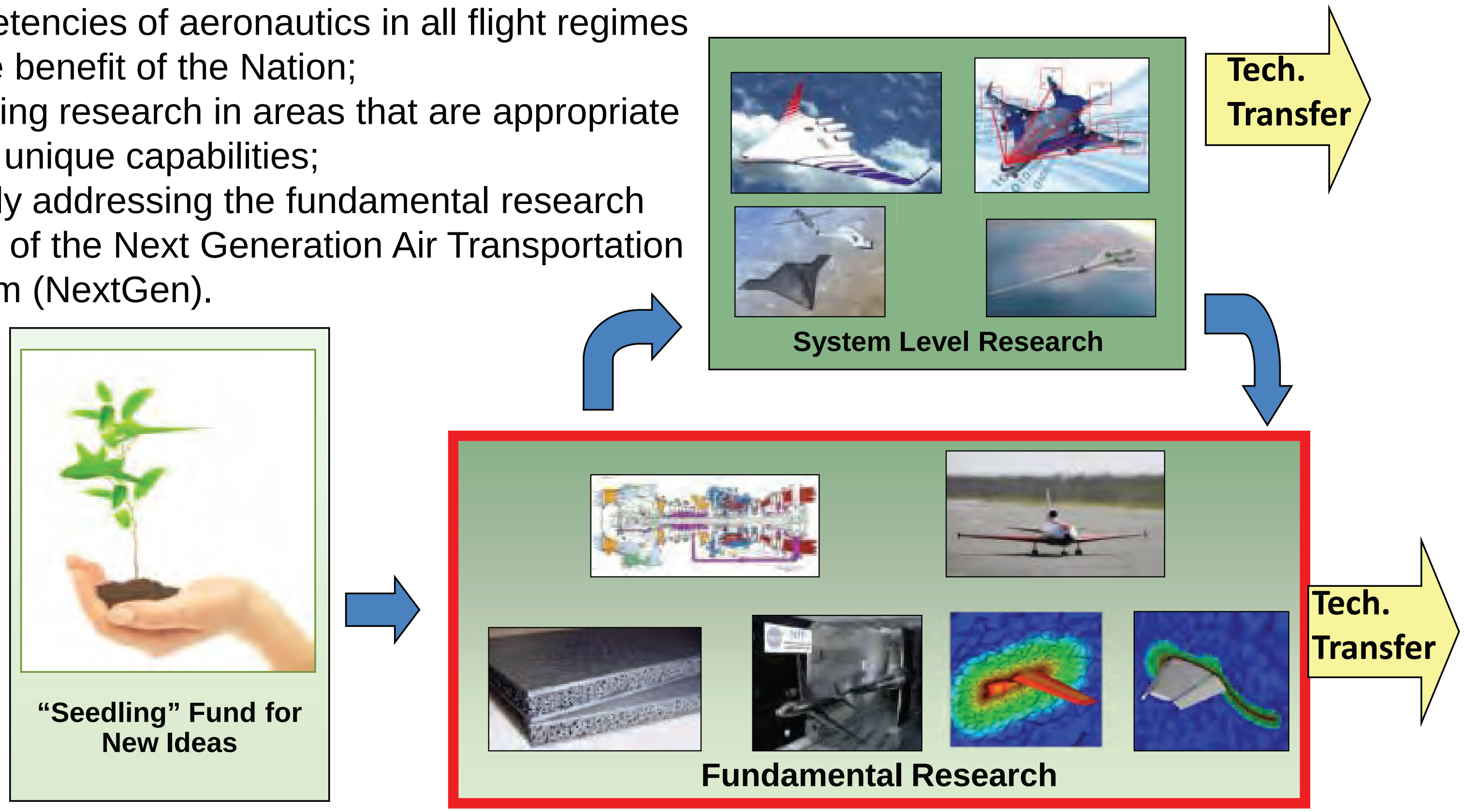
- NextGen: The Next Generation Air Transportation System
  - Revolutionary transformation of the airspace, the vehicles that fly in it, and their operations, safety, and environmental impact

- NASA Strategic Plan
  - Sub-Goal 3E: "By 2016, develop multidisciplinary analysis and design tools and new technologies enabling better vehicle performance in multiple flight regimes and within a variety of transportation system architectures." (updated)

NASA Aeronautics Investment Strategy

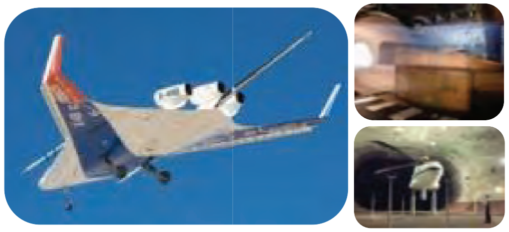
ARMD Principles:

- Maintaining our commitment to the mastery & intellectual stewardship of the core competencies of aeronautics in all flight regimes for the benefit of the Nation;
- Focusing research in areas that are appropriate to our unique capabilities;
- Directly addressing the fundamental research needs of the Next Generation Air Transportation System (NextGen).



Enabling "Game Changing" concepts and technologies from advancing fundamental research ultimately to understand the feasibility of advanced systems

NASA Aeronautics Programs in FY2010

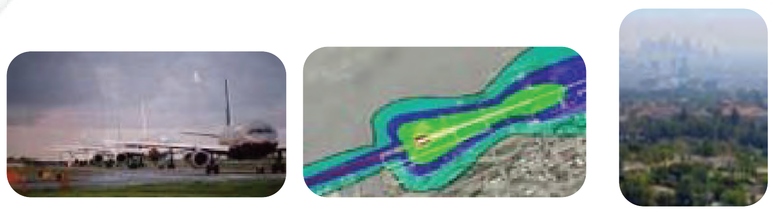


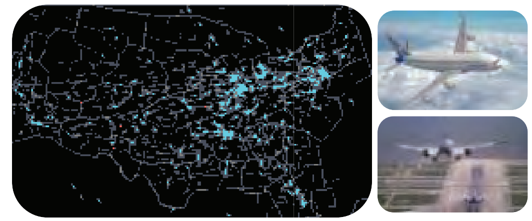
Fundamental Aeronautics Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

Integrated Systems Research Program

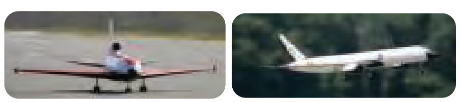
Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment





Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.



Aviation Safety Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.

Aeronautics Test Program

Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.

Integrated Systems Research Program Overview

***Program Goal*:**
Conduct research at an integrated system-level on promising concepts and technologies and explore, assess, or demonstrate the benefits in a relevant environment

Environmentally Responsible Aviation (ERA) Project

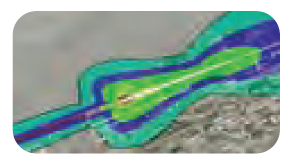
Explore and assess new vehicle concepts and enabling technologies through system-level experimentation to *simultaneously* reduce fuel burn, noise, and emissions

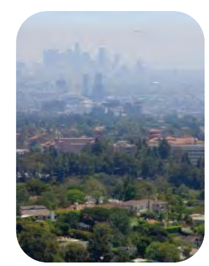
Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

Transition design guidelines, algorithms, technologies, operational concepts, and knowledge to the FAA and the UAS stakeholder community to assist them in establishing requirements for routine UAS NAS operations

Innovative Concepts for Green Aviation (ICGA) Project

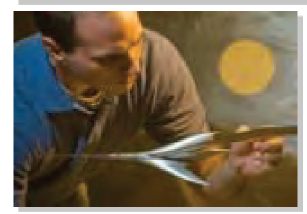
Spur innovation by offering research opportunities to the broader aeronautics community through peer-reviewed proposals, with a focus on making aviation more eco-friendly. Establish incentive prizes similar to the Centennial Challenges and sponsor innovation demonstrations of selected technologies that show promise of reducing aviation's impact on the environment.





Fundamental Aeronautics Program Overview

Goal: The overarching goal of the FA Program is to achieve technological capabilities necessary to overcome national challenges in air transportation including reduced noise, emissions, and fuel consumption, increased mobility through a faster means of transportation, and the ability to ascend/descend through planetary atmospheres. These technological capabilities will enable design solutions for the performance and environmental challenges of future air vehicles – vehicles that fly through any atmosphere at any speed.



Subsonic Fixed Wing (SFW)

Develop improved prediction methods and technologies that enable dramatic improvements in noise and emissions reduction, and increased performance (fuel burn and reduced field length) characteristics of subsonic/transonic aircraft.

Subsonic Rotary Wing (SRW)

Radically improve the transportation system using rotary wing vehicles by increasing speed, range, and payload while decreasing noise and emissions.

Supersonics

Eliminate environmental and performance barriers that prevent practical supersonic vehicles (cruise efficiency, noise and emissions, performance, boom acceptability).

Hypersonics

Enable airbreathing access to space and high mass entry into planetary atmosphere.

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

SFW Approach

- Conduct Discipline-based Foundational Research

- Investigate Advanced Multi-Discipline Based Concepts and Technologies

- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes

- Enable Major Changes in Engine Cycle/Airframe Configurations

Primary Focus on Four Technical Challenges

- Actively-Controlled, Efficient Rotorcraft (ACER) (FY19): Simultaneously increase aerodynamic efficiency, control dynamic stall, reduce vibration, reduce noise
  - **Goal**: 100 kt speed improvement over SOA; noise contained within landing area; 90 pax /10 ton payload
  - **Benefits**: very high-speed, efficient cruise; efficient hover; reduced noise; improve ride quality
  - Performance, dynamic and acoustic benefits for tiltrotors and edgewise rotors

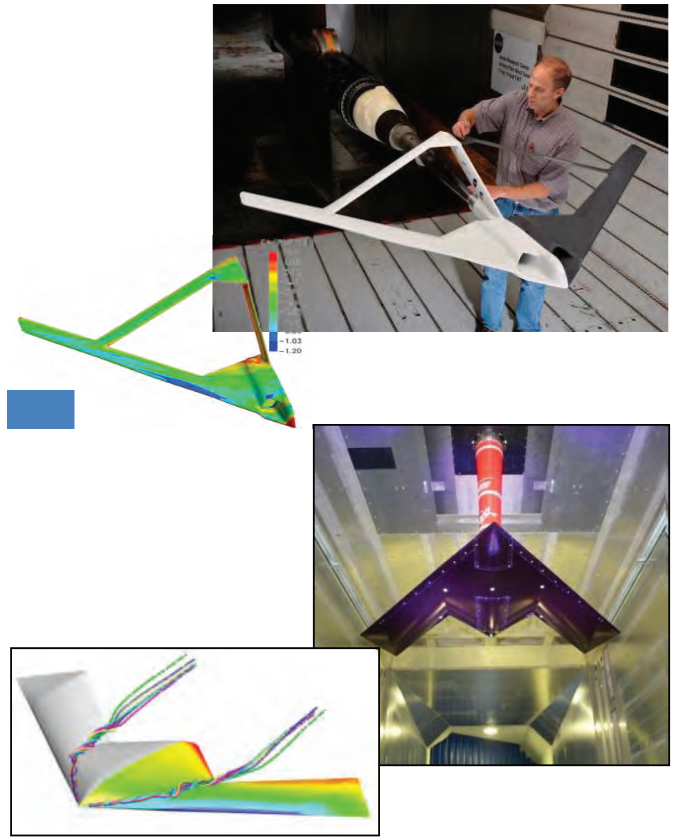
- Integrated Aeromechanics/Propulsion System (IAPS) (FY21): Develop and demonstrate technologies enabling variable-speed rotor concepts
  - **Goal**: 50% main rotor speed reduction while retaining propulsion efficiency
  - **Benefits:** very high-speed, efficient cruise; efficient hover; reduced noise, increased range
  - Reducing rotor rotation in high speed cruise will
    - ✓ mitigate compressibility effects on advancing side for edgewise rotors
    - ✓ Improve propulsive efficiency for tiltrotors

- Quiet Cabin (QC) (FY17): Reduce interior noise and vibration
  - **Goal**: Internal cabin noise at level of regional jet with no weight penalty
  - **Benefit**: passenger acceptability; increased efficiency through weight reduction
  - Cabin noise research benefits for tiltrotors and edgewise rotors

- NextGen Rotorcraft (FY21): Foster, develop and demonstrate technologies that contribute to the commercial viability of large rotary wing transport systems in NextGen.
  - **Goal**: mature technologies (icing, crashworthiness, condition based maintenance, low noise flight operations, etc) needed for civil, commercial operations
  - **Benefit**: enables vehicle acceptability for passengers and operators
  - Research benefits tiltrotors and edgewise rotors

Summary

- Addressing the Environmental Challenges and Improving Performance
- Undertaking and Solving the Enduring and Pervasive Challenges
- Understanding and Assessing the Game Changers for the Future
- Strong Foundational Research in partnership with Industry, Academia and Other Government Agencies



Technologies, Tools and Knowledge

N+3 Advanced Concepts
NRA Phase 1 Studies (SFW)

Description: Completed four 18-month "Advanced Concept Studies for Commercial Subsonic Transport Aircraft Entering Service in the 2030-35 Period" intended to stimulate far-term thinking towards future aircraft needs, and identify key technology needs to meet the challenges.

Results: Phase 1 final reports submitted March 31, 2010; final reviews held April 20-23, 2010

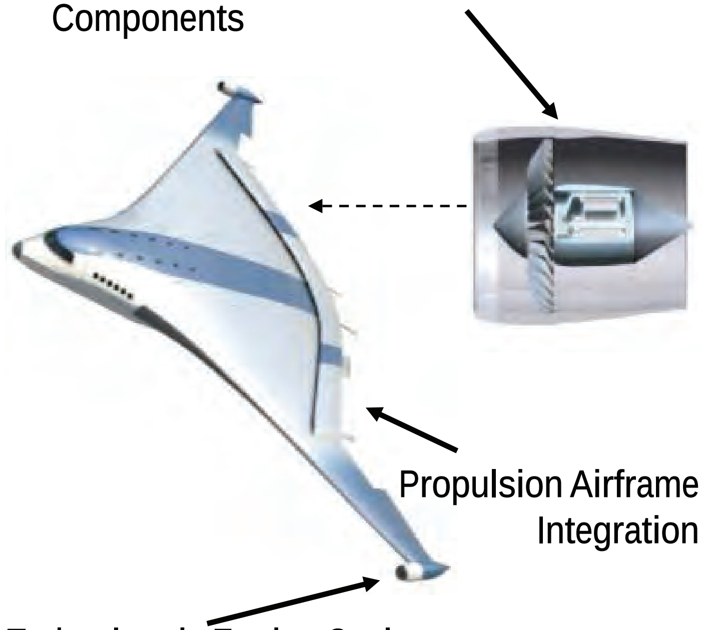
- Trends
  - Lower cruise speeds at higher altitude (~40-45k ft)
  - Heading toward BPR 20 (or propeller) with small, high efficiency core
  - Higher AR and laminar flow to varying degrees
- Uniquely enabling concepts/techs emerged (strut/truss, double bubble, hybrid-electric (battery) propulsion for example)
- Broadly applicable technology advances needed (for example lightweight materials, high temp materials, gust load alleviation)
- Energy: conventional/biofuel most prevalent, plus hybrid electric

Impact: Results will be used as key information to guide future investment in the SFW project, also basis for Phase 2 proposals currently under evaluation.

Additional N+3 Studies

Distributed Turboelectric Propulsion

NASA In-house



Truss-Braced Wing (TBW) Research

NASA In-house, NIA, Virginia Tech, Georgia Tech

High Span Truss-Braced Wing with Fold

Goldschmied Propulsor

Laminar Flow

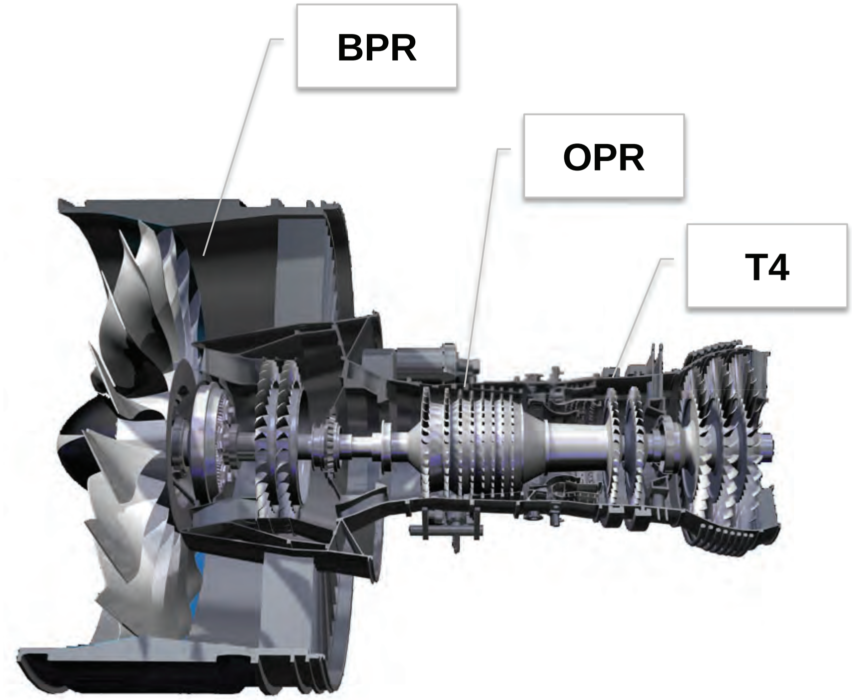
NASA/CP—2020-220327

NASA-Industry LPT/PT Efficiency Improvements Workshop, August 10-11, 2010

Introduction -- Workshop Motivation

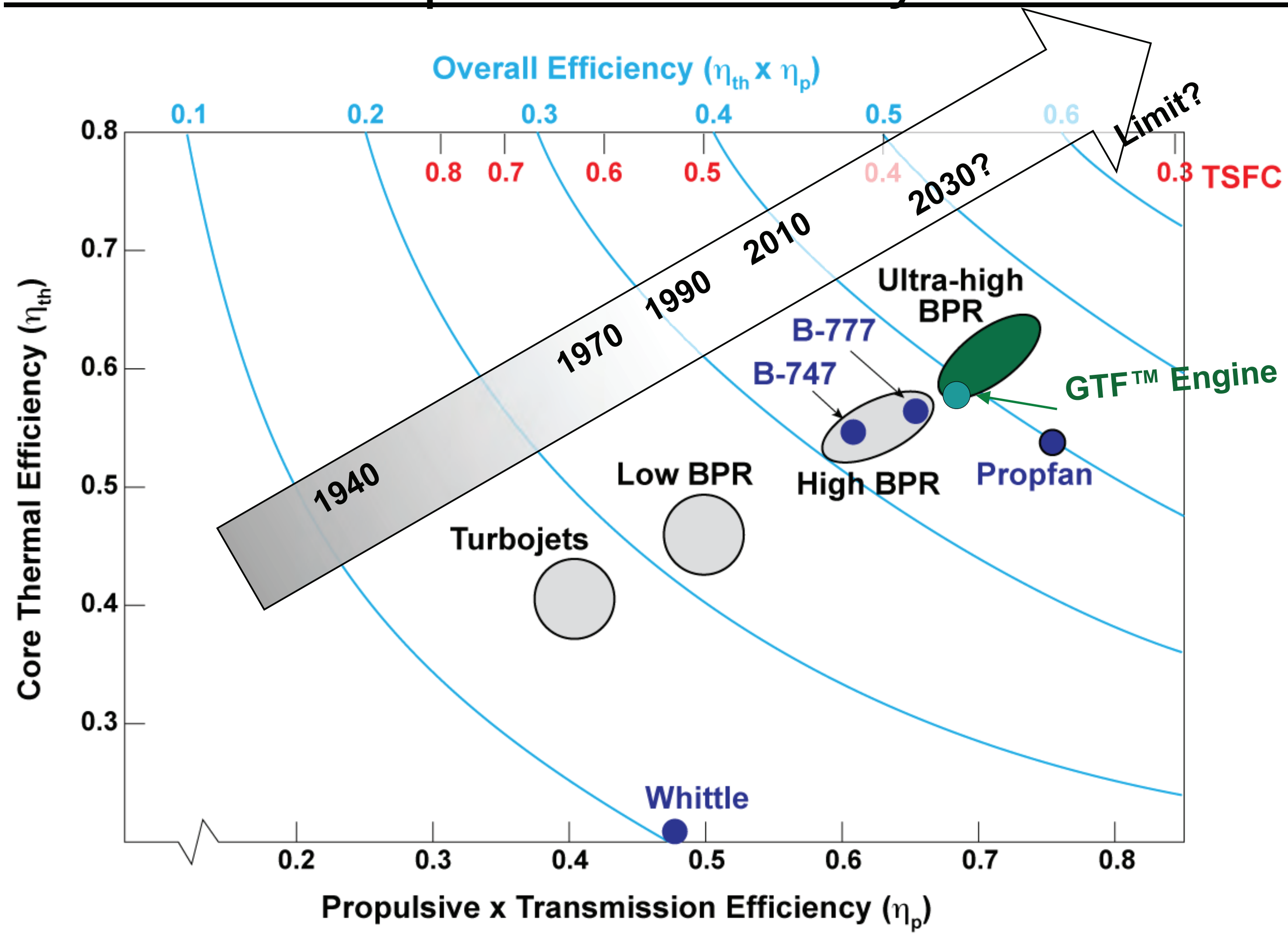
Om Sharma
UTRC

Gas Turbine Energy Efficiency Drivers



- Efficiency has improved on average 1%/year over last half century
- How much further can we go?
  - There are still improvement opportunities!

Thermal & Propulsive Efficiency Set Fuel Burn



TSFC Reduction

- Increased BPR, OPR
- Improved component efficiency:

Component efficiency enhancement over the last 25 years:

- Fan ~ 3-5%
- High Pressure Compressor ~ 2-4%
- High Pressure Turbine ~ 1.5-4%
- Low Pressure Turbines ~ 0-0.5% (more for some OEMs)

- 1% HPT efficiency = 0.5-0.6% in TSFC
- 1% HPC efficiency = 0.5-0.6% in TSFC
- 1% Fan efficiency = 0.7-0.9% in TSFC
- 1% LPT efficiency = 0.8-1%% in TSFC

IMPROVING LPT EFFICIENCY PROVIDES MOST COST EFFECTIVE OPPORTUNITY TO REDUCE FUEL CONSUMPTION

SOURCES OF LOSSES IN LPT

- Profile Losses ~ 60%
- End-wall Losses ~33%
- Leakage and Cooling Losses ~7%

- Loss Generation Mechanisms:
  - Boundary layers (laminar, transitional, turbulent), Reynolds #., Tu, Mach #
  - Airfoil loading levels
  - Gas turning, convergence ratio, inlet to exit velocity ratio
  - Flow-path divergence, aspect ratio
  - Interaction (HPT- LPT, Adjacent Airfoil Rows, LPT- Exit Guide Vane)
  - ………………………………………

LPTs have been the most efficient component in large commercial engines since late 1970s, with efficiencies exceeding 92%

NASA/CP—2020-220327

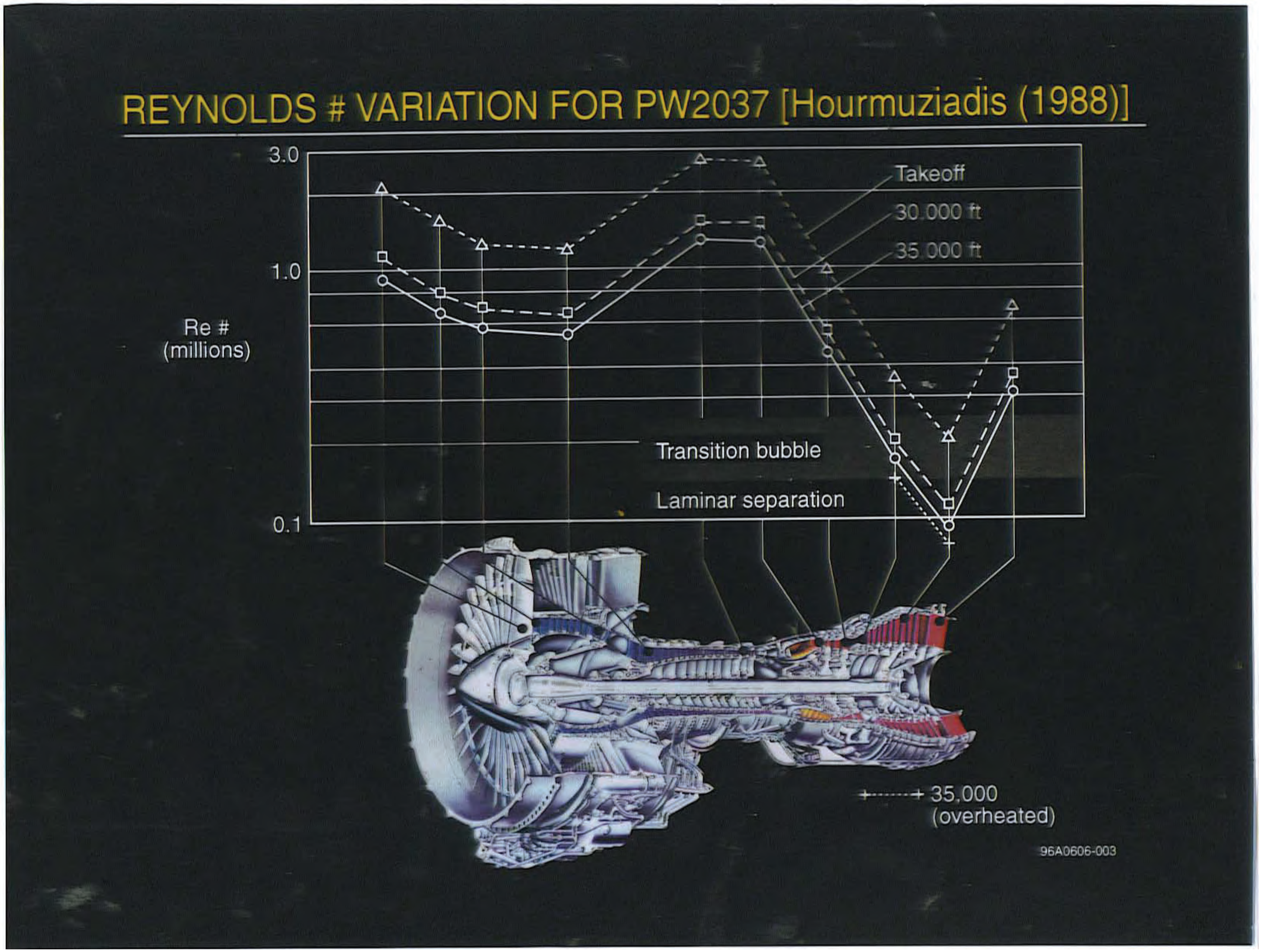
Profile Losses

• Significant progress made to develop understanding of loss generation processes (NASA, AFOSR support)

• Developed design criteria and CFD based models with empirical transition correlations to facilitate design execution

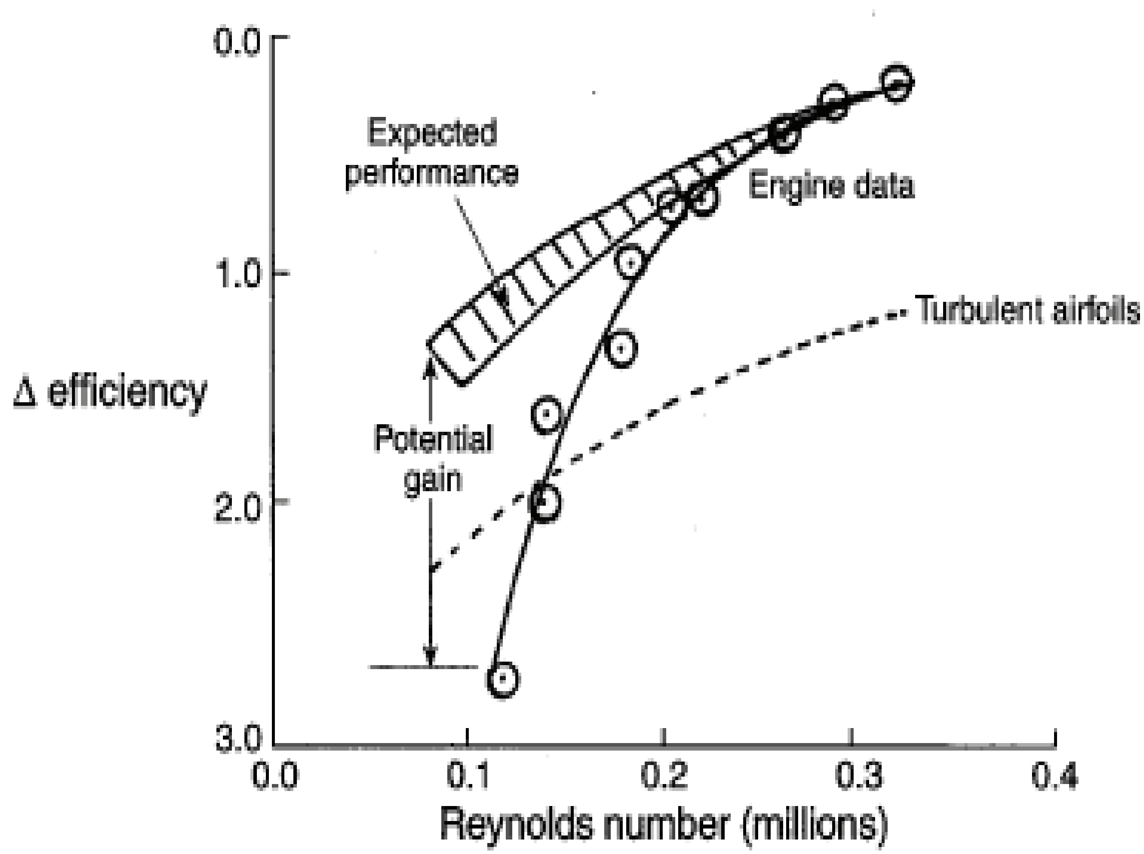
• There is a need to develop 1st principle based models for the transition onset in separated boundary layers (Need support)

•"High-lift" LPT designs developed to reduce part count. Application of this concept , however, has not yet yielded expected efficiency improvements


REYNOLDS # VARIATION FOR PW2037 [Hourmuziadis (1988)]
3.0
1.0
0.1
Re #
(millions)
Takeoff
30,000 ft
35,000 ft
Transition bubble
Laminar separation
35,000
(overheated)
96A0606-003

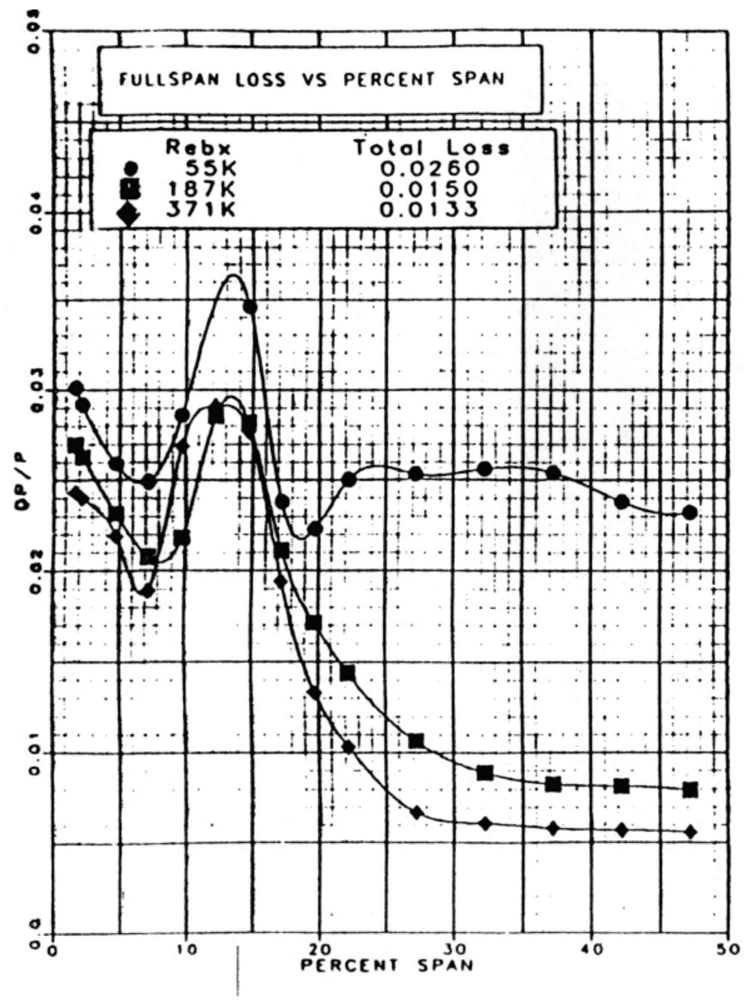
LOW RE # OPERATION CAUSES SIGNIFICANT PERFORMANCE REDUCTION

LOW PRESSURE TURBINES

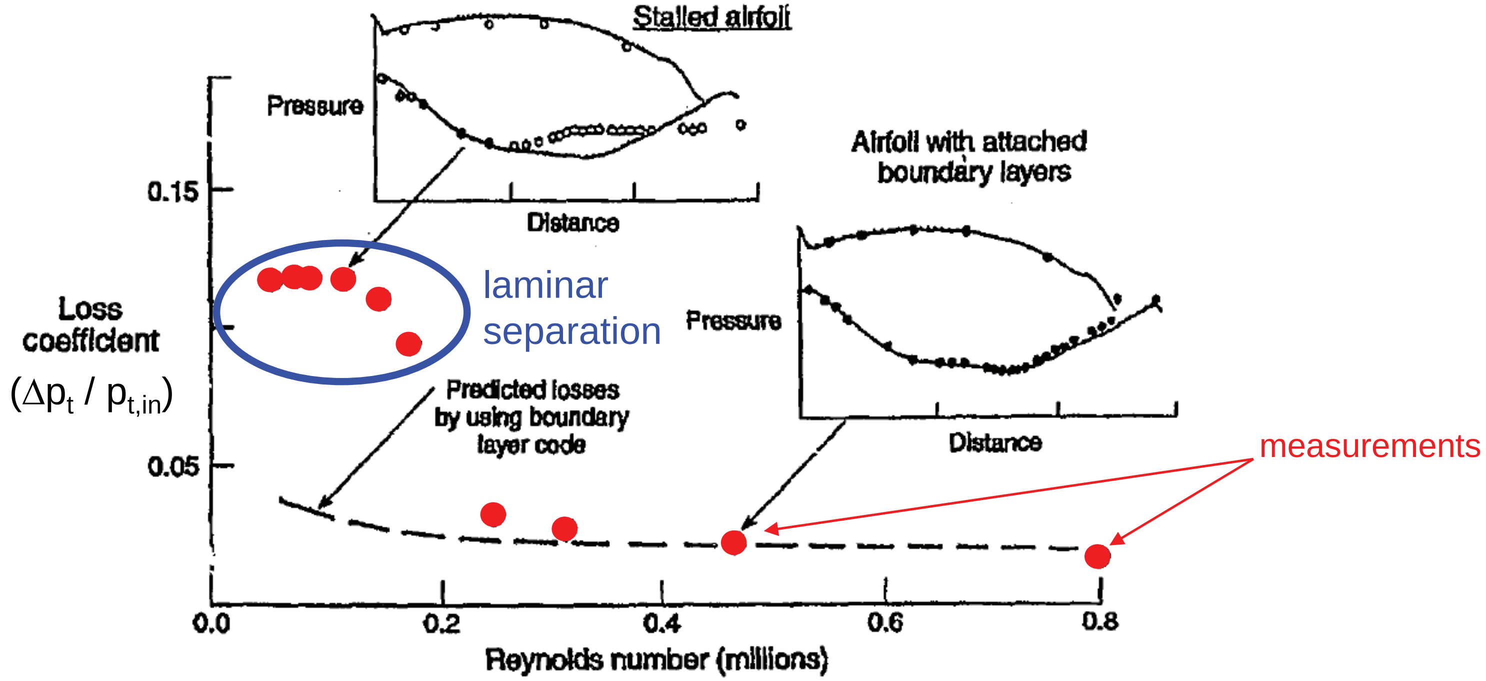


- Loss in performance due to drag on airfoils

LARGE INCREASE IN MID-SPAN (PROFILE) LOSS MEASURED FOR THE AIRFOIL WITH REDUCTION IN REYNOLDS



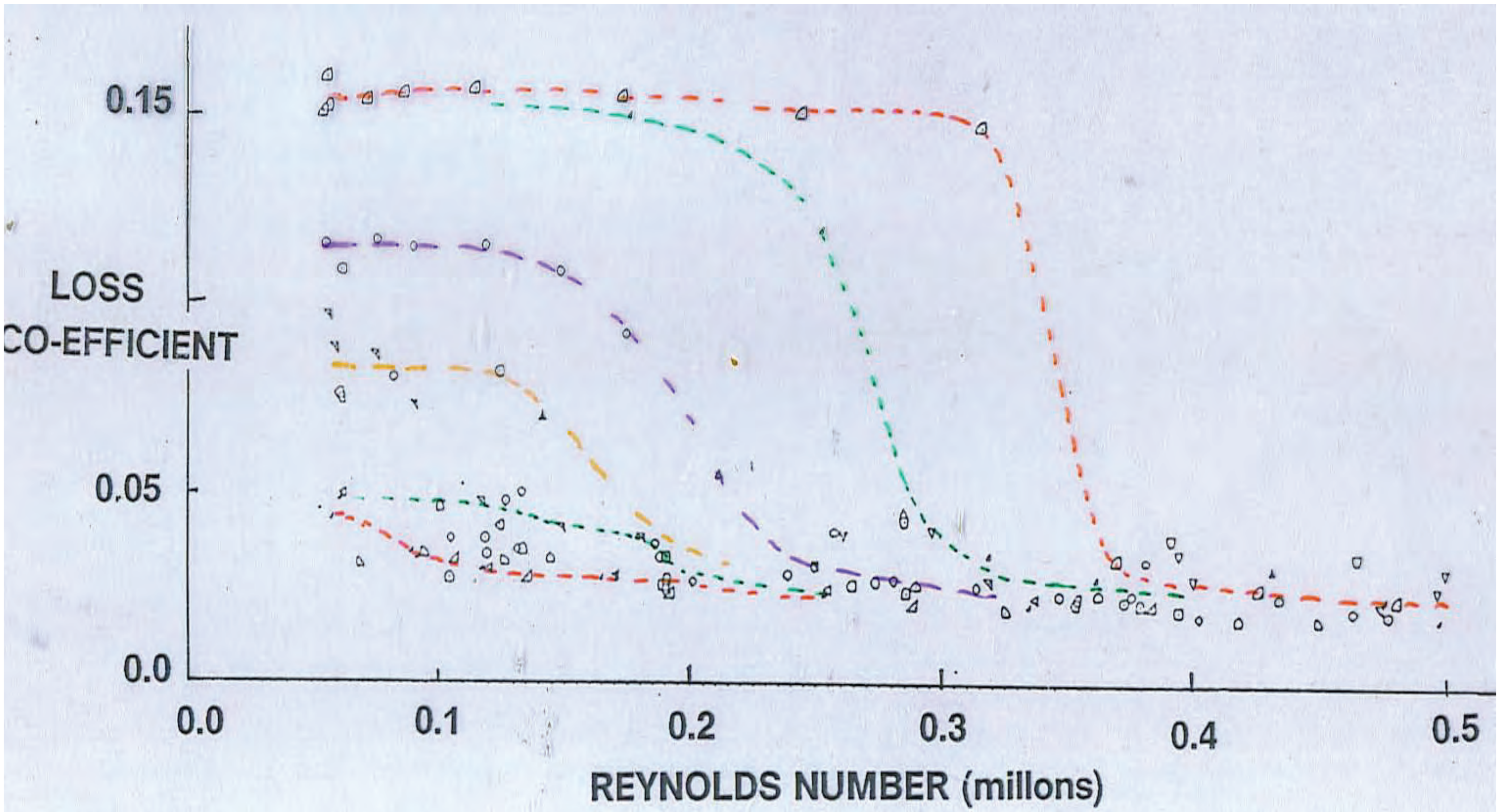
Losses in Turbine Airfoils Influenced by Reynolds#



Predicted vs. measured losses in a low-pressure turbine cascade (reproduced from Sharma, 1998)

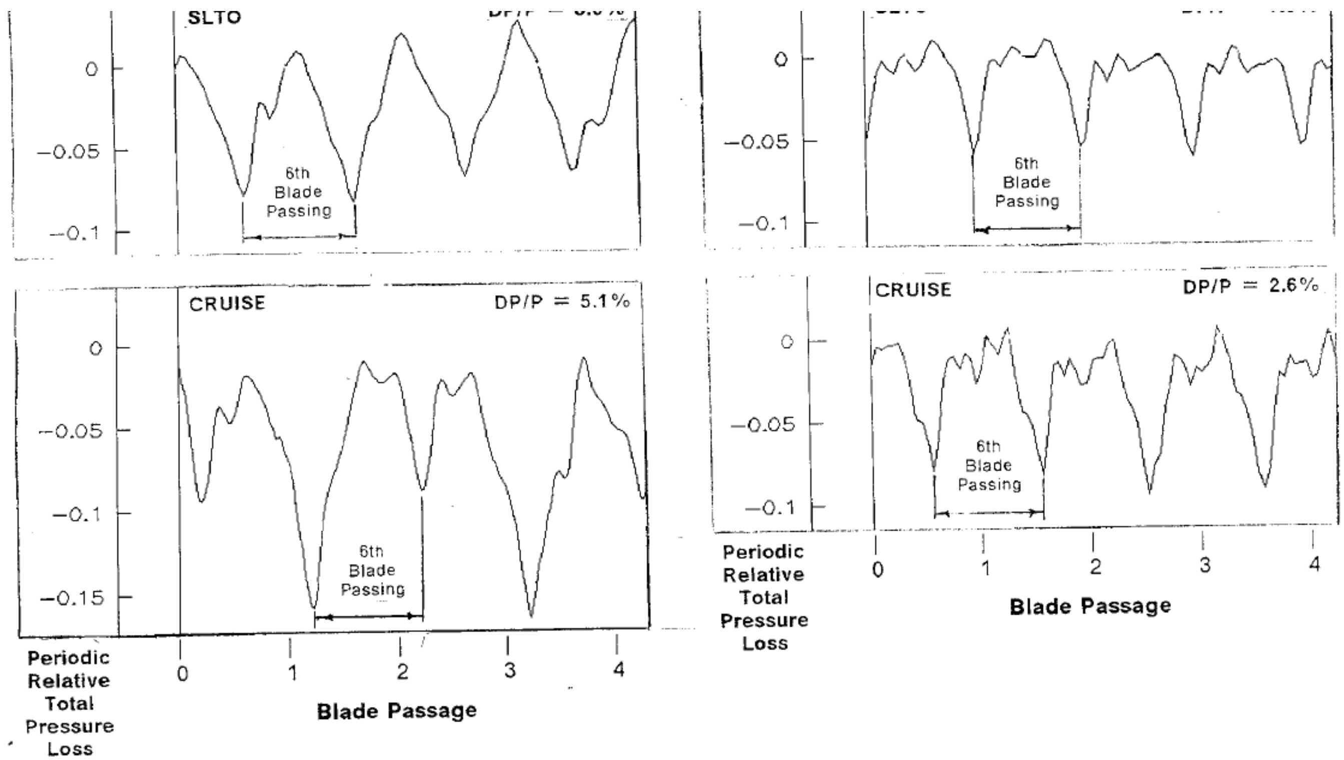
Large Variation In Profile Losses Measured For Airfoils Over A Range of Reynolds#

Design Criteria / Processes Developed To Desensitize The Impact of Re # on Losses



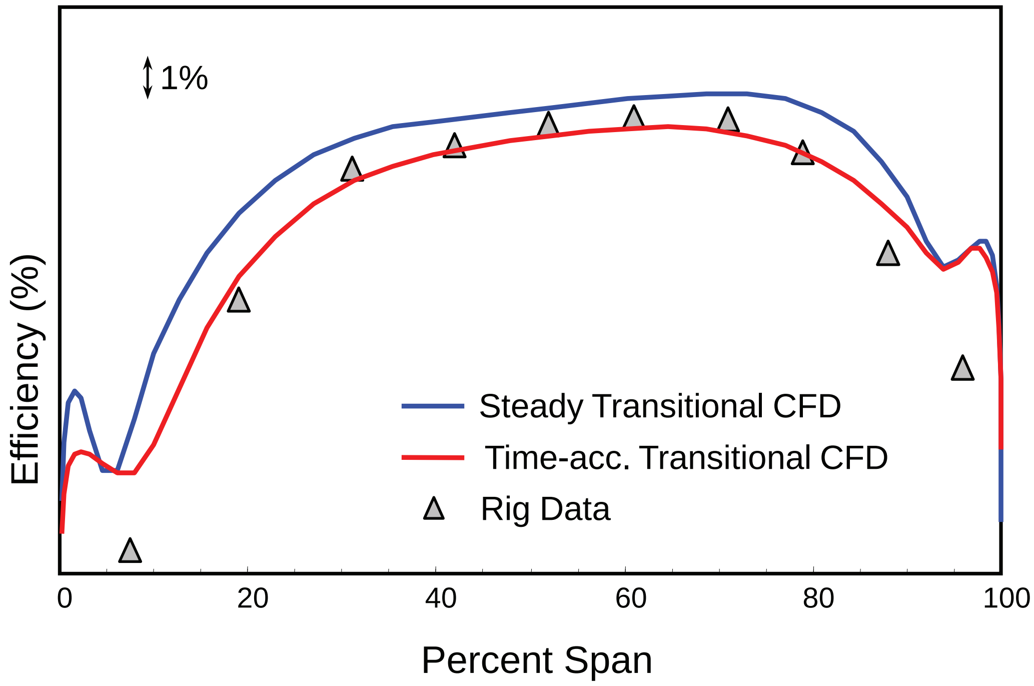
LPT REDESIGNED TO IMPROVE EFFICIENCY AND TO REDUCE REYNOLDS # LAPSE RATE

Baseline | Redesigned



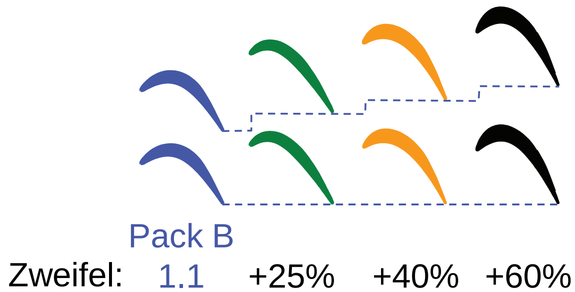
Transition Correlations Developed (GT2004-54109) to Provide Good Estimate of Performance in core regions using Ni's CFD code

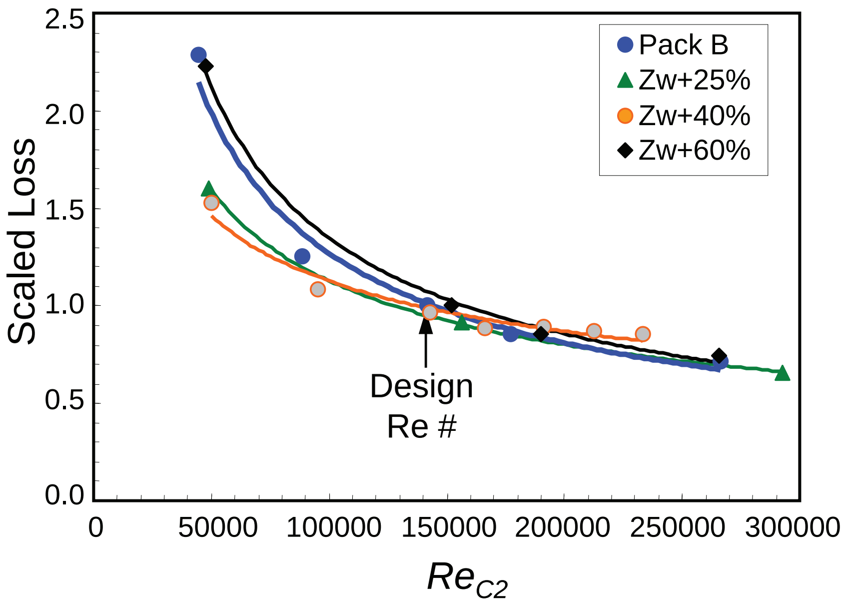
"Models can be used to optimize airfoil counts – high lift airfoil concept"



High Lift Airfoil Designs Demonstrated To Yield Airfoil Profile Performance Improvement (RR, GE, MTU, P&W…)

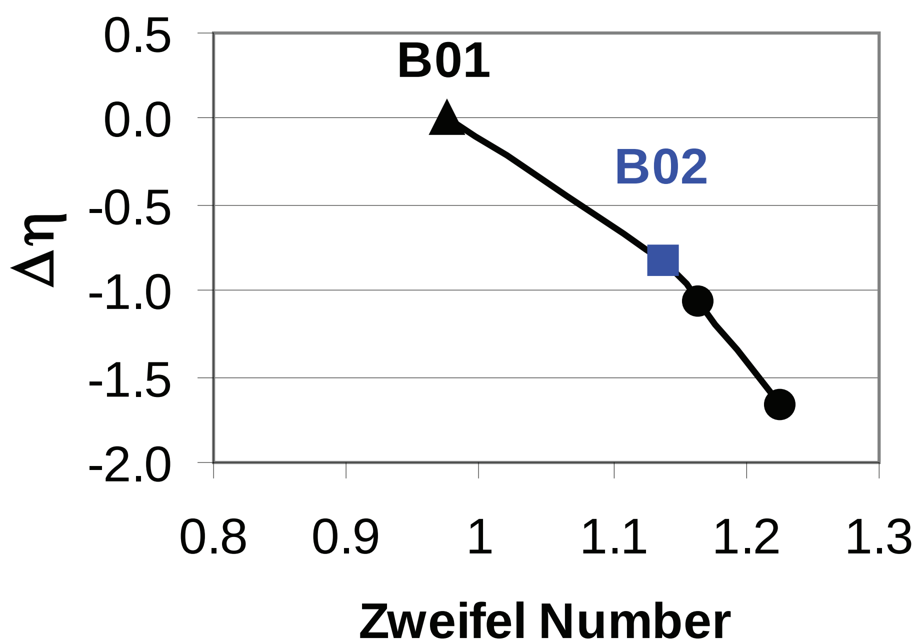
[Praisner 2008]





High Lift Designs Did Not Yield Expected Performance Improvement in Multistage LPTs (MTU, RR & GE)

[Gier (2008)]



Important boundary conditions:

- flight altitudes
- stage loading
- stage pressure ratio
- operating range
- …

End-Wall Losses

- Low loss design concepts developed by utilizing non-axi-symmetric end-walls and a variety of design tools.

- Clear description of the loss generation and reduction processes in these configurations has not yet been documented.

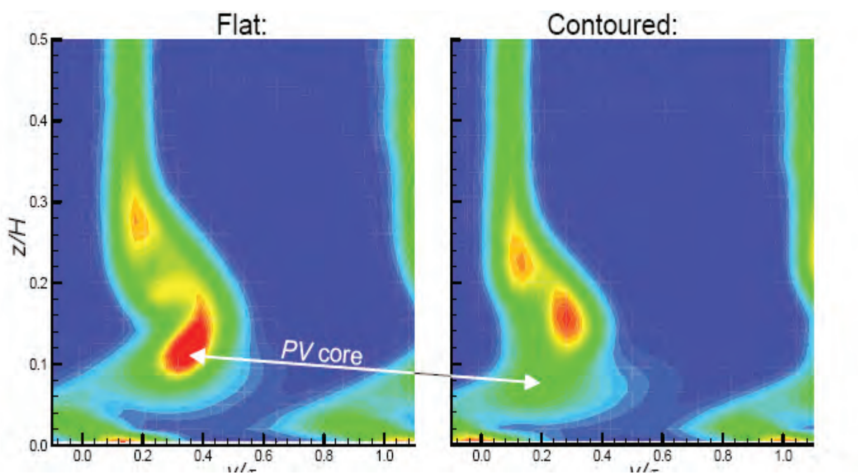
- Application of these concepts in LPTs has not yet been demonstrated.

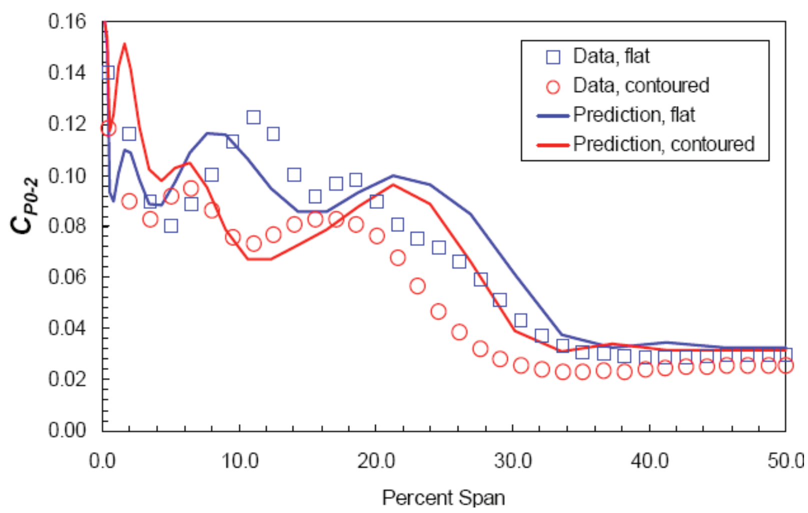
- End-wall losses in airfoil rows with flat or converging walls can be fairly well predicted and managed.

- End-wall losses in airfoil rows with diverging walls are normally higher and are not well predicted

Loss Reduction Through Non-Axi-Symmetric Wall Contouring Demonstrated (Praisner and others)

25% Total Pressure Loss Reduction for an Airfoil Row, Potential To Improve LPT Efficiency by 1-2%



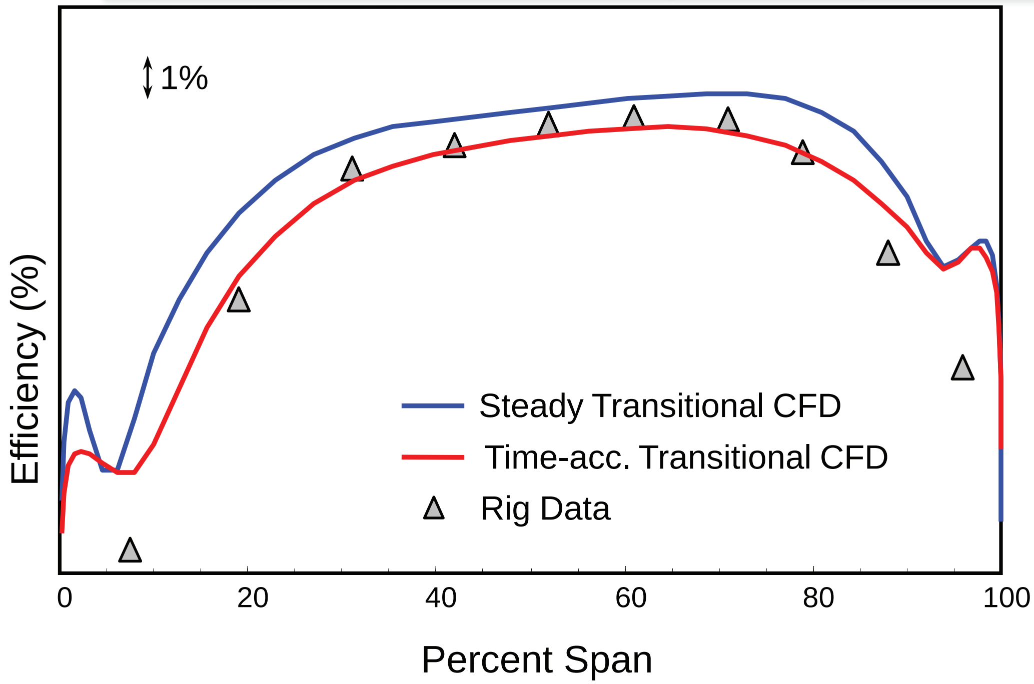


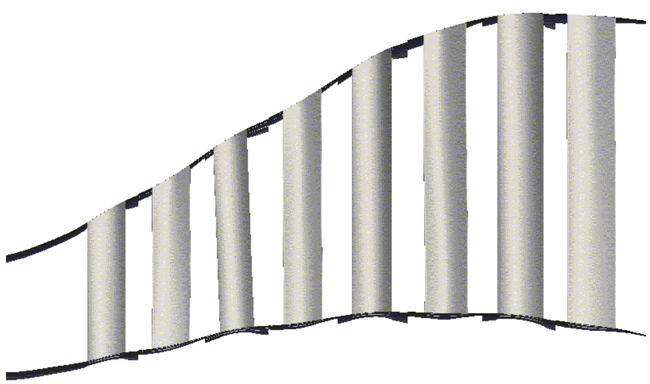
Unsteady Flow Simulations (GT2004-54109) Provide Poor Estimate of Performance in End-Wall Regions

End-Wall flows dominated by:

- -Interaction with Under-platform Flows
- -Diverging flow-paths generate higher than calculated losses
- -Decay of wakes and vortices generated in end-wall regions

Opportunity to reduce losses through non axi-symmetric end-walls / improved vortexing





Interaction Losses

• Interaction between adjacent airfoil rows, unsteady pressure distributions, wake and potential flow interaction yield higher losses than measured in a steady flow environment.

• Losses generated due to interaction between HPT and LPT

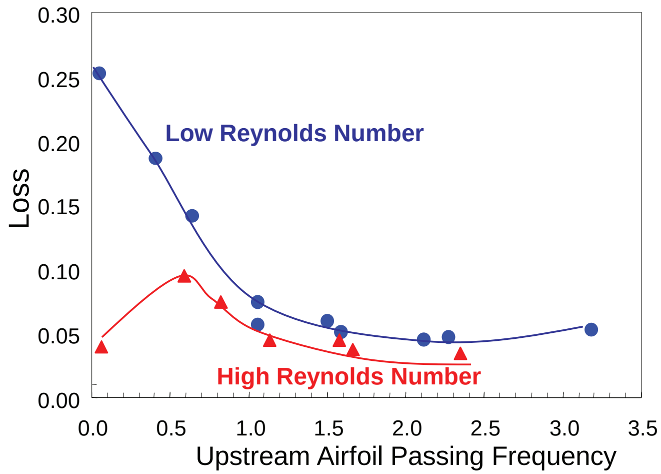
• Role of transition duct and turbine exit guide vanes

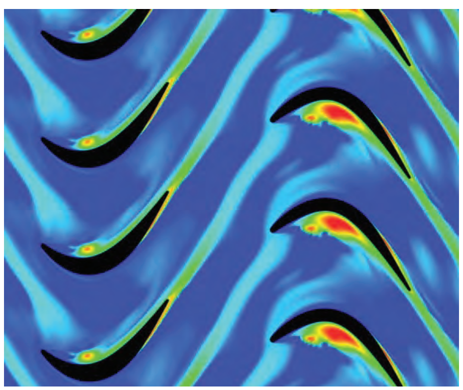
•Understanding of the losses generated due to interaction are based on “experience” in each organization.

•As problems related to interaction losses become large they are solved…clear understanding of the physical mechanisms and solutions is invariably not established!

Unsteady Flow Management is Critical to Performance

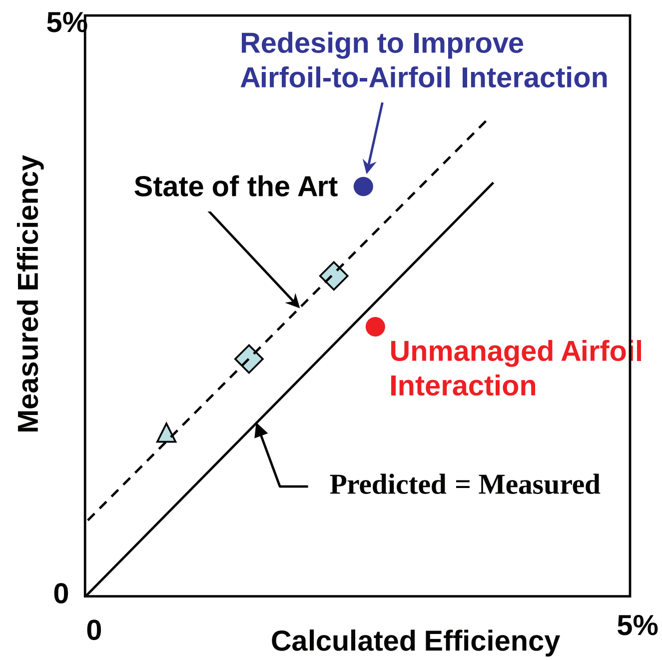
Losses impacted by airfoil Interaction





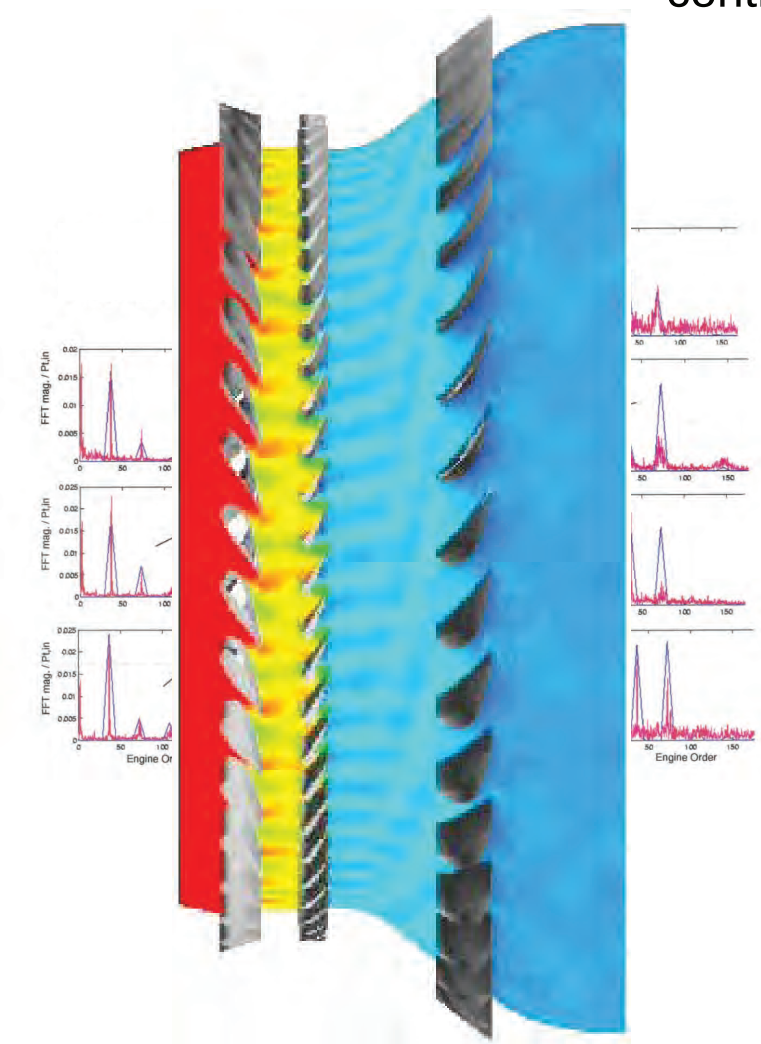
Unsteady Flow-field Interaction
[Time-Accurate Transitional RANS Based Simulations Using Ni's Code (Praisner et al)]

Redesign for airfoil interaction to improve performance



Flow Interactions in Transonic Turbines Need More Accurate Predictions - Clark & Koch (2006)

A1+1/2 stage transonic turbine with contra-rotation (2000-GT- 446---).



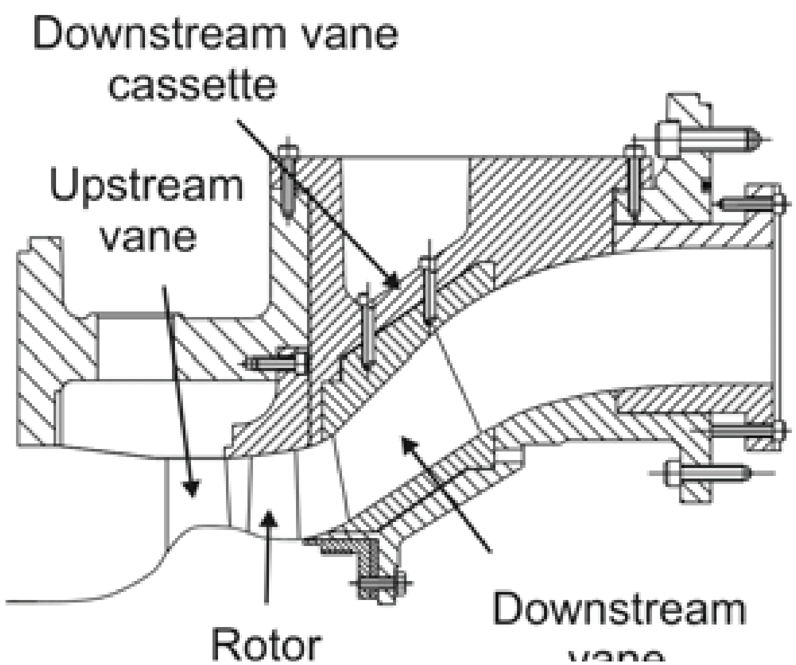
HPT-LPT Interaction Experience:

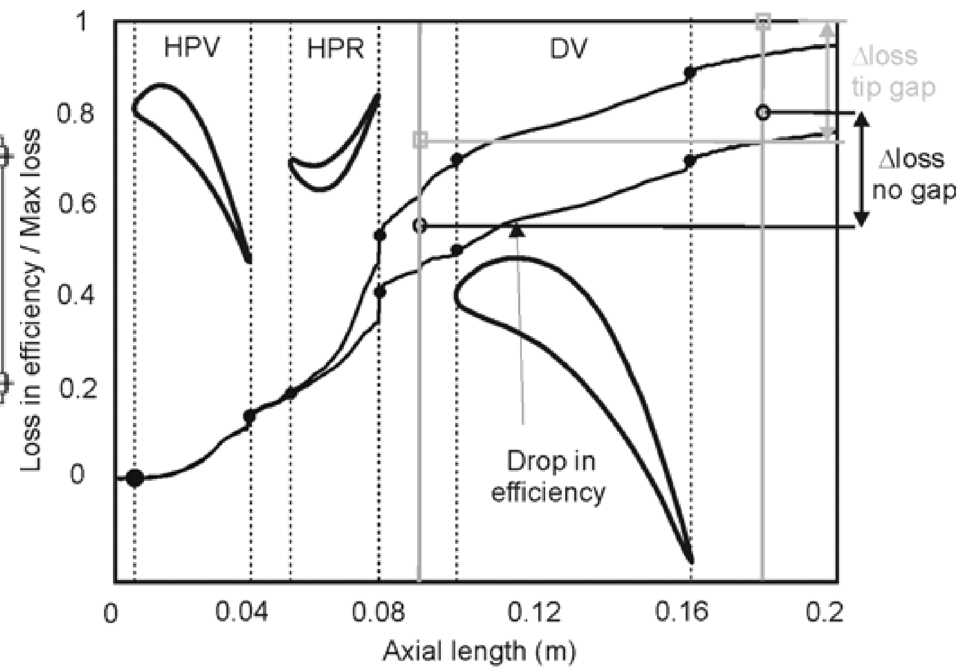
~ 1-3% loss in LPT efficiency due to adverse impact of HPT rotor shocks on LPT inlet vane flow

~ LPT efficiency loss and structural integrity issues in HPT & the “downstream turbine”

Transition Duct with A Vane (Rob Miller)

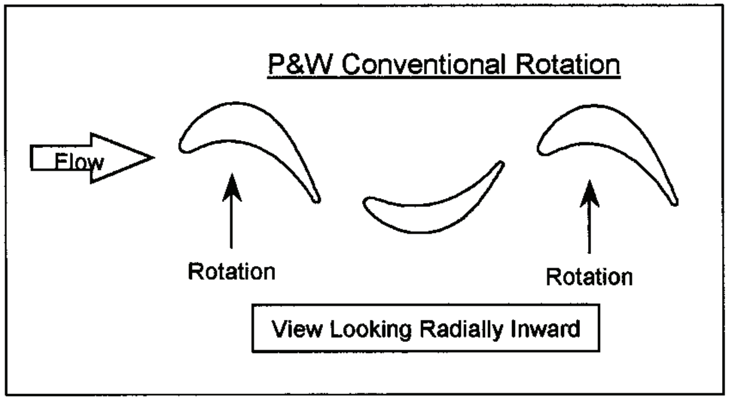
Vane Provides Flow Acceleration In The Flow-path between the HPT & LPT Rotors
Facilitating Increased Velocity Ratio & Efficiency for the LPT

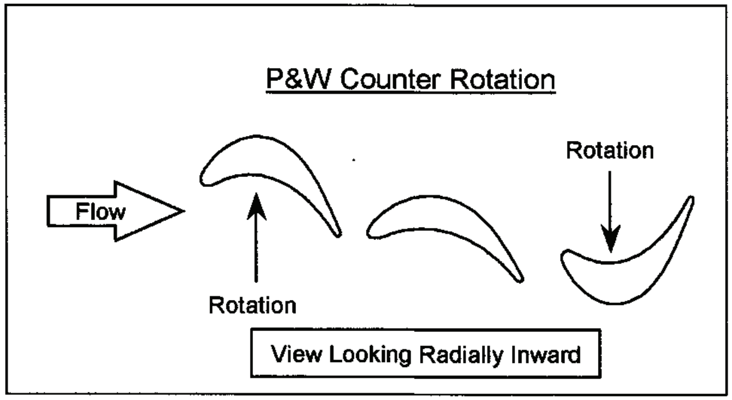




Counter Rotating High and Low Pressure Turbines To Enhance Performance

Counter Rotation Yields Reduced Turning (and hence reduced end-wall losses) in the LPT 1st Vane





Summary

- Progress in understanding of profile loss generation mechanisms (NASA)

 - need predictive models for unsteady transitional flows (Need Support)
- Identify root cause of "High Lift Airfoil" performance surprises in LPTs (Industry, NASA……)
- End-wall loss reduction concepts developed

 - need to validate their performance enhancement potential in LPTs (Industry, NASA……)
- Need to develop improved understanding and modeling of loss evolution in end-wall regions of highly loaded LPTs (NASA, Industry….)

Recommendations

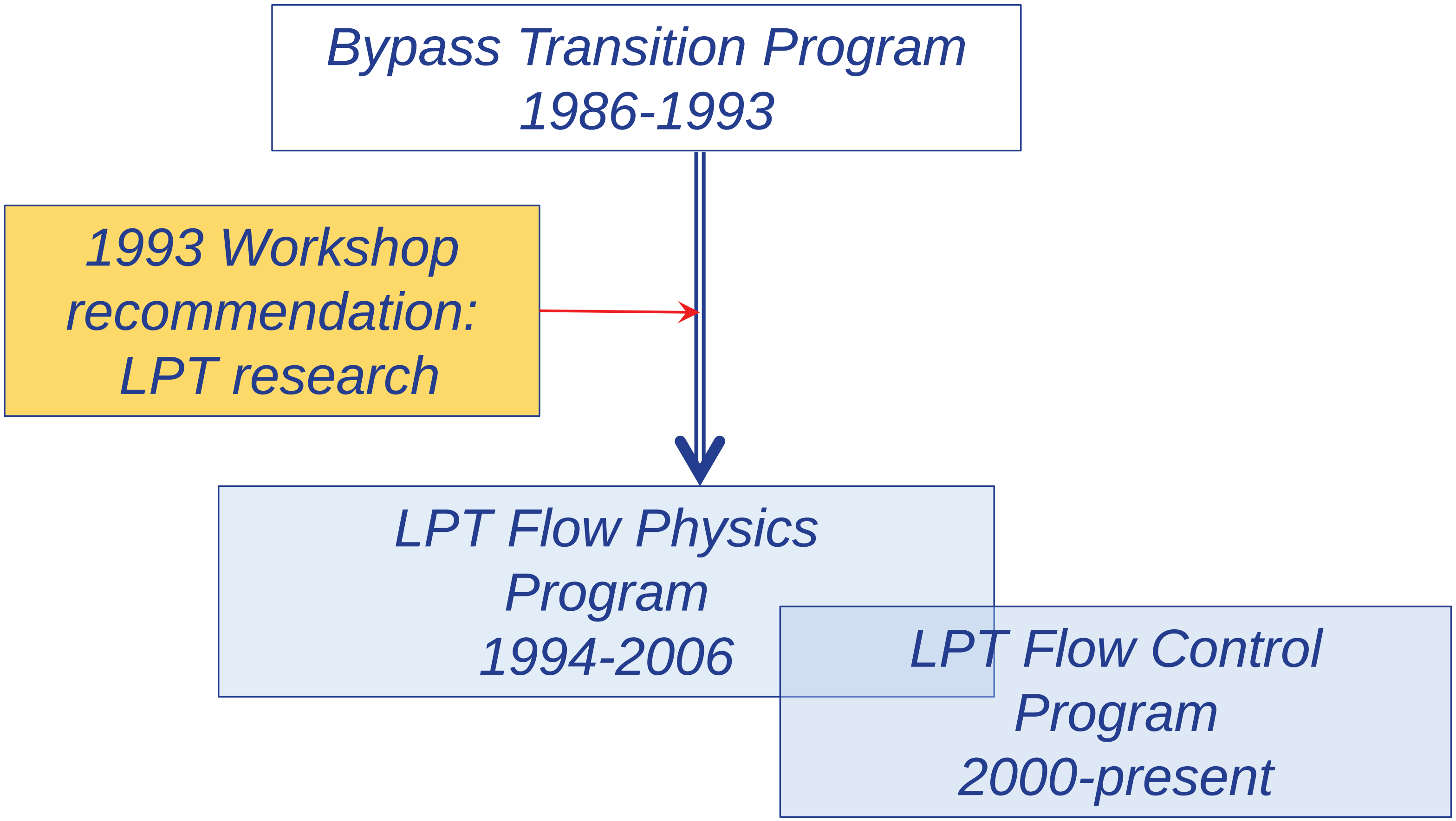
- Establish a "State-of-the-Art" LPT with "World Class" performance level (NASA, Industry…)
- Document the process used to design this turbine
- Establish performance gain achievable above this SoA turbine and define a plan to achieve it through a joint NASA-Industry Program
- Execute the plan and demonstrate the performance of the redesigned LPT through a clear experiment (NASA, Industry….)
- Document the process used to achieve this design (NASA….)

Overview of LPT Research at NASA Glenn Research Center

David E. Ashpis
Turbomachinery & Heat Transfer Branch
Louis A. Povinelli
Senior Technologist

NASA Glenn Research Center
NASA-Industry LPT/PT Efficiency Improvement Workshop
August 10-11, 2010

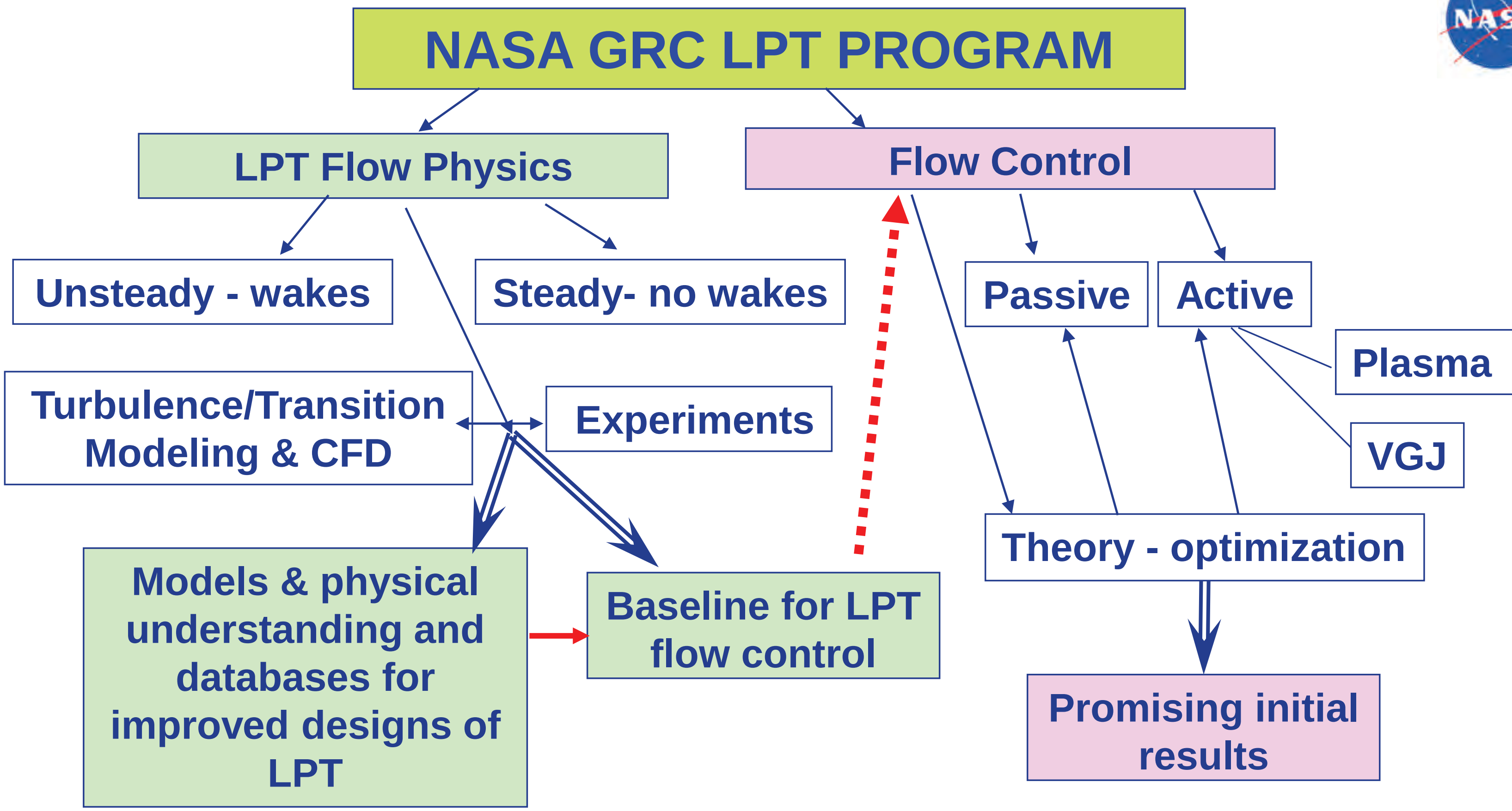
History of LPT Research at NASA GRC



LPT Flow Physics Program

- *Objective: Develop models and physical understanding for accurate prediction of LPT flows*
- *Benefit: Enable High lift designs, reduce efficiency degradation between takeoff and cruise, reduce part count, weight and cost*
- *LPT Challenge: Low Reynolds Number, High FSTI, Separation, Transition, Wake interaction*
- *Approach: Experiments & Model development and computation*
- *Team: In-house, Academia, Industry & Small Businesses, AFRL*
- ***Acknowledge PW 's contribution of providing Pak B airfoil to the community (Om Sharma & Gary Stetson)***

National Aeronautics and Space Administration



In-house & universities team

<u>Experiments</u>: GRC/CW7, U. Minnesota, Texas A&M, USNA, OAI/GEAE,U. Notre Dame

<u>Modeling/CFD</u>: U. Kentucky, Dorney, PSU, ICOMP

In-house & universities team

<u>Experiments</u>: GRC/CW7, USNA, Notre Dame

<u>Theory</u>: U.Arizona <u>SBIR</u>: Techsburg, SPA

LPT Experiments

Organization	PI	Facility	Geometry
NASA/GRC	Shyne, Sohn, Volino & Hultgren	CW/7 Tunnel Flat-plate	Pak B
Minnesota	T. Simon	Curved passage Retractable wake generator	Pak B
GE	Solomon	LSRT (piggy-back)	Proprietary
Texas A&M	Schobeiri	Cascade Continuous wake generator	Pak B
USNA	Volino	Curved passage	Pak B
Notre Dame	Corke	Cascade	Pak B
Collaboration – data:			
AFRL	Lake	Cascade	Pak B
GE	Halstead	LSRT	Proprietary

Turbulence/Transition Modeling & CFD

Organization	PI	Description
WMU, GMI, Virg. Comm.	*Dorney*	*CFD, K-e, Modified Baldwin-Lomax*
Kentucky	*Huang & Suzen*	*Intermittency-based models* *CFD of unsteady LPT flows*
PSU	*Lakshminarayana & Chernobrovkin*	*Two-Equation models*
Kentucky	*Hauser & Huang*	*DNS/LES*
NASA/ICOMP	*Liou*	*K-e models*
NASA	*To*	*K-e model spectral element, MSU Turbo*
MIT/PW	*Burry/Tan*	*Laminar DNS new high lift airfoils* *PW funding, NASA provided supercomputing*
Syracuse	*Lewalle & Ashpis*	*Wavelet techniques for transition & unsteady flows*

➢ ***Strong interaction with experimentalists***

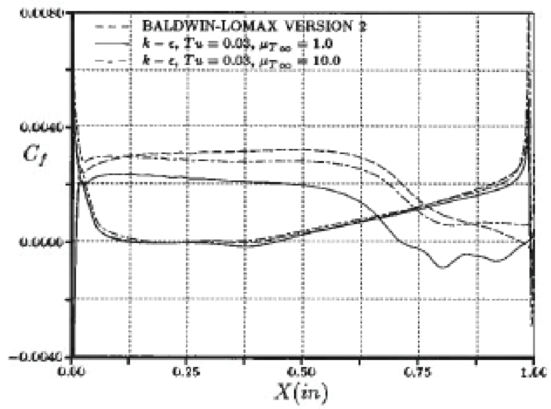
LPT Flow Control

	Organization	PI	Description
Experiments	*NASA/GRC – CW/7*	*Hultgren & Ashpis*	***Plasma** flow control*
	U. Notre Dame	*Corke, Thomas & H. Huang*	***Plasma** flow control in Pak B cascade*
	Tel Aviv Univ.	*Siefert & Wygnanski*	*Effects of FST on active flow control*
	Tecsburg (SBIR)	*Guiliot*	*LPT flow control with ejector jets + optimization*
Modeling	*U. Kentucky/GRC*	*Huang, Suzen, Jacob, & Ashpis*	*Models of DBD plasma actuator*
	PW/UTRC	*Misc*	*Study of flow controlled HP-LPT transition-duct*
Analysis	*U. Arizona/GRC*	*Tumin & Ashpis*	*Optimization of placement of FC devices based on Transient Growth Theory*

LPT Flow Control – Current program Supported by the Subsonic Fixed Wing (SFW) Program

	Organization	PI's	Description
NASA	GRC	Ashpis	DBD **Plasma** Actuators CW-7 tunnel experiments
NRA	Princeton	Miles, Shneider & Macharet	DBD **Plasma** Actuators Experiments & Computation
	Wisconsin	Hershkowitz	DBD **Plasma** Actuators Experiments & Computation
	Minnesota	T. Simon, Kortshagen & Ernie	DBD **Plasma** Actuators + Pak B tunnel experiments
	OSU	Bons	VGJ + aspiration Pak B Cascade with wakes
	USNA/CSU	Volino/Ibrahim	VGJ + LES in Pack B cascade with wakes
SBIR	Tech-X/Princeton	Likhanskii	Software for DBD **Plasma** Actuators
	Spectral Energies/Notre Dame U.	Gogineni Morris & Corke	**Plasma** flow control in turbine rig – baseline runs

CFD - Dorney



Pak B
Rey=80k
Tu=3%

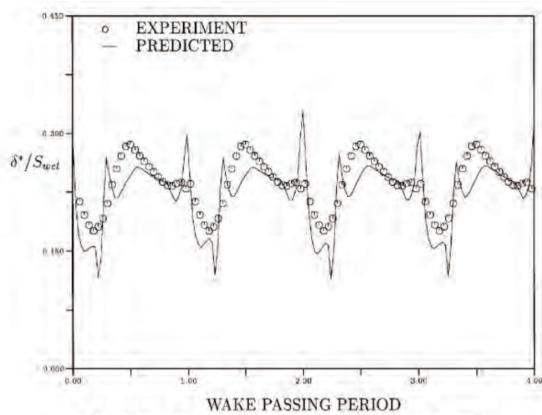
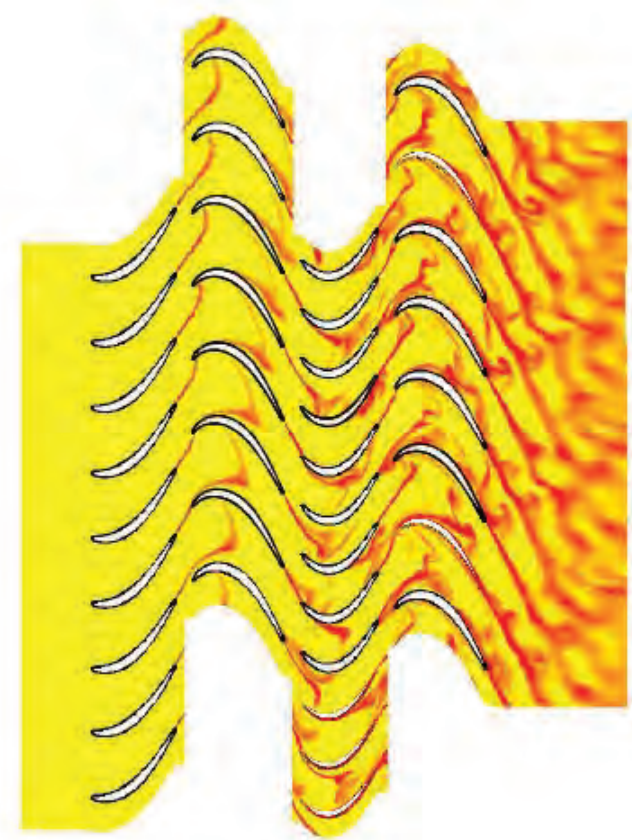


Fig. 3 Unsteady displacement thickness, nozzle 2, 82% suction surface length.

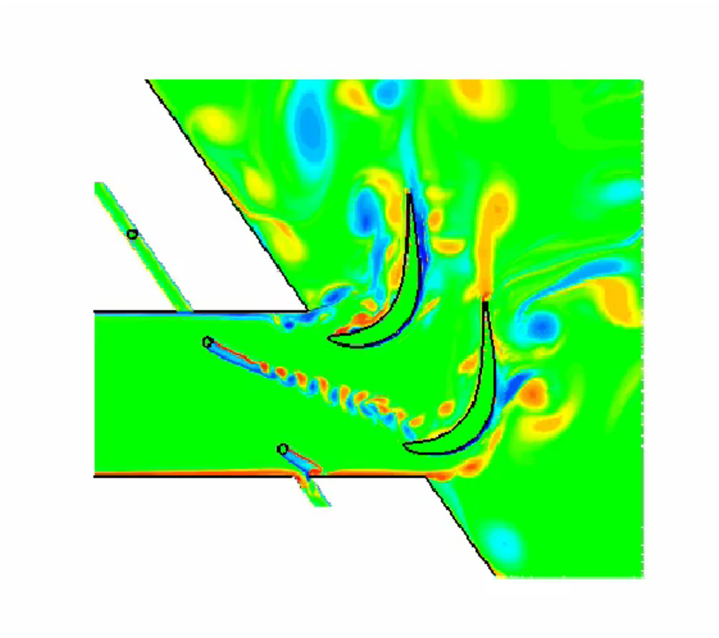
Dorney et al. AIAA 99-0742



Dorney et al. AIAA–2000–0742

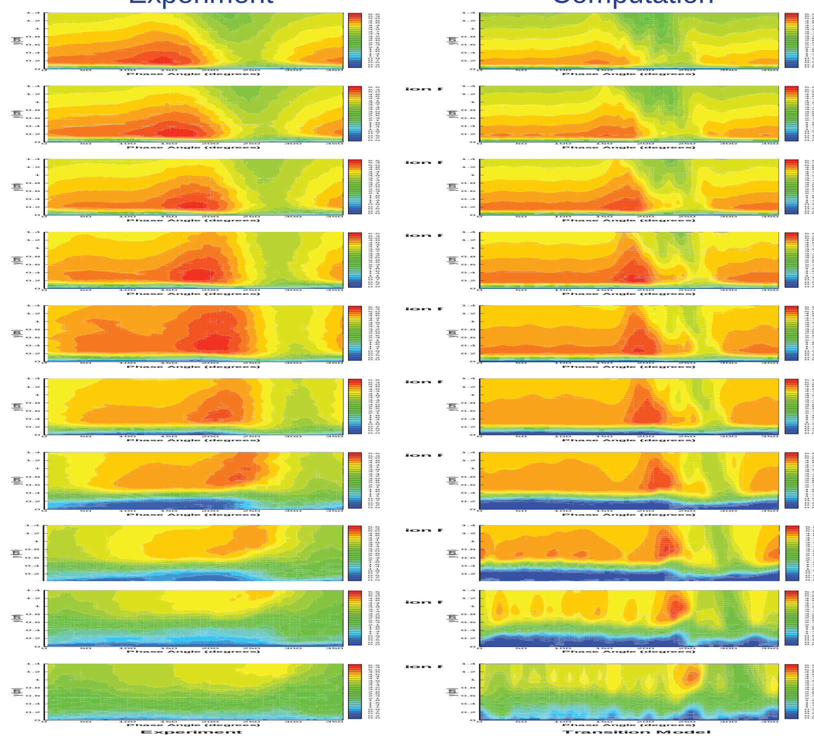
Simulations of GEAE Halstead's experiments (1995)

Unsteady Computations Comparisons with Experiments



Movie

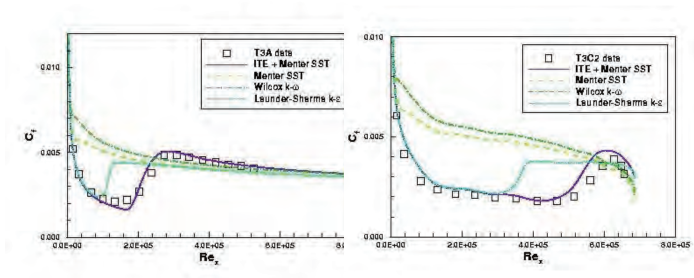
Experiment Computation



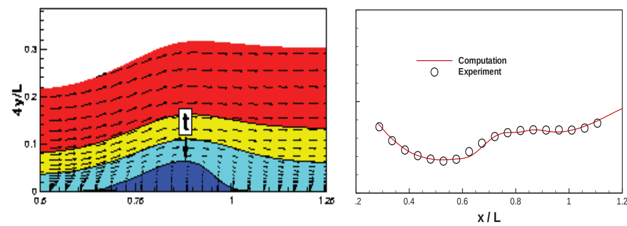
Unsteady – wakes
Simulation (Huang & Suzen- U. Kentucky) of experiment with moving bars
(Simon et al. - U. Minnesota)

National Aeronautics and Space Administration

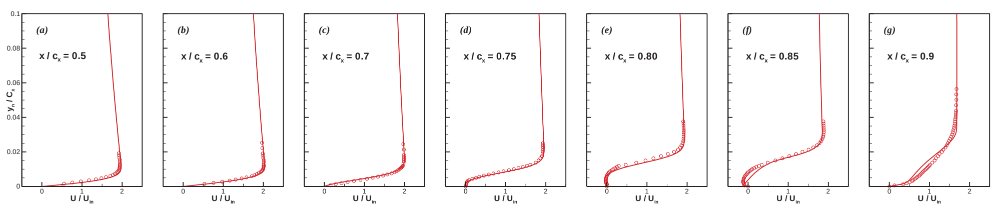
Computations (Suzen & Huang U. Kentucky) – intermittency transport model
Comparisons with various experiments (steady, no wakes)

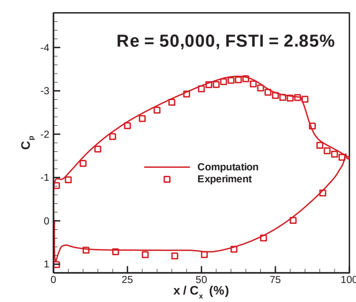


ERCOFTAC Benchmarks

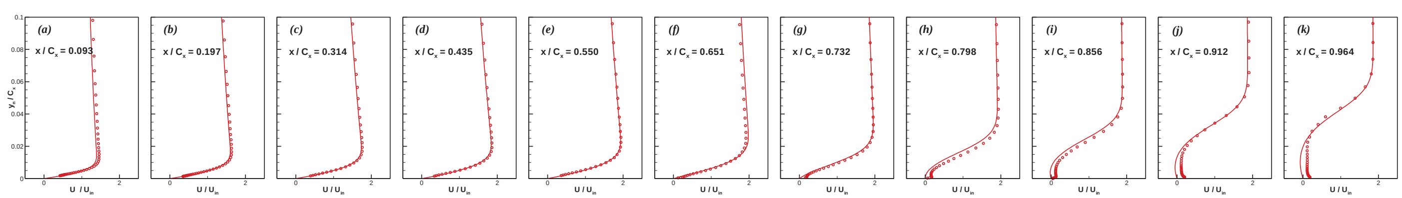


GRC CW-7 Experiments (Volino & Hultgren 2000)





Experiments (Corke et al U. Notre Dame) Rey = 50,000 FSTI=2.85%



Volino (USNA) experiments Rey=10,000

Program Accomplishments

- *Generated experimental data bases*
- *Development of CFD approaches*
- *Validation of intermittency-based model*
- *Insights into LPT flow physics*
- *Demonstrate feasibility of flow control*
- *Large number of publications and reports, quick dissemination*
- *Education and training for students*
- *Advocacy for LPT research*
- *Influenced numerous outside work (e.g., Durbin)*
- *NASA/GRC workshops*
- *Minnowbrook Workshops I -VI, 1993-2009*

  http://ntrs.nasa.gov Document ID: 20130009102 *(DVD of all workshops)*

➢ ***Focal point for LPT research***

Session 2
Industry Reviews

NASA/CP—2020-220327

Overview on RR LPT design

Frank Haselbach

Chief of Function, Turbines
Rolls-Royce plc

Overview

- Introduction
- Brief historic summary
- Major design aspects of RR LPTs
- Toolset importance
- Way forward

Introduction

- RR is designing LPTs throughout it's jet engine history
- Since the mid 1990's most of the large LPTs have been done with a RRSP partner (ITP)
- RR still conducts design of small and medium sized engine LPTs
- This presentation will just give a brief overview and will not go in the level of detail requested by the session organiser, as it is impossible to share the requested level of detail (also in the time of 20 mins)
- However, it will address:
  - Brief history of designs
  - Current design parameters, main influence factors and operational envelopes
  - Future trends

Brief historic summary

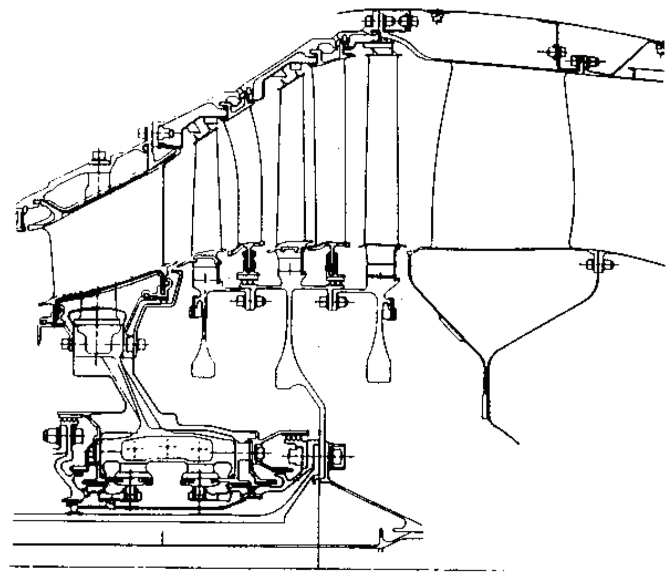
- Pre -1970's – Free Vortex design OK!
  - No computers, Slide rules and Log tables only !
  - Building of the core aerodynamic design criteria !
- 1970's – Dawn of Computer Methods
  - RB211's with first technology features based on new methods (streamline curvature)
  - Design for noise
- 1980's – Foundation of modern LP Aerodynamic Design
  - 3D CFD & more forced vortex design
  - Orthogonal stacking, airfoil cloning, LE and TE shapes
- 1990's – Trent Family & BR700/AE3007 family
  - Integrated 3D aerofoil design process
  - More sophisticated trough flows & good correlations (inc. Data base)
  - High lift designs, extensive rig testing
- 2000's – Trent family growing
  - 3D multirow CFD in design and design of secondary gas path and tertiary flow introduction (cooling and leakage flows)

Major design aspects of RR LPTs

- Airfoil loading – High lift story
- Altitude performance
- Orthogonality
- Some typical numbers

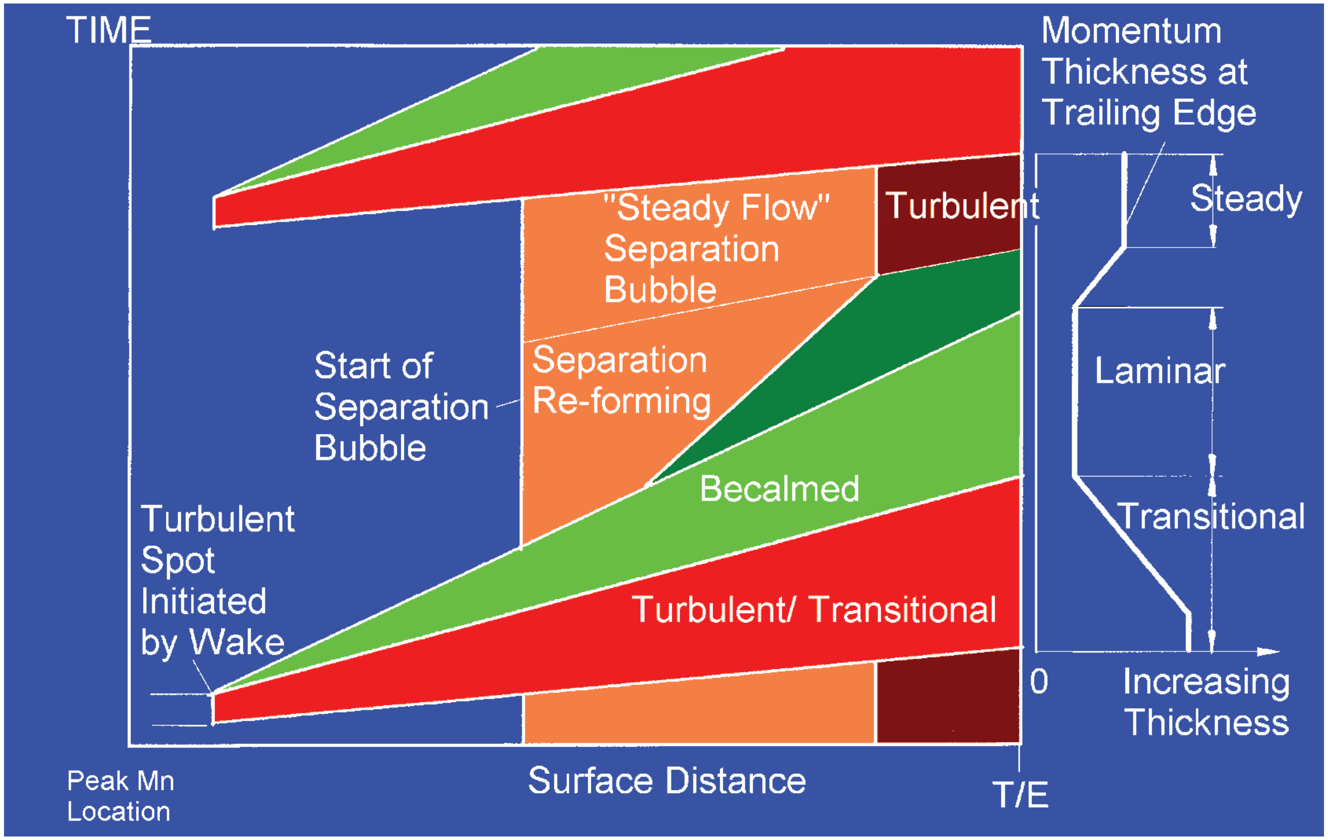
BR715 LP turbine aerodynamics

- **High lift blading**
  - First application by RR
  - New design rules
  - Additional CFD tools
- **Design rules**
  - Generic velocity distribution style
  - Increased back surface diffusion
  - Aft loading
- **Methodology**
  - Steady flow analysis, 2-D Euler solver MISES
  - Unsteady effects implicit
- **Rig Test**
  - Validation of design methodology

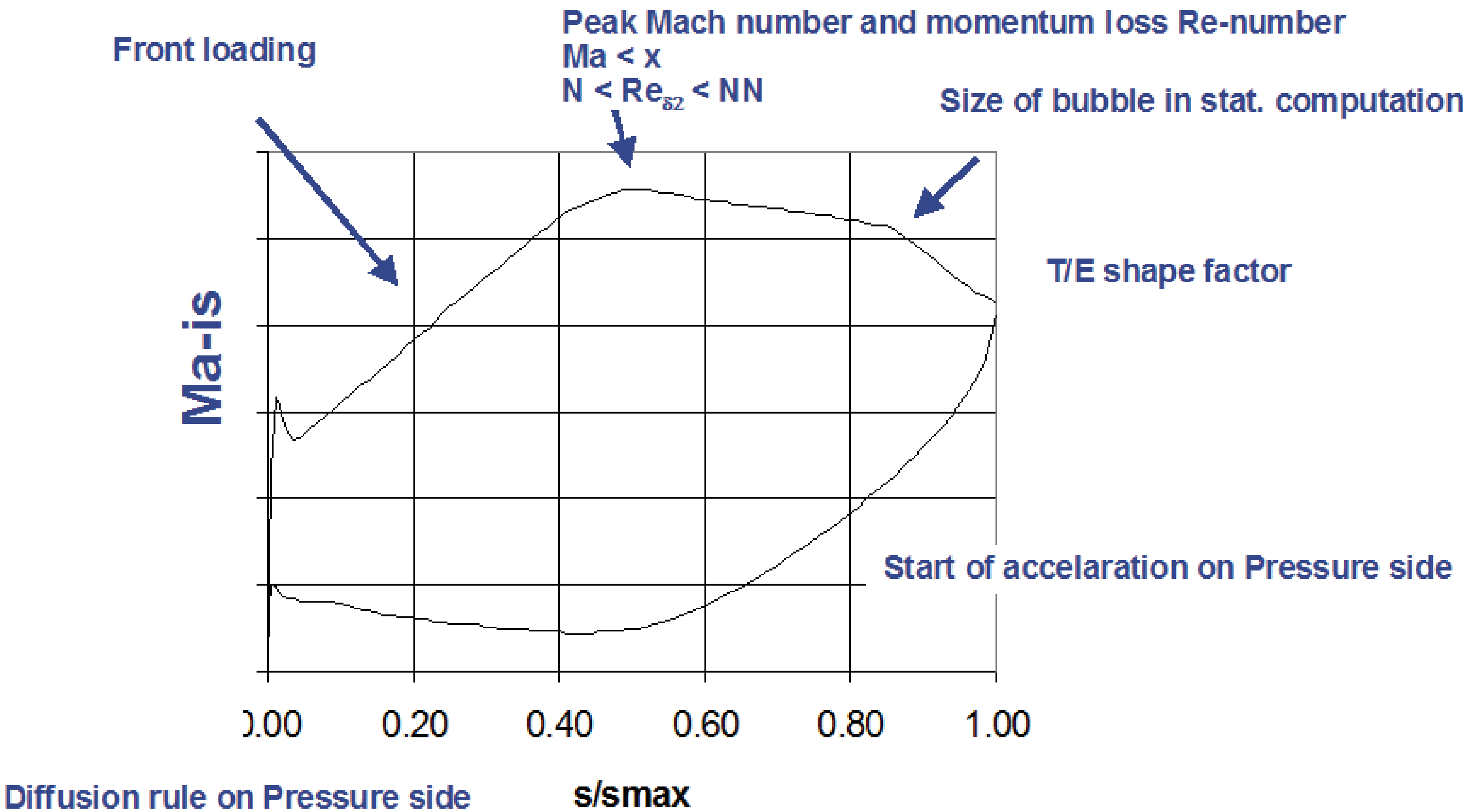


High lift – understanding

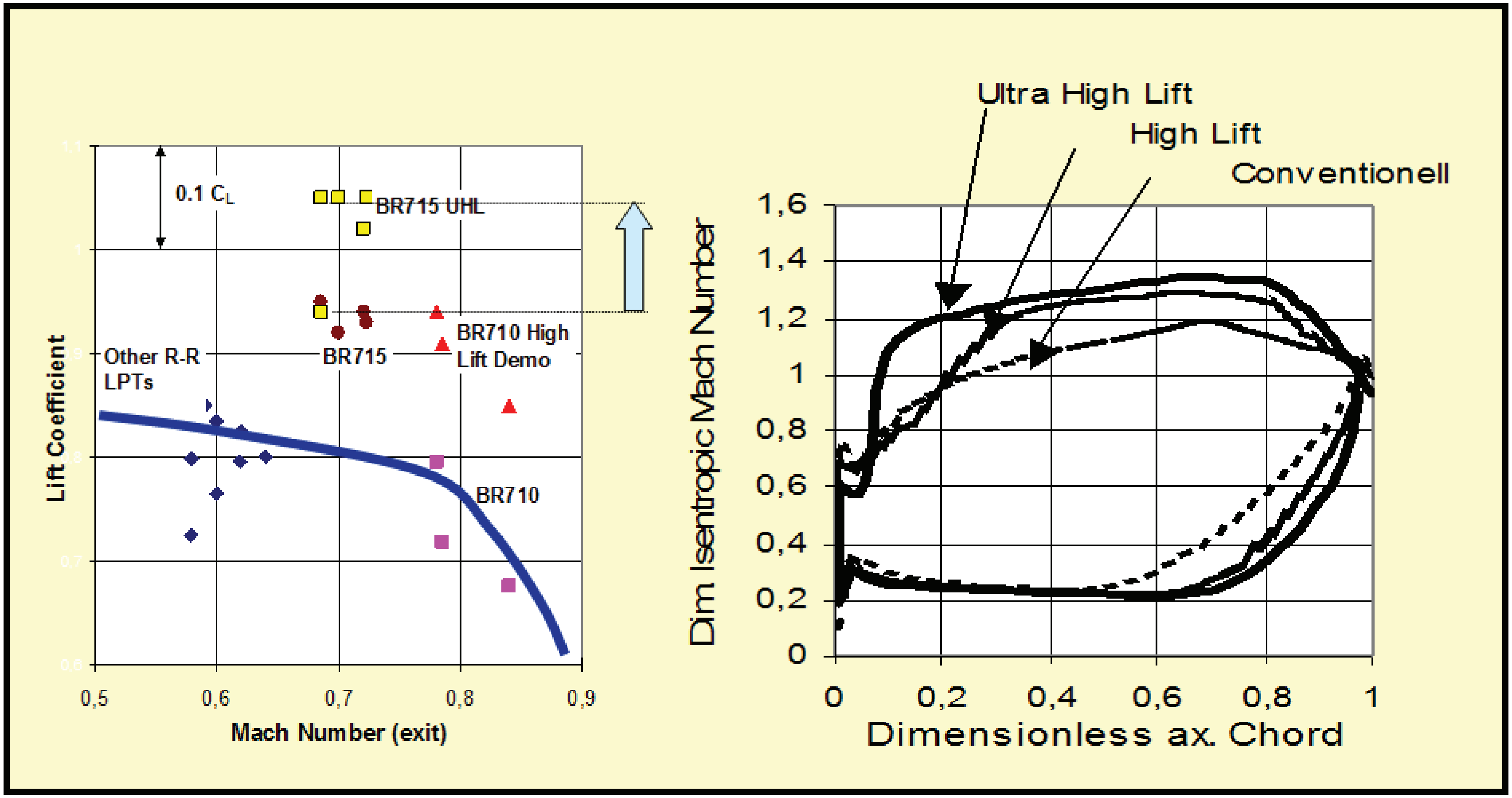
- Wake / bubble interaction
- Periodic “becalmed” (pseudo-laminar) regions



Design criteria

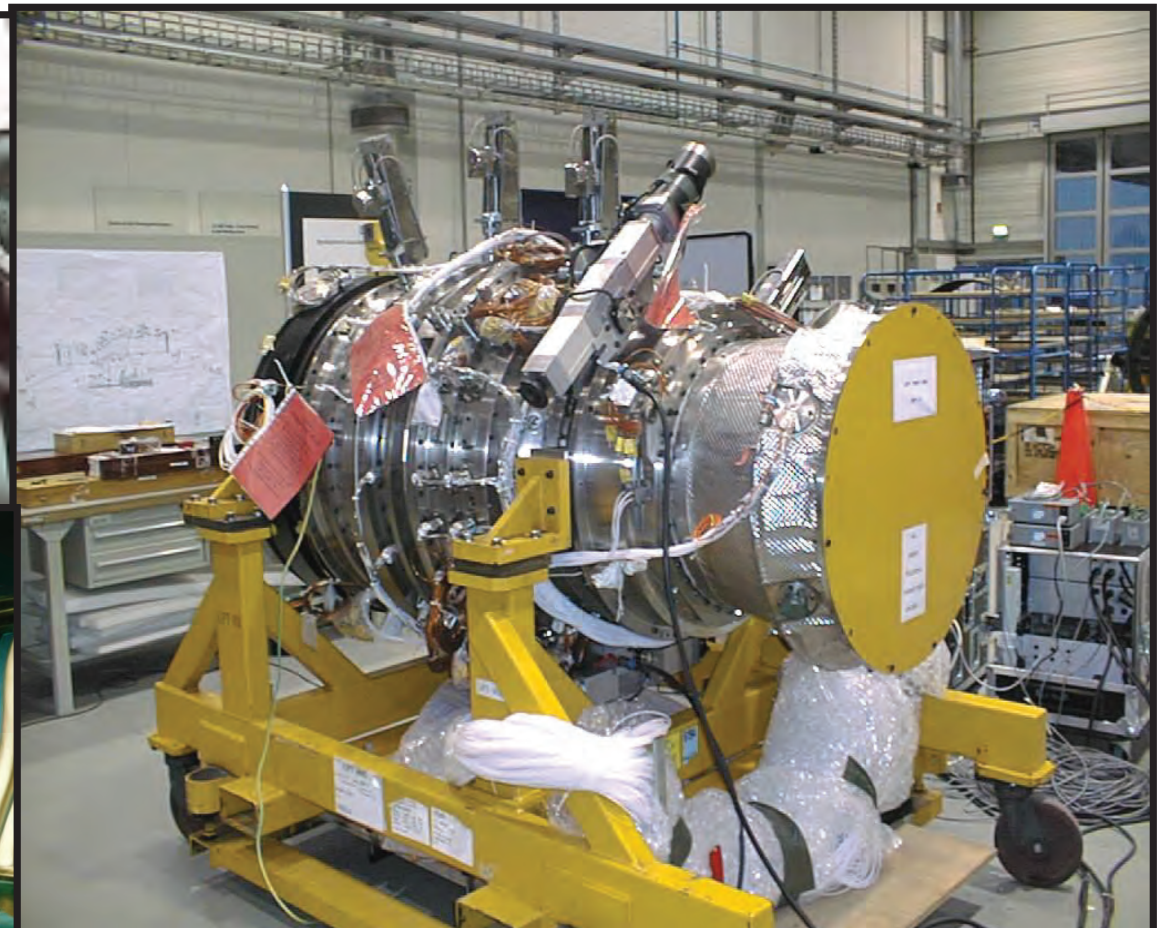


Ultra High Lift – Profil design



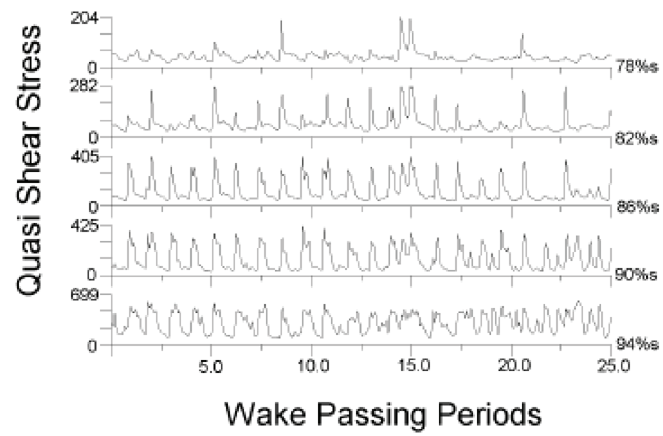
 10th August 2010 – NASA Glenn Frank Haselbach

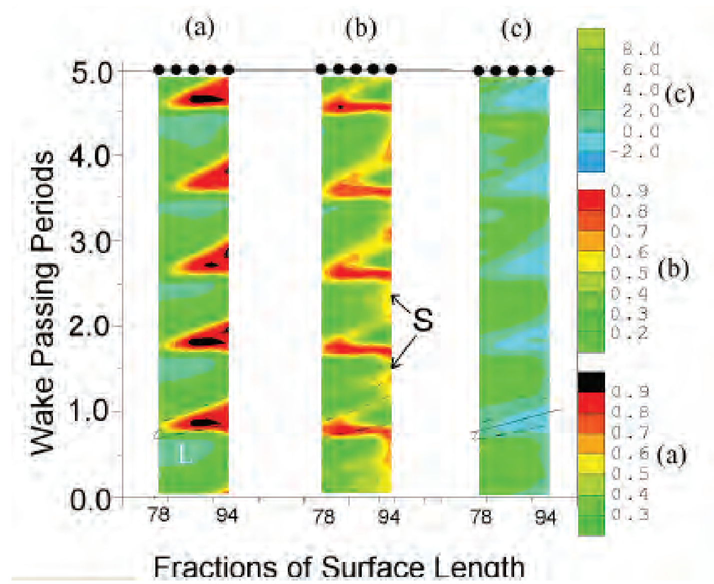
Rig test



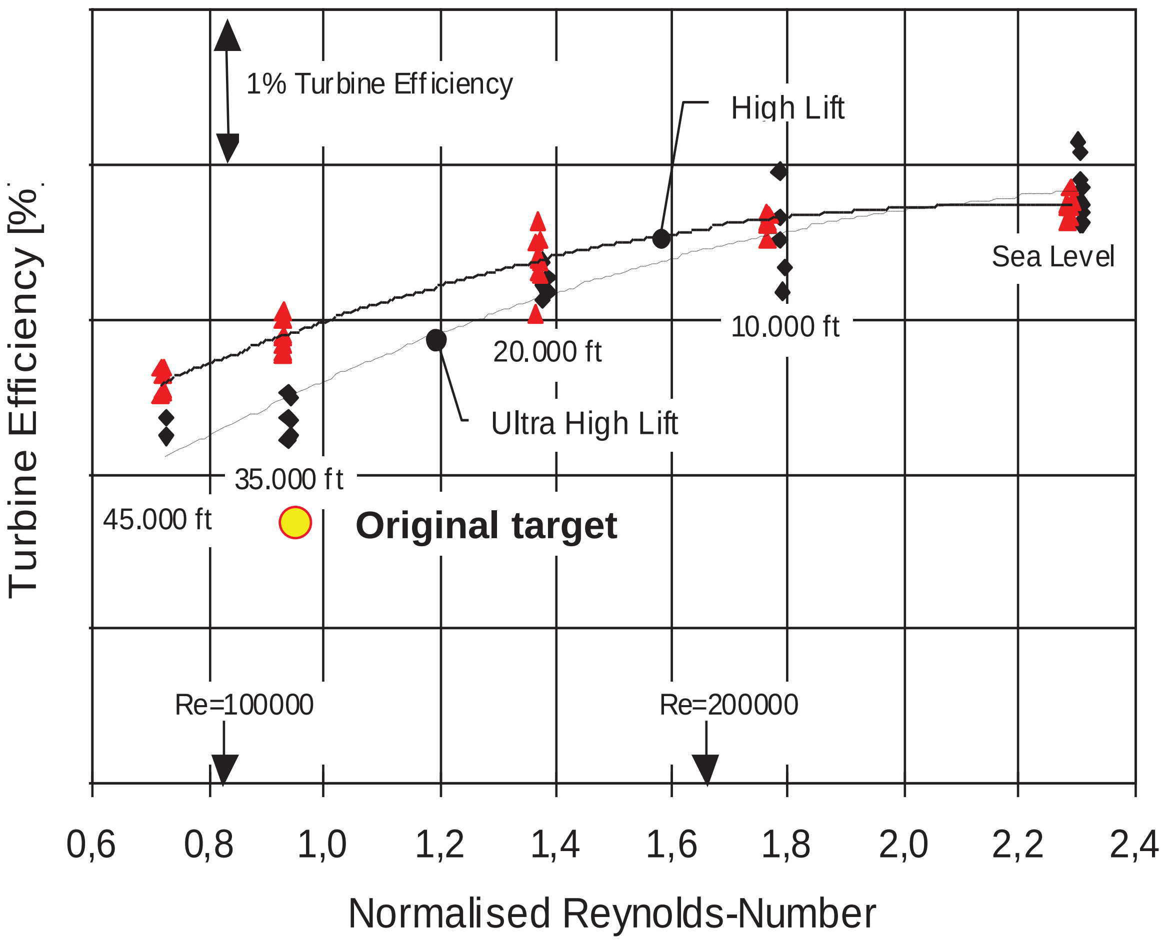
Summary of the RR LPT Design : 1970…2010

High lift – in Engine

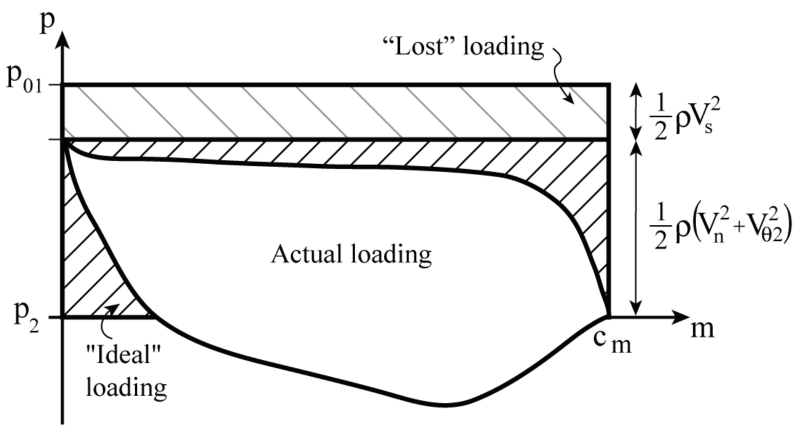


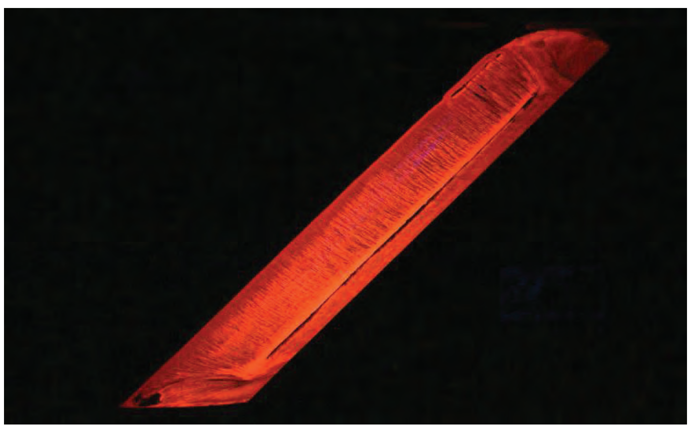


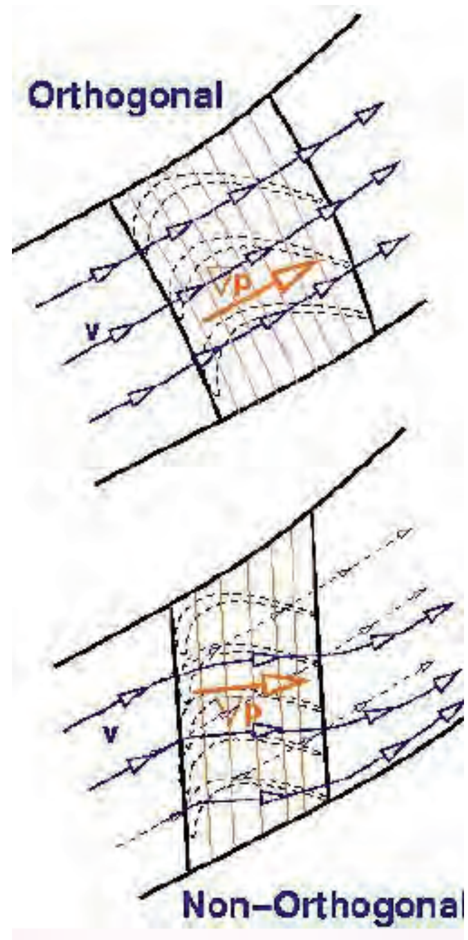
BR715 UHL RE-Number Characteristic



Orthogonality







Some typical numbers:

- Cruise Efficiencies: 89 ... 93+
- Weight: small ~ 400-600 lbs / big: 1500 – 2500 lbs
- Number of stages: 1-6
- Size:
  - Exit Diameter: typically about 60% of Fan dia.
  - length ~4''/stage
- Blade exit Mach numbers: 0.55 – 0.9
- Blade Re-numbers (cruise) (exit & chord): 25.000 – 400.000
- Turning angles: 100 - 110 deg
- Stage loading (DH/U2): 1.6-3.2 (stages)...1.7-2.5 (mean)
- Flow function (Va/u): 0.7-1.0
- Rotational speed (NL): 2500-4000 / 5000-8000

Summary of the RR LPT Design : 1970…2010

Toolset:

	Prediction	Analysis
2D loss	Parameterisation of the profiles	Transition modelling
3D loss	Secondary flows, features loss	Modelling of the relevant geometrical features
Rows interactions	Loss carry over, clocking	Loss carry over, Clocking

Turbine efficiency

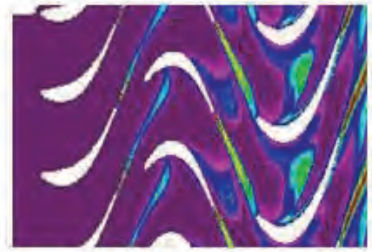
Off design	Fit of experimental curves & throughflows	3D unsteady / or simplifications

Turbine map

Analysis Toolset Importance

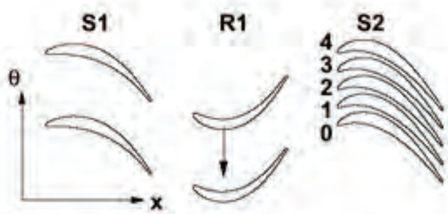
- Transition modelling

Wake-BL interaction

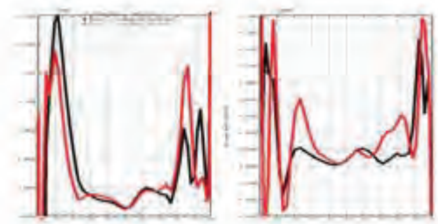


- Unsteady effects

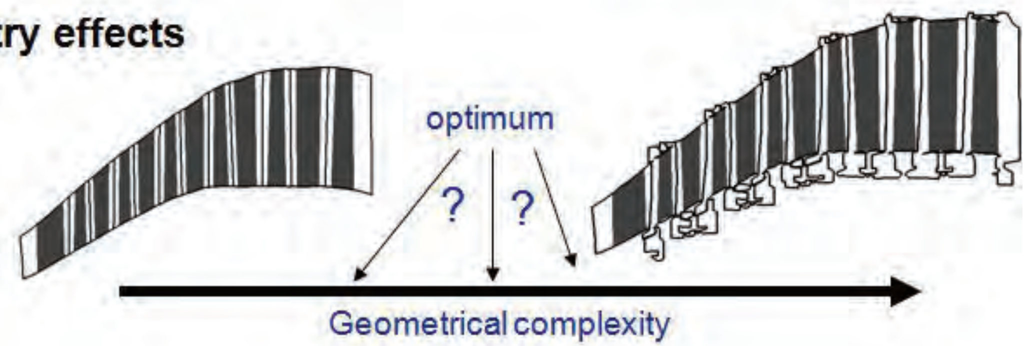
clocking



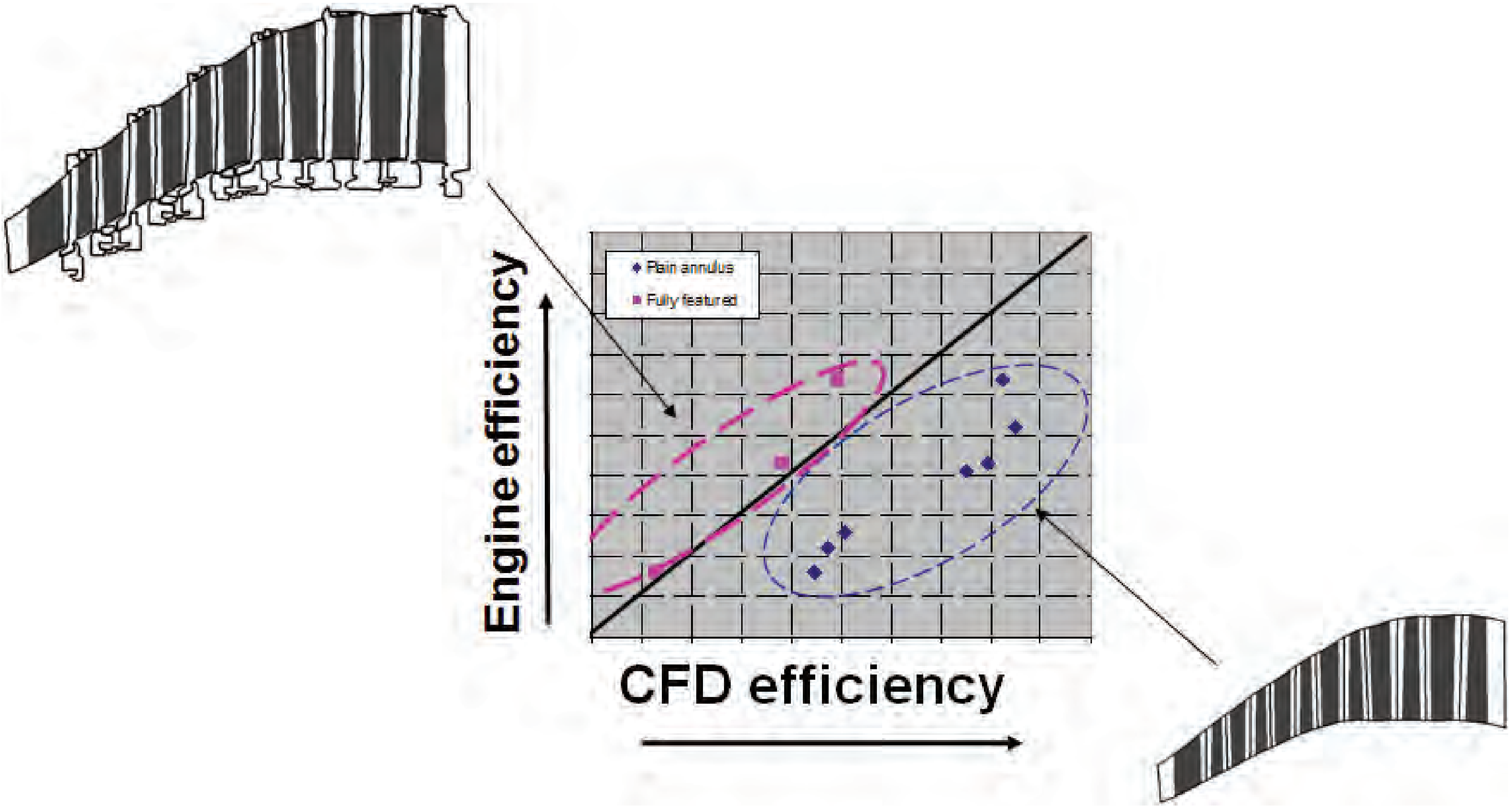
Loss carry-over



- Real flow/Geometry effects



Analysis Toolset importance



Things to come...(1)

- **Weight management: Next generation materials TiAl & CMC**
  - **density of γ-TiAl is half of Ni-based alloys**
  - **temperature capability good for rear LPT stages**
  - **ductility reduced compared to Ni-based alloys (different design)**
  - **expensive procurement and manufacturing needs reduction**

- **Thermal management: highly accurate RTDF/OTDF& thermal prediction (BC's and clearance control)**

Things to come...(2)

Multirow 3D CFD based optimization consumes massive HP computer resources & complex geometries need flexible optimisation with high amount of free variables and constraints

Industry needs:

1. meaningful target and limiting functions, optimization target related & flexible optimization strategies
2. Very efficient acceleration techniques with good scalability for
   - the evaluation of target functions and sensitivities, e.g. adjoint CFD code
   - advanced gradient based algorithms, response surface functions
3. Automation (parallel) of calculations by an efficient optimisation system
4. user friendly post processing of extensive result information

Really BIG Lift coefficients

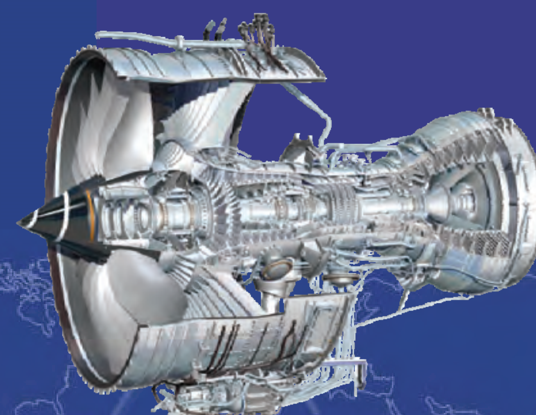
Summary of the RR LPT Design : 1970…2010

End……

NASA/CP—2020-220327

GRUPO

Industria de Turbo Propulsores, S.A.



Review of LPT Design & Development at ITP

R. Vázquez

August 2010

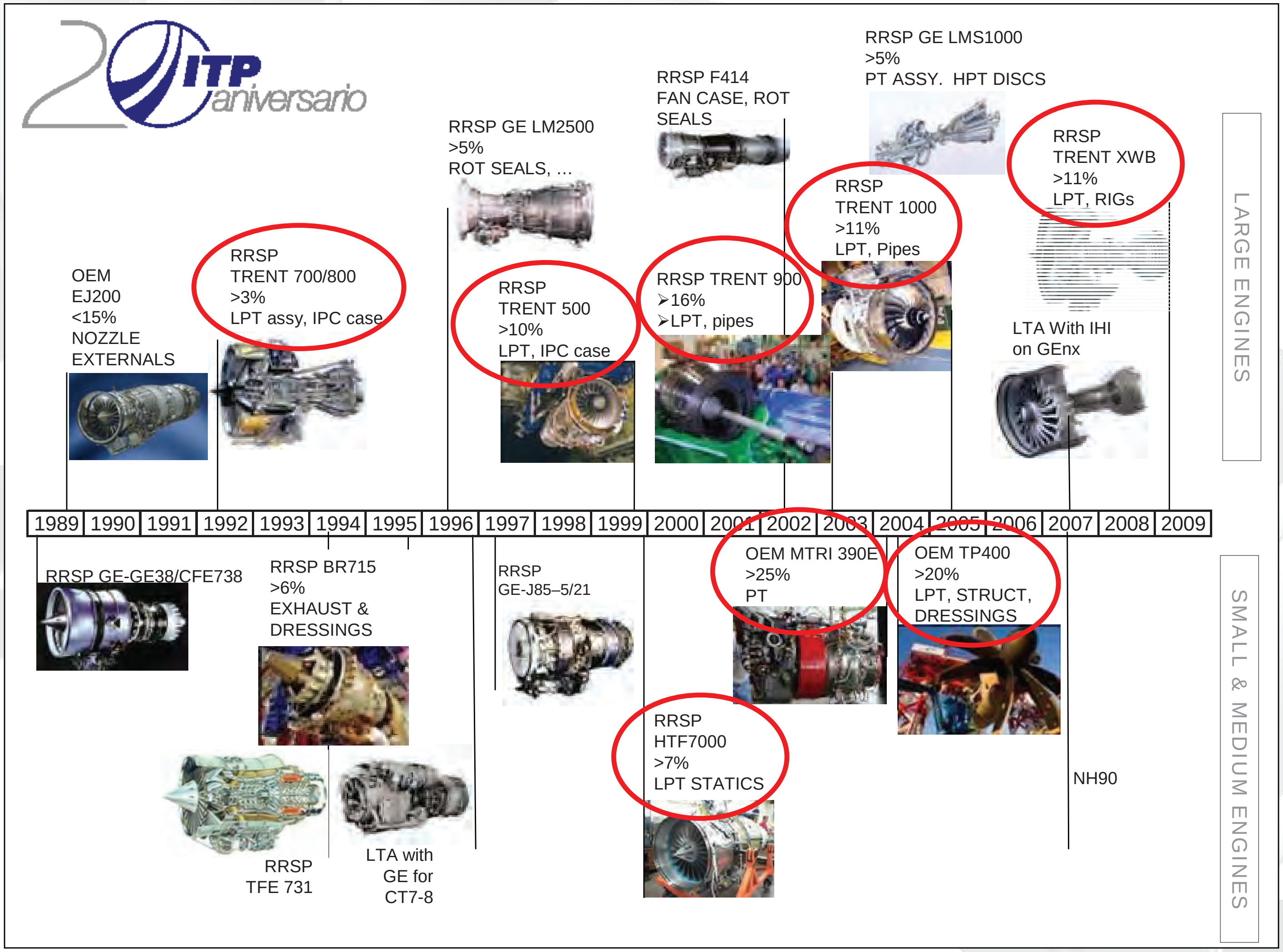
Outline

Industria de Turbo Propulsores,S.A.

1. Review of ITP's LPT.
2. Operational Envelope.
3. LPT airfoil design philosophy.
4. Loss distribution in LPTs
5. Effect of altitude on efficiency.
6. LPT design cycle and methods used.
7. Experimental Facilities.
8. Future trends and requirements

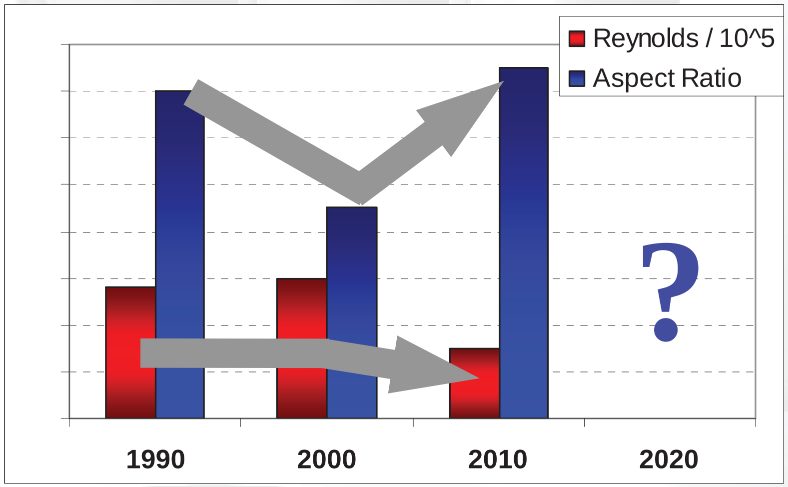
Review of ITP's LPT

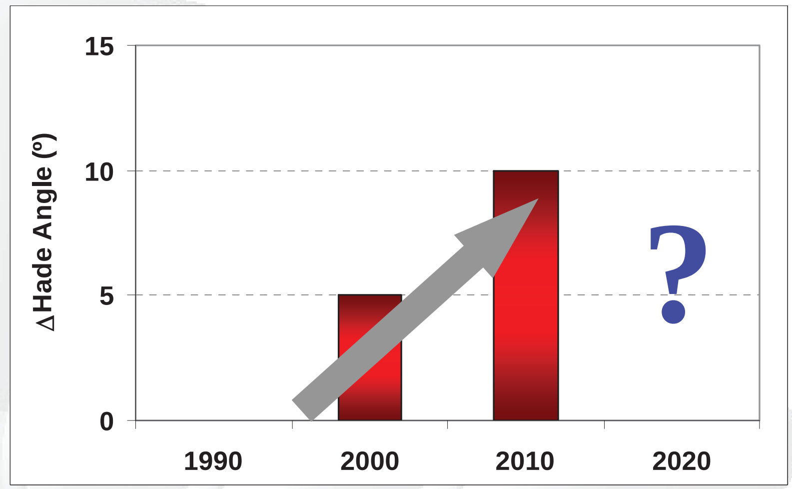
Industria de Turbo Propulsores,S.A.

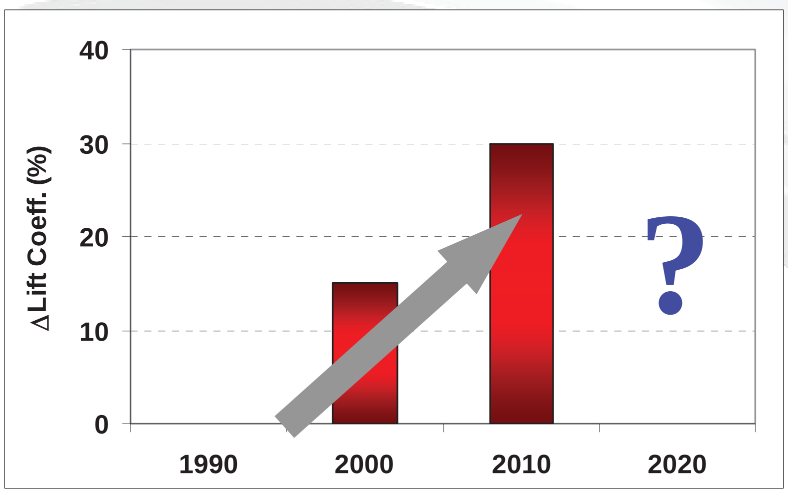


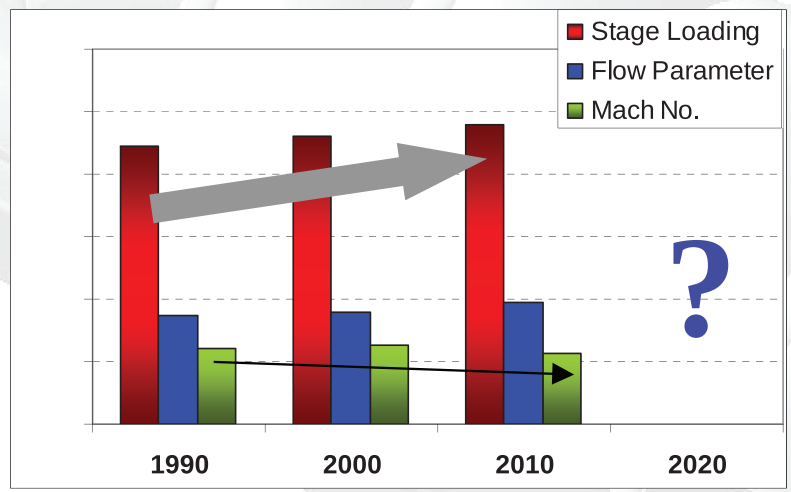
Operational Envelope

Industria de Turbo Propulsores,S.A.







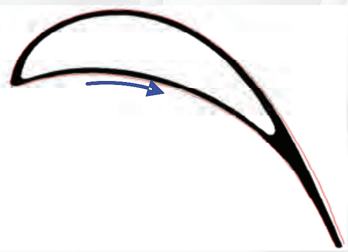


LPT airfoil design philosophy

Industria de Turbo Propulsores, S.A.

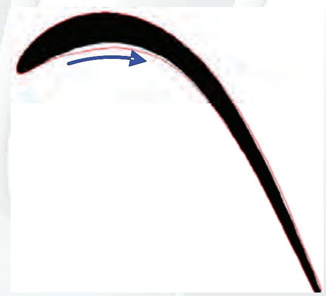
2000

Thick Hollow
High Lift
NAE



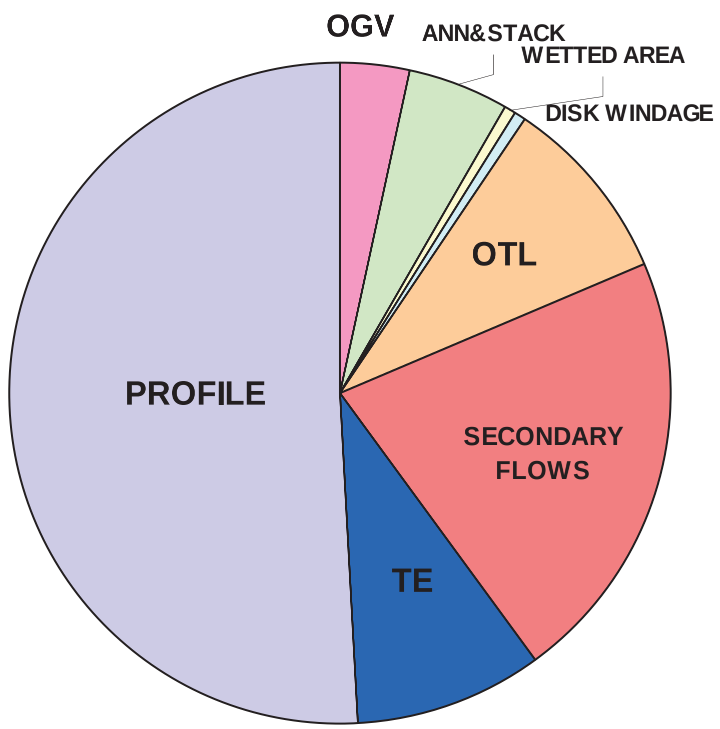
2010

Thin Solid
Ultra High Lift
AE



Loss distribution in LPTs

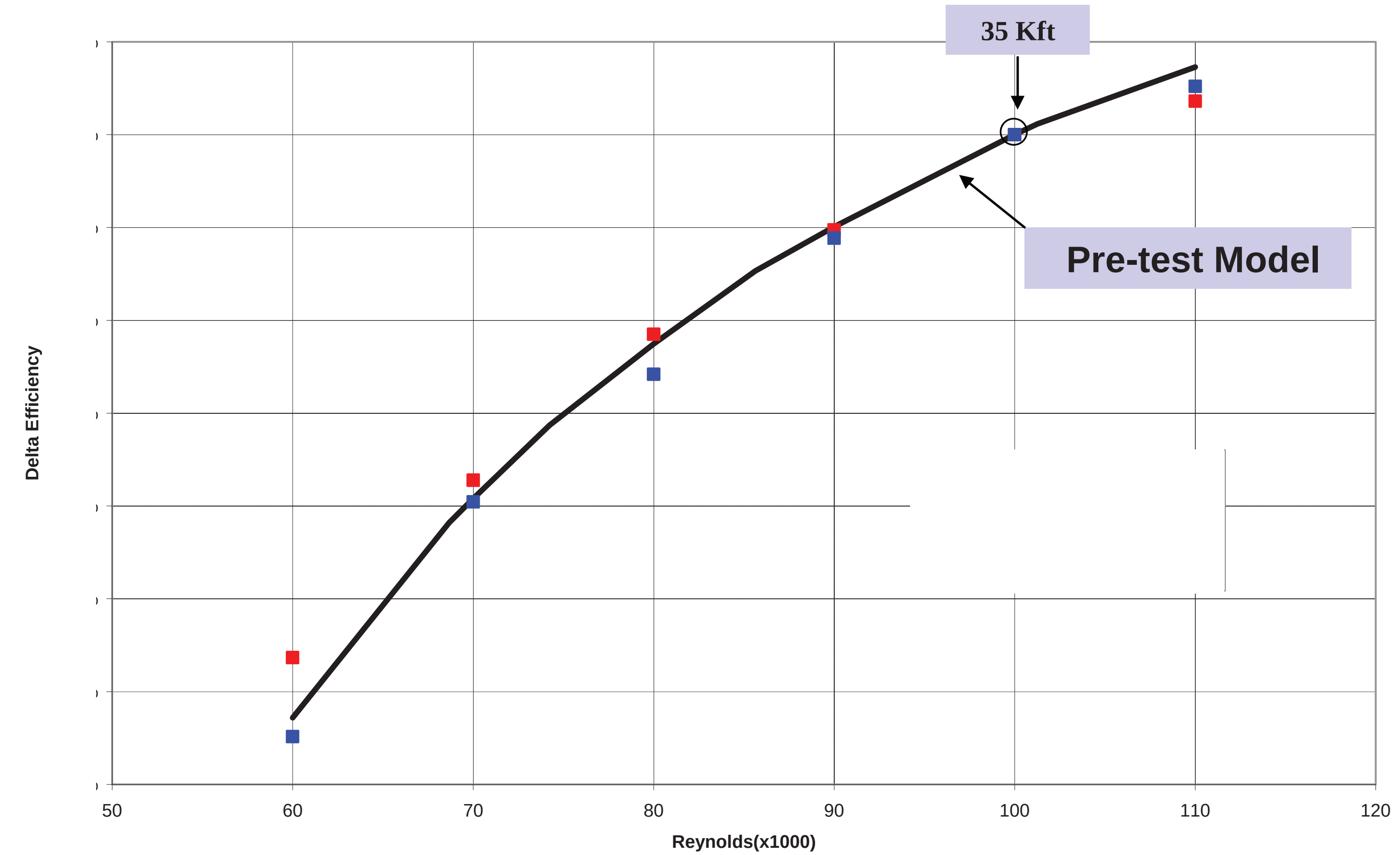
Industria de Turbo Propulsores,S.A.



Effect of altitude on efficiency

Industria de Turbo Propulsores,S.A.

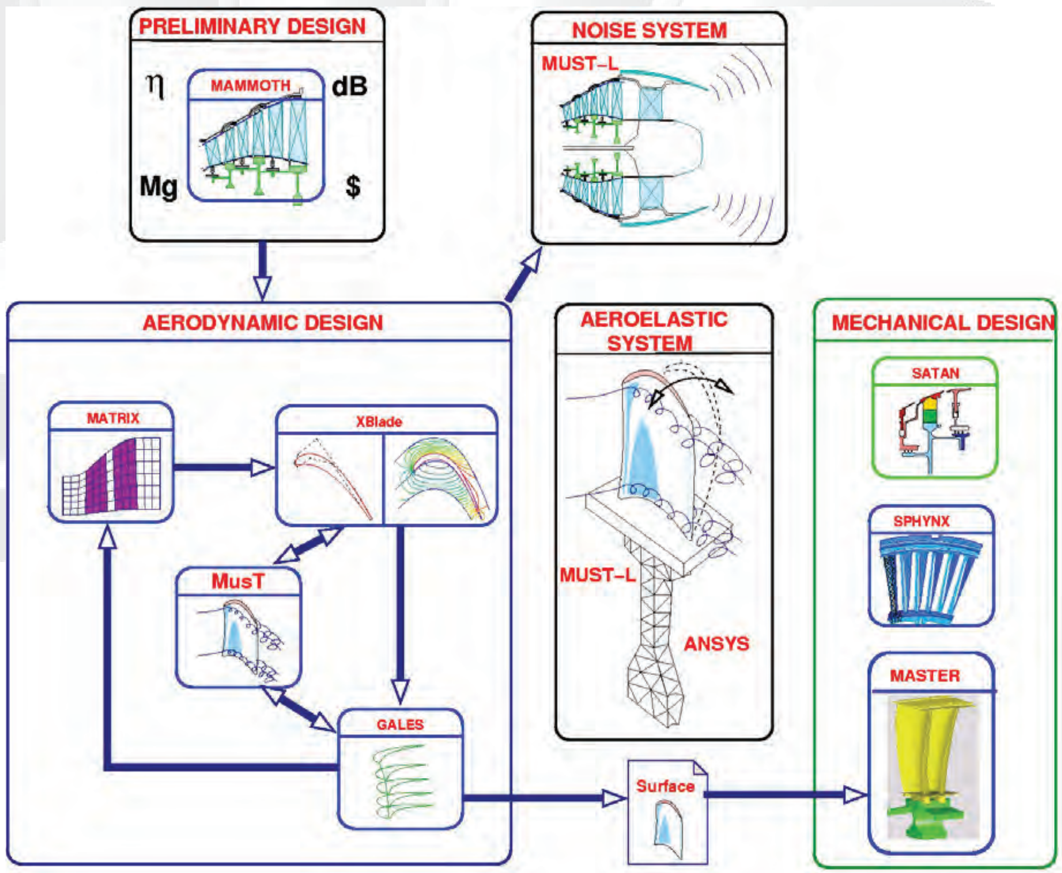
Delta of Efficiency vs. Reynolds No. at ADP operating conditions::



LPT design cycle and methods used

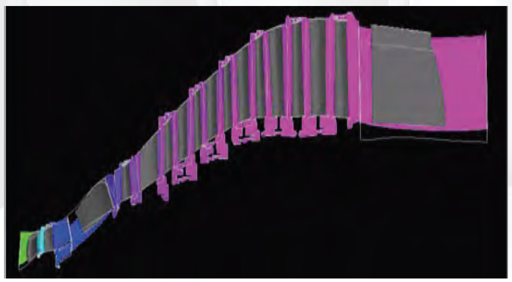
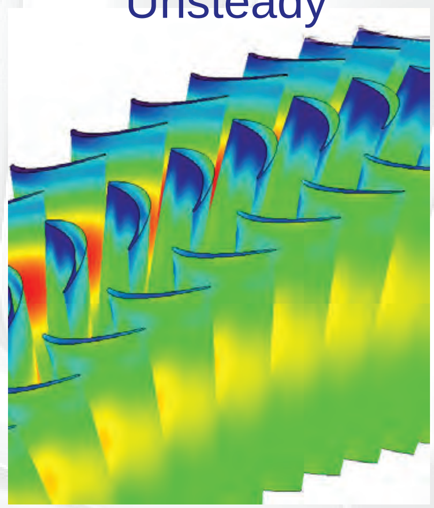
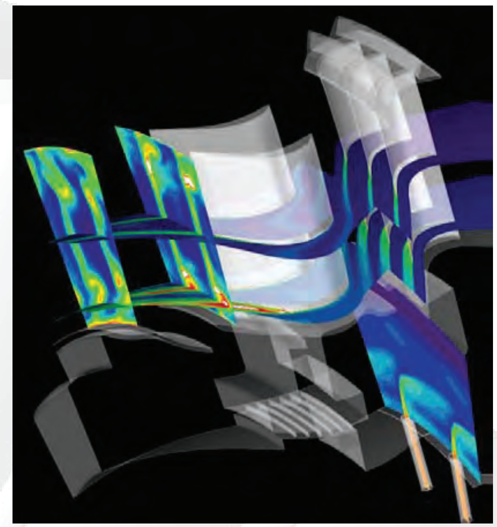
Industria de Turbo Propulsores,S.A.

Functional Design System:



LPT design cycle and methods used

Industria de Turbo Propulsores,S.A.

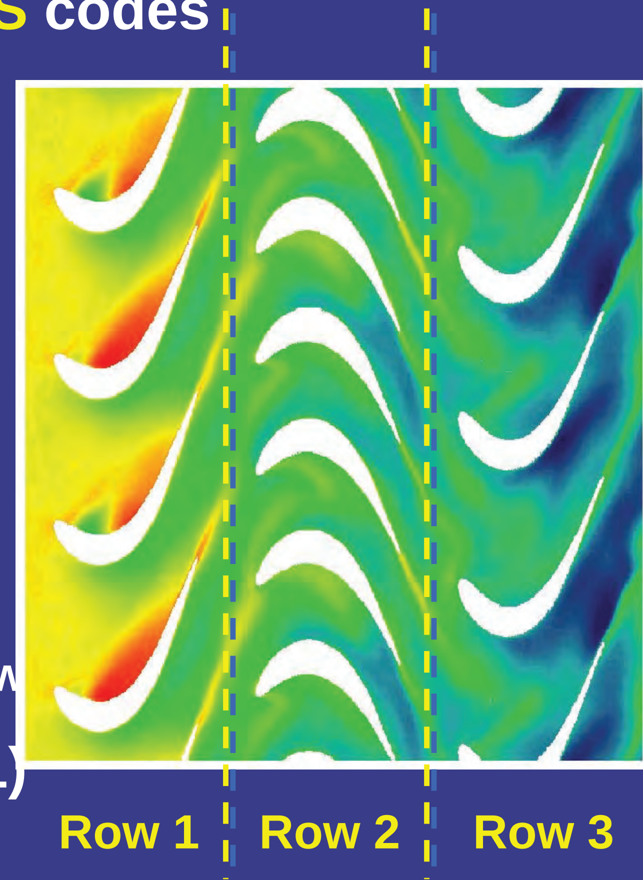
Multi-Stage Steady	Multi-Stage Linear Unsteady	Multi-Stage Unsteady
		
• Real Geometry • CPU time ~ hours	• Real Geometry • CPU time ~ hours	• Real Geometry • CPU time ~ Days

- **Functional Design Time ~ 6 months**
- **Multi-Stage Steady ~ o(10³)**
- **Multi-Stage Linear Unsteady ~ o(10²)**
- **Multi-Stage Unsteady ~ o(10⁰)**

The Mu^2s^2T Suite of Codes

- Mu^2s^2t is a consistent suite of RANS codes
  - Same Numerical Techniques
    - Hybrid unstructured grids
    - Preconditioning
    - Multigrid
    - Parallelization …
- It is split in 3 blocks
  - Non-Linear: $\partial U/\partial t = F(U)$
  - Harmonic Linear: $i\omega u = (\partial F/\partial U)_0 u$, w

    $U(x,t) = U_0(x) + \varepsilon\, u(x) e^{i\omega t}$ $(\varepsilon << 1)$
  - Adjoint: $\partial v/\partial t = (\partial F/\partial U)^T v$



Experimental Facilities

Industria de Turbo Propulsores, S.A.

CTA

San Fernando de Henares (Madrid)

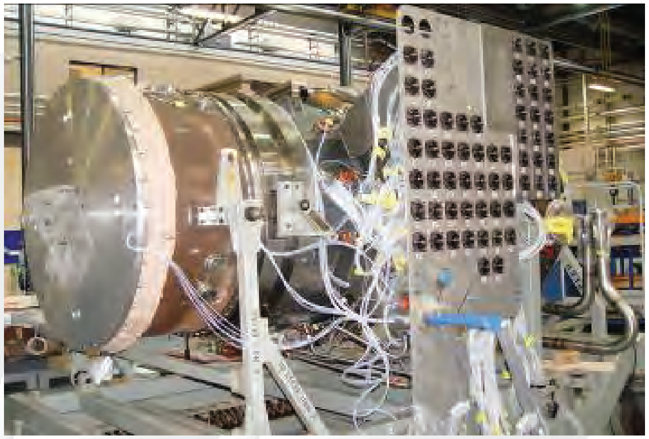
Industria de Turbo Propulsores, S.A

UPM (Madrid)

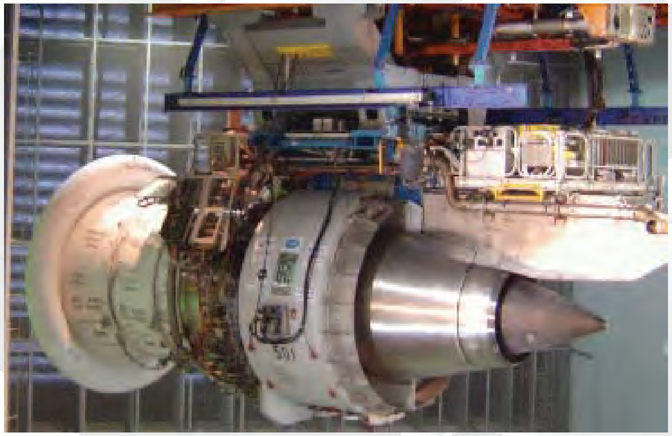
Experimental Facilities

Industria de Turbo Propulsores, S.A.

TRL 1/2	Basic Principles /Concept
TRL 3	Analytical and/or experimental proof of concept
TRL 4	Component validation in a Laboratory environment.
TRL 5	Component validation in a relevant environment.
TRL 6	System/subsystem in a relevant environment.
TRL 7	System demonstration in a operational environment.



TRL 6 (Multistage Rig)



TRL 7 (Engine Testing)

Experimental Facilities

Boundary Layer Studies (TRL3)

Wind Tunnel BV3

- Continuous flow blow-down wind tunnel.
- Flat Plate.
- Closed Cell Operation.
- Test Section with Full Optical Access.
- Software Controlled Operation.
- Low speed flow conditions.
- Reynolds No. Range: 6 104 - 5 105
- Boundary Layer studies.
- LDV and PIV diagnosis.
- Moving Bar Mechanisms

TEST RIG PARTIAL VIEW

Experimental Facilities

Industria de Turbo Propulsores, S.A.

Steady Profile Optimization (TRL4)

Wind Tunnel BV2

- Continuous flow blow-down wind tunnel.
- Linear Cascades.
- Closed Cell Operation.
- Test Section with Full Optical Access.
- Software Controlled Operation.
- Low speed flow conditions.
- Reynolds No. Range: 6 104 - 5 105
- OGV & LPT airfoil testing
- LDV and PIV diagnosis.

Experimental Facilities

Industria de Turbo Propulsores,S.A.

Unsteady Profile Optimization (TRL4)

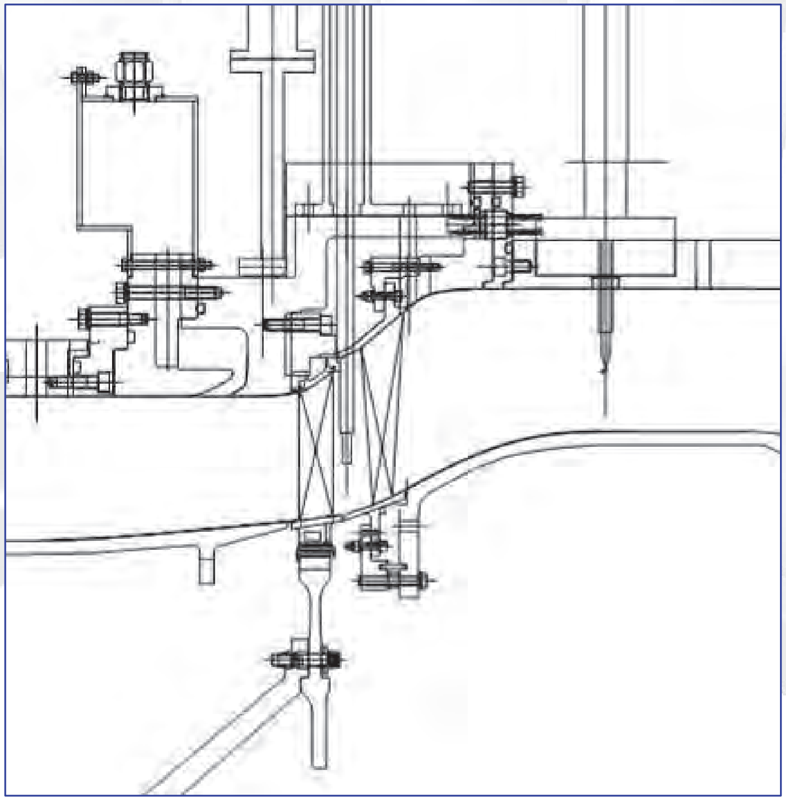
Wind Tunnel BV1

- Continuous flow blow-down wind tunnel.
- Linear Cascades.
- Closed Cell Operation.
- Test Section with Full Optical Access.
- Software Controlled Operation.
- Passing Bars Mechanism for unsteady studies.
- Low speed flow conditions.
- Reynolds No. Range: 6 104 - 3.5 105
- LDV and PIV diagnosis.

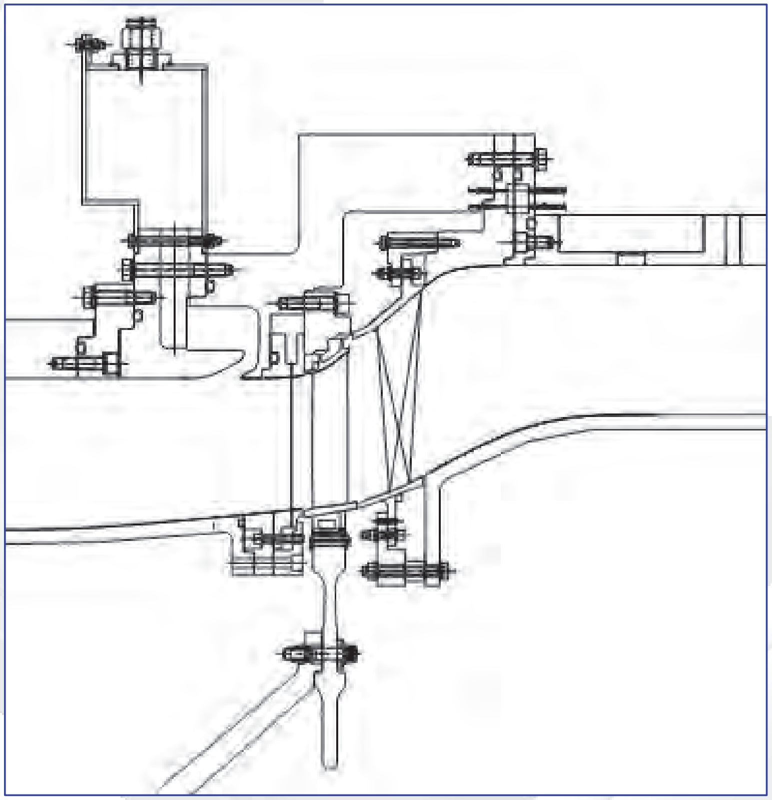
Experimental Facilities

Industria de Turbo Propulsores,S.A.

Single Stage Optimization (TRL5)



Rotor-Stator Interaction

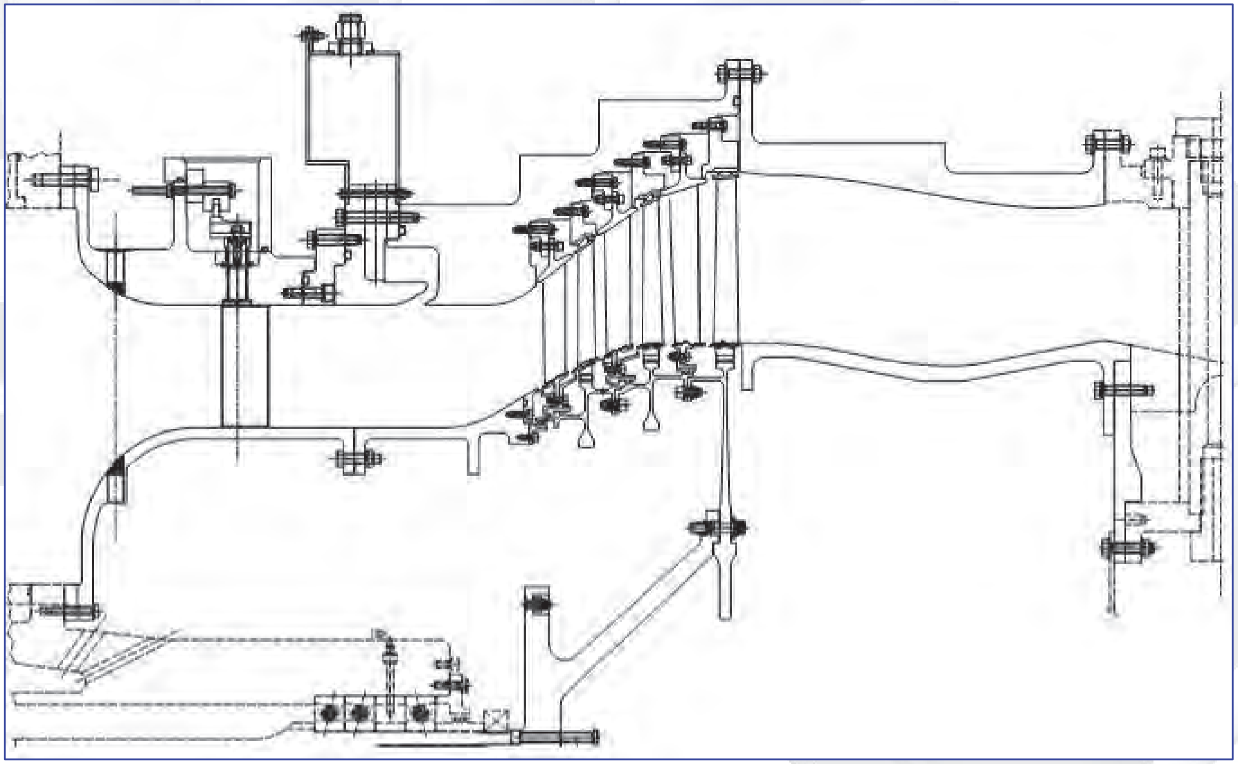


Stator-Stator Interaction

Experimental Facilities

Industria de Turbo Propulsores,S.A.

Multistage Optimization (TRL6)



Example of a multi-stage rig

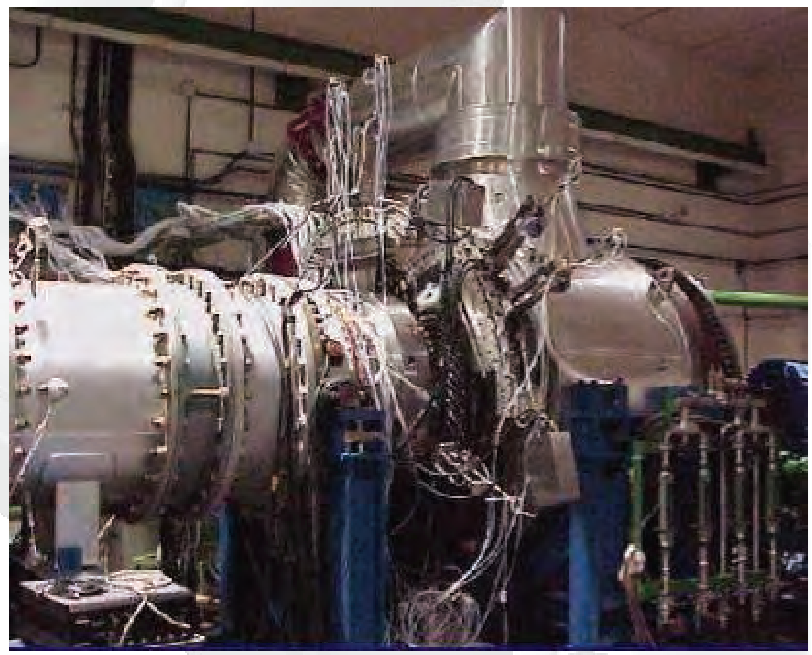
Experimental Facilities

Industria de Turbo Propulsores, S.A.

Multistage Optimization (TRL6)

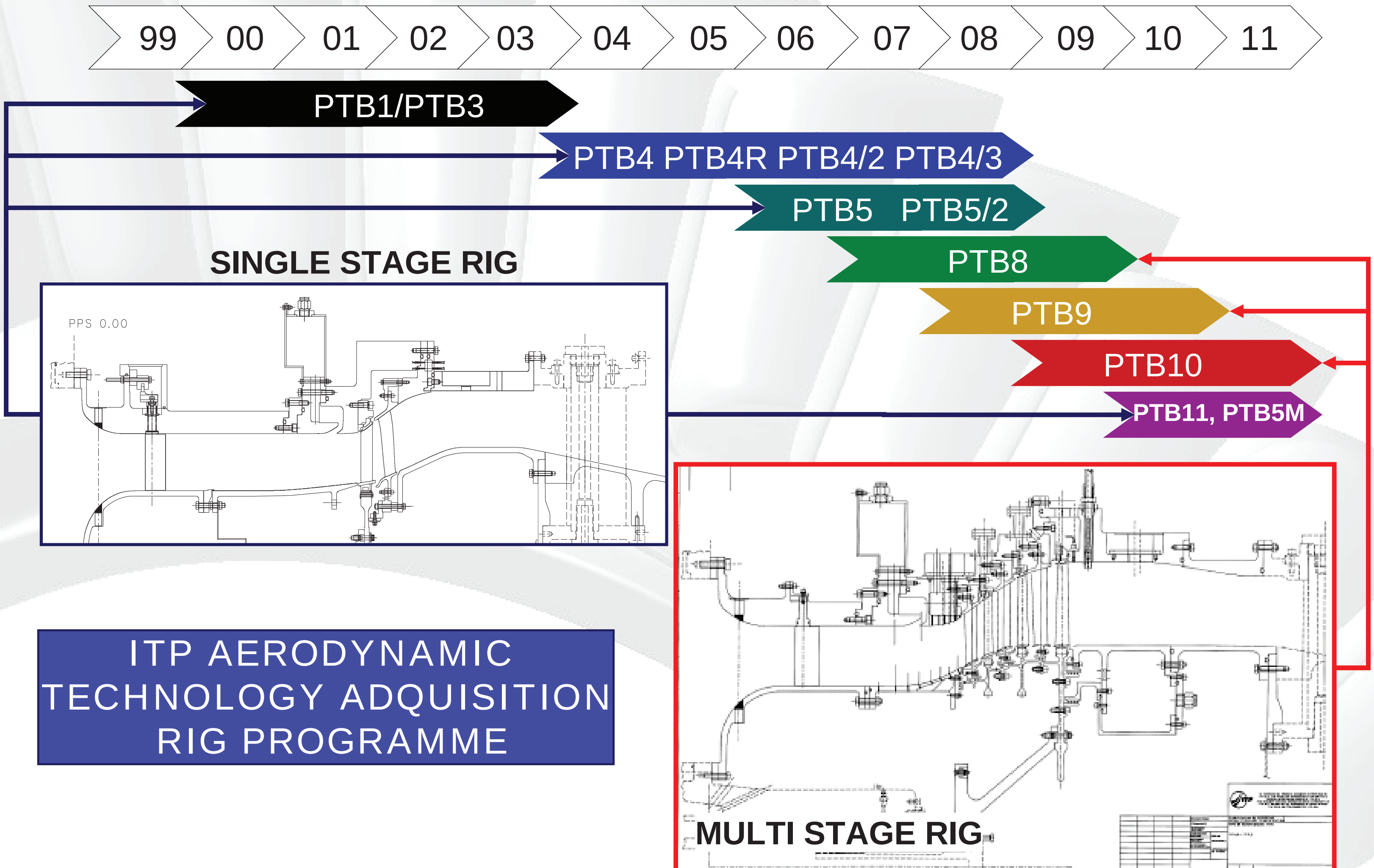
Wind Tunnel AV1

- Continuous flow open-circuit variable density transonic wind tunnel where Reynolds and Mach number can be fixed independently.
- Software Controlled Operation.
- High speed flow conditions.
- Annular Cascades and Turbine Stages.
- Max. Temperature 450K
- Max. Inlet Pressure 450 kPa.
- Max. Mass Flow 20 kg/s.
- More than 1000 pressure and temperature measurement channels of high precision.
- Fast Response Miniature Probes.
- Noise Measurement Module.



Experimental Facilities

Industria de Turbo Propulsores, S.A.



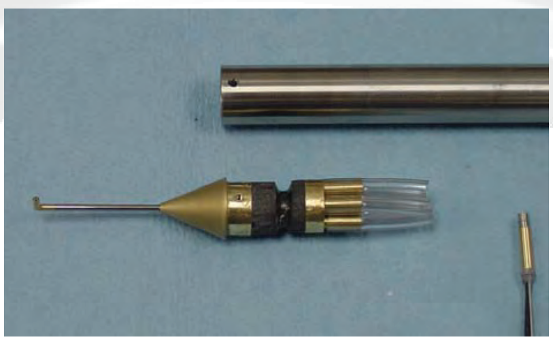
ITP AERODYNAMIC TECHNOLOGY ADQUISITION RIG PROGRAMME

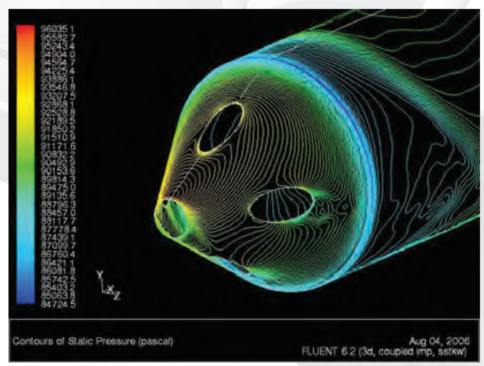
NASA/CP—2020-220327

Experimental Facilities

Industria de Turbo Propulsores,S.A.

EQUIPMENT	# SYSTEMS	# CHANNELS
LASER-DOPPLER	3	2
HOT WIRE / HOT FILM	4	14
PIV	1	2
FAST RESPONSE PROBES	8	40
MINIATURE PROBES	7	27





Experimental Facilities

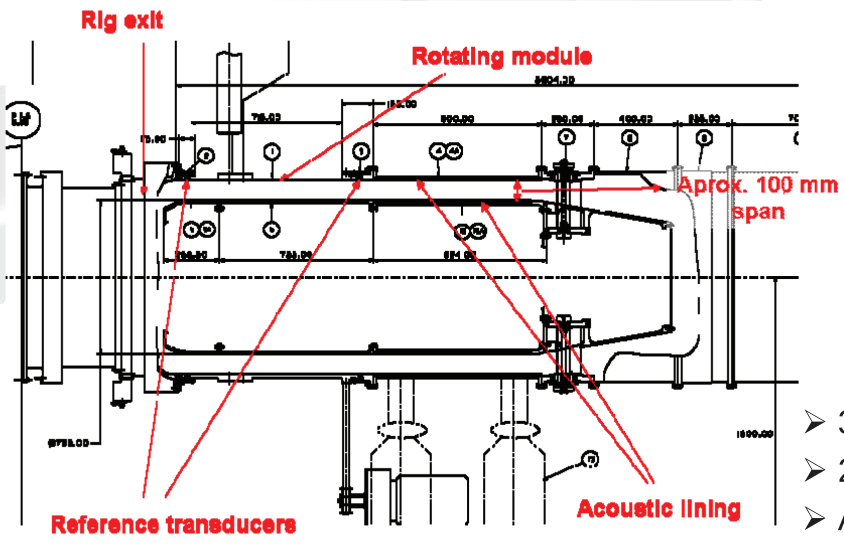
Industria de Turbo Propulsores,S.A.

Experimental Capabilities for Noise Measurements

Noise Tests Background

- Facility Commissioning
- One stage preliminary measurements
- Noise Measurement Module Installation.
- Single & Multi stage measurements.

Single Stage Rigs tested in CTA: Noise Measurement Module

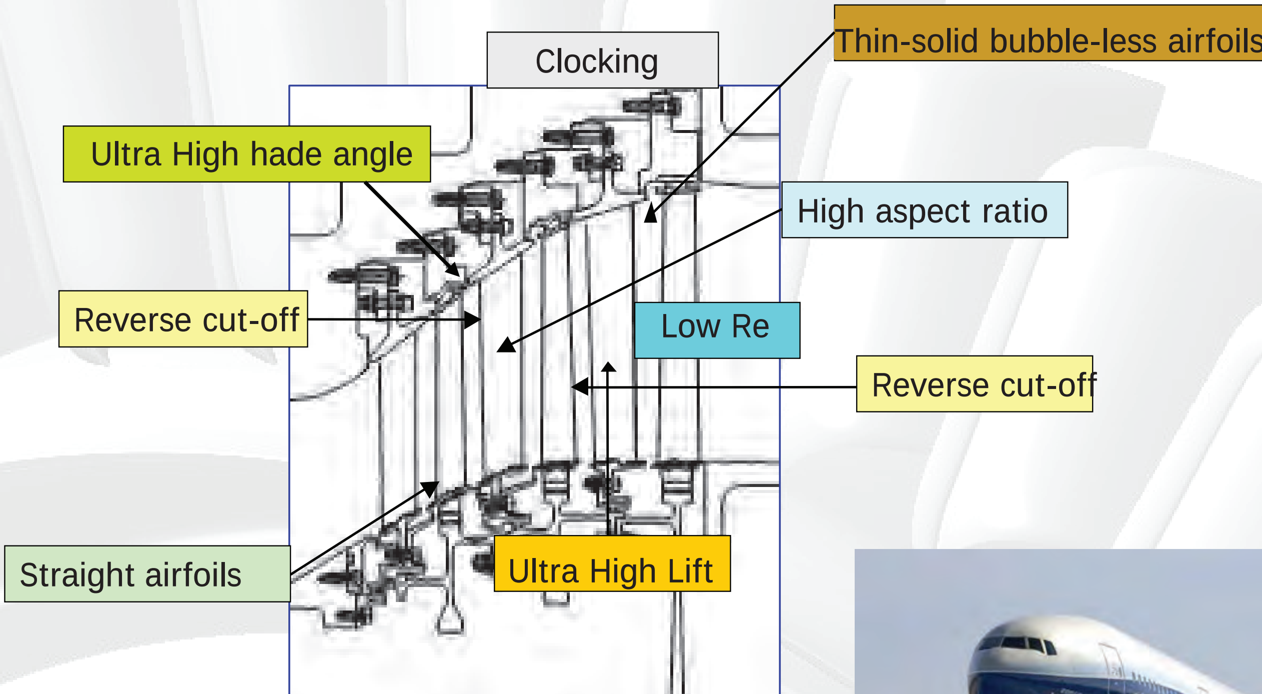


- 360º rotating casing
- 2 reference transducers for cross mode detection.
- Axial spacing optimized for an accurate mode detection.

Future trends and requirements

Industria de Turbo Propulsores,S.A.

State of the art of LPT technology in 2010



Trent XWB

Future trends and requirements

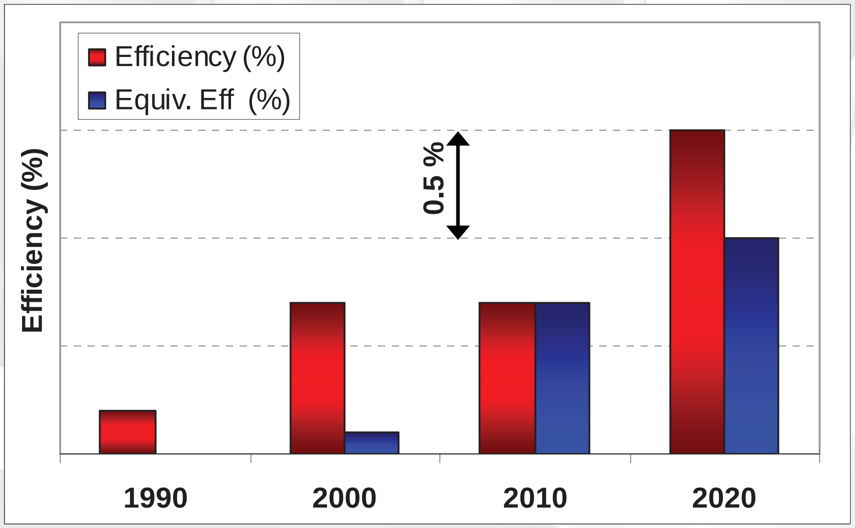
Industria de Turbo Propulsores, S.A.

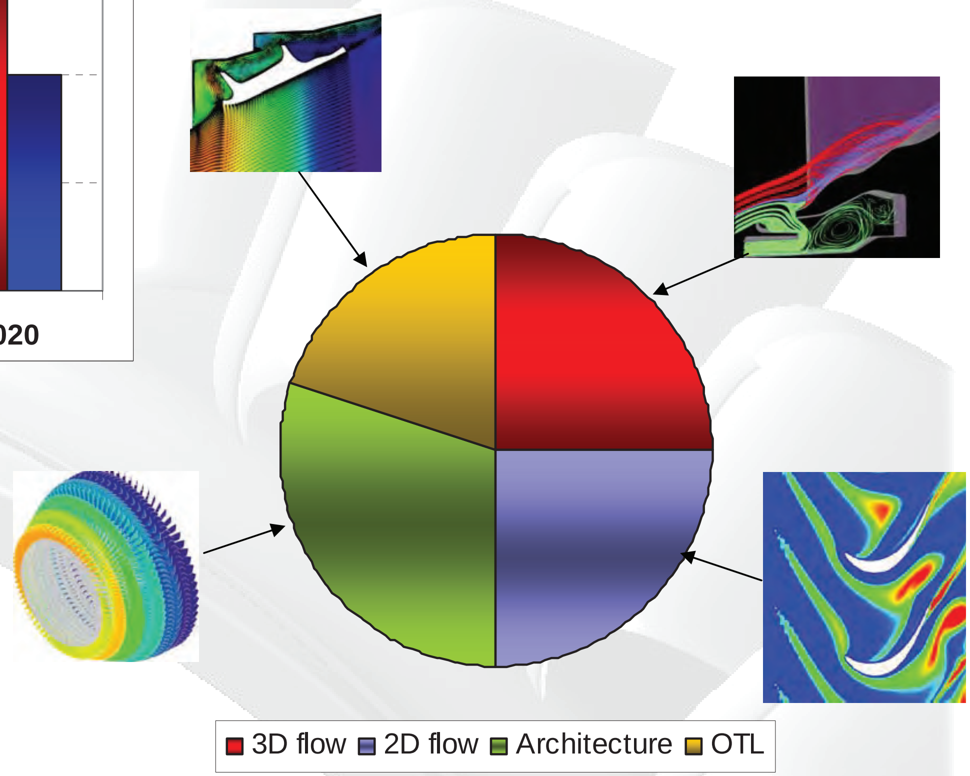
Main Researching Areas

- Aggressive LPT Architectures.
- 2nd Family of UHL Airfoils.
- Smart Endwall Design.
- Tip Clearance Control
- Silent Turbines.

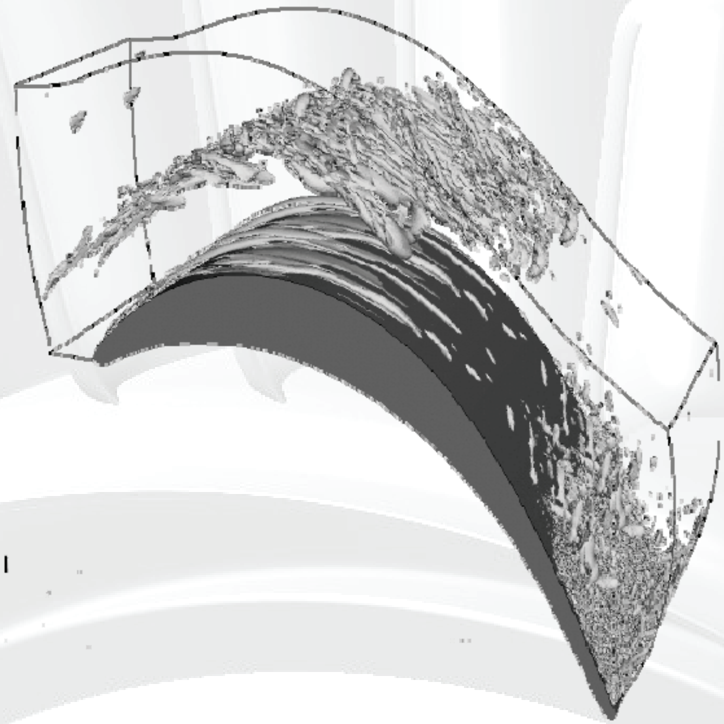
Future trends and requirements

Industria de Turbo Propulsores, S.A.

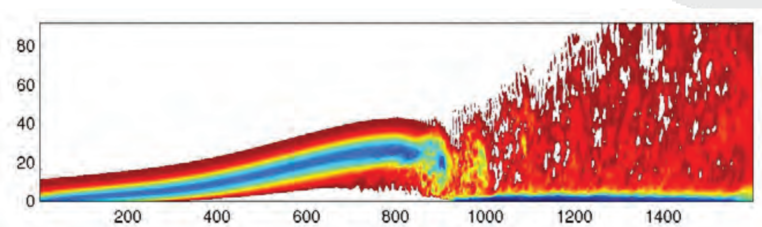


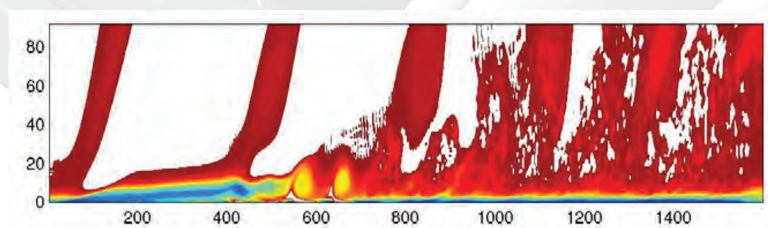


Main Research Fields: 2D Aerodynamics



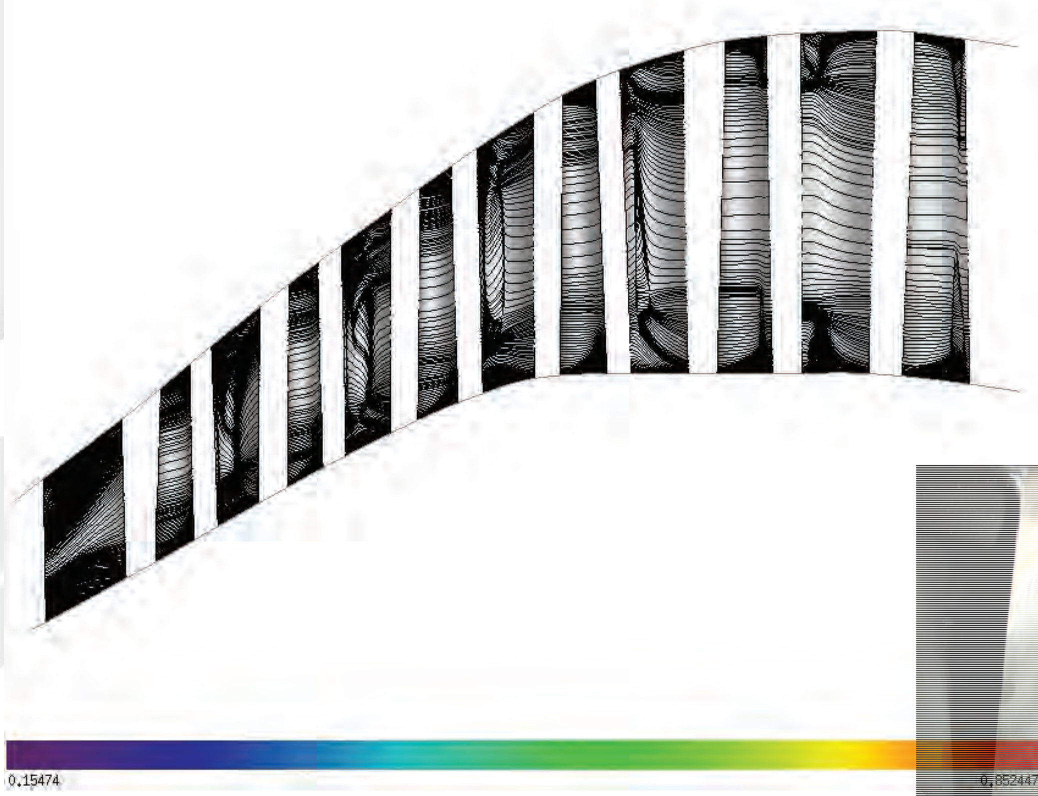
- Turbulent Models fail to predict Transitional Bubbles
- Efficiency strongly depends:
  - Unsteadiness
  - Incoming Turbulence
- Today we are performing DNS
- Computational Requirements:
  - Accuracy & Efficiency
  - Number of nodes 10^8-10^9





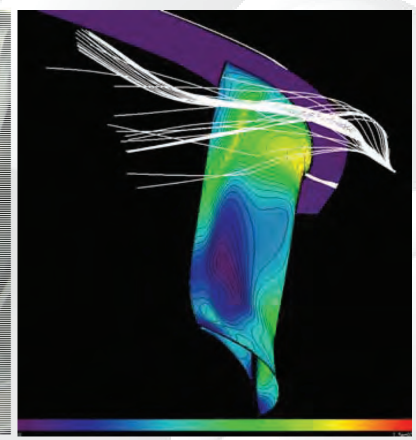
Main Research Fields: 3D Aerodynamics

Industria de Turbo Propulsores,S.A.



- **Strong radial migration that amplify the multistage coupling**

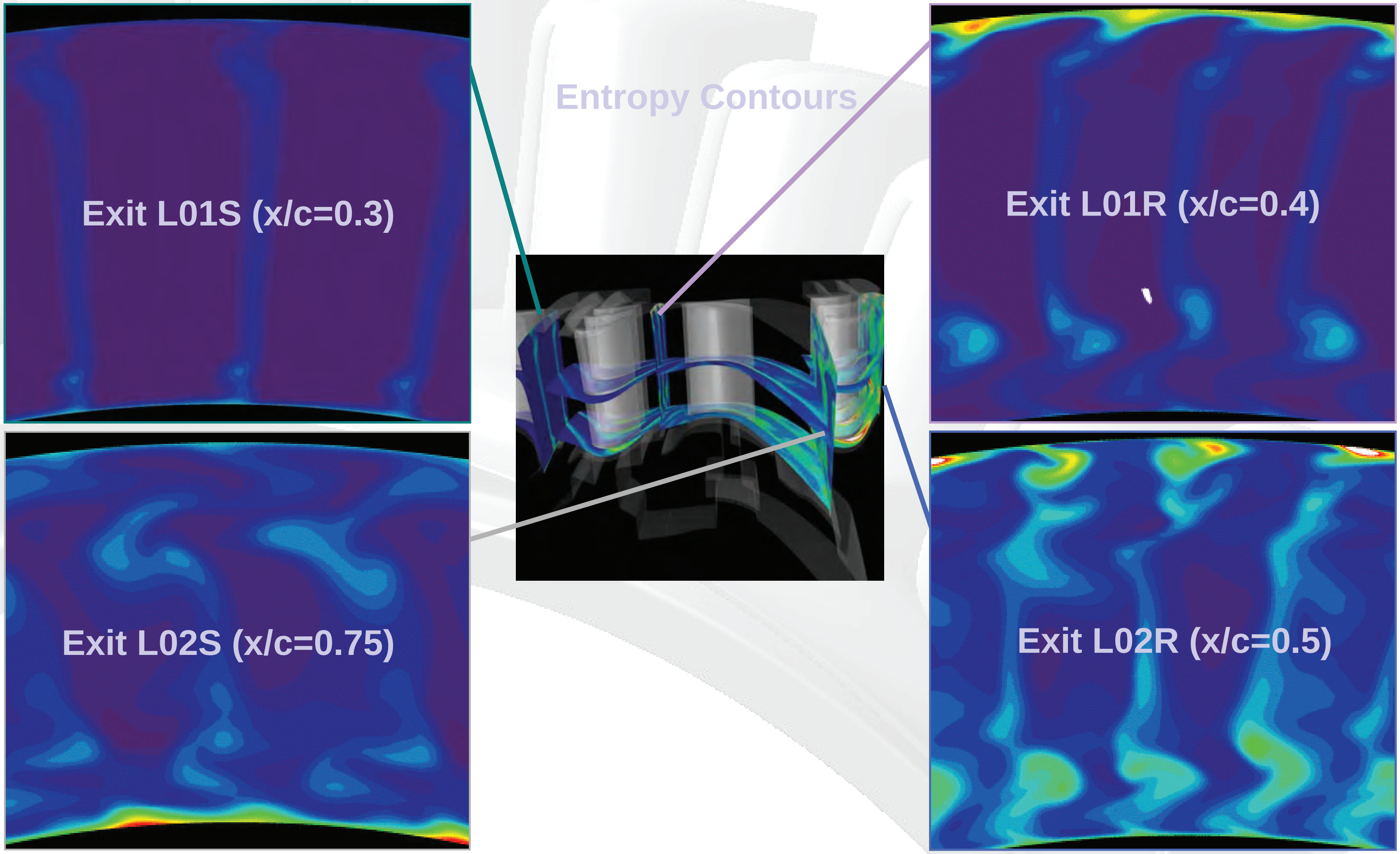
Zinc acetate engine 3/1



Trent 1000 NGV1

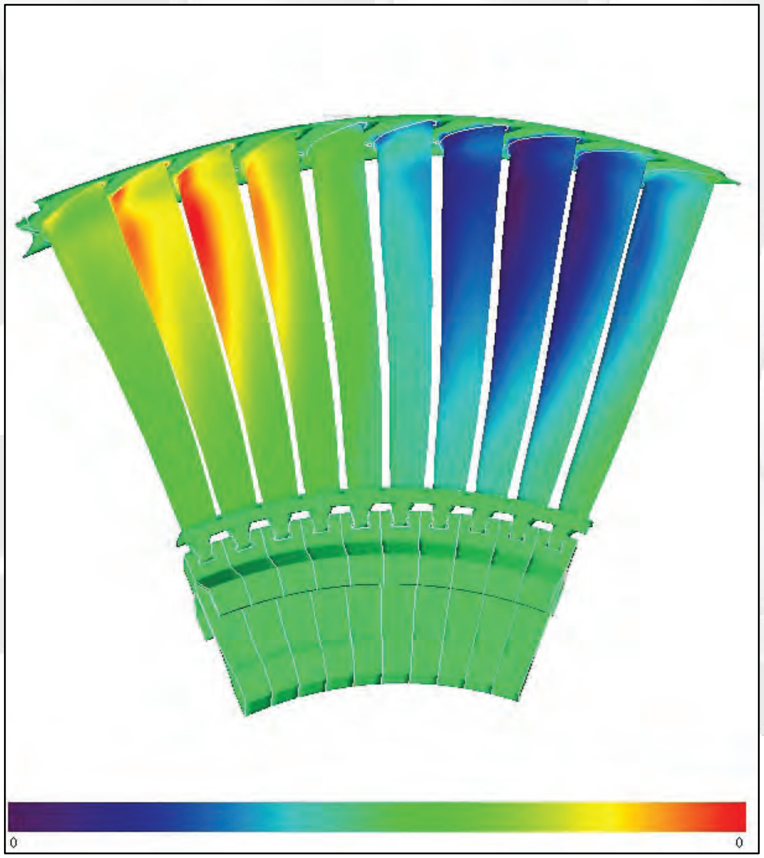
Main Research Fields: Multistage

Industria de Turbo Propulsores,S.A.



Main Research Fields: Aeroelasticity

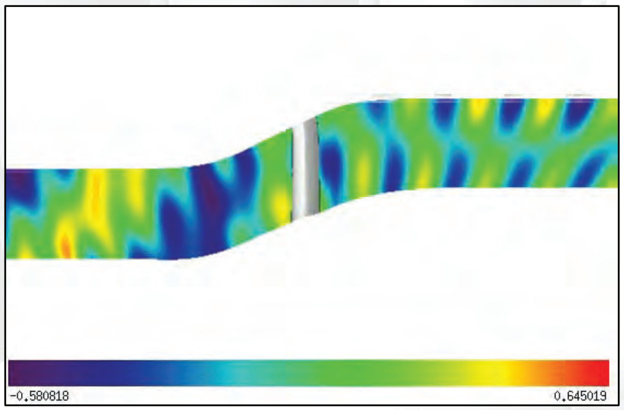
Industria de Turbo Propulsores,S.A.

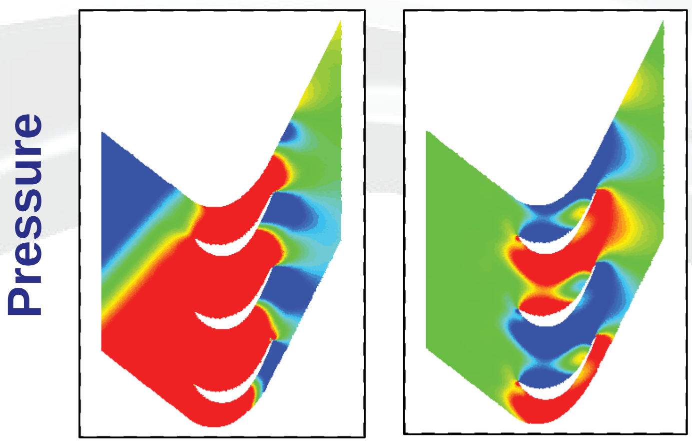


- Understanding and prediction of Flutter behaviour of welded-in-pair rotors
- Understanding and prediction of Flutter behaviour of vane packets
- Experimental and Numerical Re-confirmation (higher order methods)
- Use of Intentional Mistuning to increase aerodynamic stability
- Forced Response Methods.
- Fully Coupled Non-Linear Aeroelastic Methods.
- 1D blade-disk contact friction numerical & exp. characterization

Main Research Fields: Aeroacoustics

Industria de Turbo Propulsores, S.A.





Cut-on (N_R/N_V=1.1)

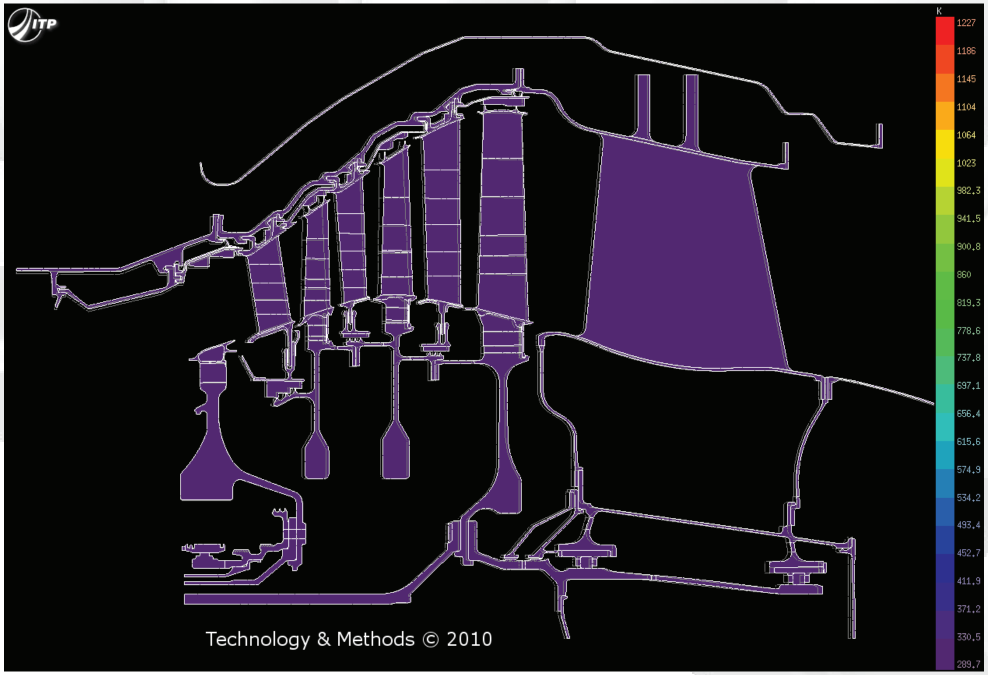
Cut-off (N_R/N_V=1.5)

- Understanding and prediction of tone noise generation, transmission and propagation.
- Understanding and prediction of haystack and broadband noise.
- Experimental and Numerical validation (both rig and engine level).
- Understanding and prediction of 3D Swirling flows.
- 3D design optimised for low noise.

Main Research Fields: 3D Thermal Analysis

Industria de Turbo Propulsores,S.A.

- Due to the small axial gaps a high accuracy thermal calc. Is required.
- Fully Coupled Non-Linear Thermal Methods.



NASA LPT Workshop

GE Industry Review
August 10, 2010

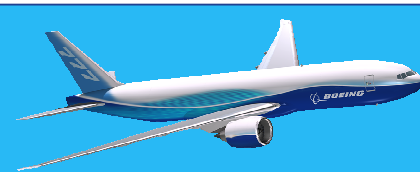
Lyle Dailey (GE Aviation)
David Halstead (GE Aviation)
Aspi Wadia (GE Aviation)
Fu-Lin Tsung (Tools COE)
Ravi Avancha (GE Research)

imagination at work

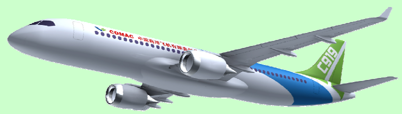
Agenda

- GE commercial LPT landscape
- LPT design challenges
- Design methodologies
- Future research needs

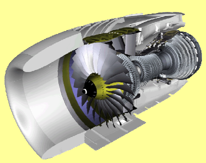
GE Commercial LPT Landscape



Wide body aircraft
- CF6, GE90, GEnx
- 5-7 LPT stages
- 2 HPT stages
- Re≈120k



Narrow body aircraft
- CFM56, LEAPX
- 4-6 LPT stages
- 1-2 HPT stages
- Re ≈70k



Regional/biz jet
- CF34, NG34, TECHX
- 4-6 LPT stages
- 1-2 HPT stages
- Re ≈30-50k

Re = cruise Reynolds number based on axial chord

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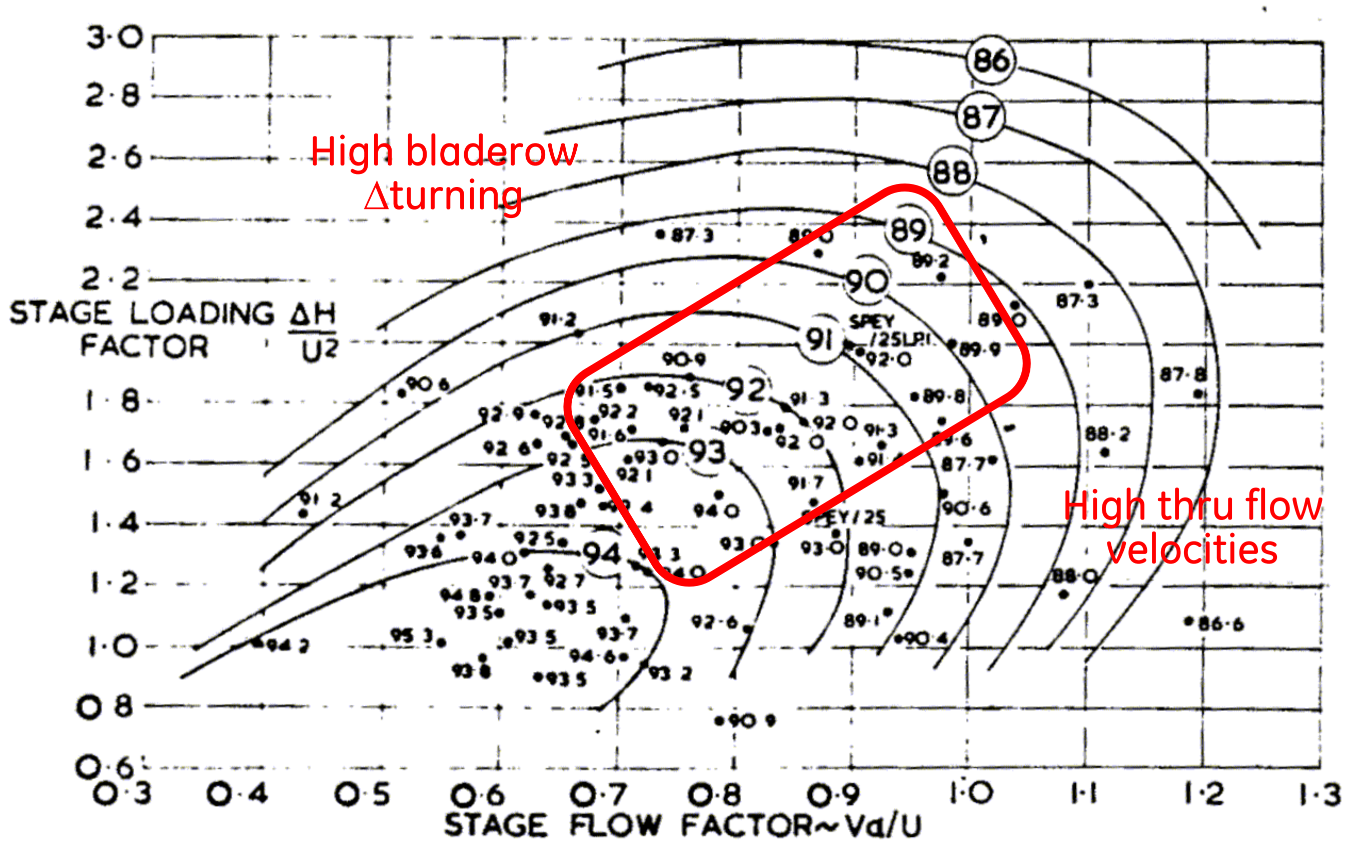
Smith Chart for "typical" LPT/PT turbines



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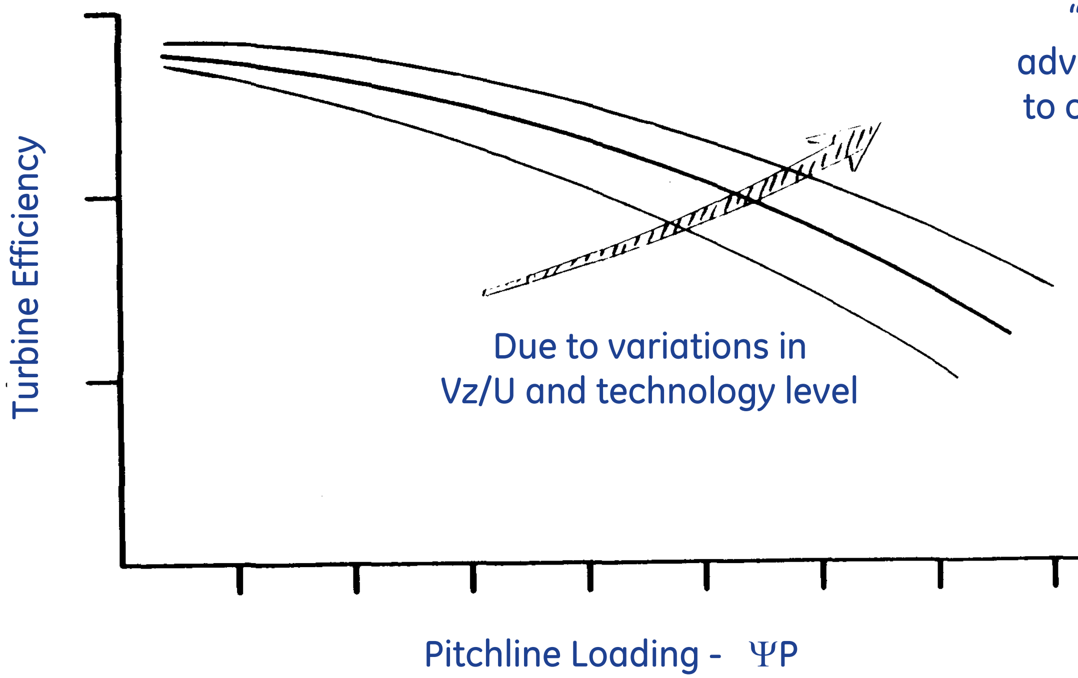
Performance Trends for LPT's

(of the three principal parameters, stage loading is most directly related to stage efficiency)



"3D aero" has provided limited advances in LPT efficiency compared to other components (fan, HPC, HPT)

LPT stage loading can vary considerably, depending upon type of engine, mission and other constraints

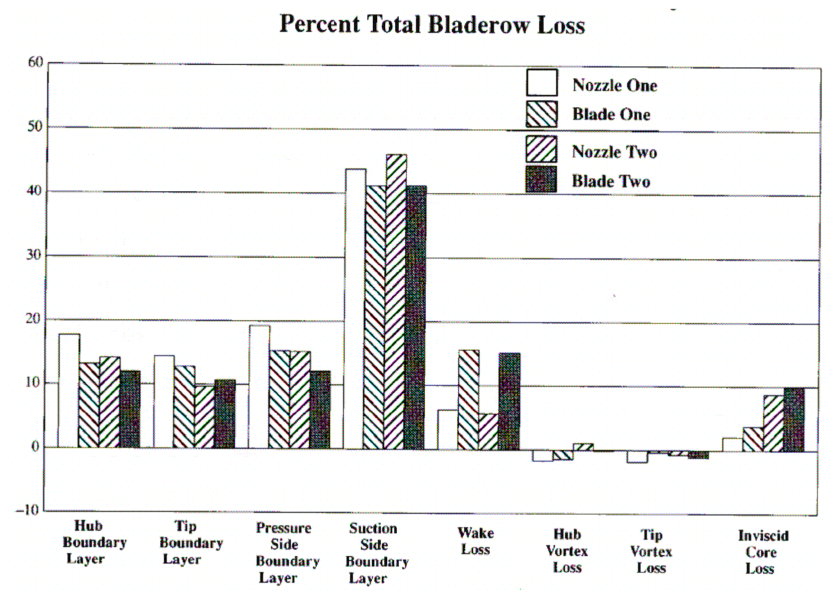
imagination at work

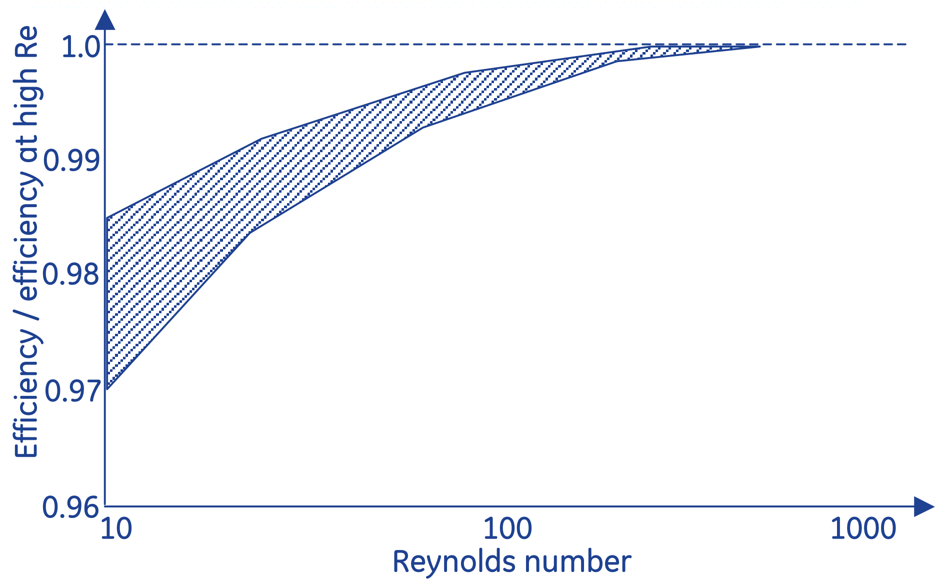
LPT design challenges

- High efficiency required due to large contribution to engine SFC
    - For 10 bypass ratio class engine, 1% LPT efficiency ~ 0.7-0.9% SFC
- While minimizing weight and cost
    - LPT one of heaviest modules in engine
    - Impacts stage count, airfoil count, material selection, mechanical sealing, engine dynamics
- Acoustics
    - Meeting acoustic requirements can impact weight, cost and aero
- Fuel burn reduction targets are driving engines to higher bypass ratios, putting additional challenge on LPT's

Loss sources in LPT

- LPT's dominated by profile losses
  - Suction side boundary layer and wake mixing
  - Especially for low Re
- Endwall losses second largest contributor
  - especially for higher stage loading and lift coefficients
  - interaction with cavities, purge, leakage
- Component interaction losses important for single HPT stage architectures
- High wall slope can lead to additional challenges





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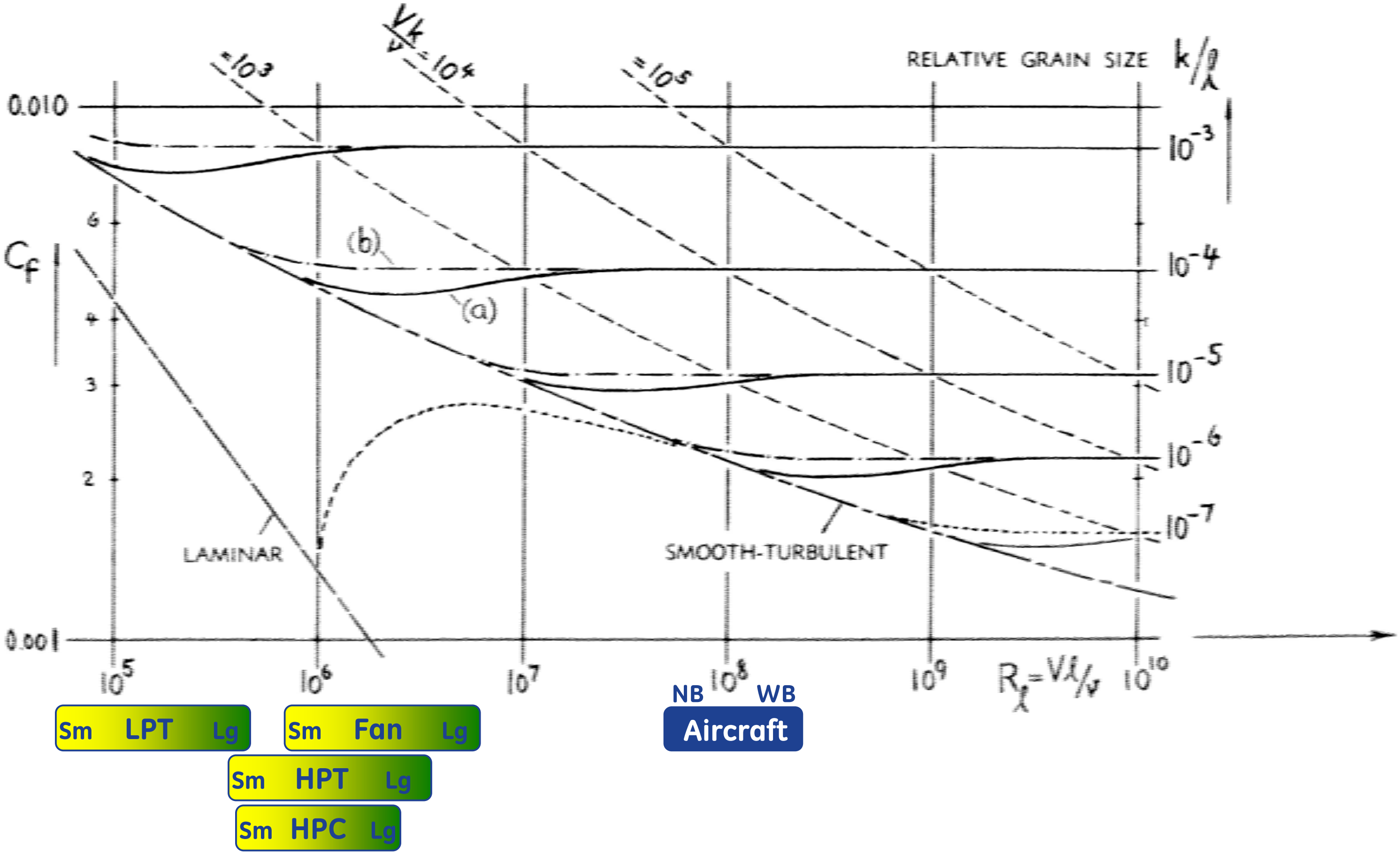
Re number regimes for comm'l engines



Small engine turbomachinery characterized by increased sensitivity to Reynolds effects / skin friction loss

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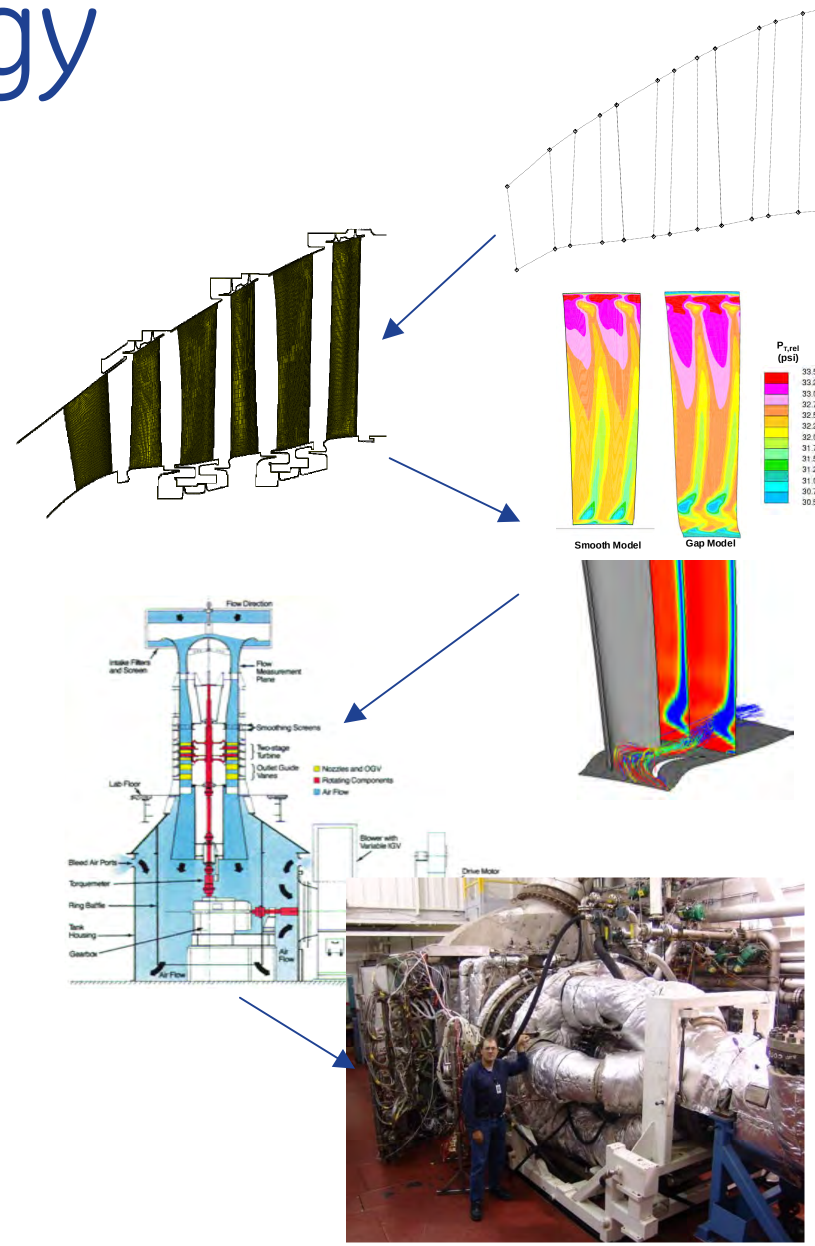
Design methodology

- Modern designs completed using increasing order tools and CFD analyses
  - 1D: pitch line prediction code based on significant empirical models
  - 2D: through-flow code with less empiricism
  - 3D: multistage CFD with advanced transition models and purge/leakage models

- Technologies / concepts beyond validation database require verification in rig tests
  - Rigs must closely replicate engine environment in terms of geometric and mechanical sealing features, operating conditions, etc



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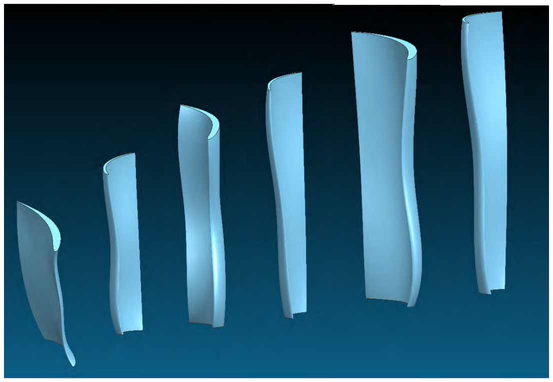
Future research needs

- Improved understanding of flow field in engine environment
  - Cavity interaction, turbulence, steady/ unsteady boundary layer behavior, unsteady interaction
  - Rigs that replicate engine environment, with detailed instrumentation
- Reducing losses at low Reynolds number
- Understanding and controlling endwall / cavity flows
- Advanced frames
- Improved CFD-driven design space exploration
  - Engineering design parameter and CAD-based



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NASA/CP—2020-220327

Pratt & Whitney
A United Technologies Company

LPT Design, Development and Challenges at Pratt & Whitney

Thomas Praisner
Shankar Magge
Richard Gacek
Om Sharma

NASA-Industry LPT/PT Efficiency Improvements Workshop, August 10-11, 2010

Summary

Pratt & Whitney
A United Technologies Company

Design Overview:

- LPT design requirements and loss breakdown
- LPT design trends (high lift)

Key Prediction Challenges lie in unsteady physics:

- Unsteady transition prediction for design purposes
- Inherent unsteadiness of endwall flows
- Unsteady mixing losses

- Summary of challenges

LPT Design Requirements and Opportunities:

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A United Technologies Company

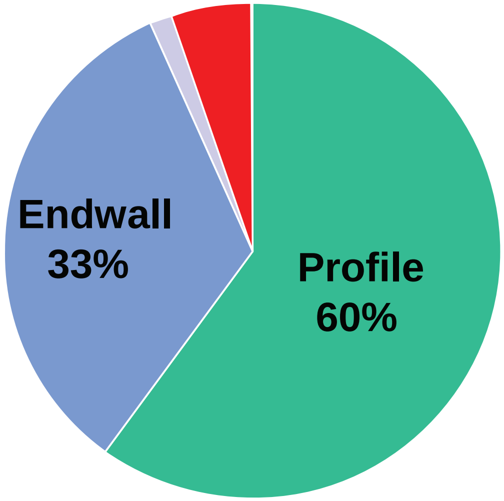
Design Requirements:

- High eff. LPT (more stages for higher bypass ratio engines)
- Speeds limited by fan
- Max diameter limited by nacelle
- LPT inlet constrained by HPT
- Reduced weight and cost
- Acoustic requirements
- 1 pt η = 0.9 – 1.0 % TSFC

Improvement Opportunities:

- Airfoil count reduction (cost, weight)
- Reduced endwall losses (contouring, cavities)
- Reduced profile losses (laminar designs)

LPT loss distribution



Recent LPT design trend has been to reduce airfoil count

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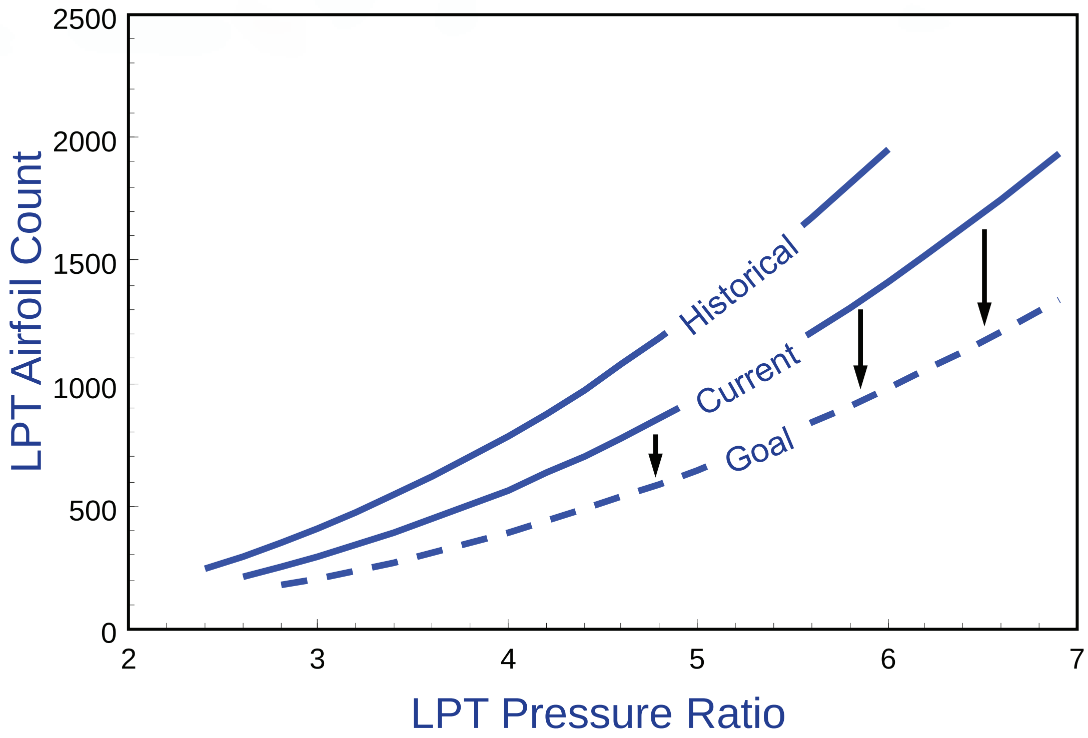
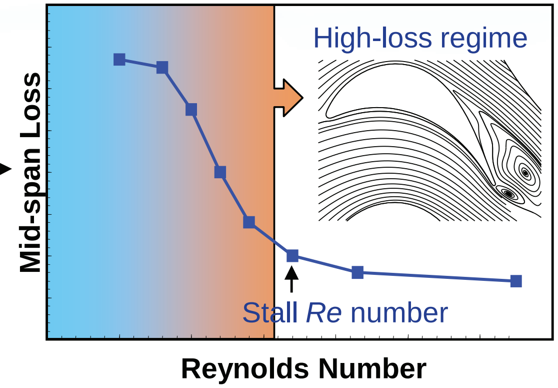
GT2008-50898



- Substantial headway in the area of high-lift LPT airfoil designs has been made in past 20 years.
- Are further count reductions possible for large commercial applications?

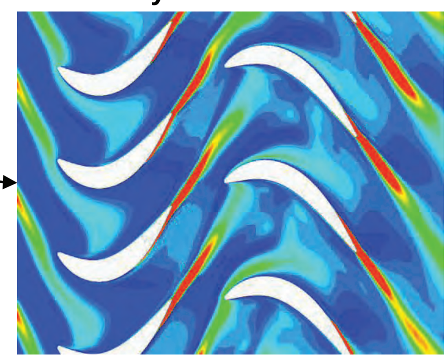
LPT high-lift technology presents significant benefits and challenges

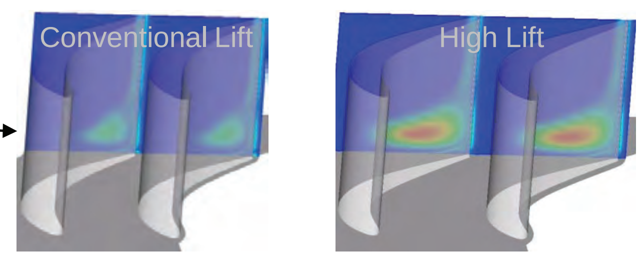
GT2008-50898



Challenges:

- Low Reynolds effects:
  - Boundary layer transition… airfoil stall
- Unsteady interactions (boundary layers, noise, vibrations…)
- Increased endwall losses
- Structural challenges (shrouds …)





Time-accurate transitional CFD enables accurate predictions of core flow performance levels

Pratt & Whitney
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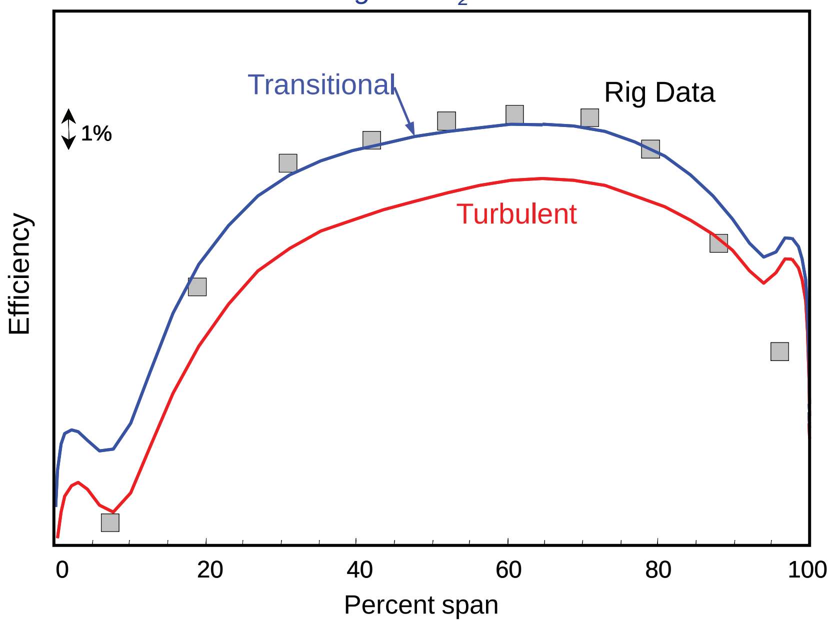
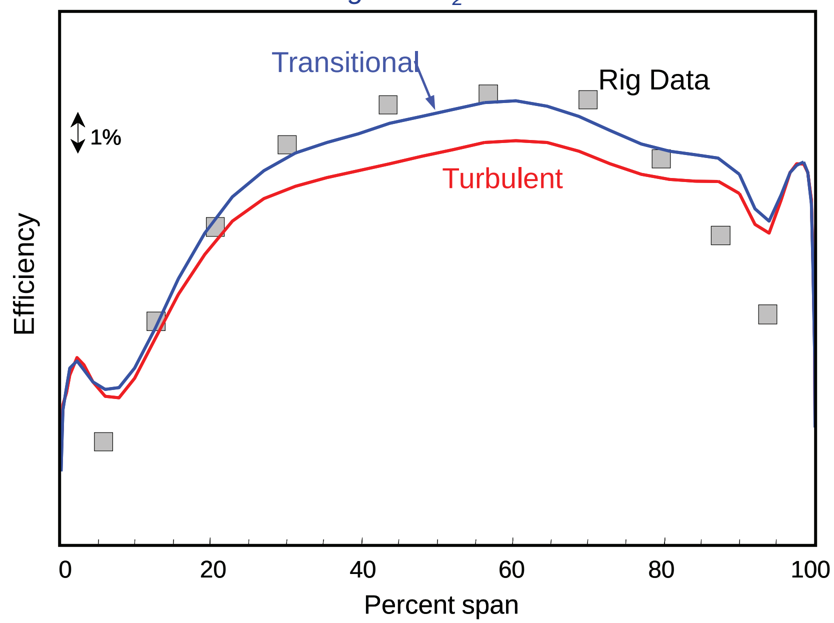
Minnowbrook 2003

For simplicity, cavities not modeled

Rig A: Re_2=1.7x10^5



Rig B: Re_2=2.0x10^5



Time-accurate transition predictions produce realistic temporal transition behavior

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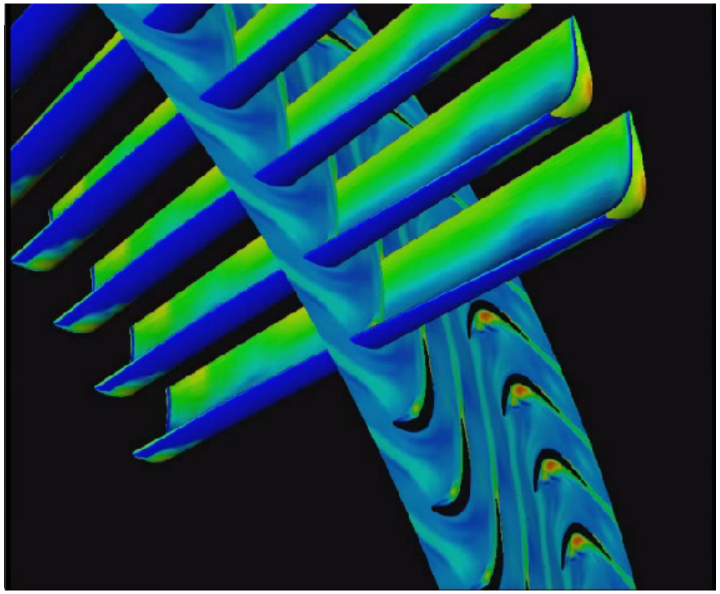
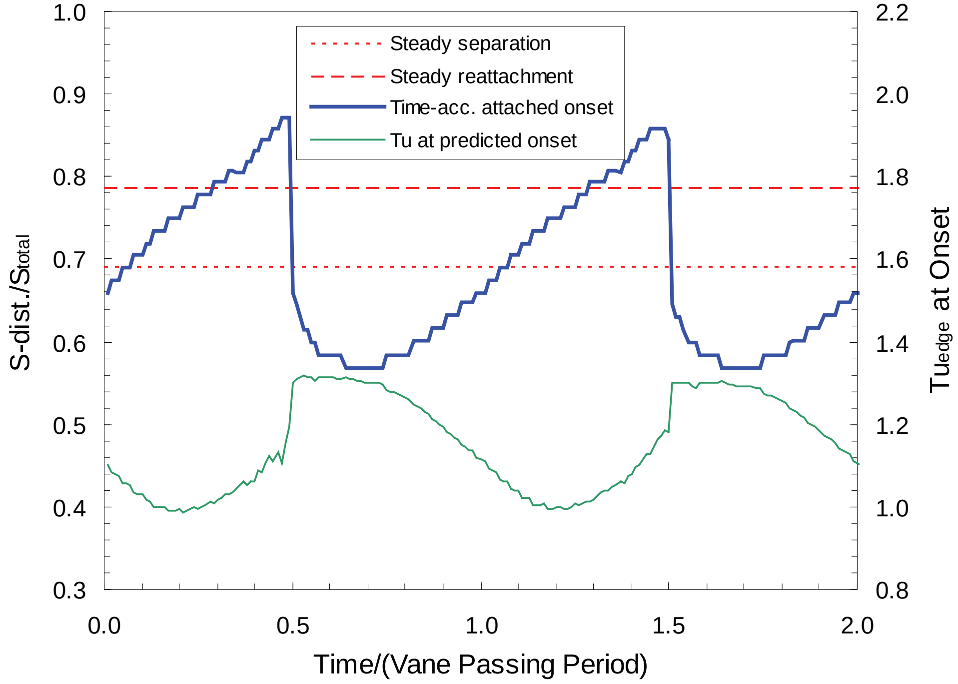
Minnowbrook 2003



Movie

Temporal behavior of midspan boundary layer transition



Endwall loss is a key challenge for high-lift designs

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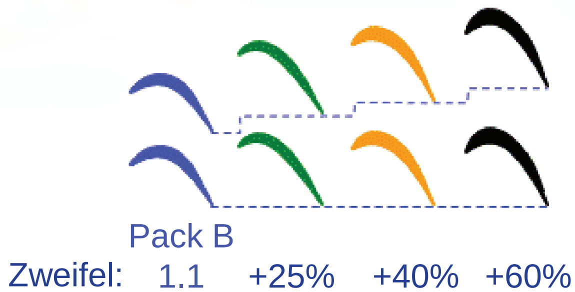
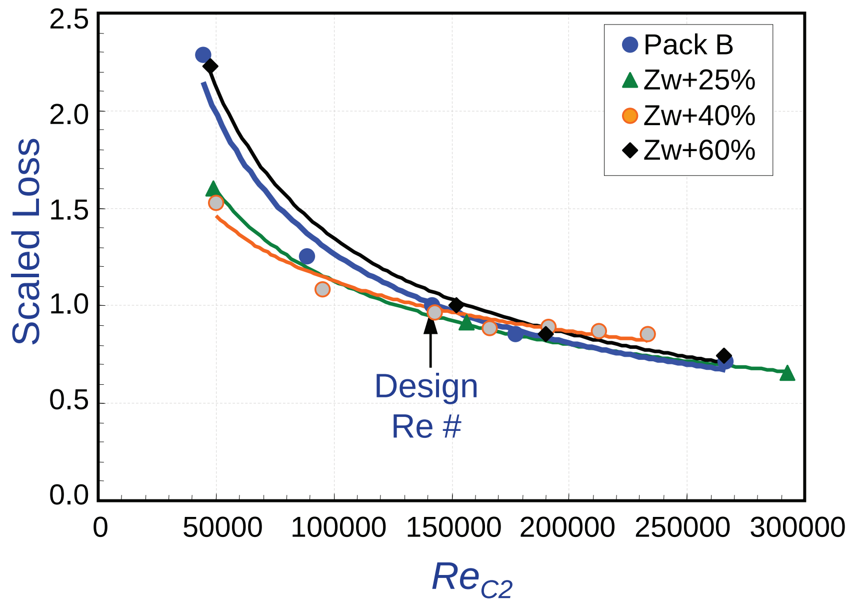
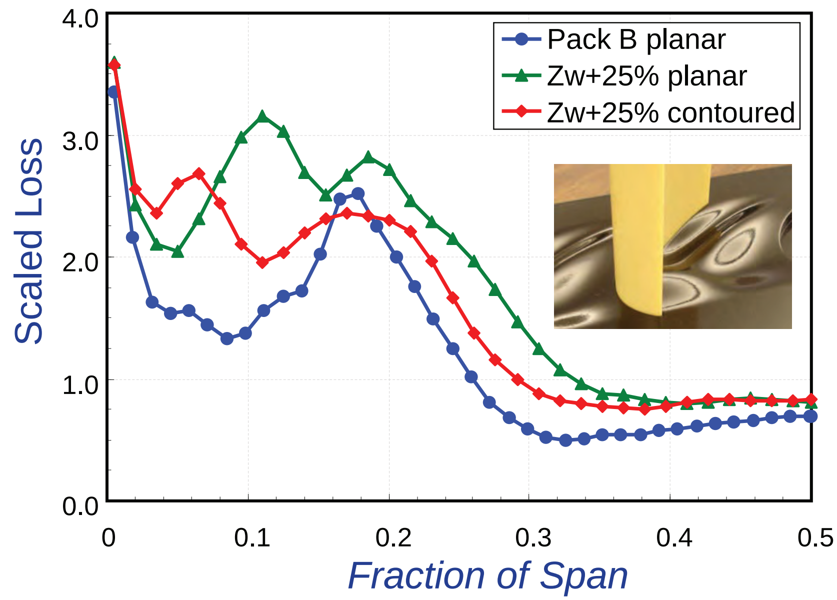
GT2008-50898



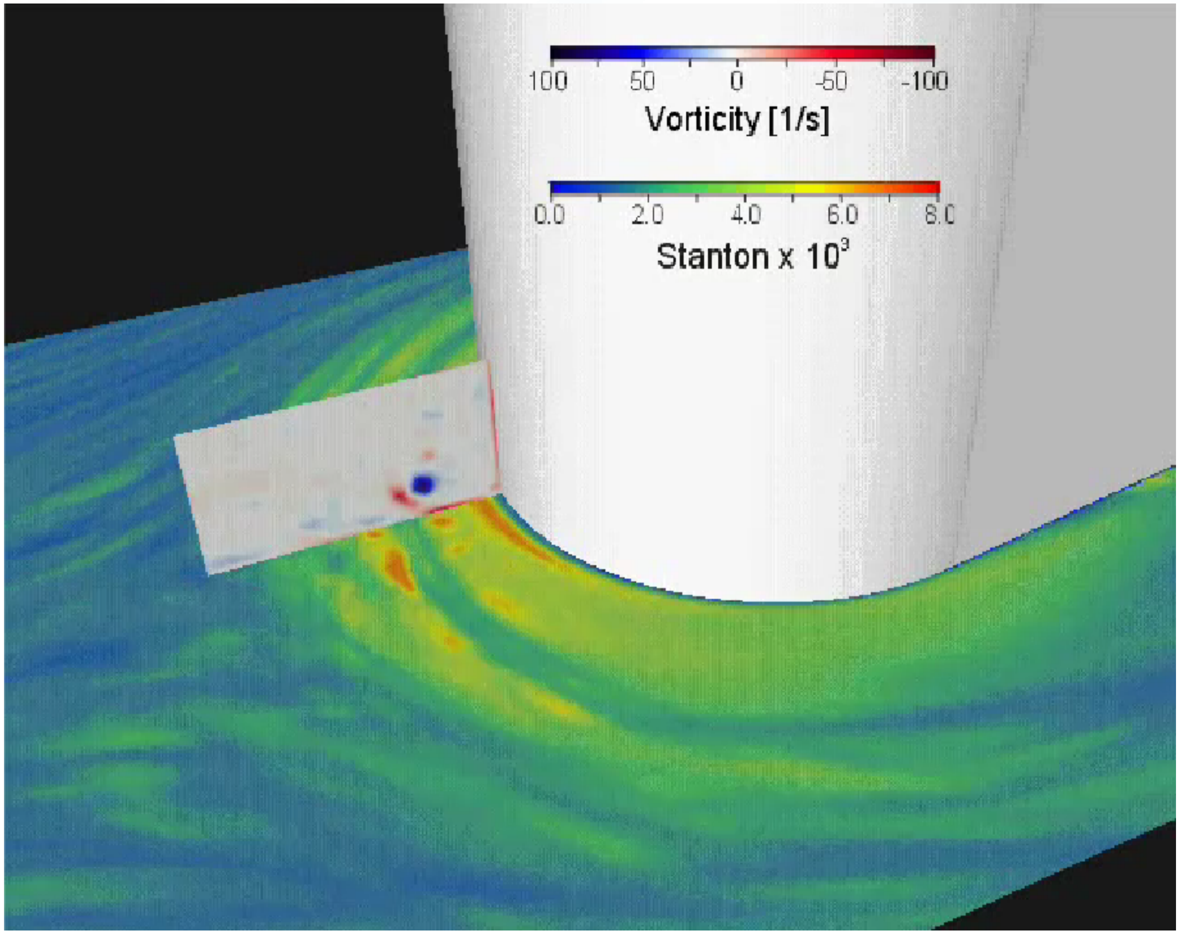
- Midspan losses can be managed for high-lift designs (no increase relative to baseline design)
- High lift exacerbates endwall losses the most, contouring alone can not fix





Endwall flow structures are inherently unsteady, RANS accuracy reduced

GT2005-69088



Movie

- Horseshoe vortex displays high levels of unsteadiness without mechanical forcing (blade passing).
- Losses and heat load difficult to predict with RANS.

Horseshoe vortex breakdown not well predicted with RANS

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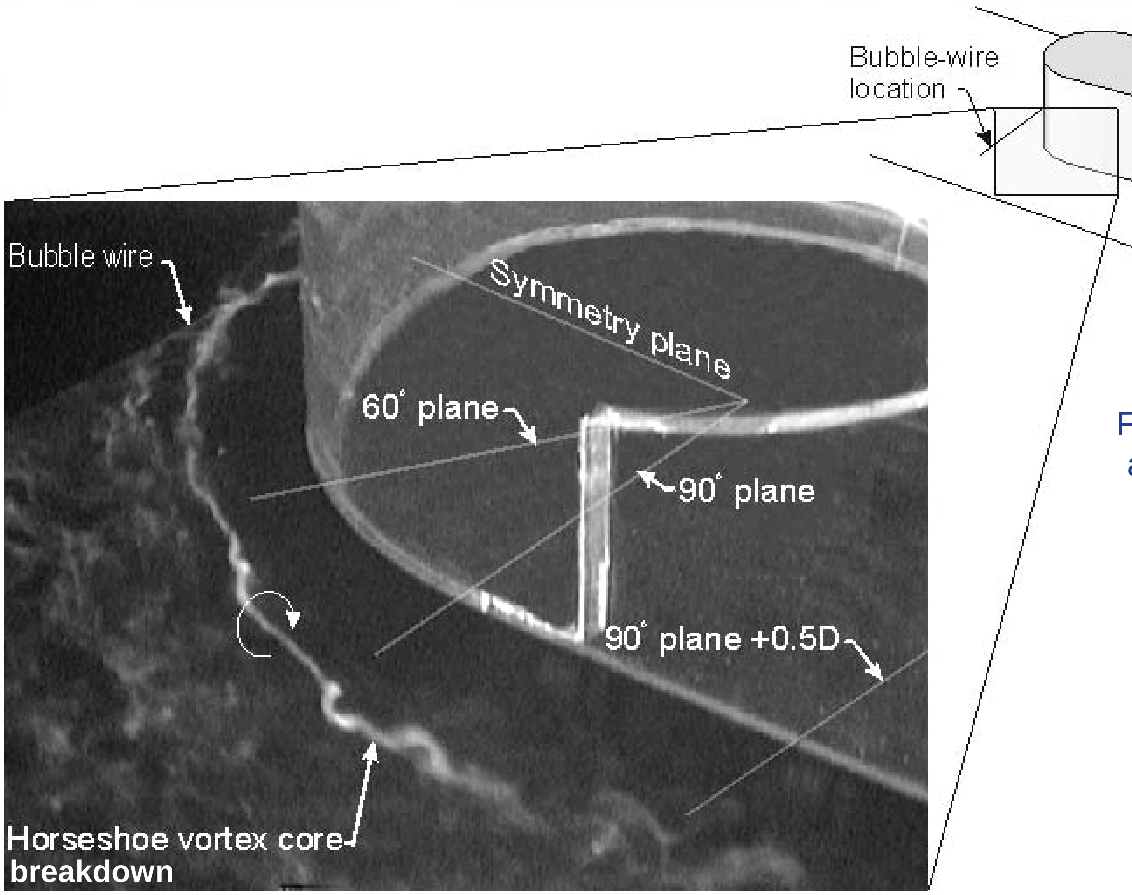

Flow-path divergence and cavities present additional issues

Multi-stage mixing losses appear well understood in compressors. How about turbines?

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GT2006-90666

Compressors:

- Wake-mixing losses are attenuated within downstream rows (Smith, 1966)

Corroborated by numerous, subsequent experimental and computational studies.

Turbines:

- In turbines wakes are "amplified rather than attenuated [as in compressors]." Smith (1966)

- "Dissipation in the wake [in turbines] will be reduced by mixing in a downstream row." Denton (1993)

- Hodson and Dawes (1998) experimentally demonstrated that wake loss could be as much as doubled, relative to constant-area mixing, as the wakes passed through a turbine cascade.

- Van de Wall et al. (2000) concluded that mixing losses of two-dimensional wakes are attenuated in *both* compressors and turbines.

So for turbines, which is it?

Time-accurate transitional CFD predictions hint at mixing-loss trends in LPTs

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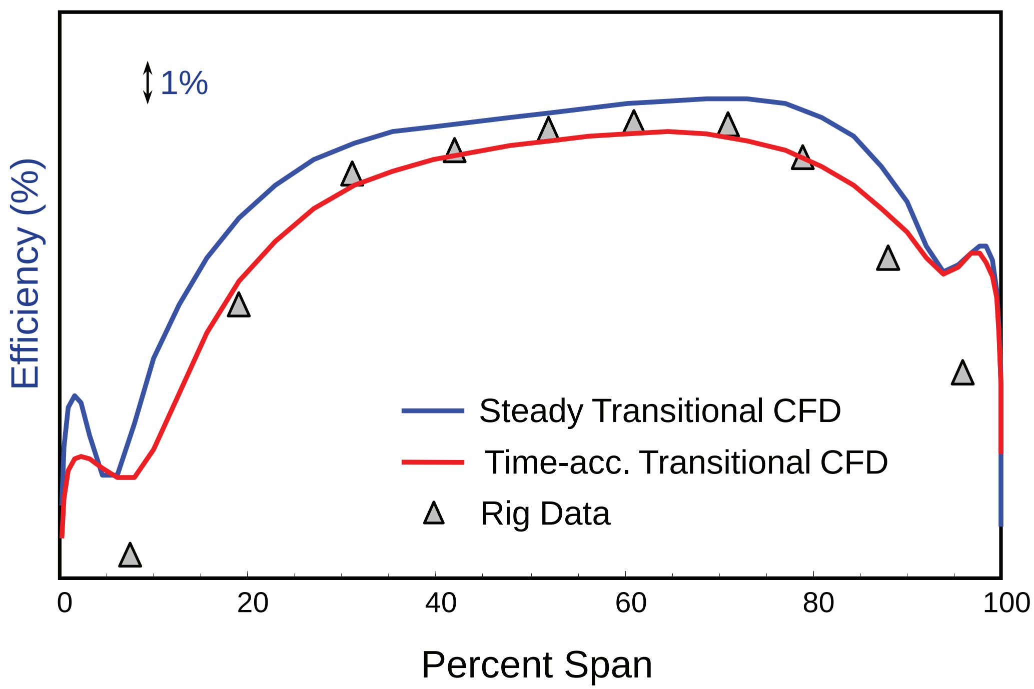
GT2006-90666



- Efficiency *drops* 0.9% between steady and time-accurate predictions.
- Boundary layer variations account for ~0.1% of the 0.9%.
- Steady simulation assumes constant-area mixing of flow distortions between rows.
- Wake mixing found to be primary cause of 0.9% drop in efficiency between steady and time-accurate predictions.

Time-mean entropy distributions highlight where multi-stage mixing losses occur

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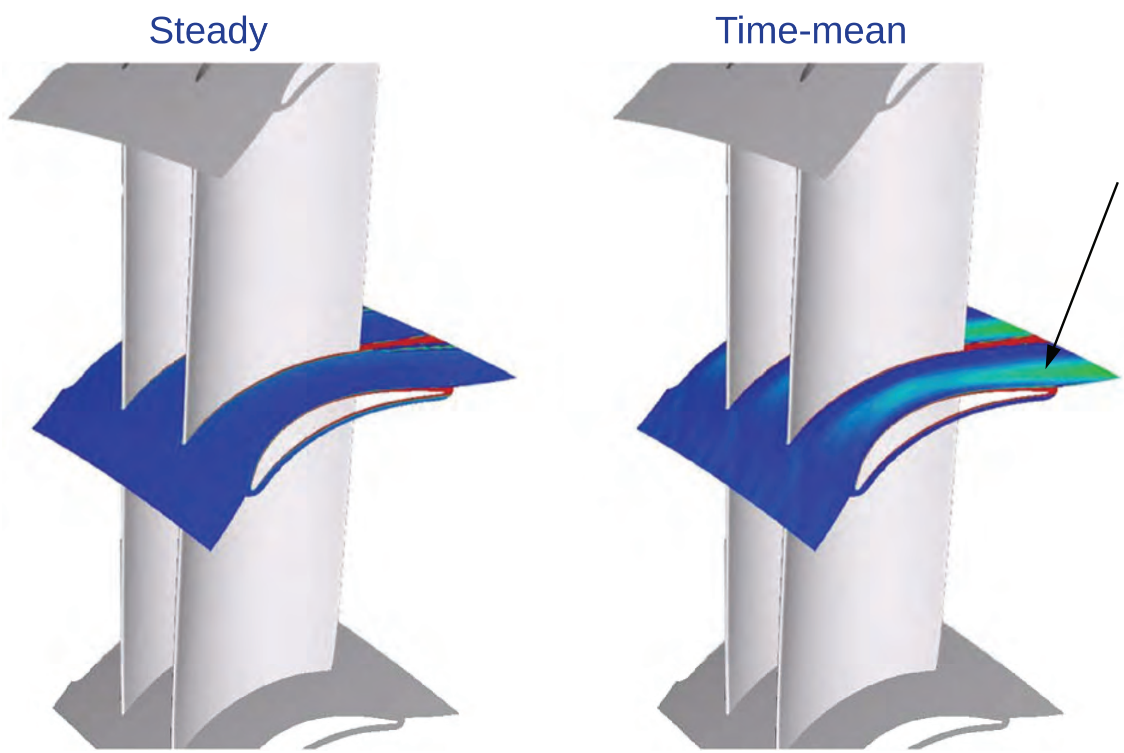
GT2006-90666

Results from steady and time-accurate simulations of an embedded row of a multi-stage LPT



Region of elevated entropy generation in core-flow (outside boundary layers) caused by upstream wakes mixing within the passage

Summary: Key LPT design challenges lie in unsteady phenomena and endwall effects

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Accuracy of *steady* predictions is limited:

- Unsteady transition prediction is necessary for accurate core-flow predictions.

- Endwall/separated flows are unsteady by nature:
  - Endwall loss generation not fully understood
  - Possibly need LES/DNS for study cases (when available)

- Multi-stage mixing losses contribute up to 1% in lost efficiency in LPTs
  - Best predicted with *time-accurate* CFD (even RANS)
  - Still some controversy regarding salient aspects of multi-stage mixing losses.

Session 3
Invited Presentations

NASA/CP—2020-220327

NASA Sensitivity Analysis of Current Technology Low Pressure Turbine

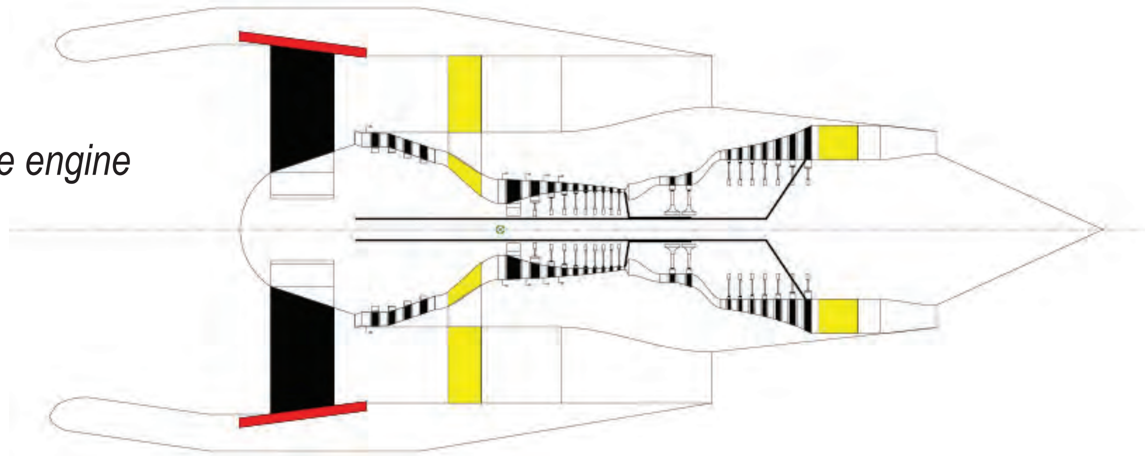
Chris Snyder
for
william.j.haller@nasa.gov
Multidisciplinary Design Analysis Optimization Branch (RTM)
NASA Glenn Research Center

August 10, 2010

NASA/CP—2020-220327

Analysis Overview

Flowpath of GEnx-like engine



- Start w/in-house thermodynamic and weight/flowpath representation of a state-of-the-art (SOA) large commercial transport engine (GEnx-like)

- Define design space to be explored

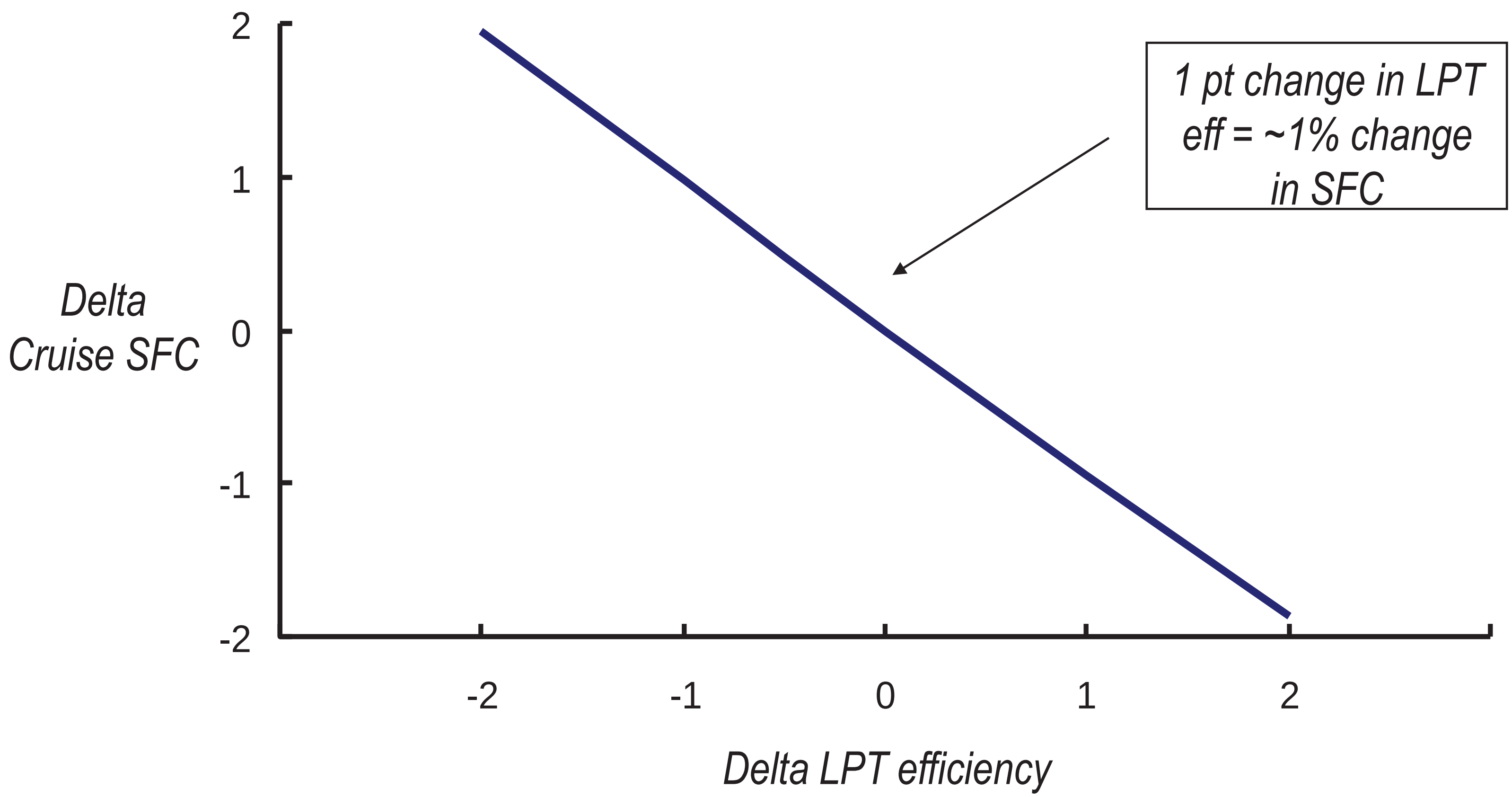
  ➢ Vary LPT efficiency (-2, -1, +1, +2 pts from SOA baseline)

  ➢ Vary LPT loading [delta h/U_{tip}^2] (-30%, -15%, +15%, +30% from SOA baseline)

- Optimize cycle and/or re-calculate engine weight

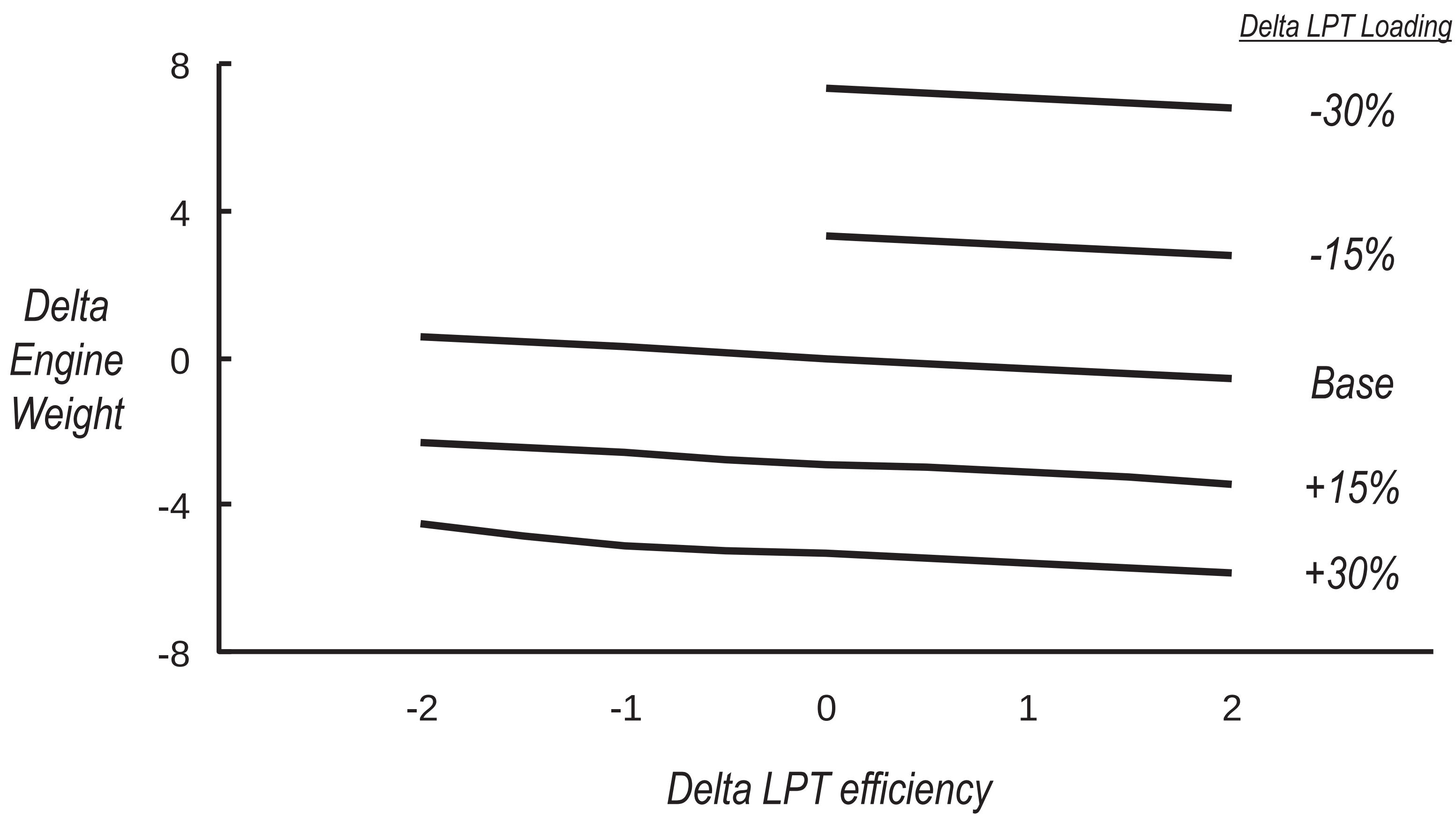
- Perform aircraft sizing to quantify mission fuel burn impacts on twin-aisle transport (787-like)

Impact of LPT efficiency on Cruise SFC
(All values quoted as % change from SOA Baseline)



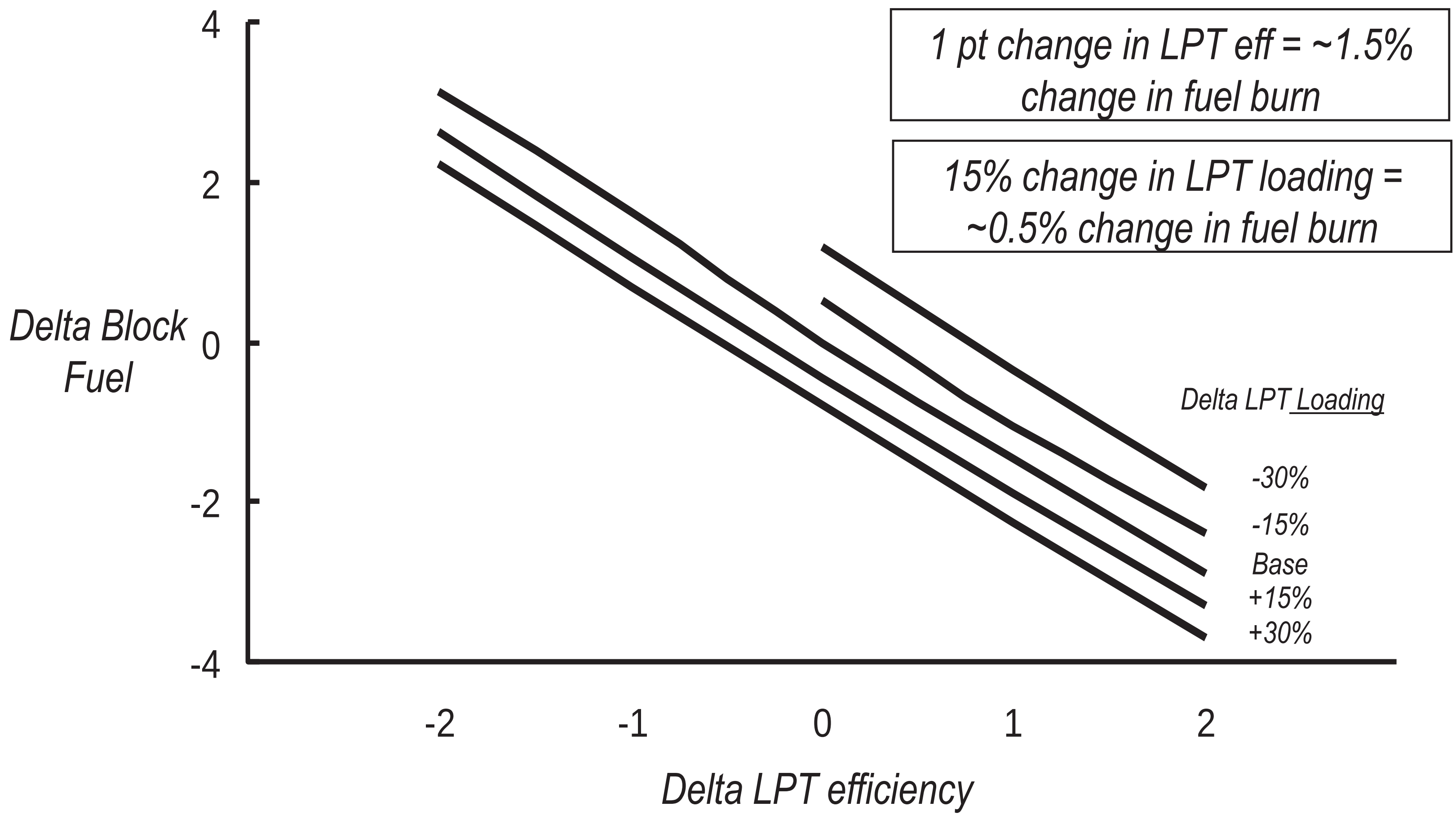
Impact of Turbine Loading on Engine Weight

(All values quoted as % change from SOA Baseline)



Impact of Turbine Loading on Fuel Burn

(All values quoted as % change from SOA Baseline)



Summary of Results

– In-house assessment findings:

- 1 pt change in LPT efficiency (@ constant loading) yields an ~1% change in cruise SFC
- 1 pt change in LPT efficiency (@ constant loading) yields a ~0.30% change in Engine Weight
- 15% change in LPT loading (@ constant eff.) yields ~3% change in Engine Weight
- 1 pt change in LPT efficiency (@ constant loading) yields ~1.5% change in Mission Fuel Burn
- 15% change in LPT loading (@ constant eff.) yields ~0.5% change in Mission Fuel Burn

For long-range aircraft / mission, efficiency improvement (+1 pt) has 3-4 times more impact than increased loading (+15%)

End

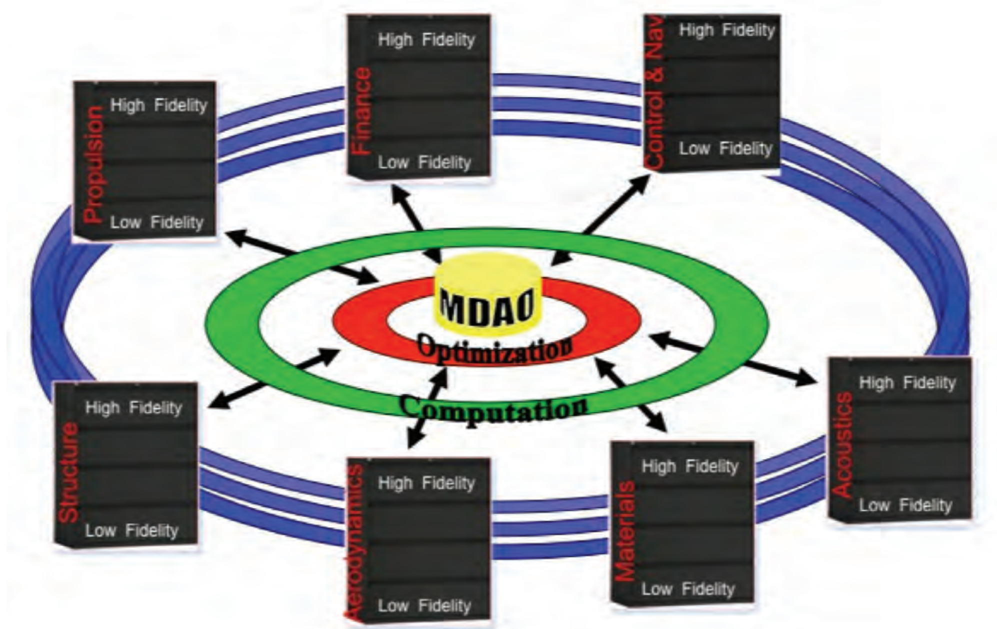
NASA/CP—2020-220327

Multidisciplinary Design Analysis and Optimization (MDAO) at GRC

Meng-Sing Liou

MDAO: Vision & Organization

❖ To provide a *reliable (accurate & robust) and fast automatic* process for *integrated design, analysis and optimization* of an engineering system



Multidisciplinary Design Analysis and Optimization at GRC

❖ MDAO Branch

➢ OpenMDAO Project (since March 2010): A computational environment (framework) for analyzing and solving MDAO (Multi-Disciplinary Analysis and Optimization) problems.

➢ Promote collaboration and cooperation through the use of open-source tools. http://www.openmdao.org/

❖ Work by me and collaborators (since *circa* 2000)

➢ Fundamental research and applications to components and complete configurations

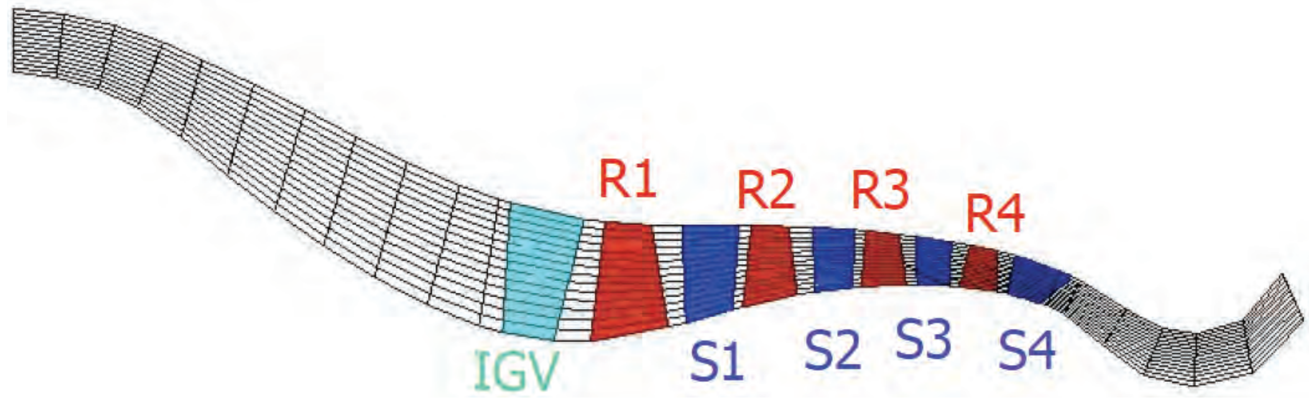
➢ Gradient-based and stochastic methods

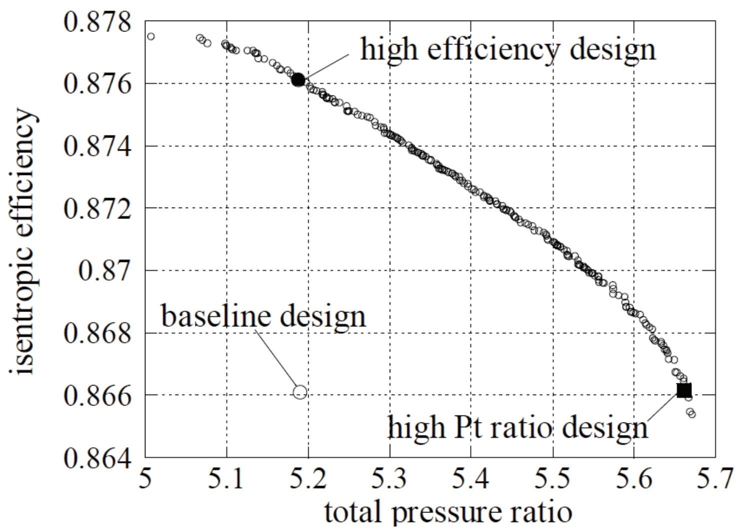
➢ Single objective, multi-objective, full and surrogate models, steady and unsteady problems

➢ Turbomachinery, Subsonic Fixed Wing and Supersonics

➢ Focus on high-fidelity analysis

Four-stage Compressor: Multiobjective optimization

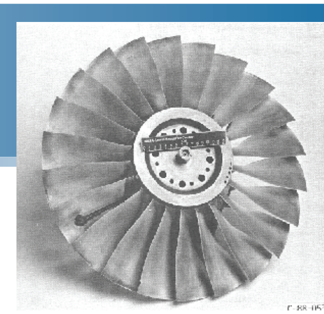


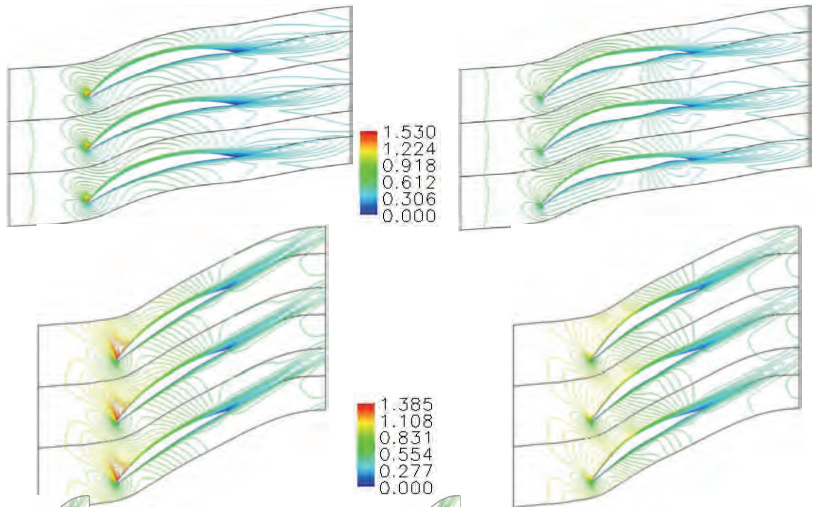


Design variables:

- radial distributions of total pressure
- solidities at rotor trailing edges
- flow angles and solidities at stator trailing edges

Rotor67

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1.224
0.918
0.612
0.306
0.000
1.385
1.108
0.831
0.554
0.277
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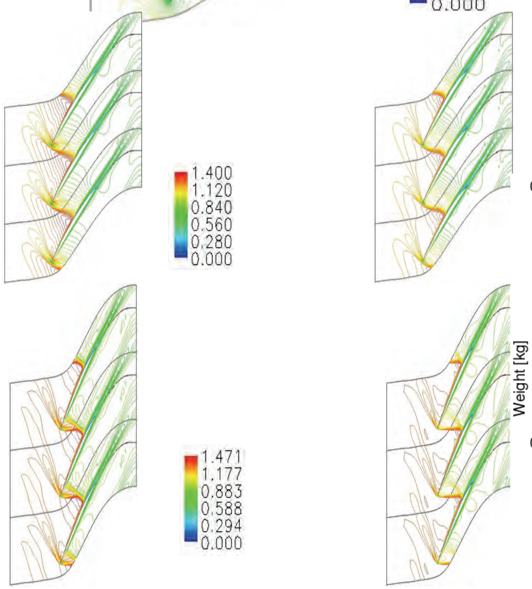
1.400
1.120
0.840
0.560
0.280
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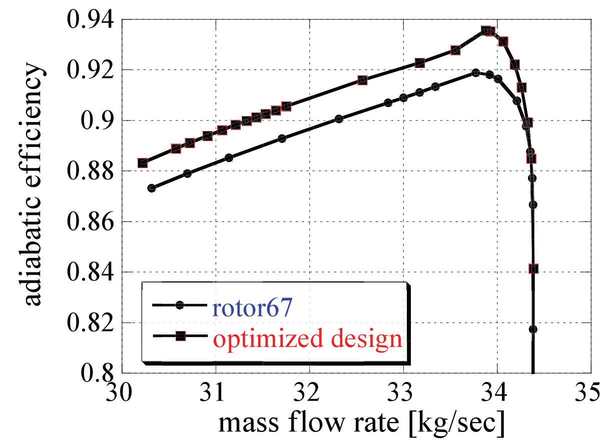
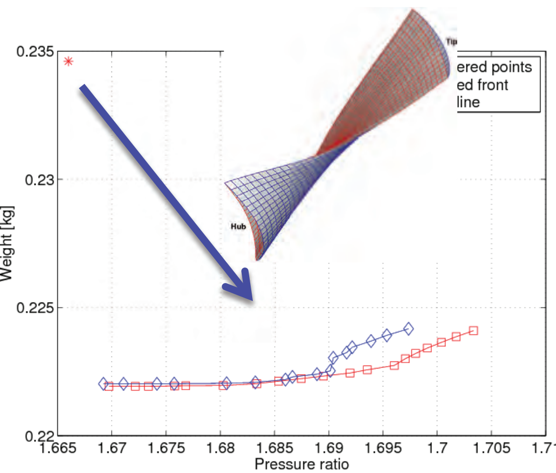
1.471
1.177
0.883
0.588
0.294
0.000


adiabatic efficiency
mass flow rate [kg/sec]
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
30
31
32
33
34
35
rotor67
optimized design


Weight [kg]
Pressure ratio
0.235
0.23
0.225
0.22
1.665
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1.675
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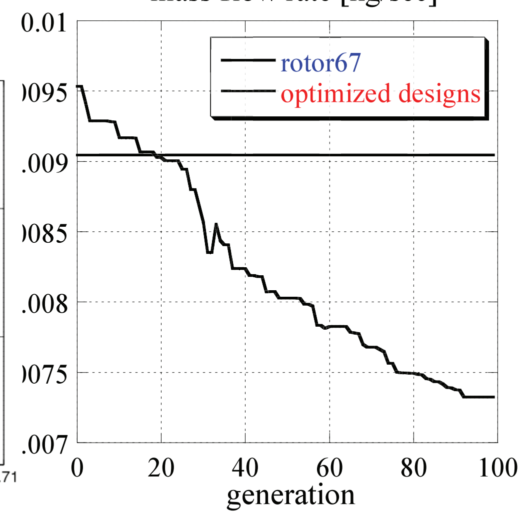
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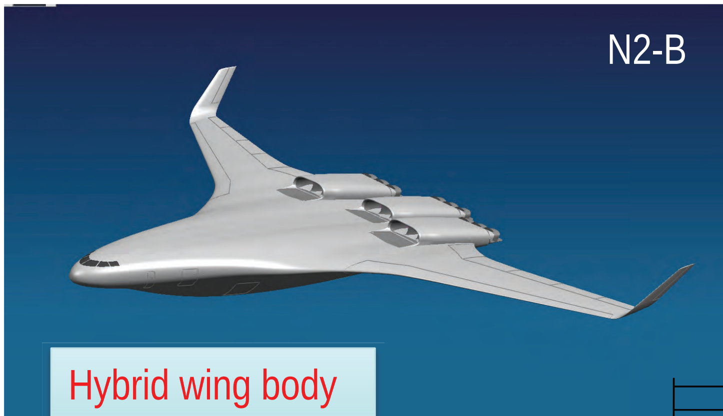
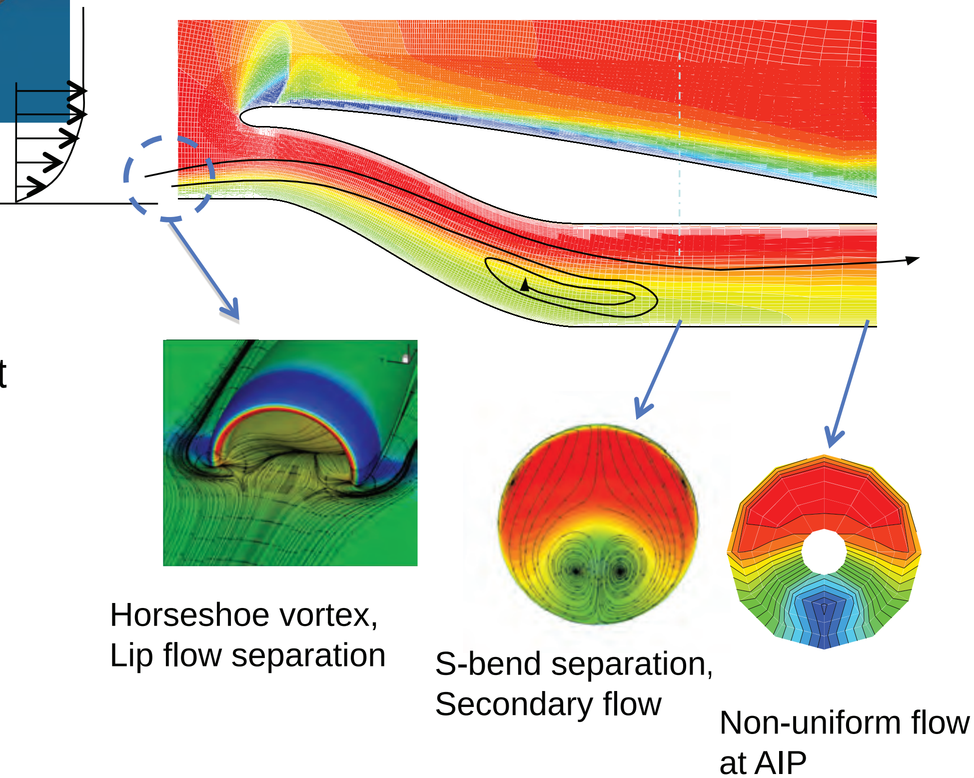
generation
rotor67
optimized designs

Key Flow Features in Embedded Offset Inlet



Impact on Propulsion System:
Thick low-momentum layer ingested into inlet,
- Significant distortion and
- Total pressure loss at AIP

Boundary-Layer Ingestion



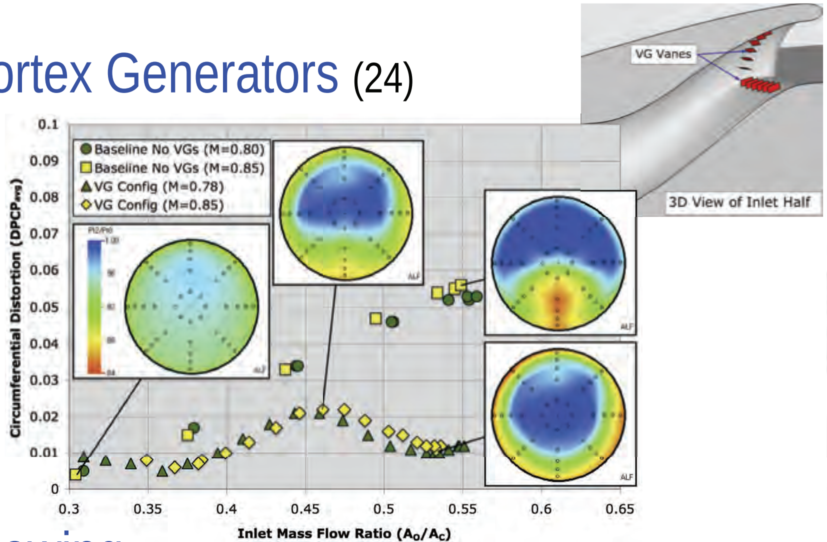
Forces:
- Viscous stresses
- Streamwise adverse pressure gradient
- Centrifugal force

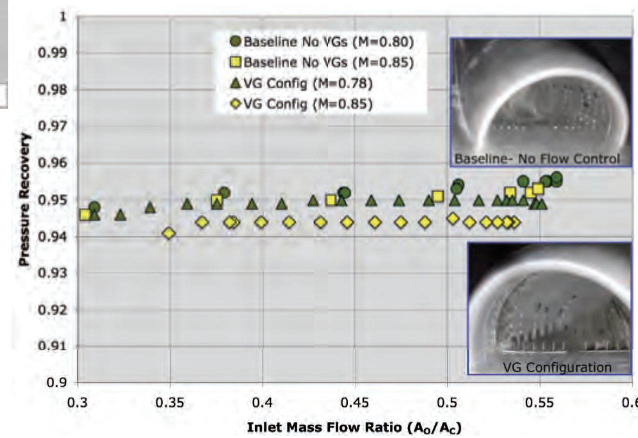
Advantages:
- Reduced ram drag
- Reduced structural weight
- Reduced wetted area
- Reduced noise
- Increased propulsive efficiency

What Were Proposed to Mitigate Drawbacks

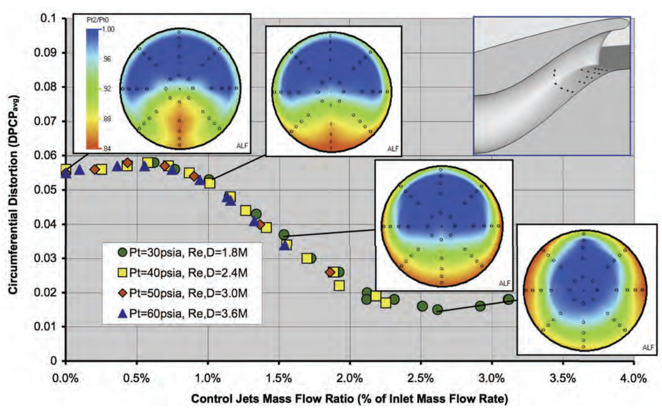
- Vortex Generators (24)

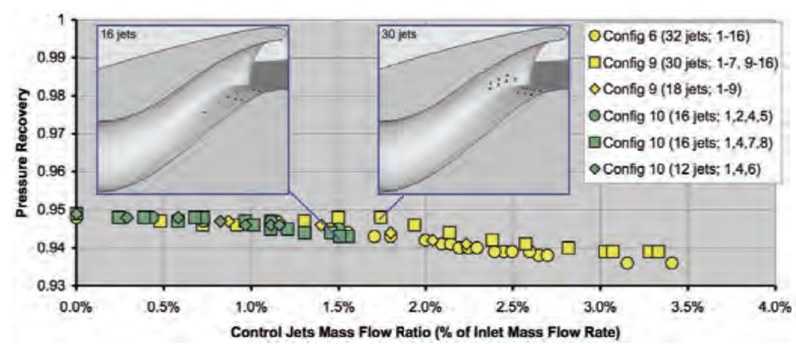
(L. Owens *et al.* AIAA 2006-839)





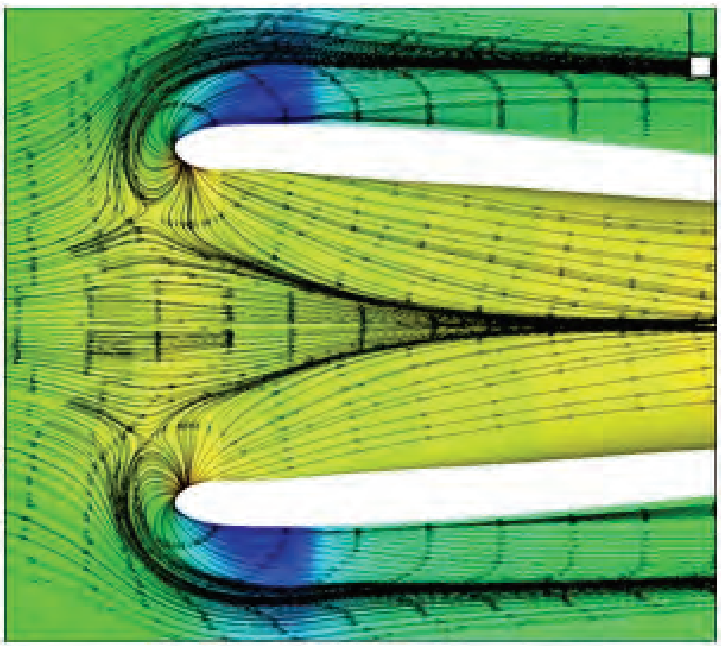
- Blowing



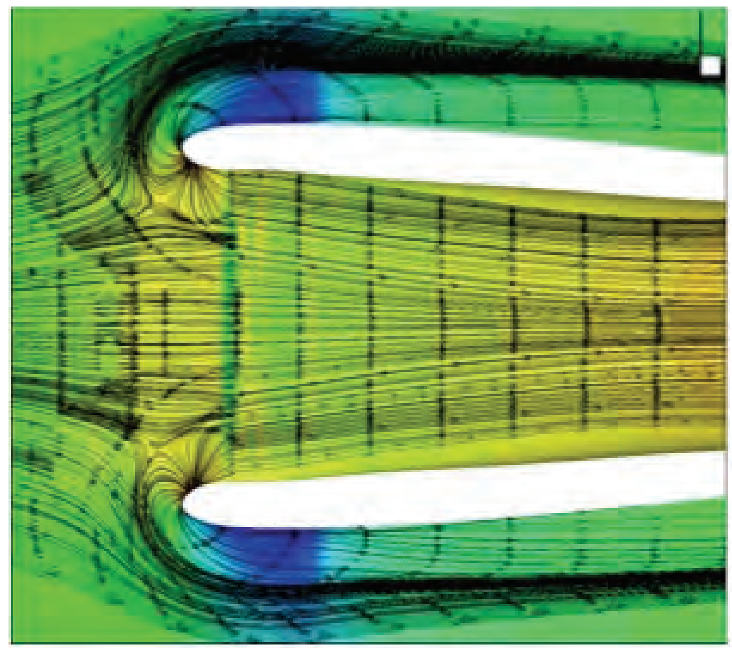


- At the expense of reduced performance: total pressure loss

What we did: *Proper* shaping of wall



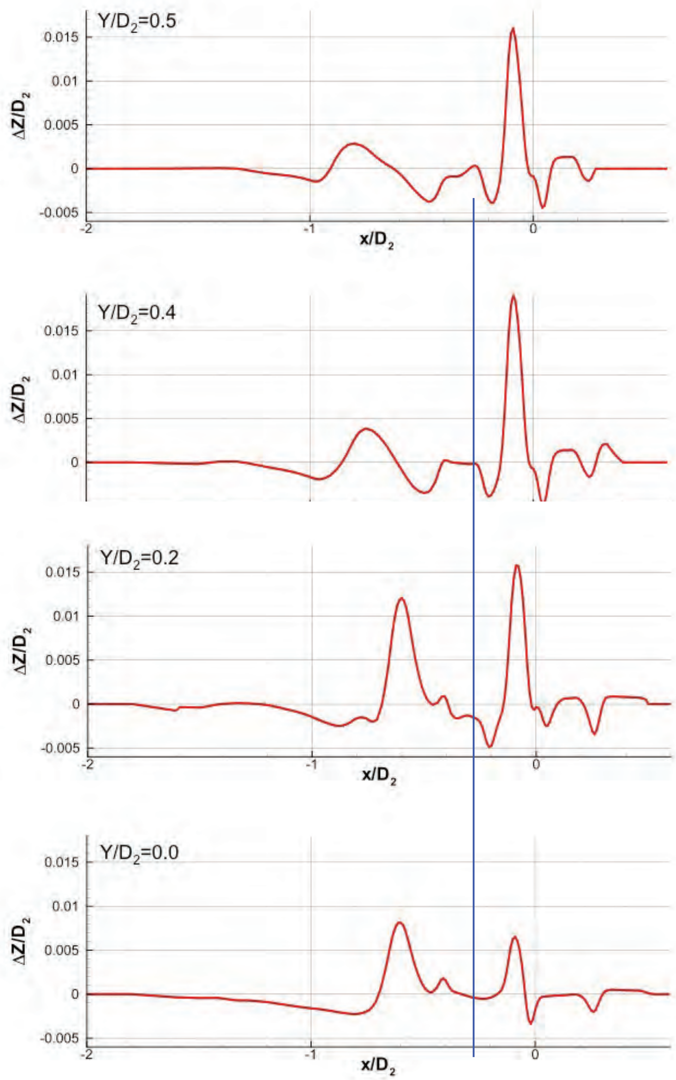
Baseline design

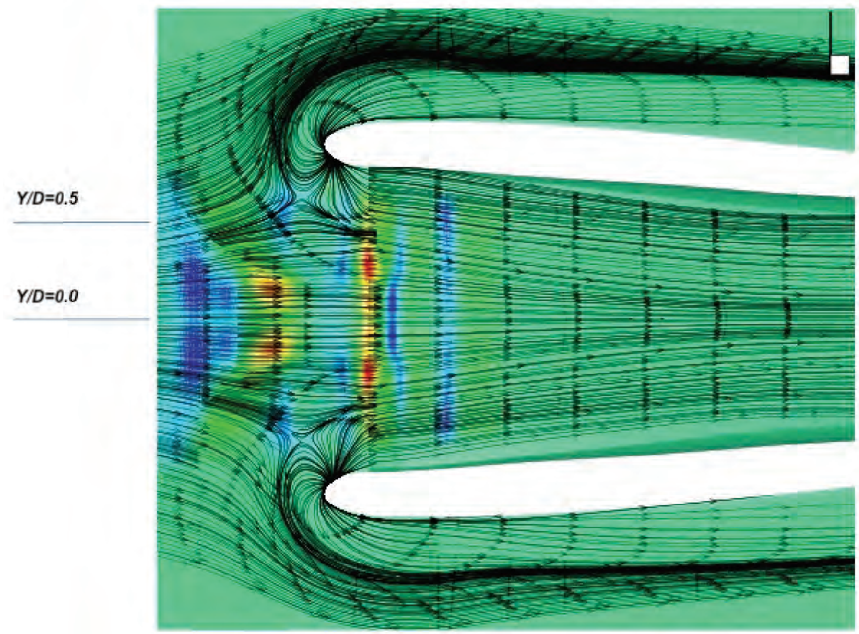


Optimized design

- ✓ Streamlining the flow!
- ✓ Lowering pressure inside the entrance

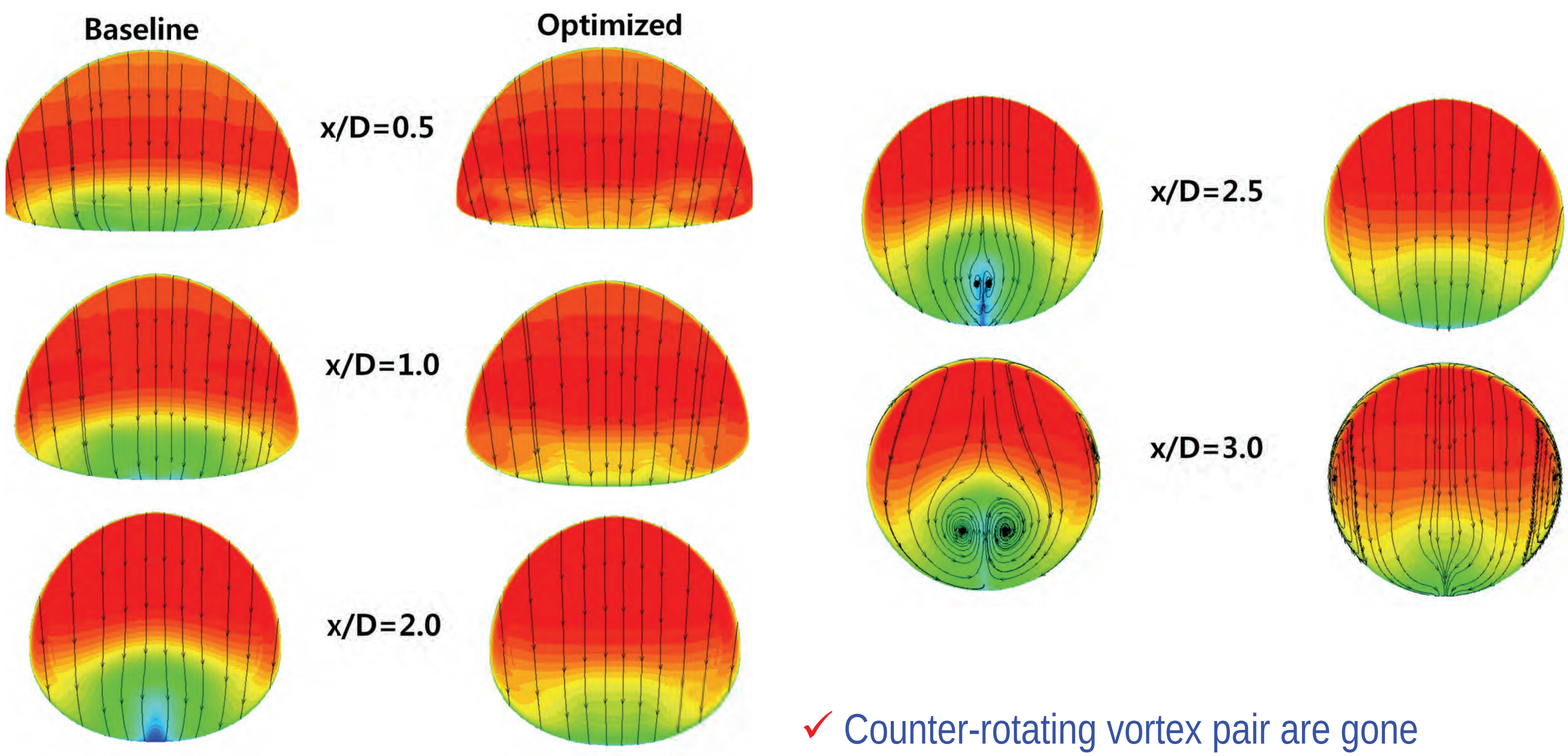
Optimized Wall Shape





- ✓ Wall modulation is O(1%) of D_2, 5% of δ !
- ✓ It begins way before the inlet

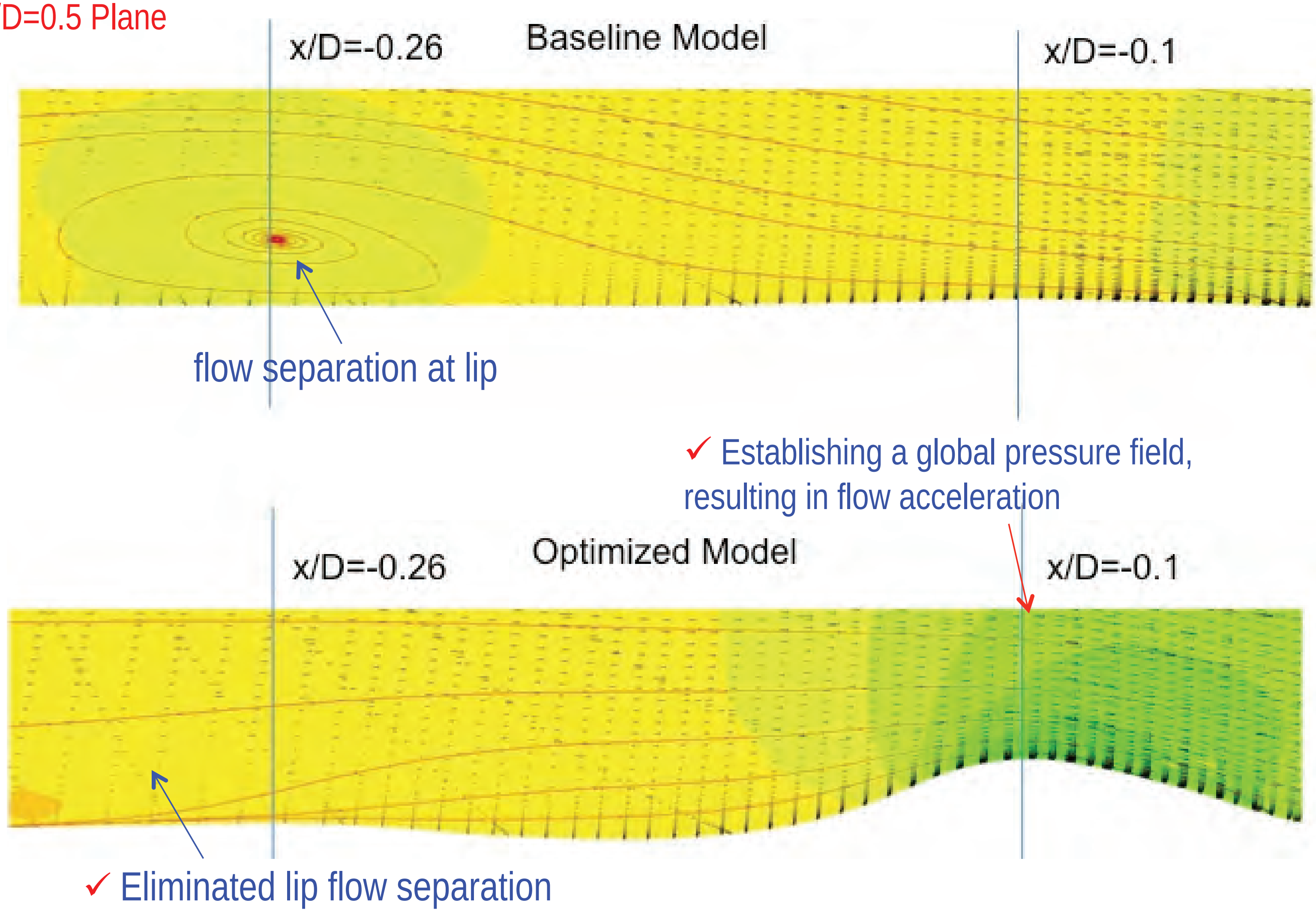
Cross-sectional Mach-number Contours



- ✓ Counter-rotating vortex pair are gone
- ✓ Larger area of high-momentum fluid
- ✓ Side boundary-layer vortex is growing, but with no apparent adverse effect

Detailed Flow Structures: Near Inlet Throat

Y/D=0.5 Plane



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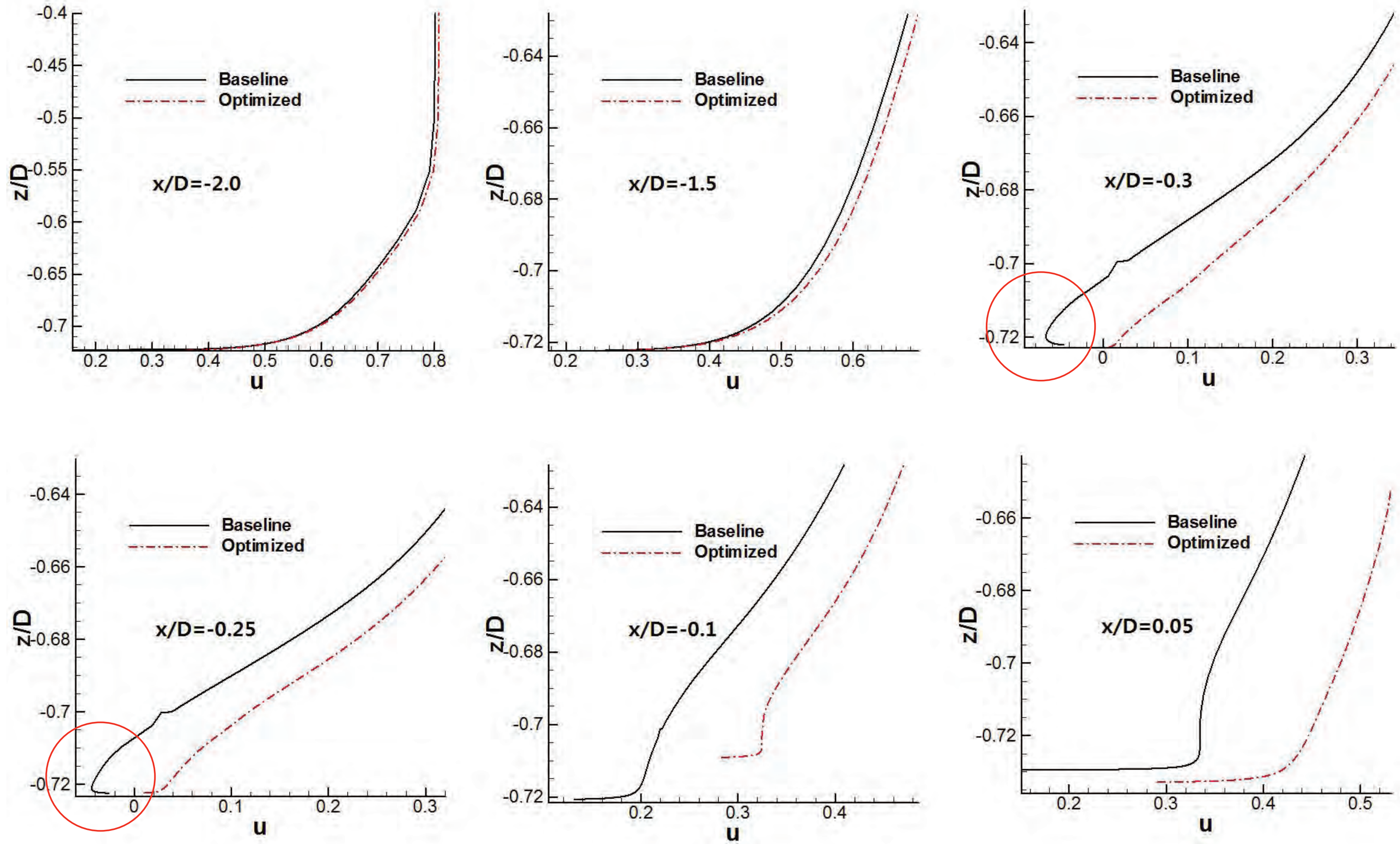
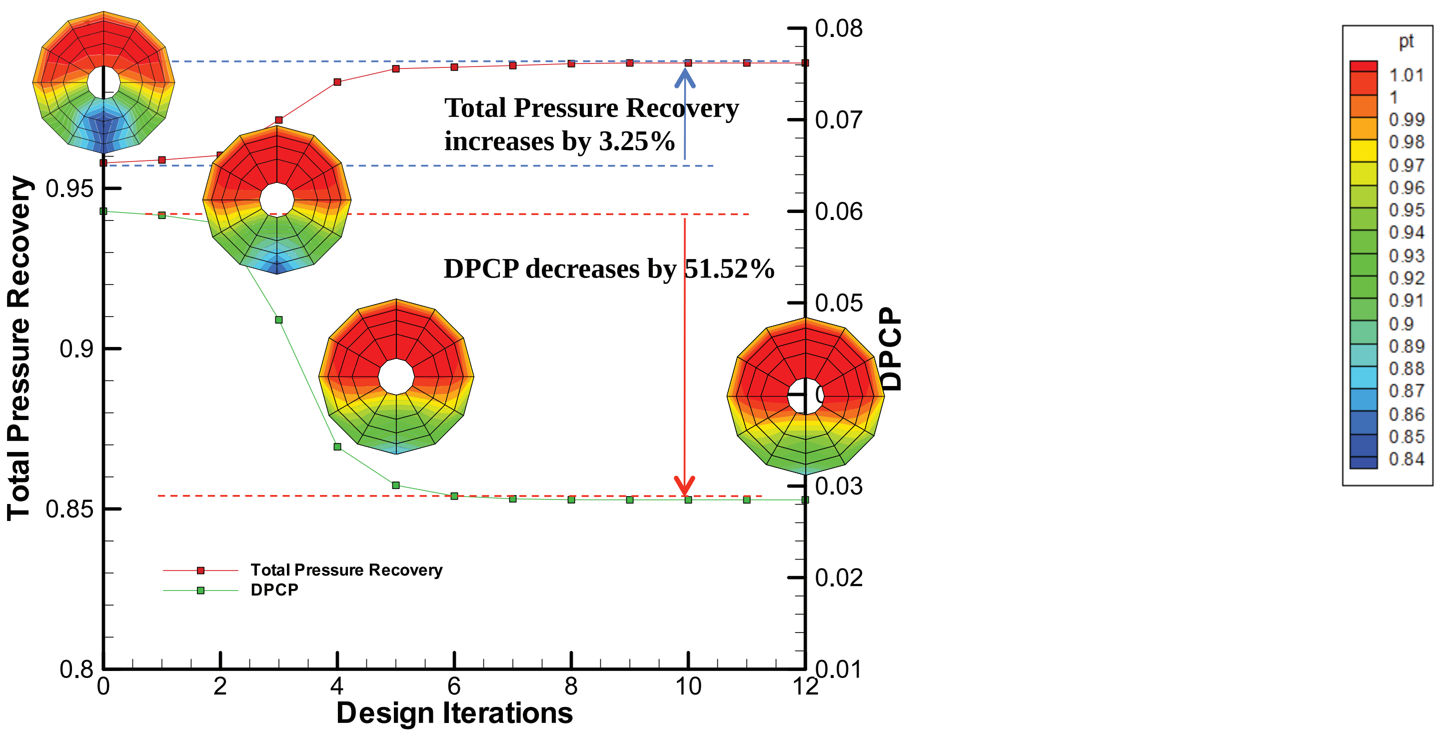
Velocity Profiles



✓ Boundary layer has been energized, with increased momentum

Clever Shape Optimization

- History of Design Improvement



✓ Simultaneous improvements in total pressure recovery and distortion

✓ Fundamental change in core region of low total pressure and boundary layer

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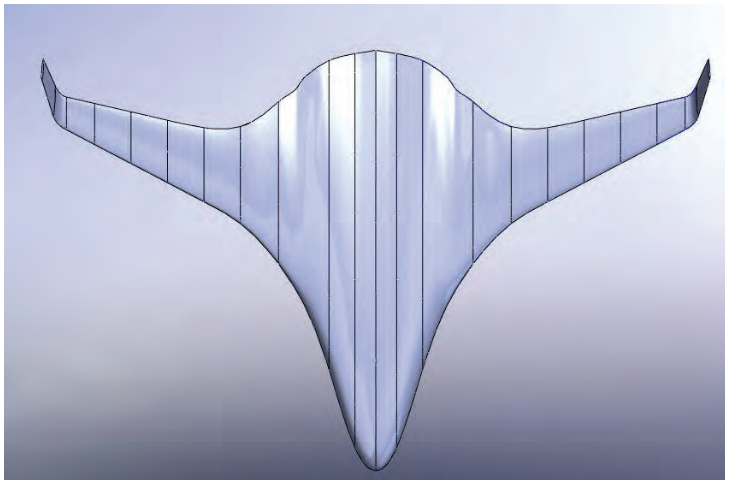
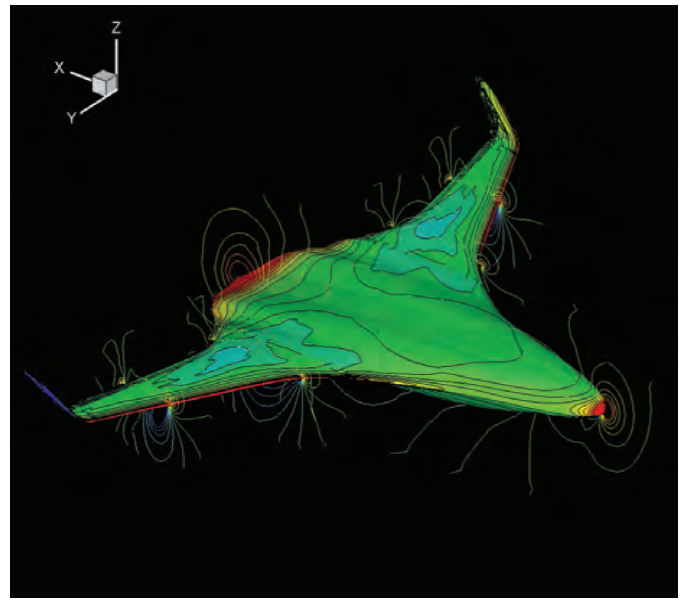
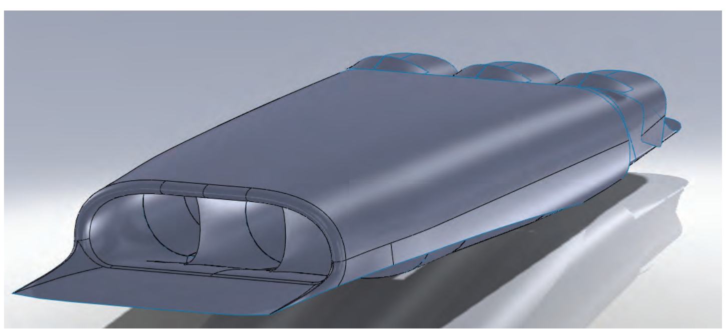
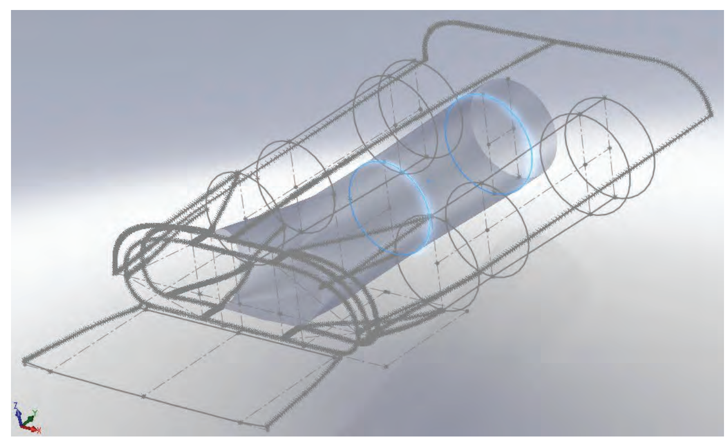
Design of Embedded Nacelle





- Build model with design intent, e.g., geometry parameterization
- Optimization via changes of parameters





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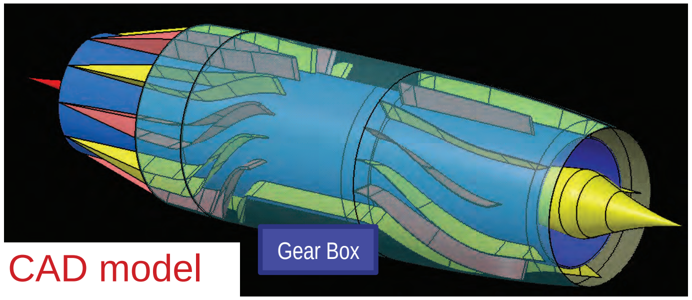
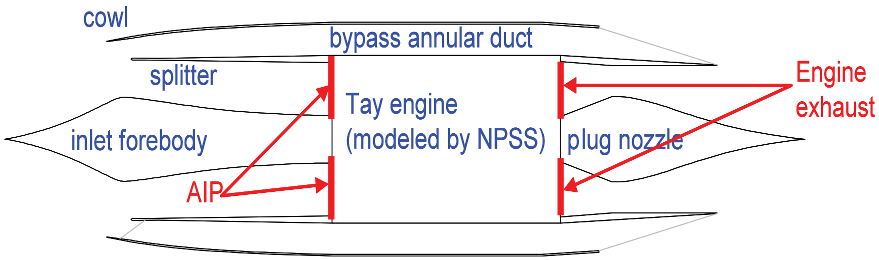
Supersonic Business Jet: Gulfstream

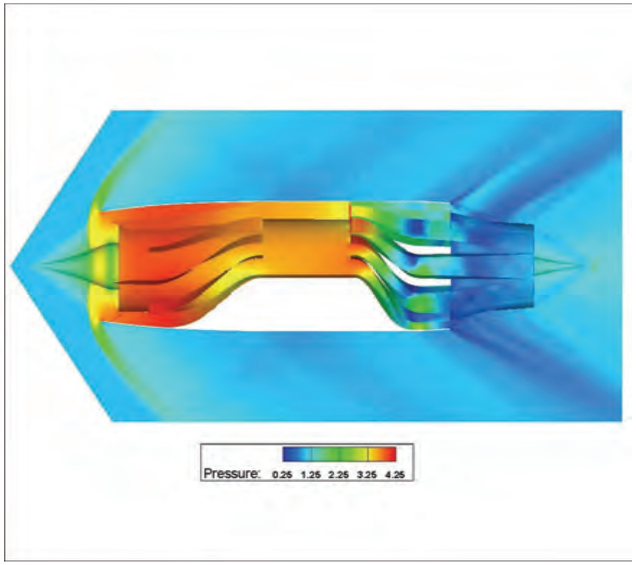
- Bypass propulsion system®

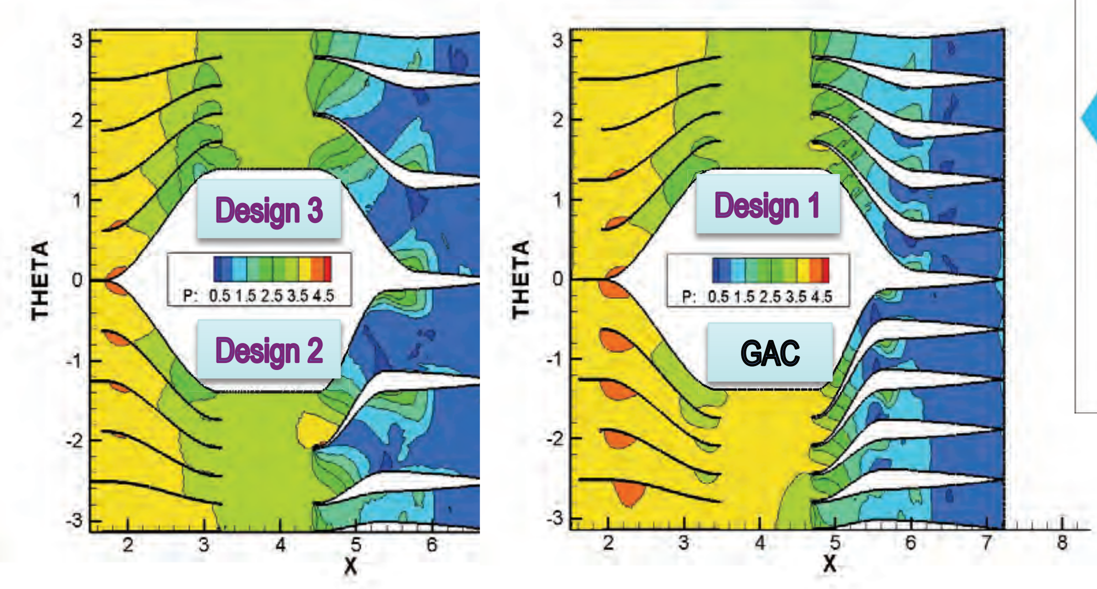


CAD model

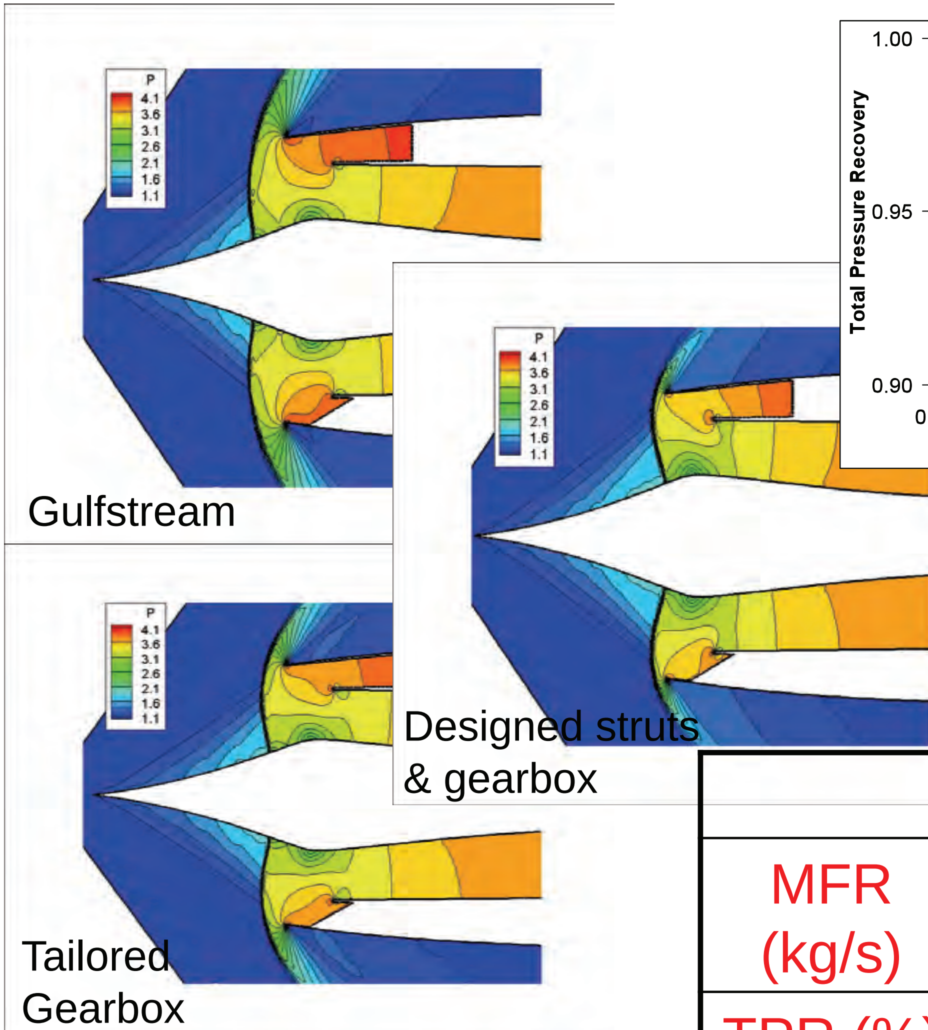
Overall Configuration

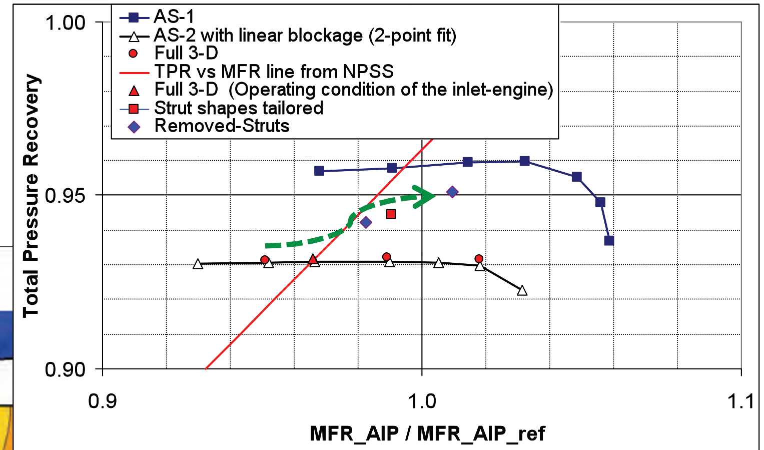






Design Results

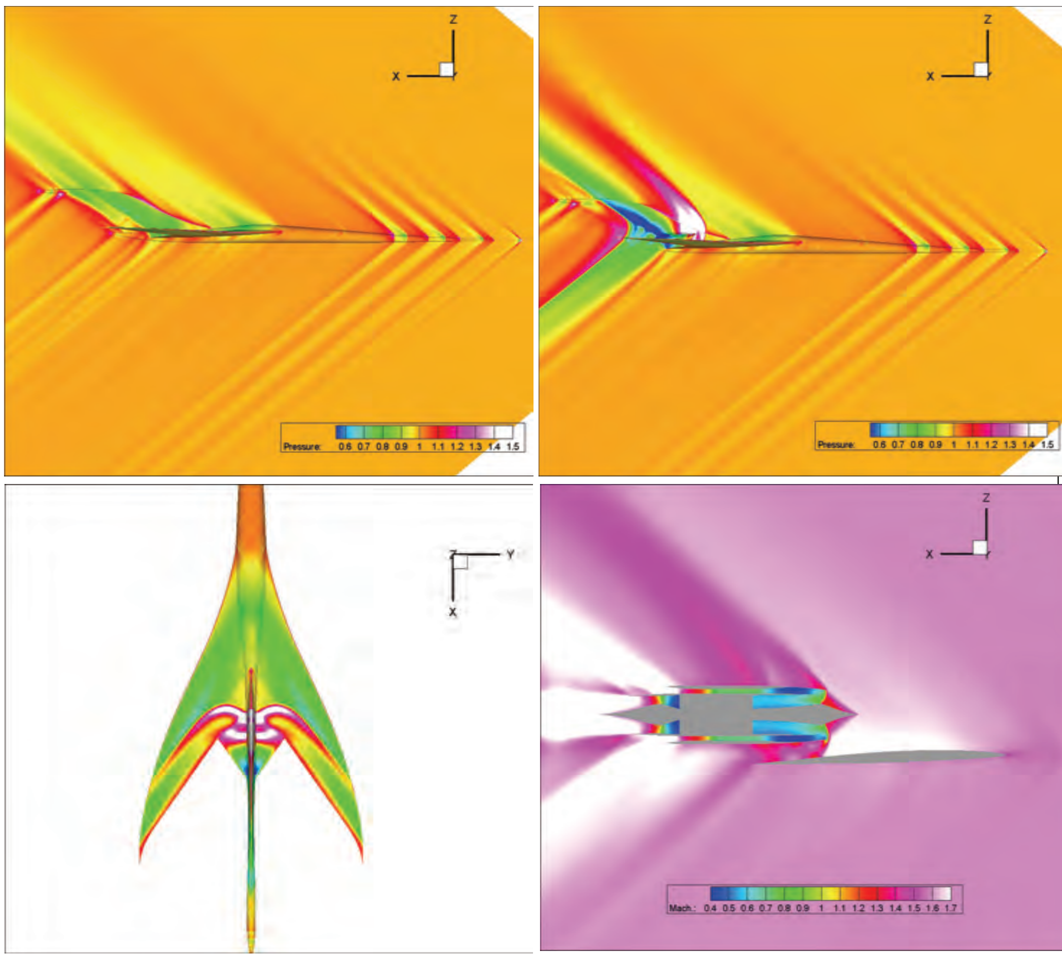


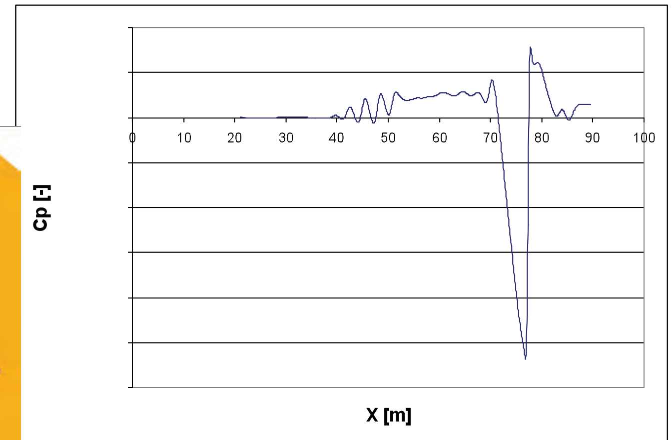


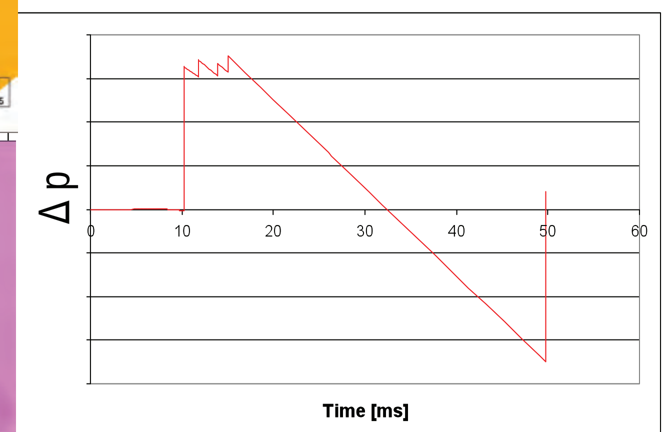
	Original	Tailored	D(%)
MFR (kg/s)	101.4	107.6	6.11
TPR (%)	93.13	95.10	2.12

Full Configuration: Aero-Propulsion Integration

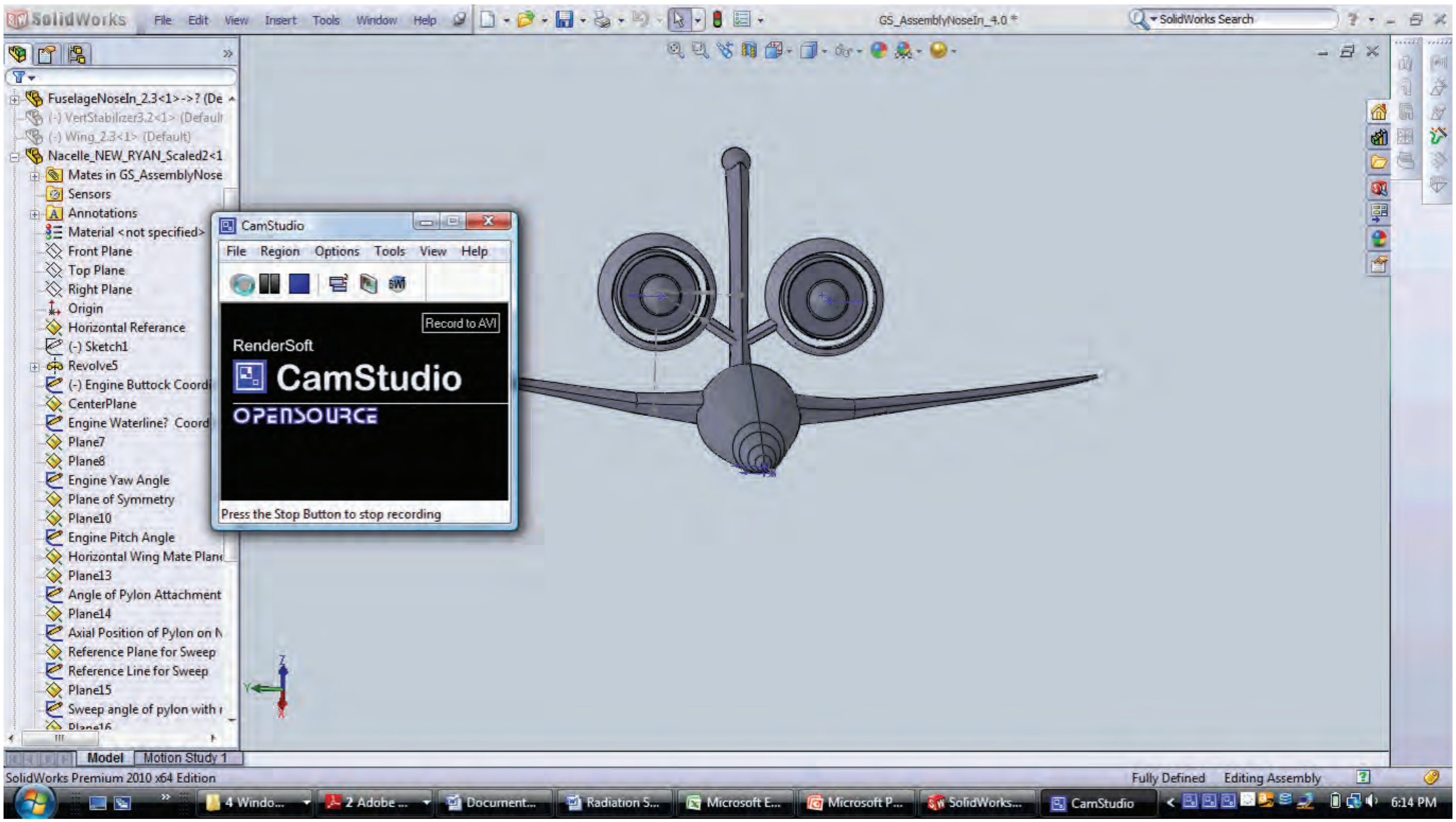
- Aero performance
- Acoustic footprint and Boom index







Design of Engine Installation



Lessons Learned

- MDAO technology has a great potential to revolutionize the way engineering design is practiced, already showing in numerous cases significant benefits being reared.
- Multidisciplinary approach is significantly more efficient and realistic than otherwise.
- Design with optimization (changes) intent must be incorporated at the early stage.
- The division between designers and analysts is blurring, actually it can be a beneficial trend that both are collaboratively contributing.
- CAD modeling 'R us, but with new contents …
- Geometry, geometry, geometry … CAD to surface tessellation to CFD-grade mesh …
- …

Session 4
Power Turbine

NASA/CP—2020-220327

AERODYNAMIC CHALLENGES OF A VARIABLE-SPEED POWER TURBINE FOR LARGE CIVIL TILT-ROTOR APPLICATION

LPT Workshop
Aug 10-11, 2010
Ohio Aerospace Institute

Gerard E. Welch
NASA John H. Glenn Research Center
At Lewis Field

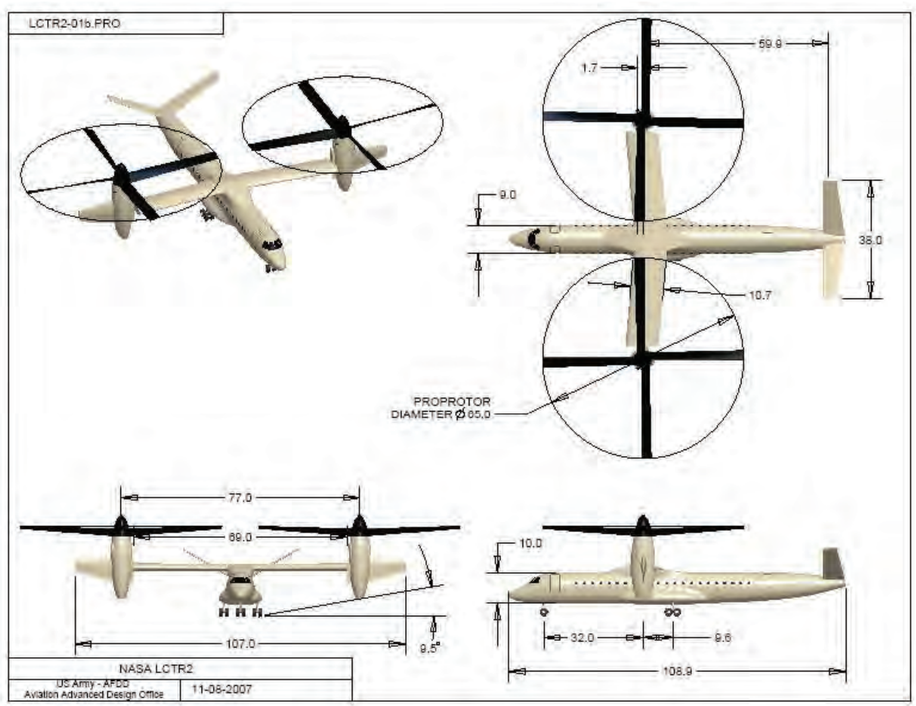
VSPT research team

- ARL-VTD / G. Skoch, D. Thurman
- NASA RTT / A. McVetta, S. Chen, G. Welch
- NASA RTM / C. Snyder
- NASA RXN / S. Howard
- NASA DER / M. Stevens
- ASRC / P. Giel, K. Loh
- Ohio State U. / A. Ameri

Assessment of Aerodynamic Challenges of a VSPT for LCTR Application

- Introduction
  - Need for variable-speed tilt-rotor
  - Solution approach using variable-speed power turbine
- Key aero-challenges
- Design approach and first-stage results
- Aero research and technology development needs
- NASA research agenda

Alleviate airport congestion utilizing LCTR



Large Civil Tilt-Rotor	
TOGW	108k lb_f
Payload	90 PAX
Engines	4 x 7500 SHP
Range	> 1,000 nm
Cruise speed	> 300 kn
Cruise altitude	28 – 30 kft

Principal challenge for LCTR is required variability in main-rotor speed:

– 650 ft/s VTOL

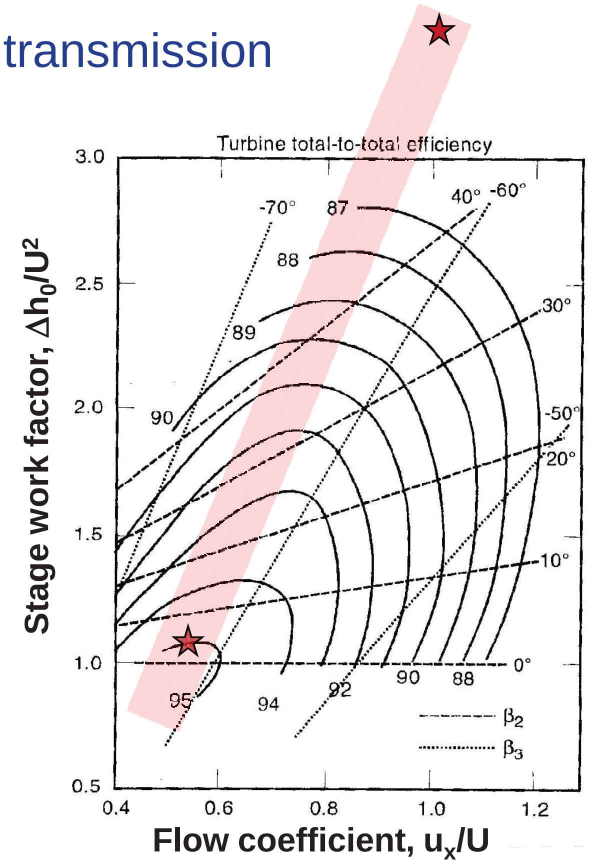
– 350 ft/s at Mn 0.5 cruise

Acree, C. W., Hyeonsoo, Y., and Sinsay, J. D., "Performance Optimization of the NASA Large Civil Tiltrotor," *Proc. International Powered Lift Conference*, London, UK, July 22-24, 2008.

Approach to vary main-rotor speed

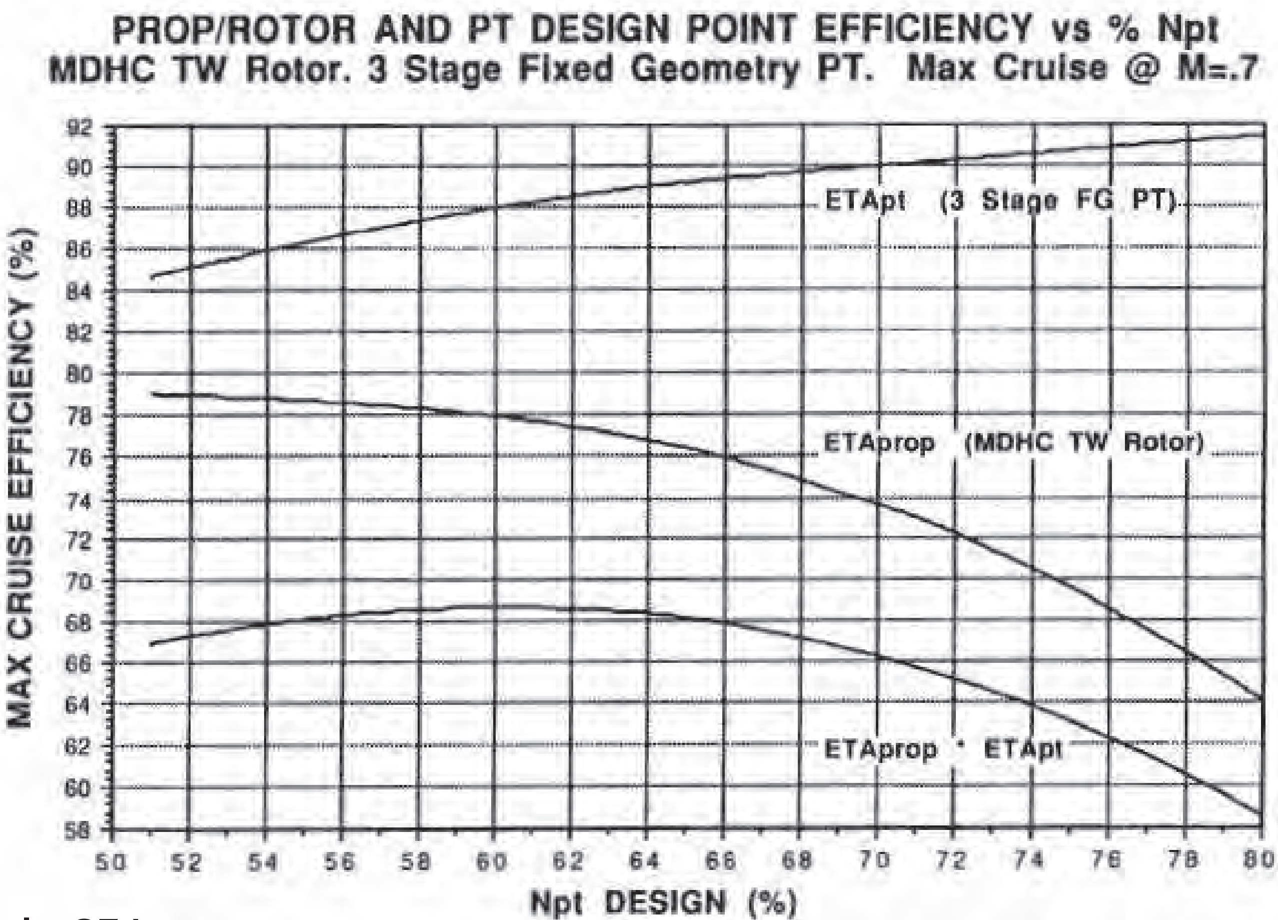
- Fixed-speed PT w/ multi-gear-ratio transmission
  - High efficiency design-point operation from take-off to cruise
  - Complexity and weight of variable transmission
  - Need to shift gears

- Variable-speed PT w/ fixed gear-ratio transmission
  - Wide PT speed range, 54% < N_{PT} < 100%
  - Lower efficiency potential
  - Added weight to turbine/shafting



Avoid complexity and weight of variable transmission & the need to shift gears

Impact of variable-speed power turbine on cruise efficiency



Martin D′Angelo, GE-Lynn
NASA CR/1995-198380

Key aero challenges for VSPT

- Efficiency at high work factor
- Incidence variation required by speed change
- Operation at low Reynolds number

Efficiency at high work factor

- Specific power is approximately 200 SHP/(lb_m/s) at 2 kft take-off and 28 kft cruise

$$\dot{W} / \dot{m} = \Delta h_0 = \Delta(u_\theta r\Omega) \approx Const$$

- If 50% speed reduction

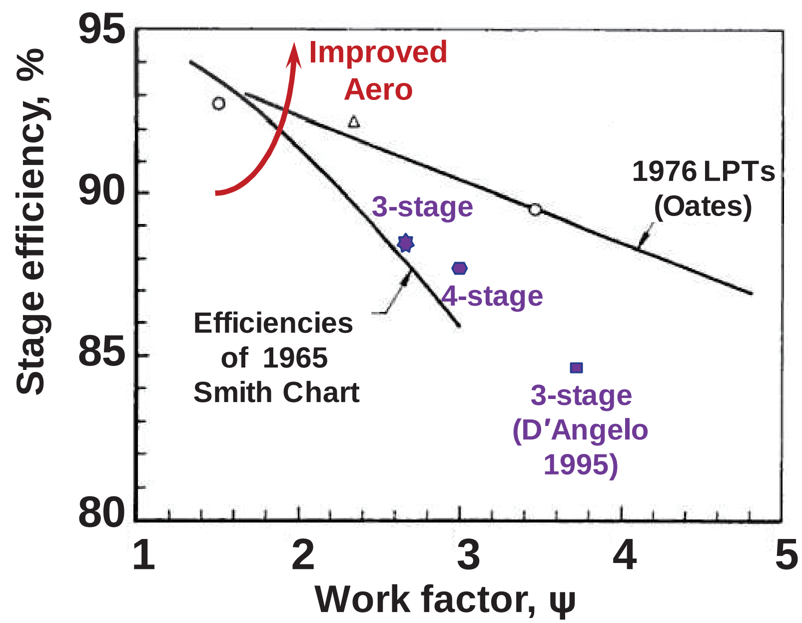
$$r\Omega \downarrow 2$$

then

$$\Delta u_\theta \uparrow 2$$

and

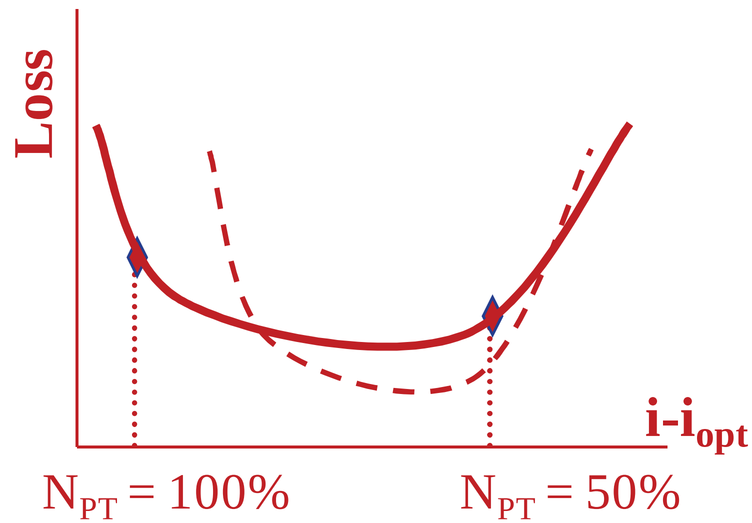
$$\psi = \frac{\Delta h_0}{U^2} \uparrow 4$$



Design-point efficiency vs. work factor

Incidence variation required by speed change

- Incidence variation – 40- to 80-degrees
- Impact of aerodynamic loading level (Zweifel)
- Impact of loading schedule
- Use of variable stators/EGVs



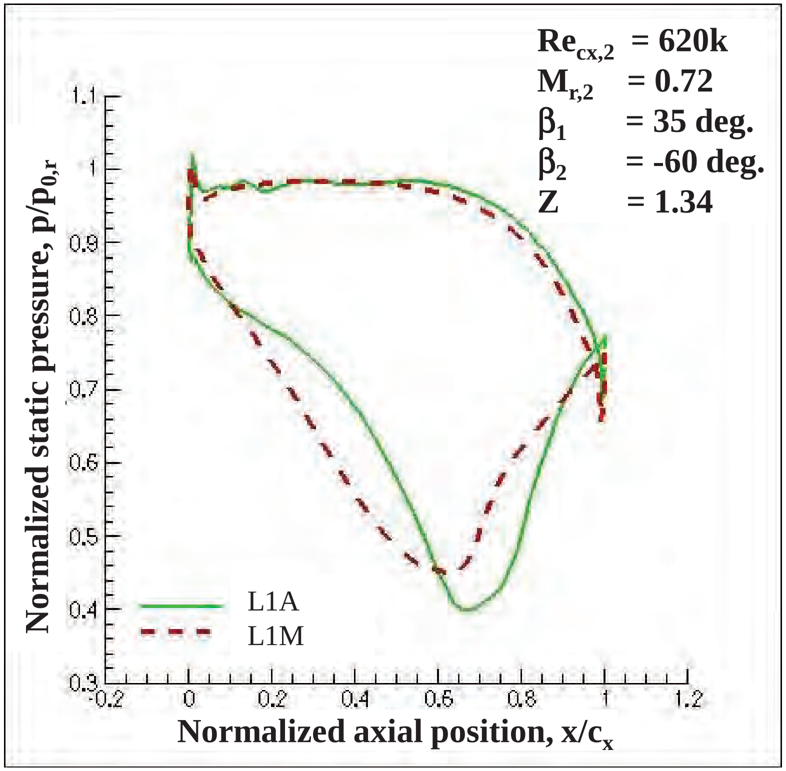
Blade row loss vs. incidence

Operation at low Reynolds number
Transitional flow

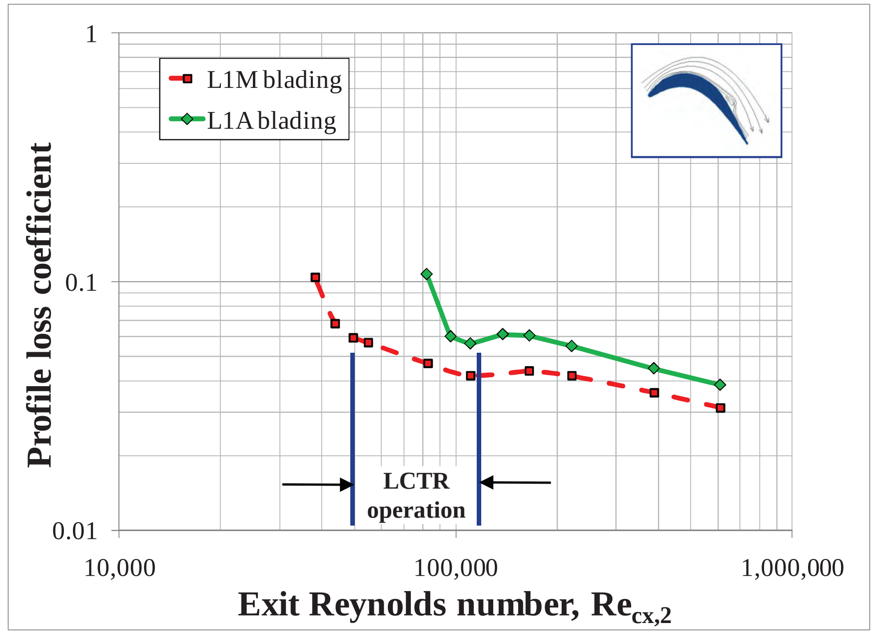
- Unit Reynolds numbers are low:
  - 50k/inch at take-off
  - 30k/inch at cruise
- Impact on design-point loss (efficiency lapse / loading)
- Impact on incidence-range at acceptable loss levels
- Influence of unsteadiness

High-load LPT blade at low-Re

Impact of loading schedule on Reynolds number lapse in high-lift blading



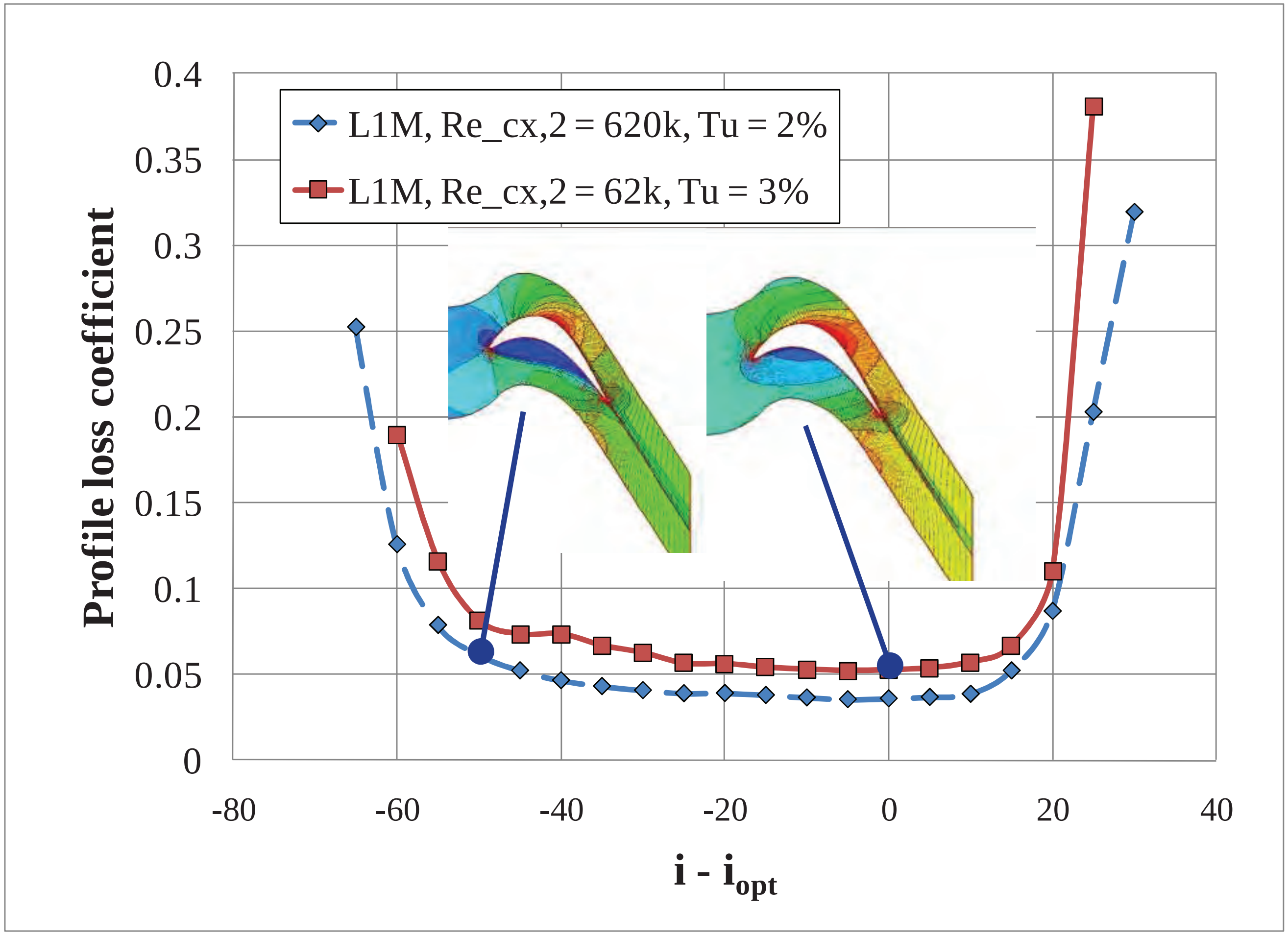
a. Loading diagrams for L1A (aft-loaded) and L1M (mid-loaded) ultra-high lift LPT blades.



b. Profile loss coefficient as a function of Re$_{cx,2}$ for L1A and L1M LPT blades.

2-D RANS computations (Chima's rvcq3d code) w/ Wilcox's low-Re κ–ω model

Impact of Reynolds number on useful flow range



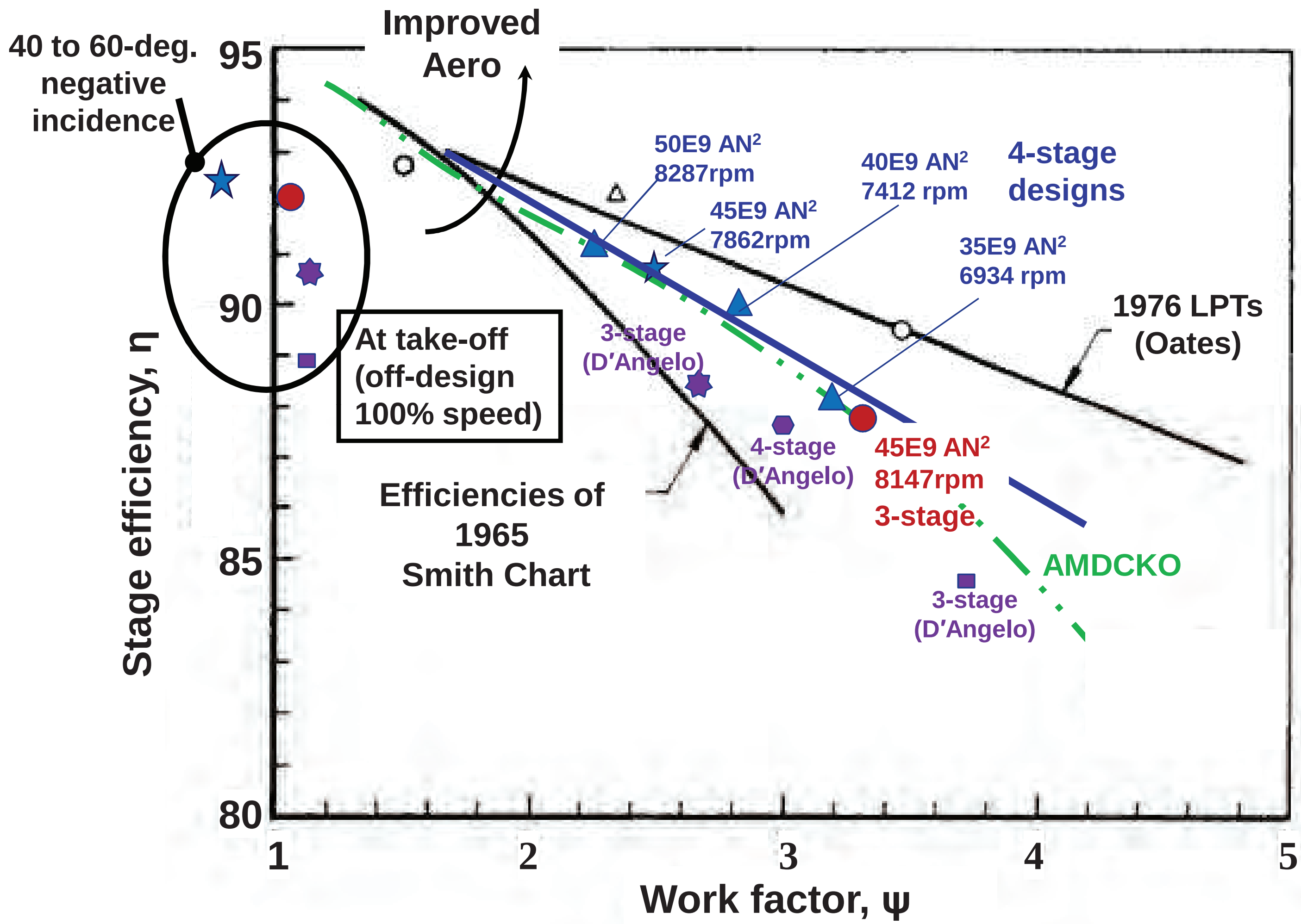
Profile loss as a function of incidence

Increased loss and decreased useful incidence range with altitude

LCTR VSPT design approach (to date)

- Meanline analysis using F. Huber's meanline tools
  - Design at 54% N_{PT}, 28 kft
  - Accept off-design performance at 100% N_{PT}
  - 4-stage turbine at Z = 1.0 to 1.1 and AN^2 = 45 E9 $rpm^2 \cdot in^2$
- 2-D blade profiles set in AFRL TDAAS for hub, mid, and tip sections
  - DOE and gradient-search optimization
  - Utilize Ni's WAND/LEO codes
- Stack sections using TDAAS to generate 3-D blade coordinates
- Currently generate 3-D single-block grids using TCGRID
- Run 3-D blading using SWIFT RANS mixing-plane solver with Wilcox's low-Re κ–ω

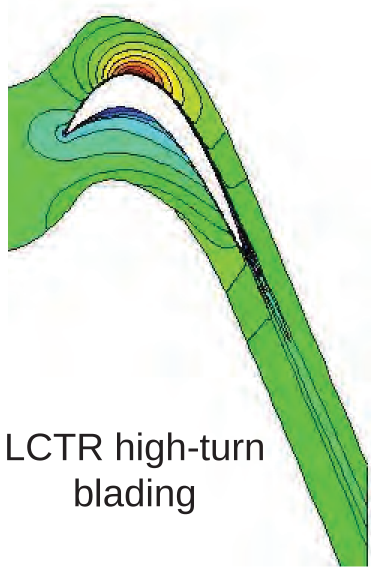
Efficiency vs. $\Delta h_0/U^2$ for conceptual designs



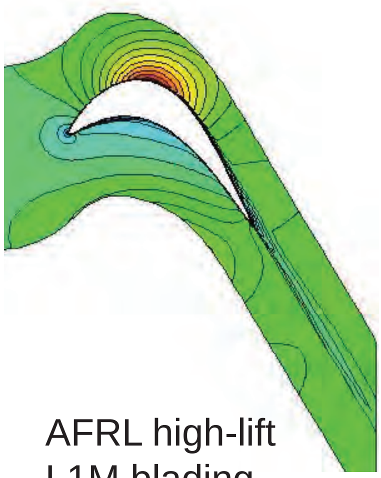
Air angles at design point

Design-point flow angles and loading for 3-stage and 4-stage rotors ($AN^2 = 45 \times 10^9$) and high-lift L1-series blading

	3-stage			4-stage			L1M			L1A		
Zweifel		1.0			1.0			1.34			1.34	
Rotor	β_1	β_2	**Turn**	β_1	β_2	**Turn**	β_1	β_2	**Turn**	β_1	β_2	**Turn**
1	55	-65	120	53	-67	120	35	-60	95	35	-60	95
2	50	-58	108	56	-66	122						
3	29	-42	70	46	-57	102						
4	--	--	--	28	-39	66						

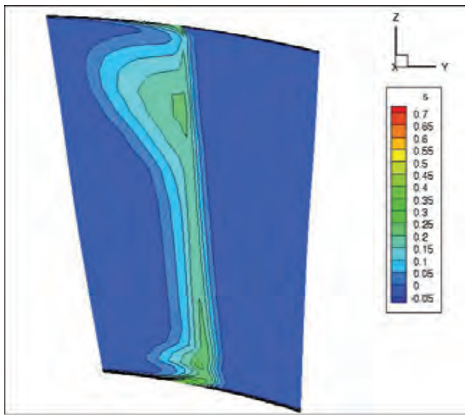


LCTR high-turn blading

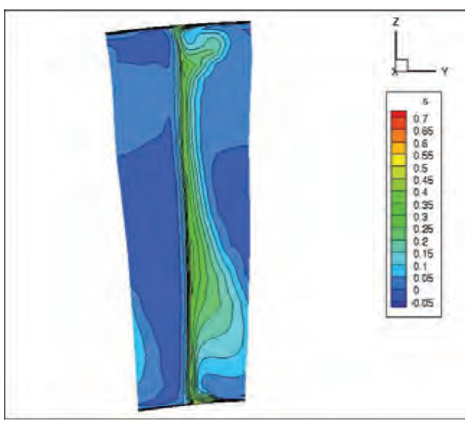


AFRL high-lift L1M blading

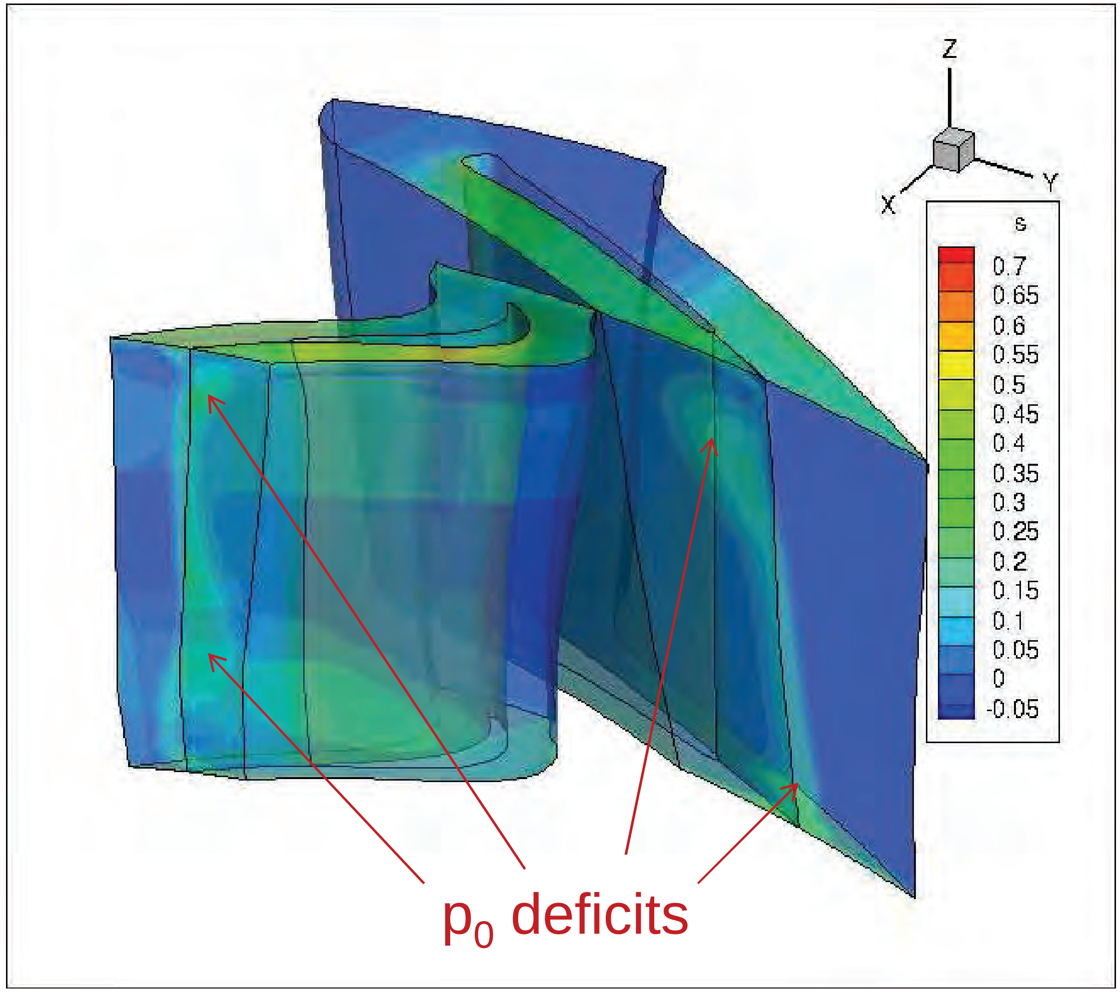
First-stage – 120-deg. turning at Z = 1.1
Computed entropy contours at design point



Vane exit



Blade exit

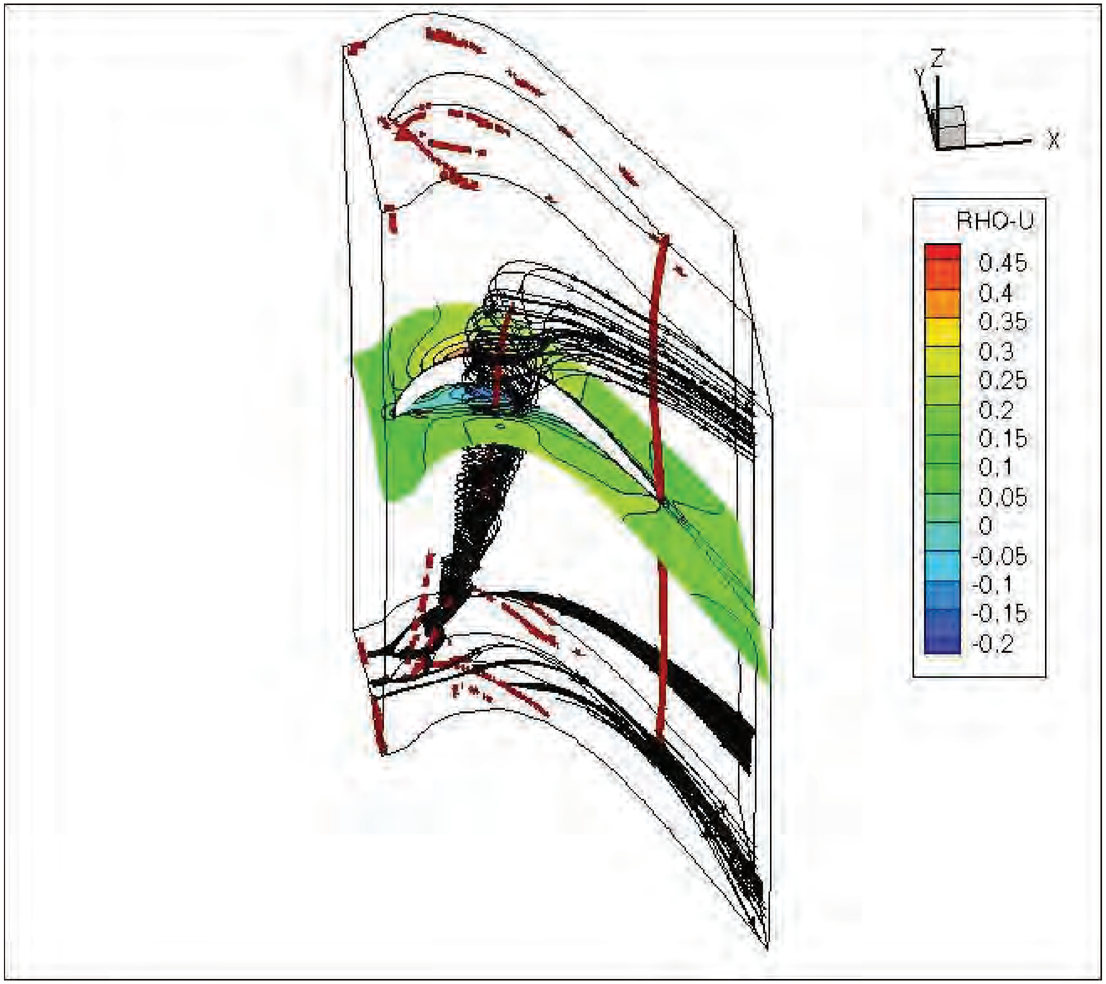


3-D challenges - secondary and endwall flows

Streamlines in cove region at off-design point associated with LCTR take-off.

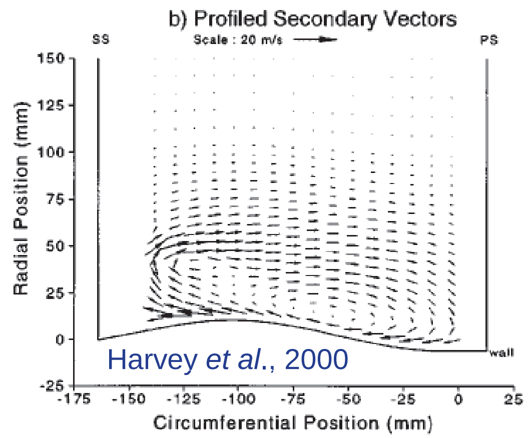
How will 3-D bite us at design and off-design?

Low-Re and endwall flows?

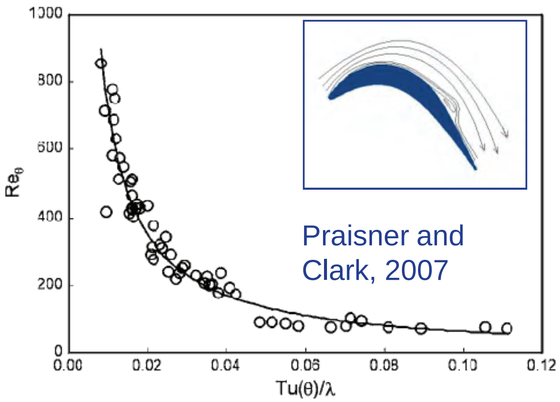


VSPT aero research and technology development needs

- MDO of variable-speed PT at component and engine level
- Efficient high-load, high-turn aerodynamics
  - Secondary flow management using 3-D blading (lean and bow) and endwall contouring
- Aerodynamics of high negative incidence
  - Characterize 2-D and 3-D loss mechanisms at high (40 to 60 deg.) negative incidence
- Aerodynamics of low-Re number flows
  - Turbulence sub-models for transitional flow into RANS/URANS solvers
  - Impact of unsteadiness
  - Impact on useful range of incidence
  - Impact of aerodynamic loading distribution



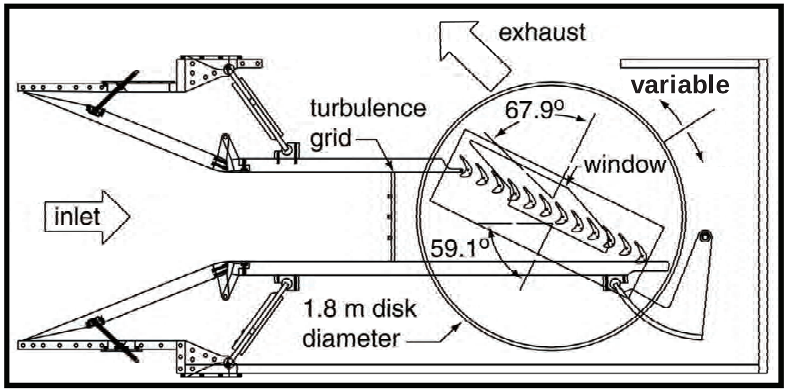
Harvey *et al*., 2000



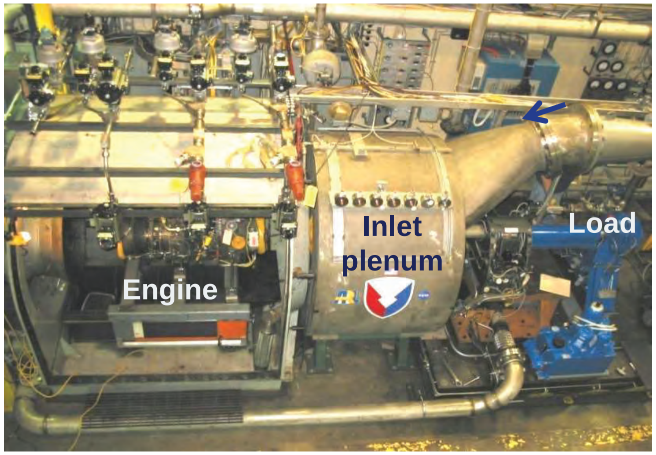
Praisner and Clark, 2007

Overview of current VSPT research effort at NASA GRC

- Incidence-tolerant blading for low-Re operation
  - Concept design of LCTR VSPT
  - Design/optimization of blading (AFRL TDAAS)
  - Utilize new and existing data sets to assess / calibrate transition sub-models within κ–ω construct
  - Linear cascade experiments – incidence (loss buckets), M, Tu and Re variations
- Rotordynamics
- Assessment of capability for in-house component-level VSPT experiments



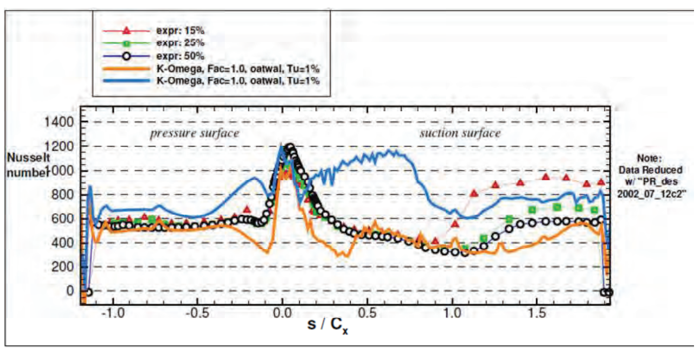
NASA GRC linear transonic turbine cascade

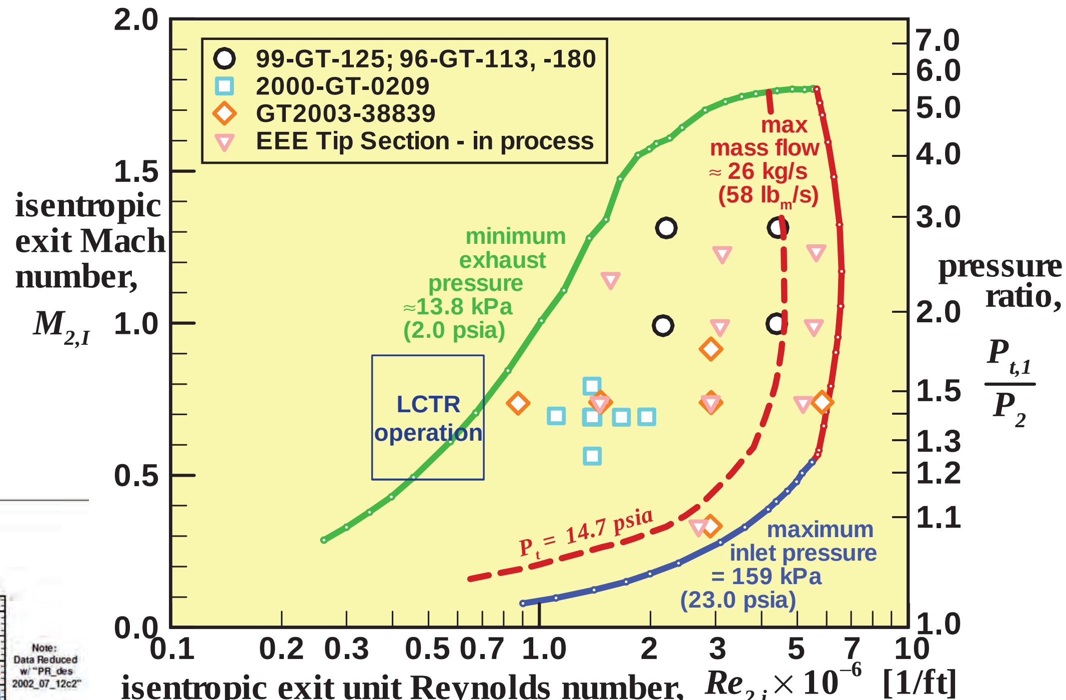


NASA Engine Component Research Laboratory

National Aeronautics and Space Administration

Transonic linear cascade
M, Re, Tu, and incidence-variation capable





Giel, P. W., Boyle, R. J, and Bunker, R. S., *J. Turbomach*, **126**, Jan, 2004

Summary

- Key aerodynamic challenges of VSPT
  - Attainment of high efficiency (> 0.88) at high work factors (3.5 to 4)
  - Wide incidence variation over mission– high negative incidence
  - Low unit Reynolds numbers ($30 < Re/c_x < 50k$ /in.)

Shared by variable-speed PT and fixed-speed PTs

- Need: low-loss, incident-tolerant vane, blade, and EGV blading
  - Trade weight (AN^2, stage count, and blade count) against efficiency and incidence range
  - Optimize: aero-loading level (Z), blade aero-loading schedule, and blade and endwall profiling

- VSPT research effort at NASA GRC
  - Develop experimentally validated design methods and computational tools/modeling for design/optimization of low-loss, incidence tolerant blading.

Acknowledgements

- Mr. Robert J. Boyle (former Distinguished Research Associate, NASA GRC) for early assistance in formulation of VSPT research effort
- Mr. Christopher A. Snyder (NASA GRC) for continual refinement of LCTR engine requirements
- Dr. Rodrick V. Chima (NASA GRC) for assistance with *rvcq3d* code
- Dr. John P. Clark (AFRL) for providing the AFRL Turbine Design and Analysis System
- Dr. Lisa W. Griffin (NASA MSFC) for permission to use the Huber meanline codes

NASA Fundamental Aeronautics program

Subsonic Rotary Wing project

Session 5
Research Laboratories Views

NASA/CP—2020-220327

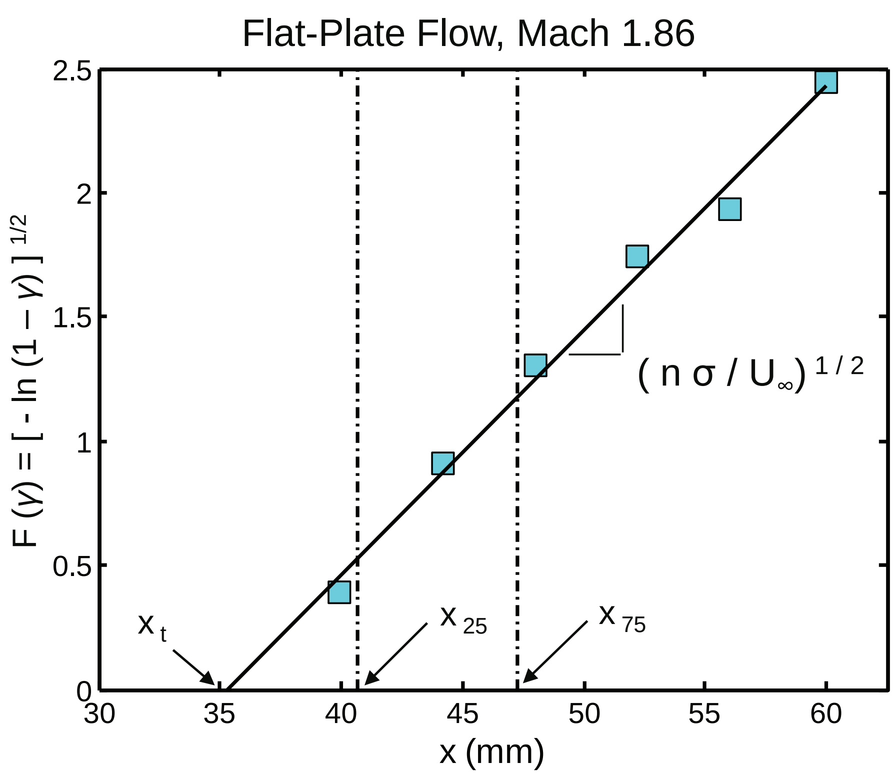
AFRL
THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

High Lift / High Work Turbine Development in the Propulsion Directorate

John Clark, AFRL/RZTT

NASA-Industry LPT/PT Efficiency Improvement Workshop
10-11 August 2010

F(γ) Technique is the Basis of Many Empirical Transition Models



- Narasimha's equation (1957)

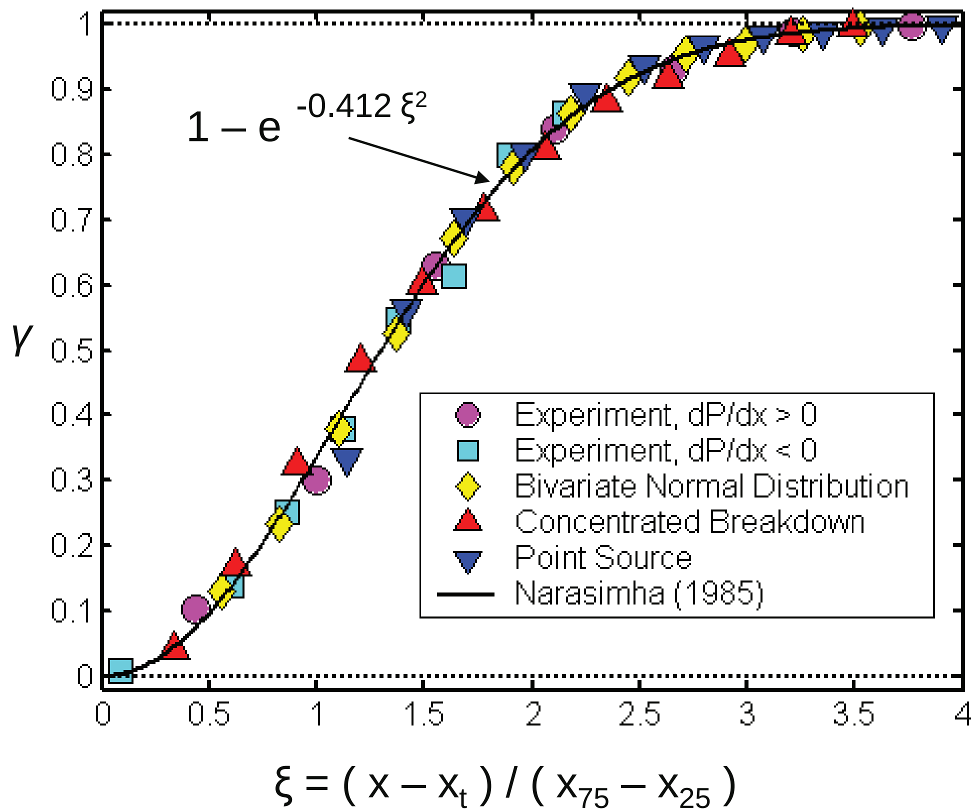
$$\gamma = 1 - e^{-(n\sigma/U_\infty)(x - x_t)^2}$$

presumed to apply.

- Derived by assuming "concentrated breakdown" in constant-velocity flow.
- Used to linearize an intermittency distribution and plot in "universal form."
- Used also by many to correlate onset, spot generation rate, and transition length.

Praisner and Clark, J of Turb., Vol. 129, pp. 1-14

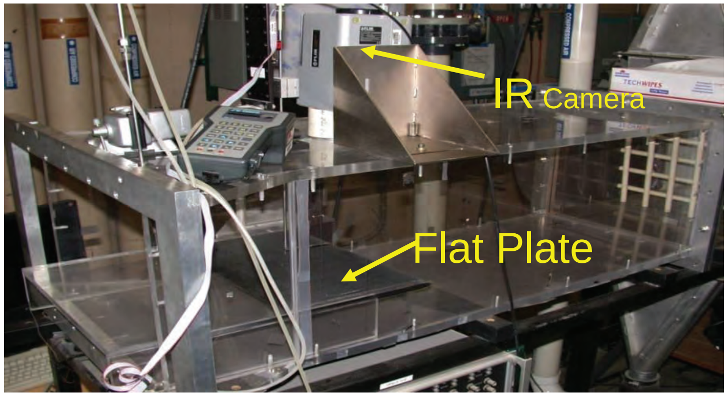
Example of Plotting Intermittency in Universal Form

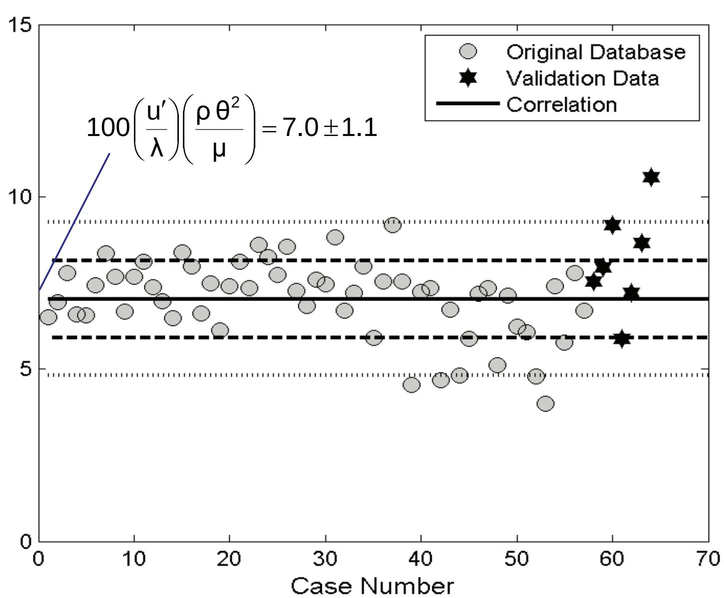


- Plots can be insensitive to variations in U_∞, σ, and even the spot-generation function.
- Not proof of transition onset by concentrated breakdown.
- It seems inadvisable to use F(*γ*) technique to develop correlations for onset, length, and spot-generation rates.
- This observation played a large part in the decision to take a different tack for model development.

Praisner and Clark, J of Turb., Vol. 129, pp. 1-14

Attached-Flow Model Derived Using Local Variables at Min Heat-Flux Locations



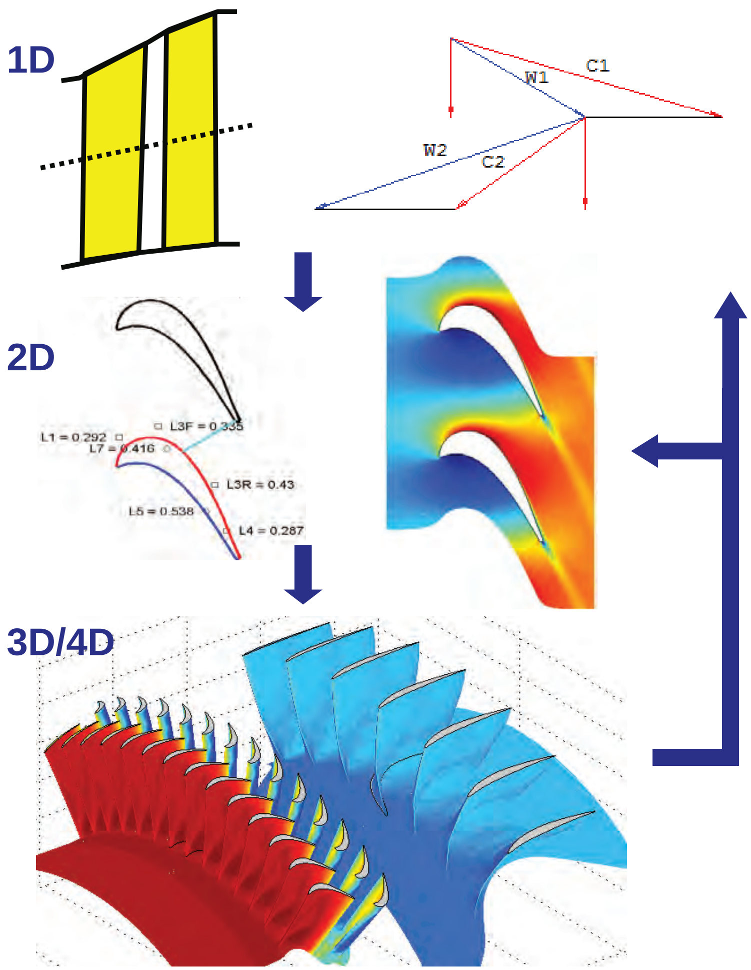


- Transition model is appealing → onset occurs when a critical ratio of laminar boundary layer and turbulence time-scales is achieved.
- Direct validation of bypass transition model was obtained in an incompressible flat-plate facility.
- Still, this is an *empirical* model:
  - Suitable for incorporation into RANS codes
  - To be used with caution

Praisner and Clark, J of Turb., Vol. 129, pp. 1-14

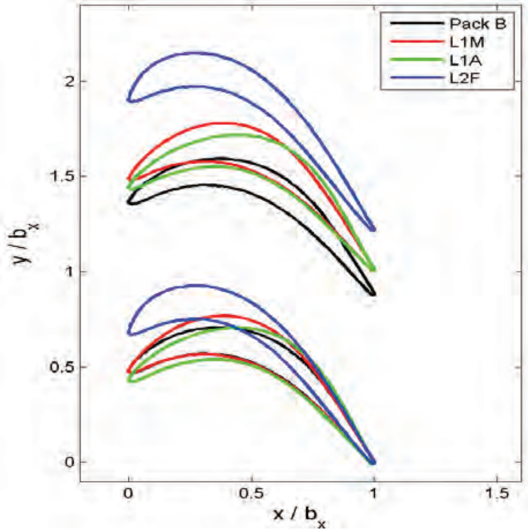
AFRL Turbine Design System : Enables Design of Research Components

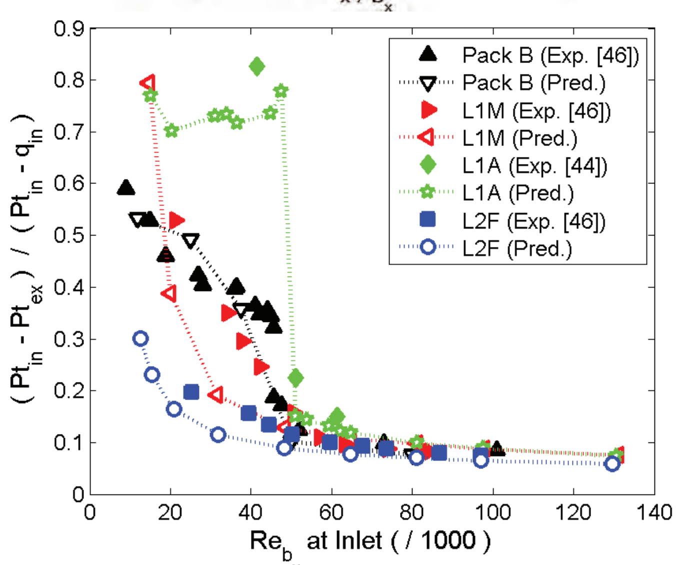
Iterative Turbine-Design Loop



- 1D: Turbine size and velocity triangles were set with a 1D meanline code (HuberLine, FTT)
- 2D: Airfoil-section design, analysis, and optimization was conducted in MATLAB
  - HuberFoil (FTT) profile algorithm
  - GUI-based flowfield interrogation
  - Optimization via SQP, genetic algorithms, and DoE
- 4D: Time-resolved 3D analysis
  - DSP-based convergence-monitoring and unsteady post-processing
  - Enables investigation of unsteady interactions and instrumentation design for code validation
- Various solvers are integrated with the system:
  - MBFLO (Davis, UCDavis)
  - LEO (Ni, Aerodynamic Solutions, Inc.)
  - Corsair (Dorney, NASA MSFC)

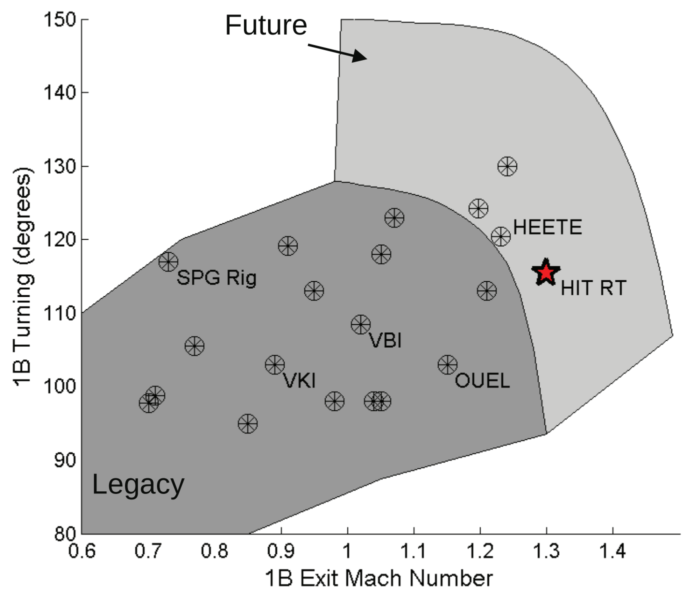
High Lift Airfoils were Designed to P&W Pack B Air Angles

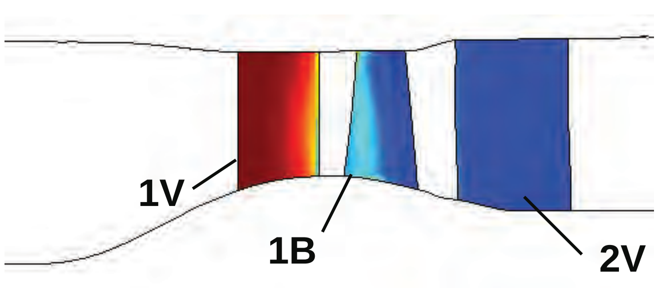




- A family of high lift airfoils was designed for incompressible cascade testing:
  - L1A (Z_w=1.34) was designed for flow control work in NASA Fundamental Aeronautics Program (OSU, USNA, Baylor, Brigham Young, Florida A&M, Cleveland State, and Arizona State)
  - L1M, L1A, L2F (and now L2A) are testing in the Low Speed Wind Tunnel at AFRL

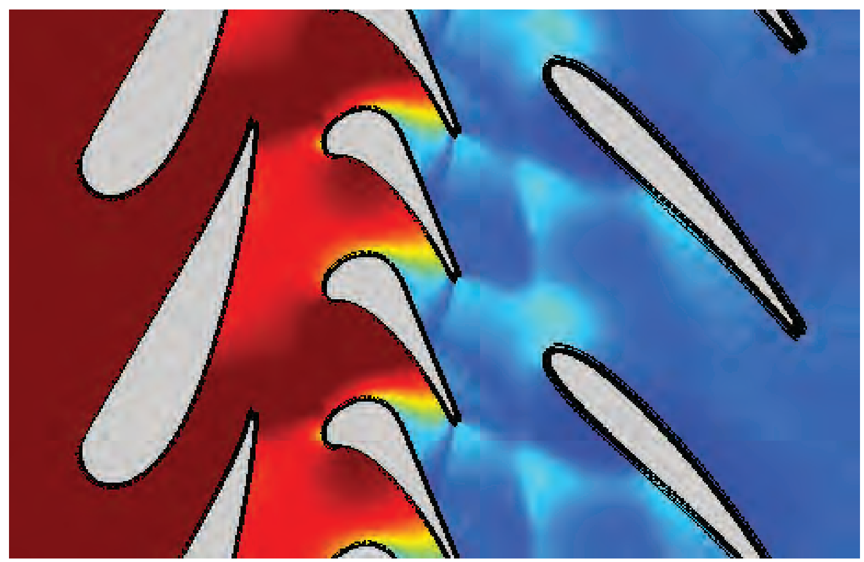
Also, a Transonic HP Turbine Rig was Designed to Investigate Unsteady Interactions



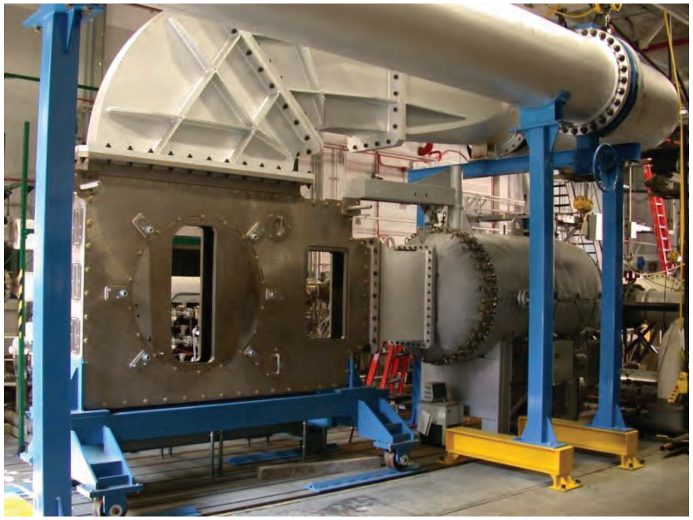


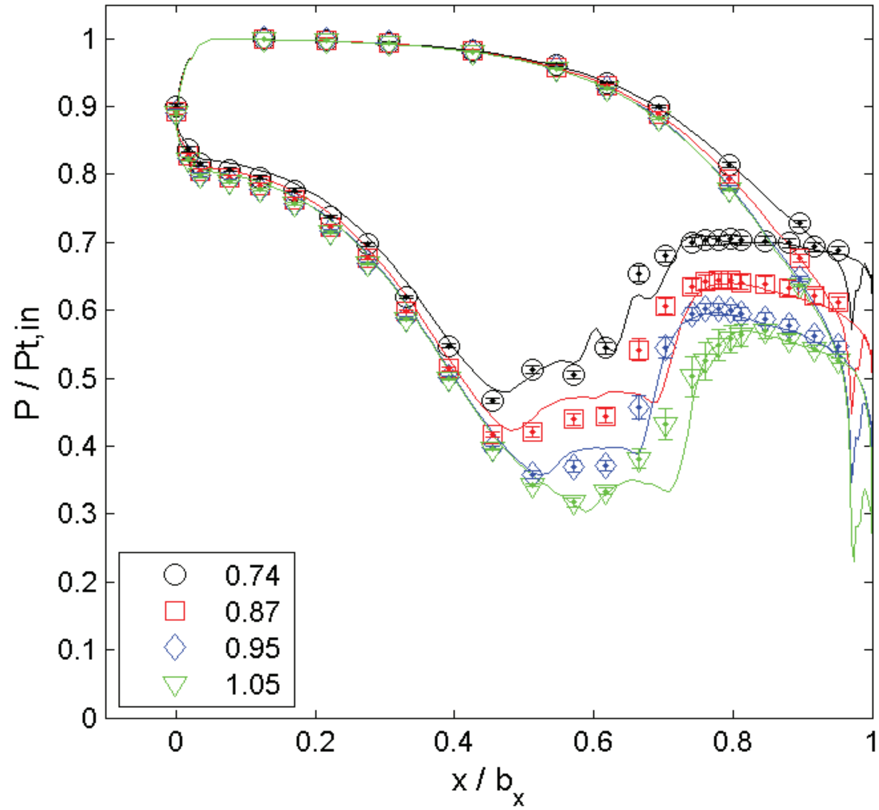
Meanline Design Parameters: HIT RT

PR	3.75 total-total		
Reaction	49.5%		
Flow Coefficient	0.71		
Work Coefficient	2.11		
AN^2 (in^2 rpm^2)	573 $\times 10^8$ (Engine)		
	1V	1B	2V
Turning	77	116	11
M_{exit}	0.88	1.30	0.89
Airfoil Count:	23	46	23



Transonic Cascade Experiments are Underway to Investigate HP Blade Aerodynamics



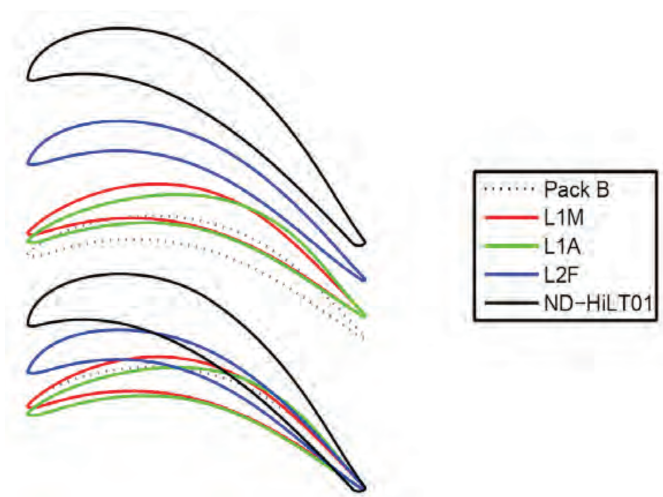


- Off-design operation results in exceptionally severe adverse pressure gradients

A Full Scale Rotating Turbine Rig was Designed for Insertion in Notre Dame Turbine Facility

<u>Meanline Design Parameters</u>

Efficiency	90.5%	
PR	1.75 total-total	
Reaction	38%	
Flow Coefficient	0.78	
Work Coefficient	2.80	
N2	6278.1 rpm	
	Vane	Blade
Turning	96	123
M_{exit}	0.76	0.78



- Rig is an embedded LPT stage consistent with a very high OPR cycle.
- Stage loading level is high
  - Between GE E^3 and Evans and Wolfmeyer (1972) LPTs.
- Blade Zweifel coefficient is consistent with L1 series (1.35).
- Allows for assessment of model-based design improvements in rotating, compressible flows.
- Baseline performance testing is complete.
  - Measured η > 1% above target.

Summary

- The AFRL turbine design, analysis, and optimization system was used here to design research geometries with both high lift and high work levels.
- Successful incompressible and transonic cascade work led to development of a full-scale rotating LPT rig that surpassed performance targets.
- While considerable caution is prudent it seems clear that *available empirical transition models allow for successful designs* up to TRL=5.
- Further LPT performance improvements are likely to come from understanding effects *less* thoroughly investigated, e.g., multi-row interactions, endwall flows, leakages, real geometries.

Acknowledgements / Collaborations

AFRL
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Shankar Magge
Om Sharma

Aerodynamic Solutions, Inc.
Bob Ni

UC Davis
Roger Davis

University of Notre Dame
John Schmitz
Joshua Cameron
Scott Morris

The Ohio State University
Jeffrey Bons

St. Louis University
Mark McQuilling

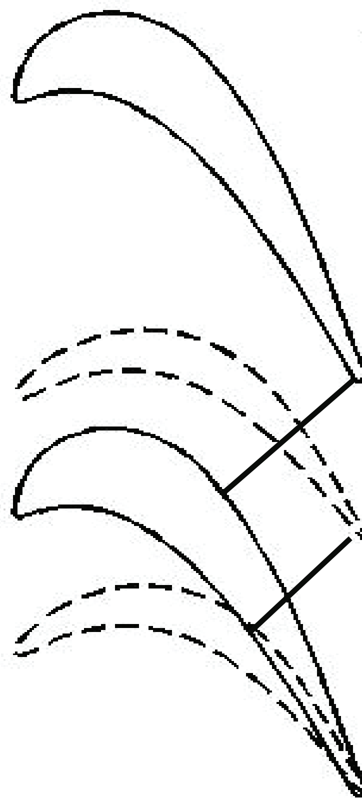
NASA
Dan Dorney
Jerry Welch

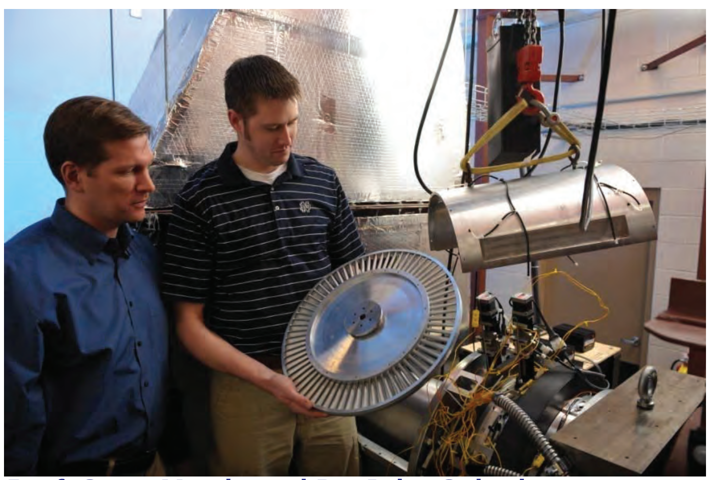
ND-HiLT01 LPT Stage

Design Parameters

Power: 238 kW / 319 hp
Mass flow rate: 4.9 kg/s / 10.9 lb/s
Blade height: 68.6 mm
Blade diameter: 0.47 m
RPM: 6280
Efficiency: 90.5% (MEANLINE TARGET)
Number of Blades: 70
Blade Turning at Midspan: 123 degrees

Work coefficient: 2.80
Zweifel coefficient: 1.35
Flow coefficient: 0.78
Pressure ratio: 1.75




Prof. Scott Morris and Dr. John Schmitz

NASA/CP—2020-220327

NRC·CNRC
Aerospace

Turbomachinery R&D

National Research Council of Canada

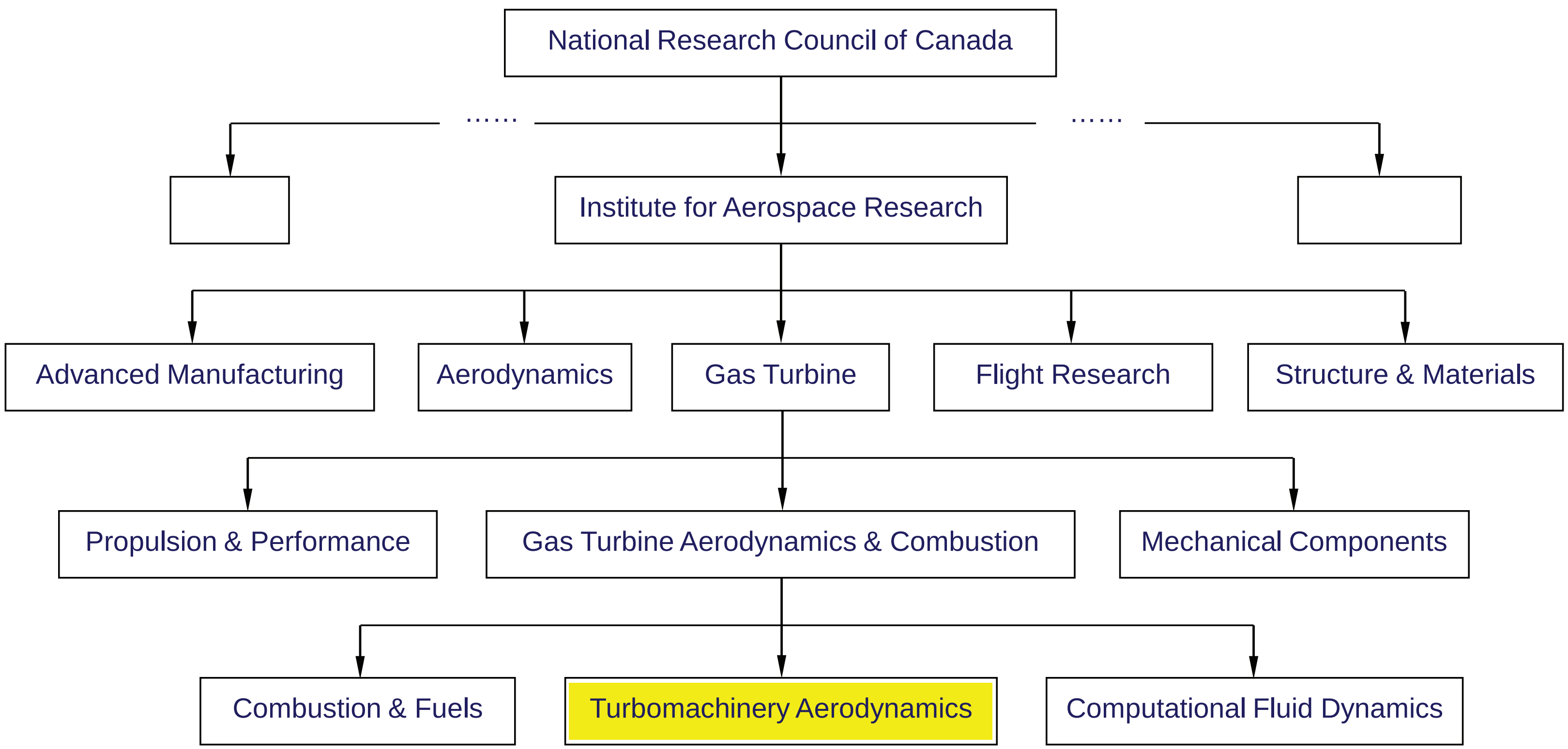
Michael Benner

Turbomachinery Aerodynamics Group, Gas Turbine Laboratory
Institute for Aerospace Research

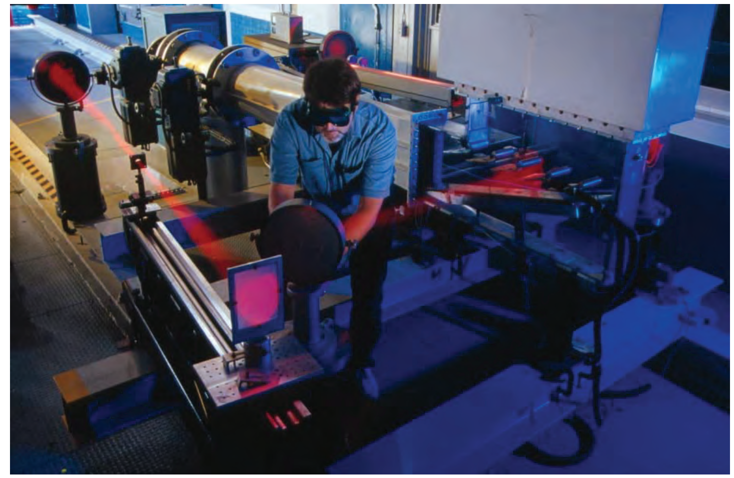
National Research Council Canada | Conseil national de recherches Canada

Canada

Turbomachinery Aerodynamcs



Our People



- 4 Aerodynamicists
- 1 Senior Technologist
- 6 Ph.D. and Masters Students

<u>Support</u>

- Mechanical design and fabrication services
  - 85 designers, engineers and machinists
- Instrumentation specialists

NRC·CNRC
Aerospace

Our Facilities

- Large-scale low-speed dual core
- Large-scale low-speed annular
- 2 Linear cascades (low- and high-speed)
- Boundary layer transition rig
- 2 Probe calibration rigs
- Large-scale transonic 1.5-stage rotating turbine rig (last operated in 1991)
- Helicopter engine inlet ducting rig (in development)
- 24-node CFD cluster + access to additional 400-nodes

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Technology Focus

- Lower weight
- Higher efficiency

} Reduced fuel burn

- Improved durability
- Lower noise

From Airliners.net

Engine Weight Reduction Technologies

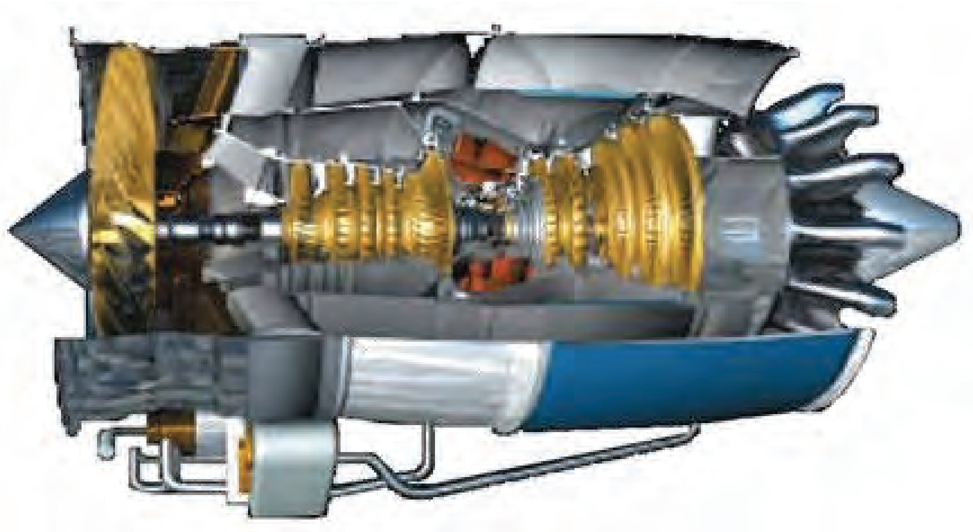
Program Objectives

1. Aerodynamic loading limits
   - Establish current-day
   - Extend with improved understanding

2. Develop innovative features for aggressive component designs

TRL 6

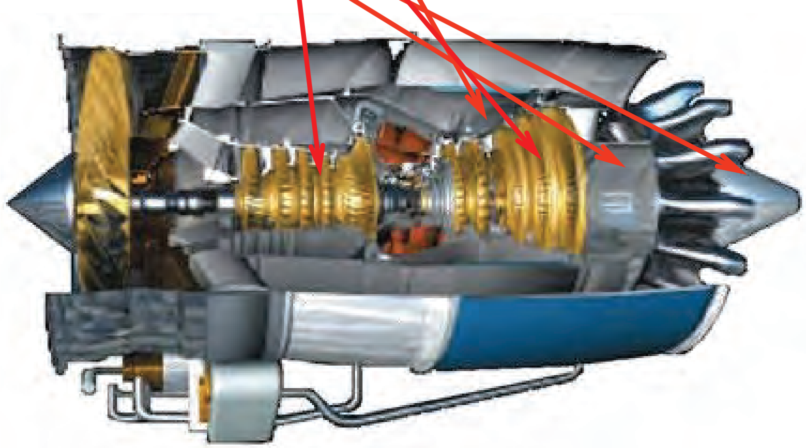
TRL 2-3



Engine Weight Reduction Technologies

Our focus

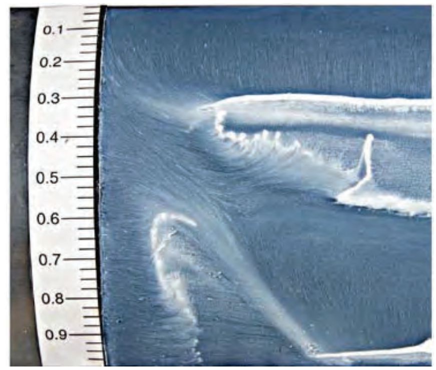
- Highly-loaded axial-flow compressors
- Highly-loaded axial-flow turbines
- Aggressive inter-turbine transition ducts
- Compact exhaust systems

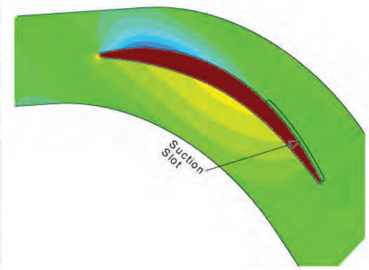


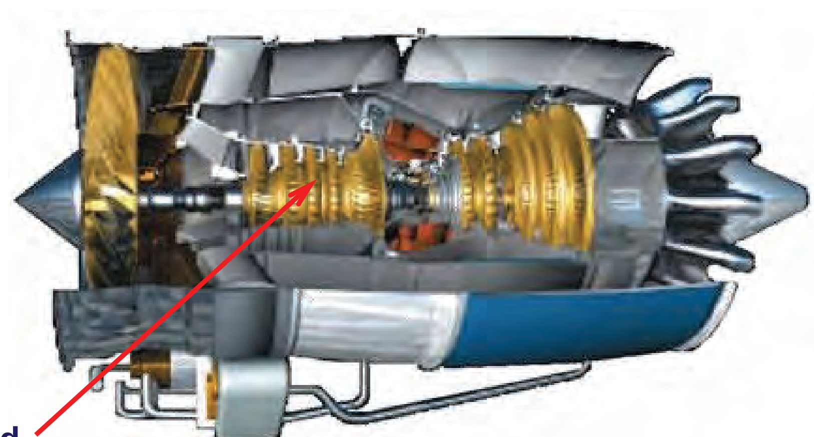
Engine Weight Reduction Technologies

Increased Compressor Airfoil Loading

1. Endwall Aspiration





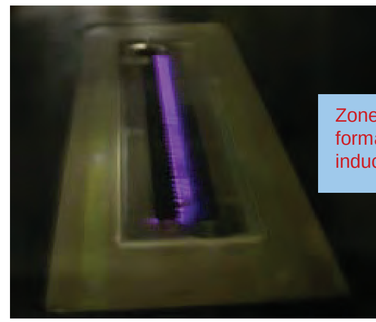


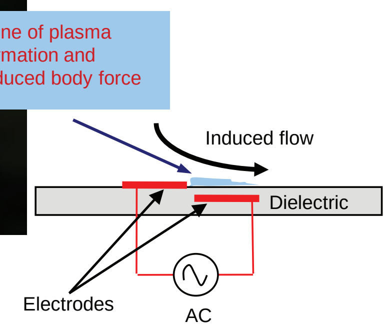
Highly-Loaded
Axial-Flow Compressors

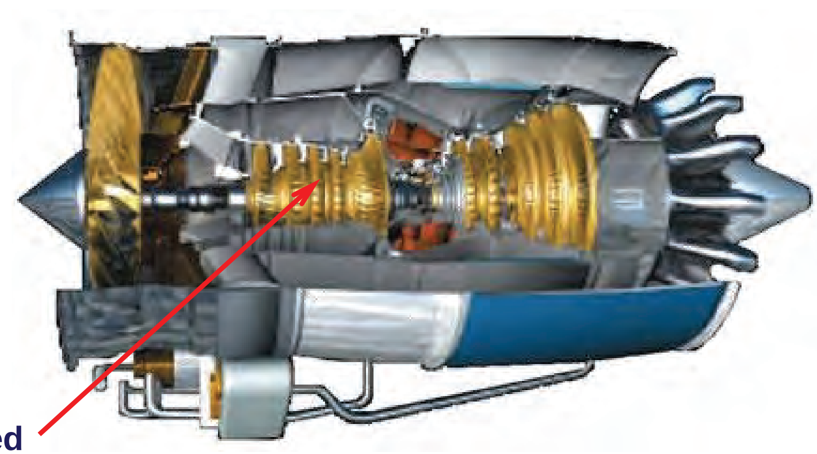
Engine Weight Reduction Technologies

Increased Compressor Airfoil Loading

1. Endwall Aspiration
2. **Plasma Actuation**





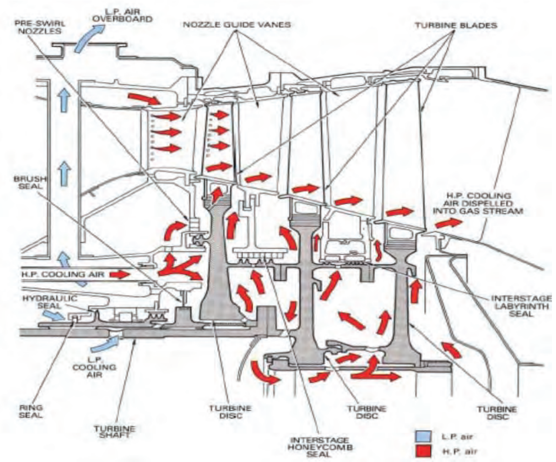


Highly-Loaded Axial-Flow Compressors

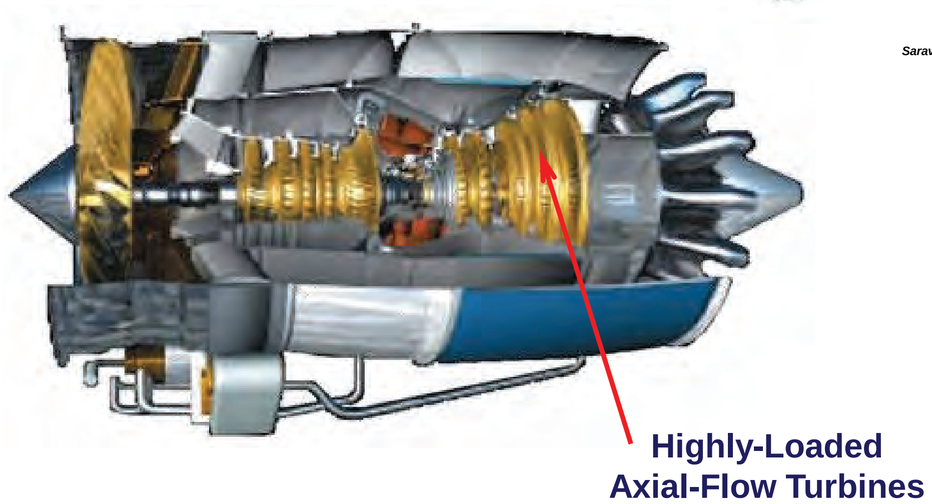
Engine Weight Reduction Technologies

Endwall Loss Reduction in High-Lift LPT Airfoils

- Mainstream/purge flow interaction and mitigation strategies



Saravanamuttoo et al. (2009)

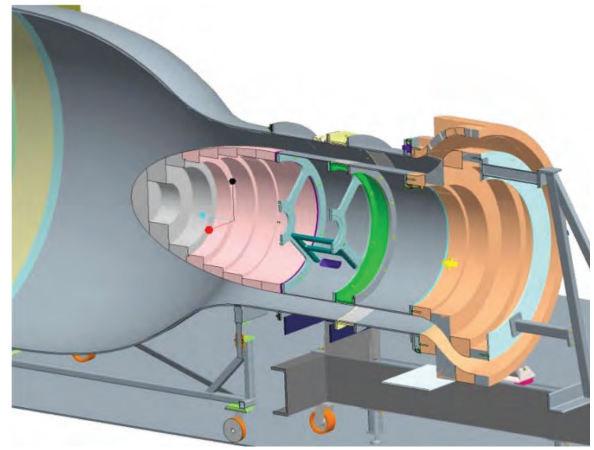


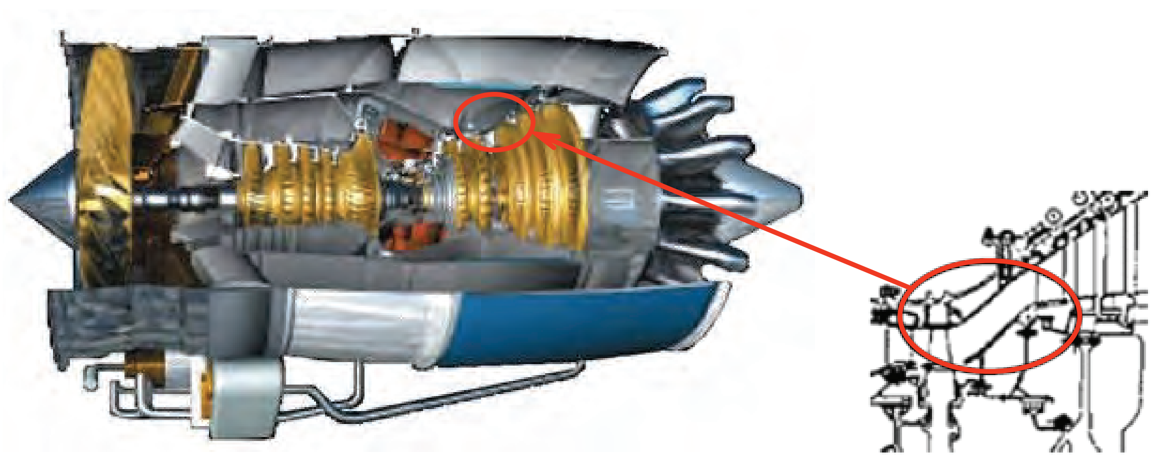
Engine Weight Reduction Technologies

Aggressive Inter-Turbine Transition Ducts

- Outlet-to-inlet mean radial offset
- Duct length
- Outlet-to-inlet area ratio

- Establish and extend design envelope



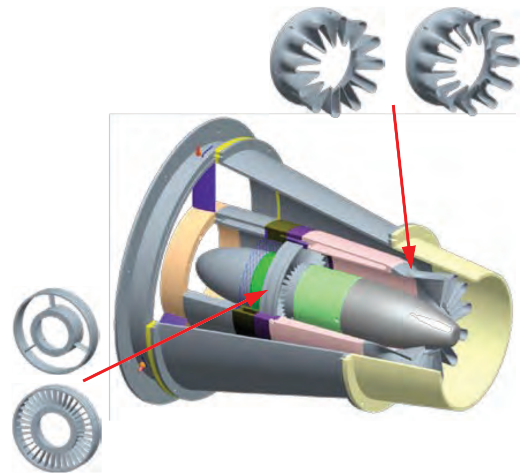


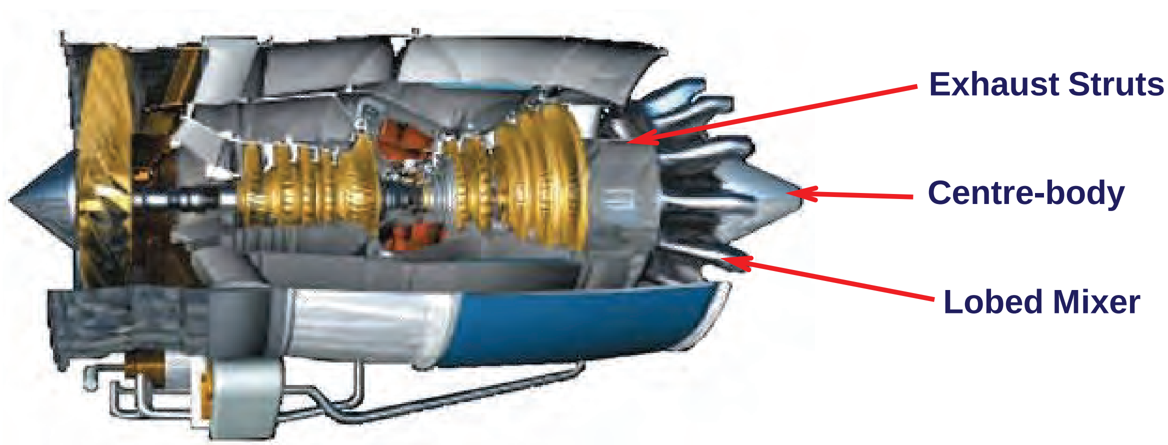
NRC·CNRC Aerospace

Engine Weight Reduction Technologies

Compact Exhaust Systems

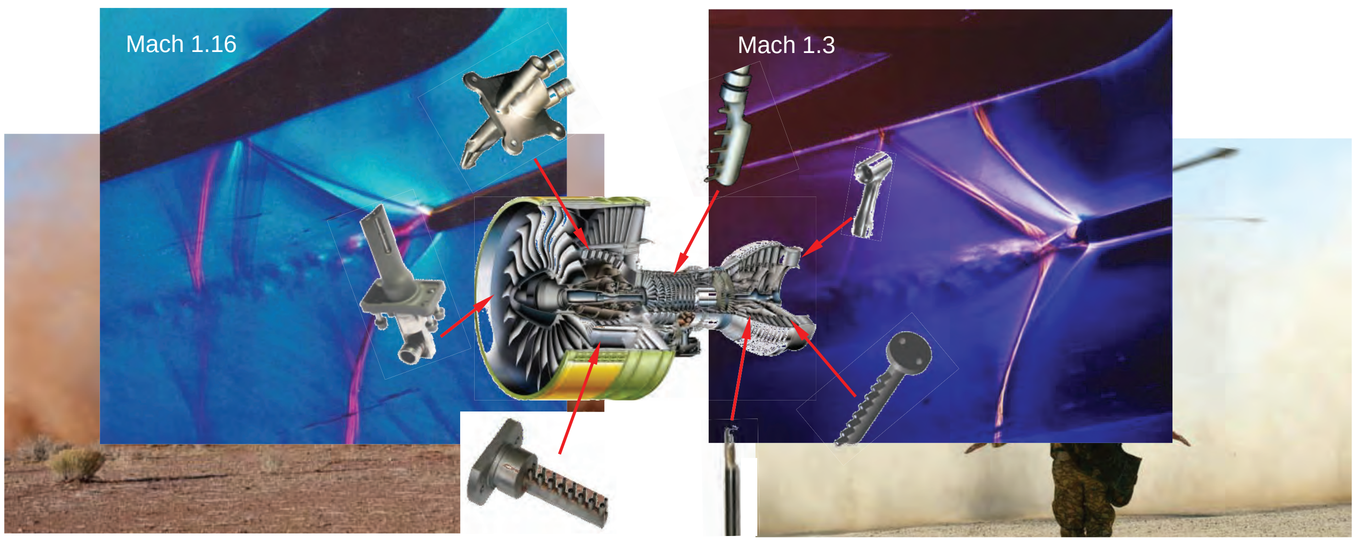
- New lobed mixer concepts
  - More tolerant to LPT exit swirl angle
  - Reduce no. of struts → Lighter engine
  - Improve mixing → Better performance





Turbomachinery Aerodynamics

- Engine weight reduction technologies
- Transonic turbine flows
  - Wake vortex shedding/energy separation
  - Improved base pressure correlation
- Gas turbine probe development and certification testing
- Helicopter sand ingestion



Session 6

Brief Overviews of Experimental Facilities

NASA/CP—2020-220327

The University of Notre Dame

Axial Turbine Facility

August 10, 2010

Joshua Cameron, University of Notre Dame

Acknowledgements

- University of Notre Dame
  - John Schmitz
  - Ruolong Ma
  - Scott Morris

- AFRL
  - John Clark

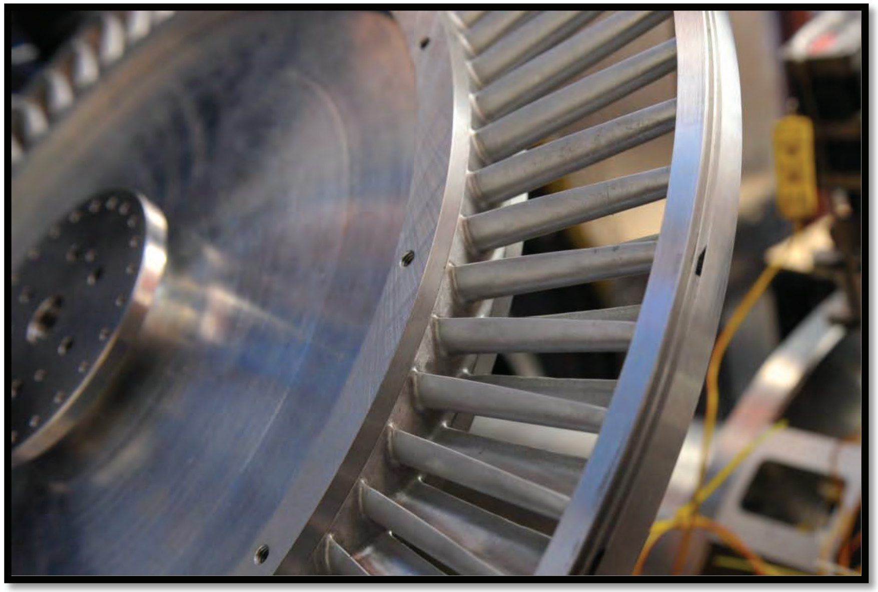
NASA/CP—2020-220327

UND Turbomachinery Research Goals

- Investigate **critical flow physics** of HPC and HPT/LPT stages at **engine relevant** conditions
- Provide **fundamental understanding** in a very **applied field**
- Provide **low-cost, flexible, continuous operation rotating rigs** of interest to government, industry, and academia

The Transonic Axial Turbine Facility

- 1000 hp compressor
- 5,000-15,000 RPM
- Magnetic bearings
- Can operate a range of low and high pressure turbine stages
- Continuous transonic operation

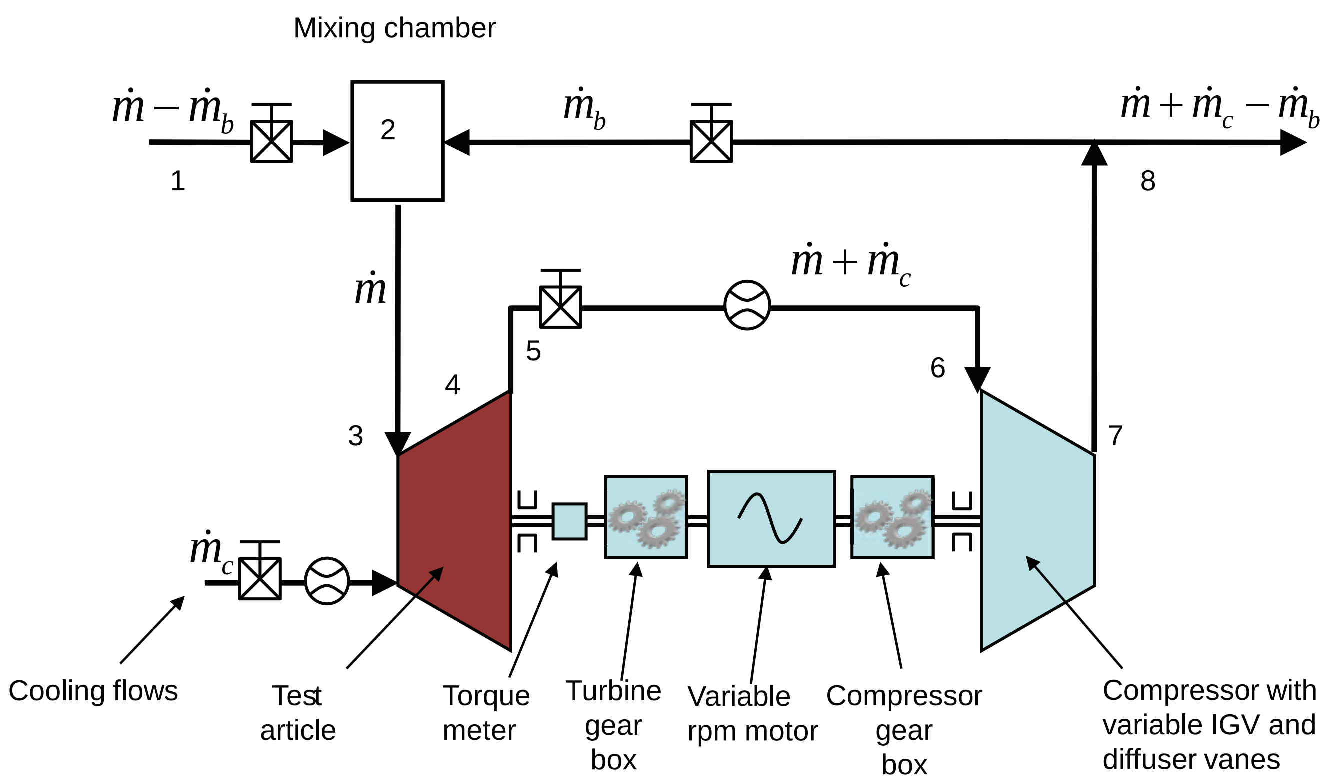


- Relevant **pressure ratio**, **stage loading, flow coefficient** and **Mach numbers** for both LPTs and HPTs

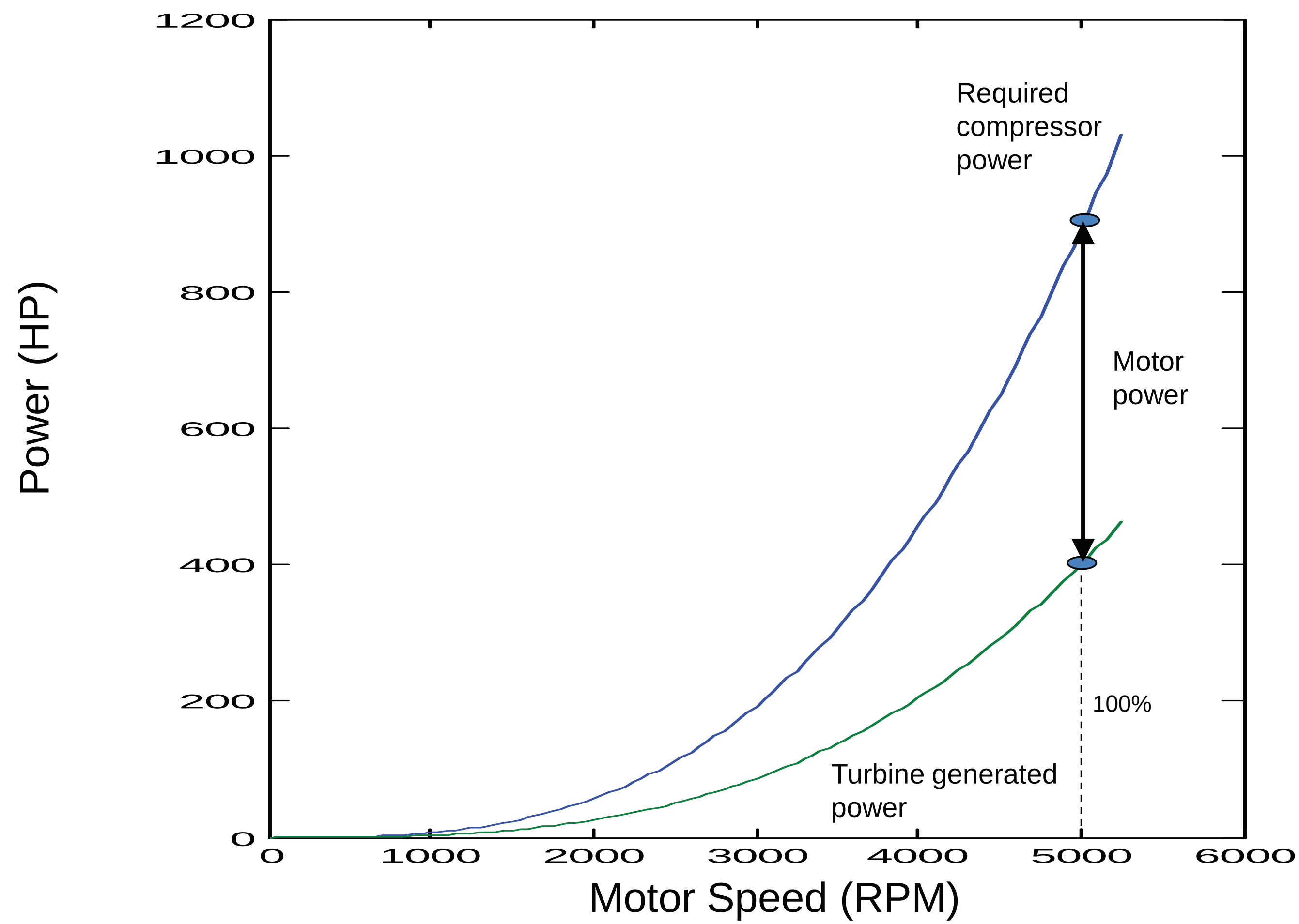
Unique Capabilities

- Magnetic Bearings
  - Zero-tare torque measurement
  - Whirl and non-uniform tip clearance
- Multiple Cooling/Purge Flows, Rotating and Stationary Possible
  - Engine relevant density ratios possible
- Optical Access
- Off-Design Mapping
  - Variable vane compressor provides wide operating range
- Turbine Power Recycling
- Flexibility
  - Low-cost operation
  - Boundary condition changes in hours/days not weeks/months

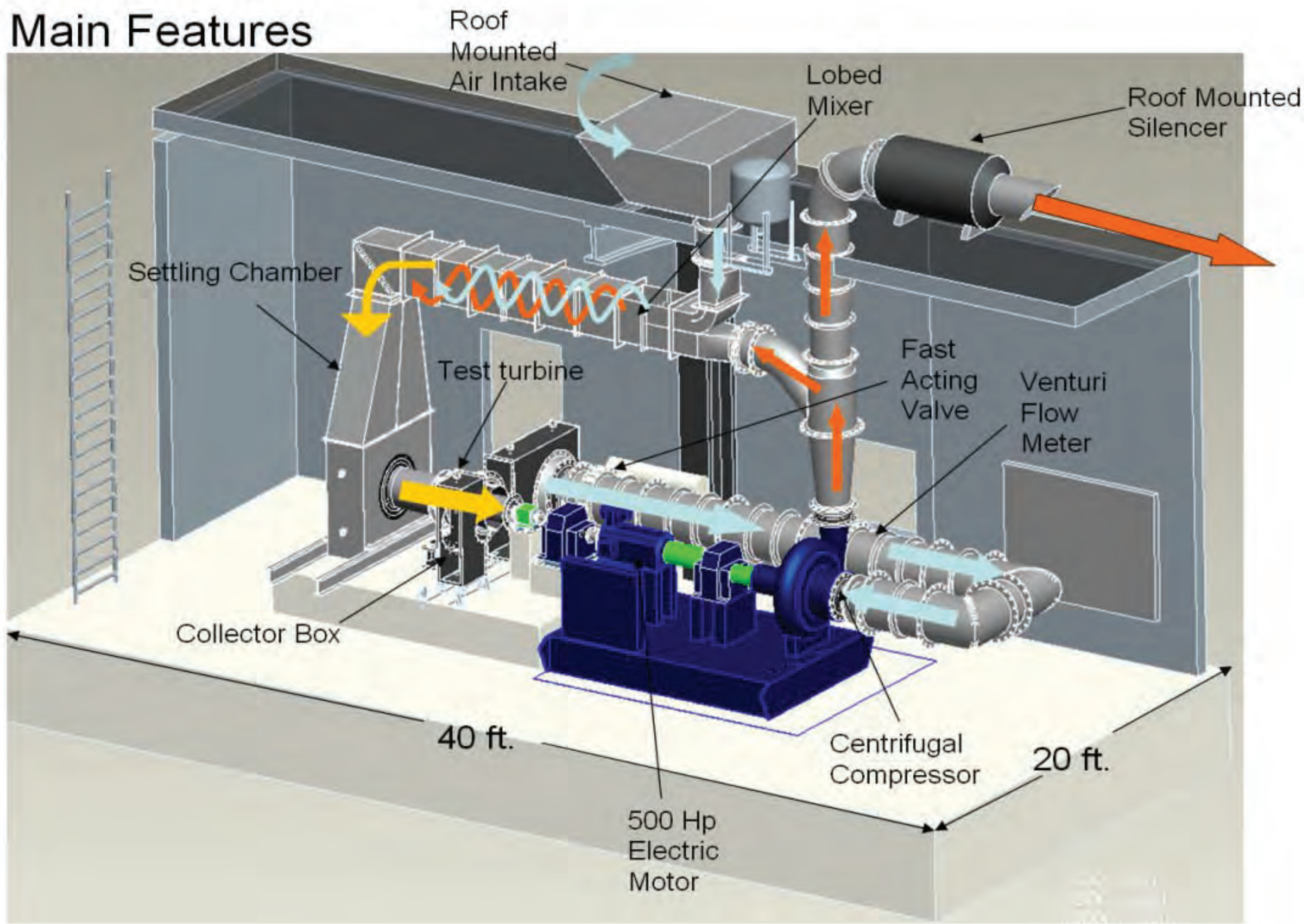
Facility Operation



Facility Operation



Facility Layout



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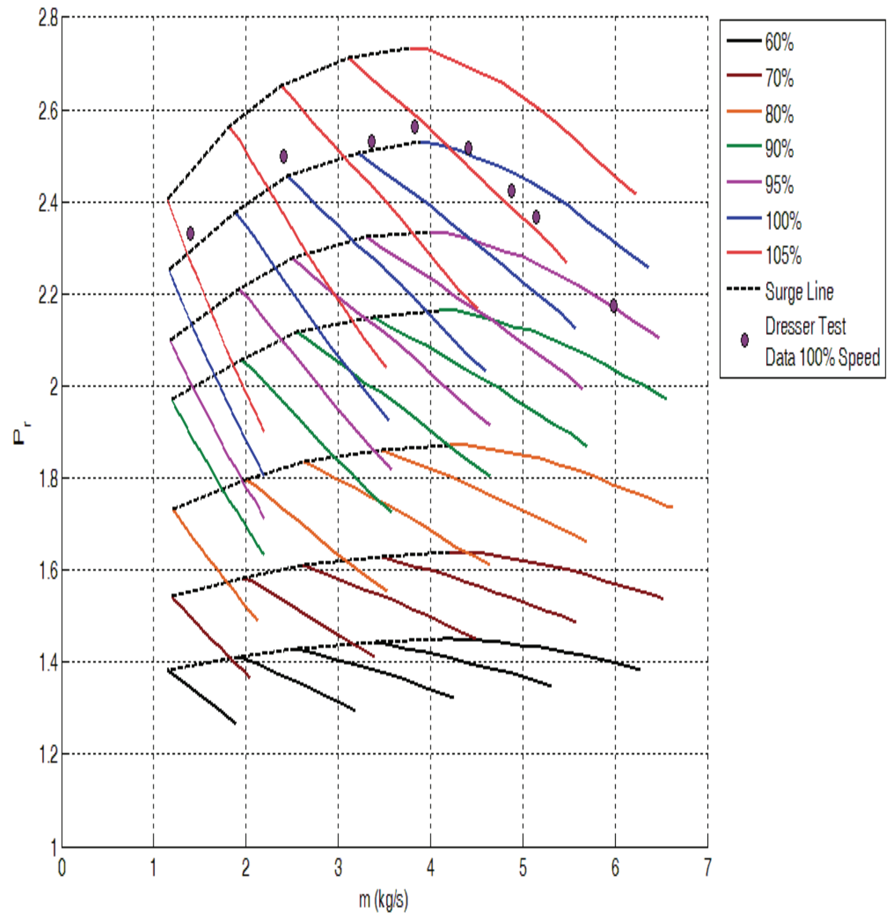
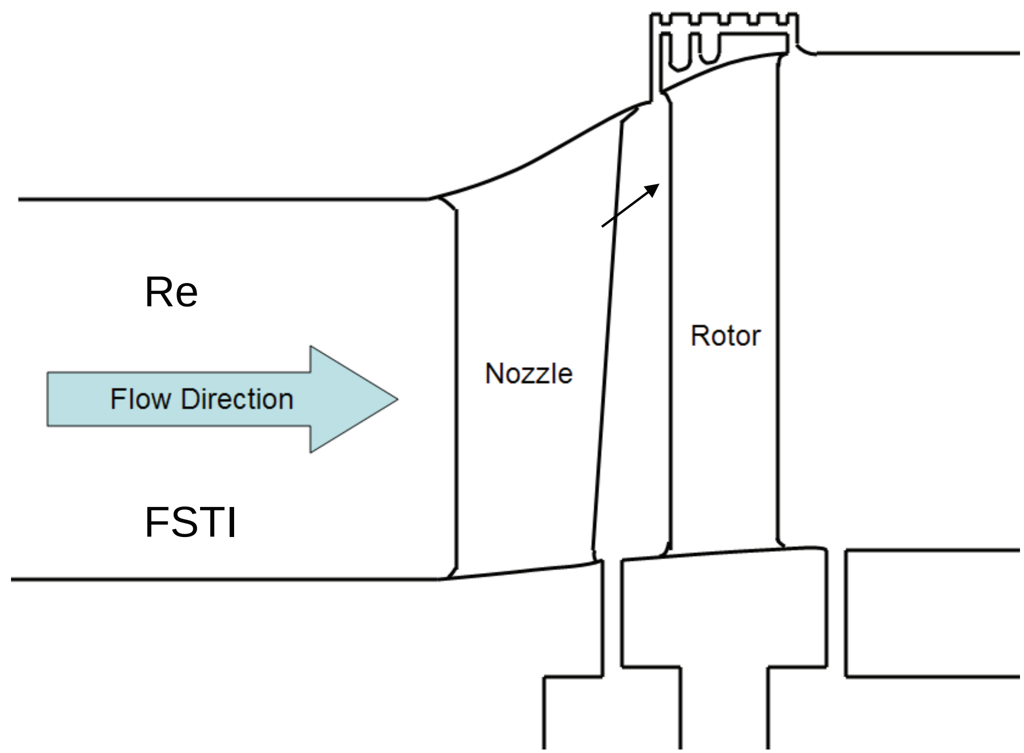
Compressor Map

- Physical Mass Flows from 2 kg/s to 6 kg/s
- Maximum compressor pressure ratios 2.3-2.6
- Maximum test article pressure ratios about 2.2

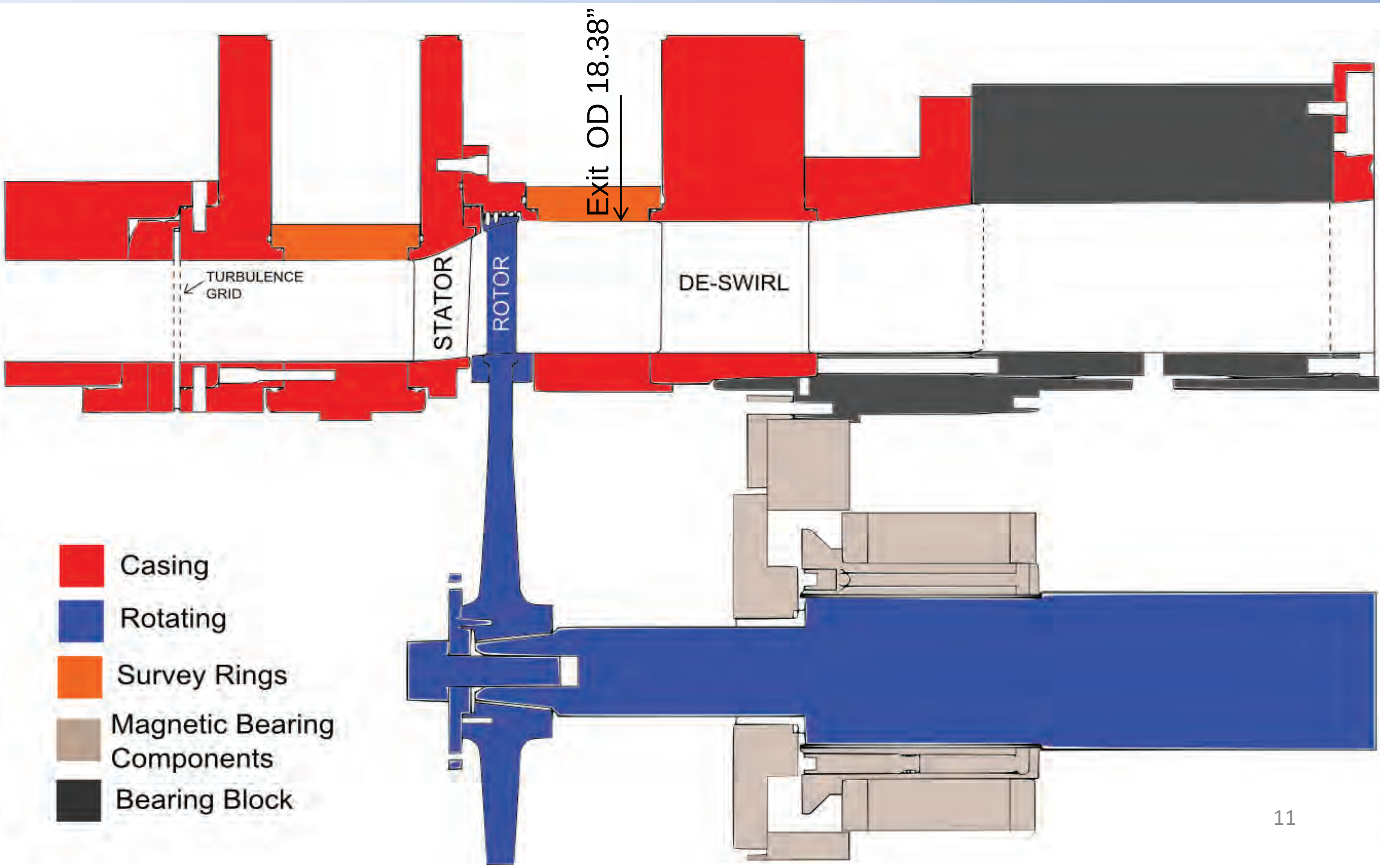


Validation of ND-HiLT01 Stage Performance

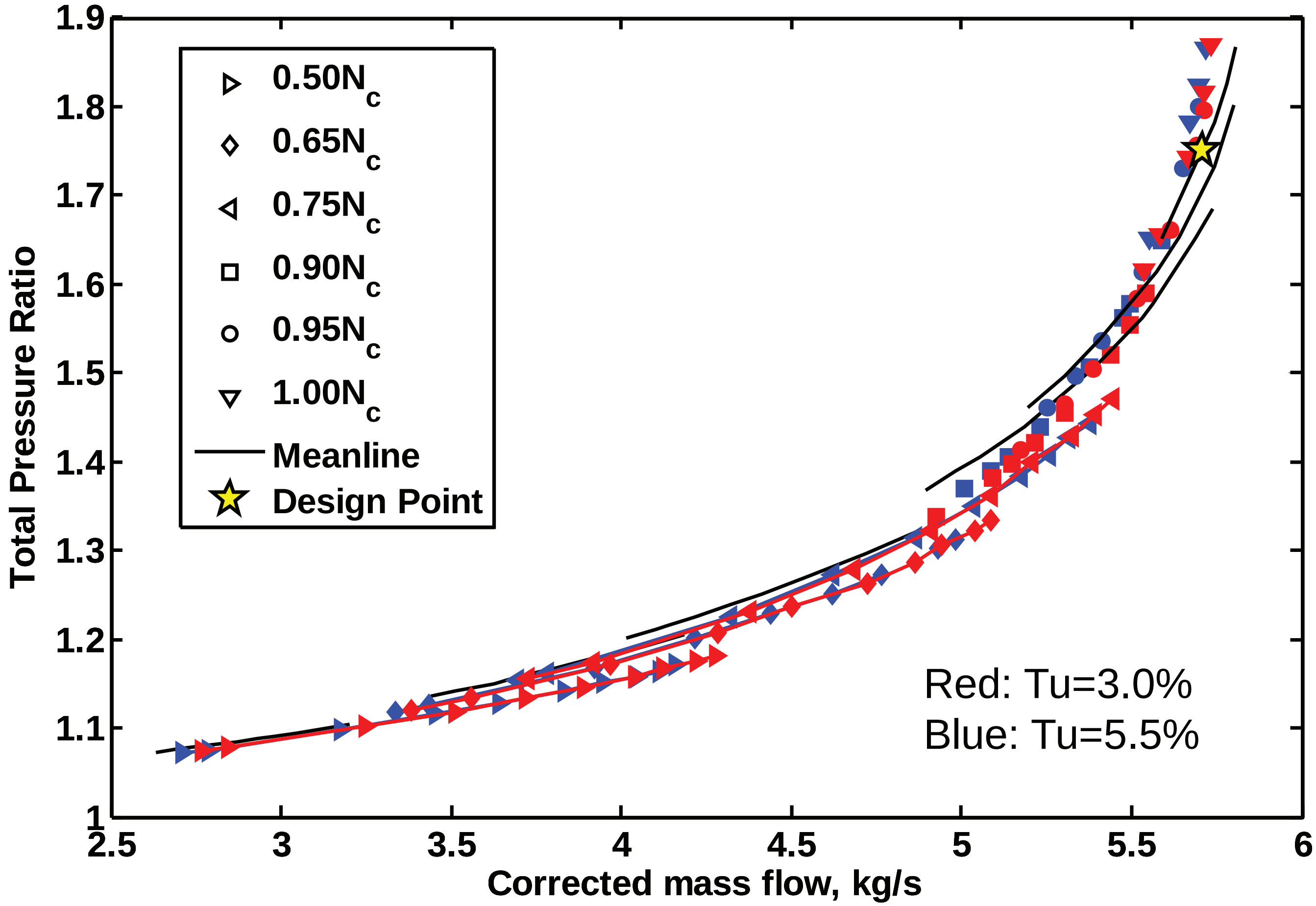
- Reynolds number
- Turbulence intensity
- Rotor incidence angle
  - PR, TR, η



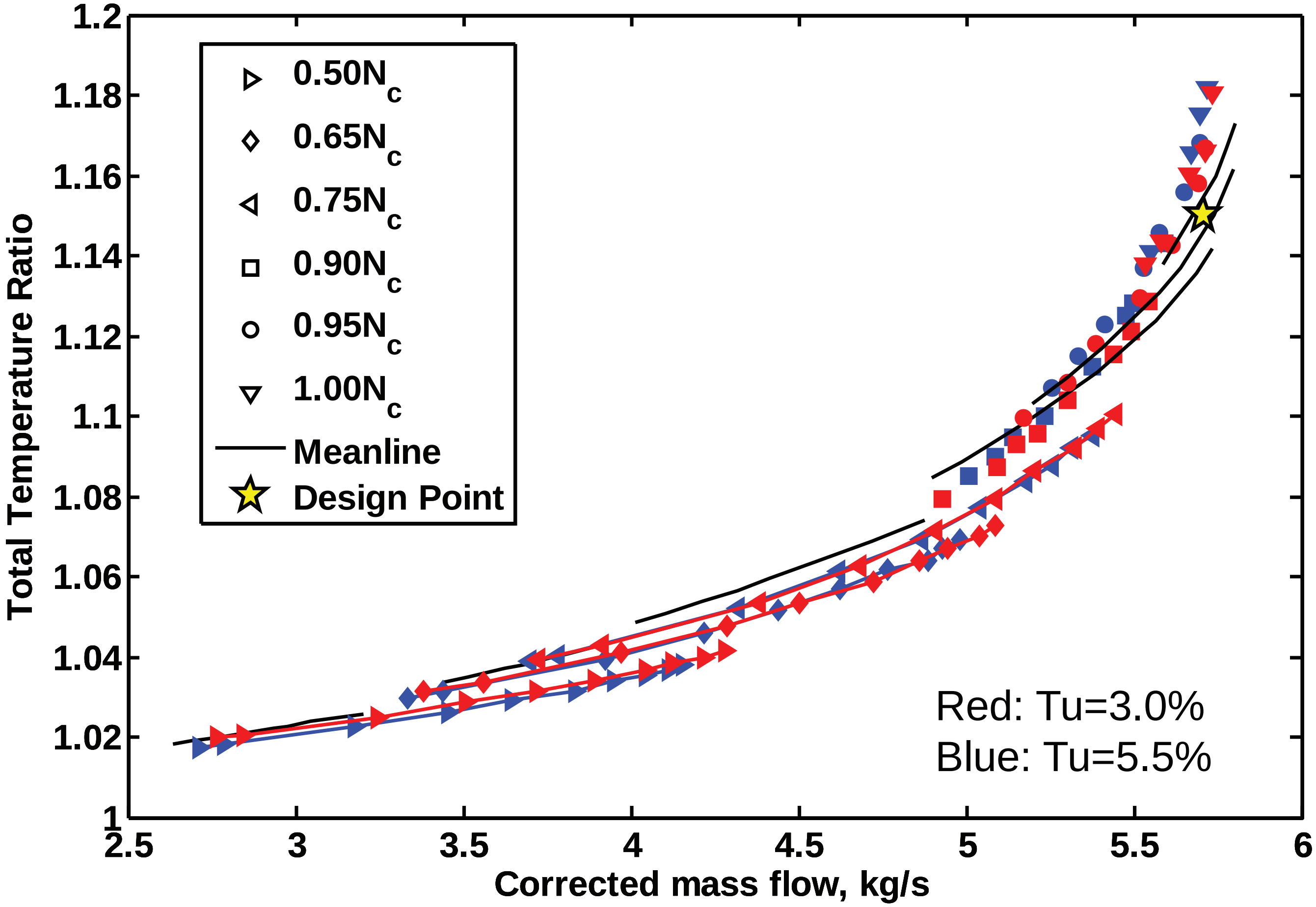
ND-HiLT01 Test Article



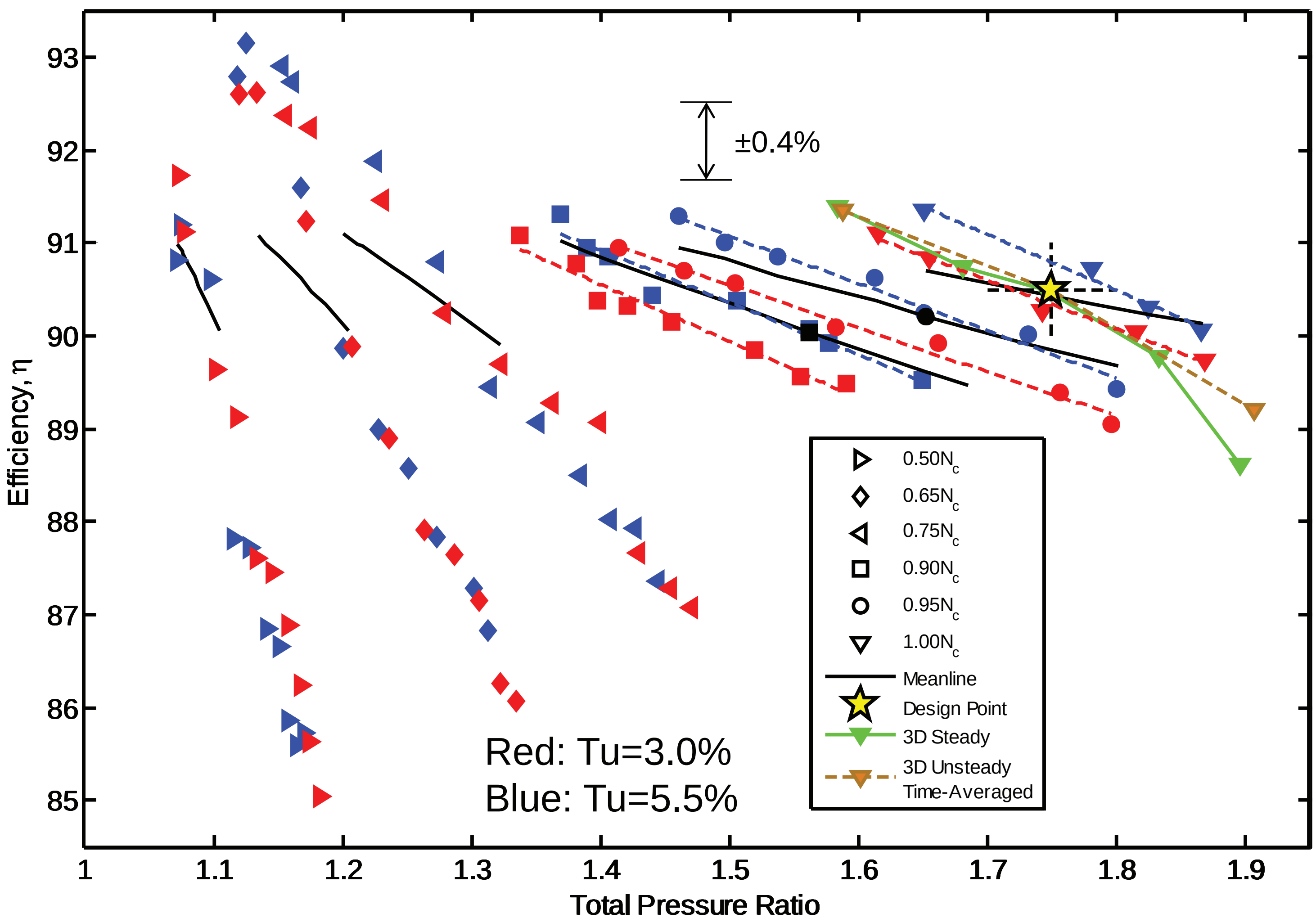
ND-HiLT01: Design and Off-design Stage Pressure Characteristics



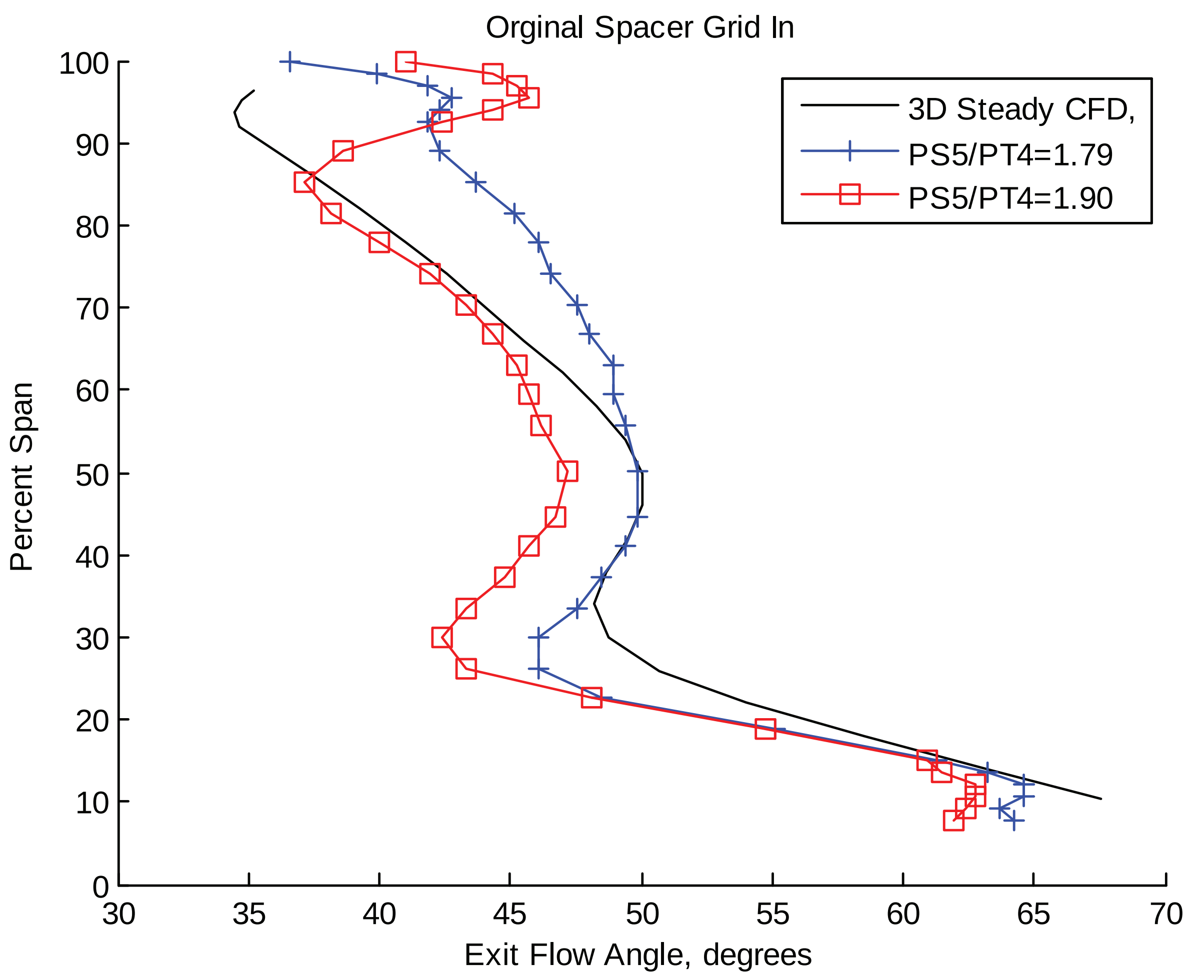
ND-HiLT01: Design and Off-design Stage Temperature Characteristics



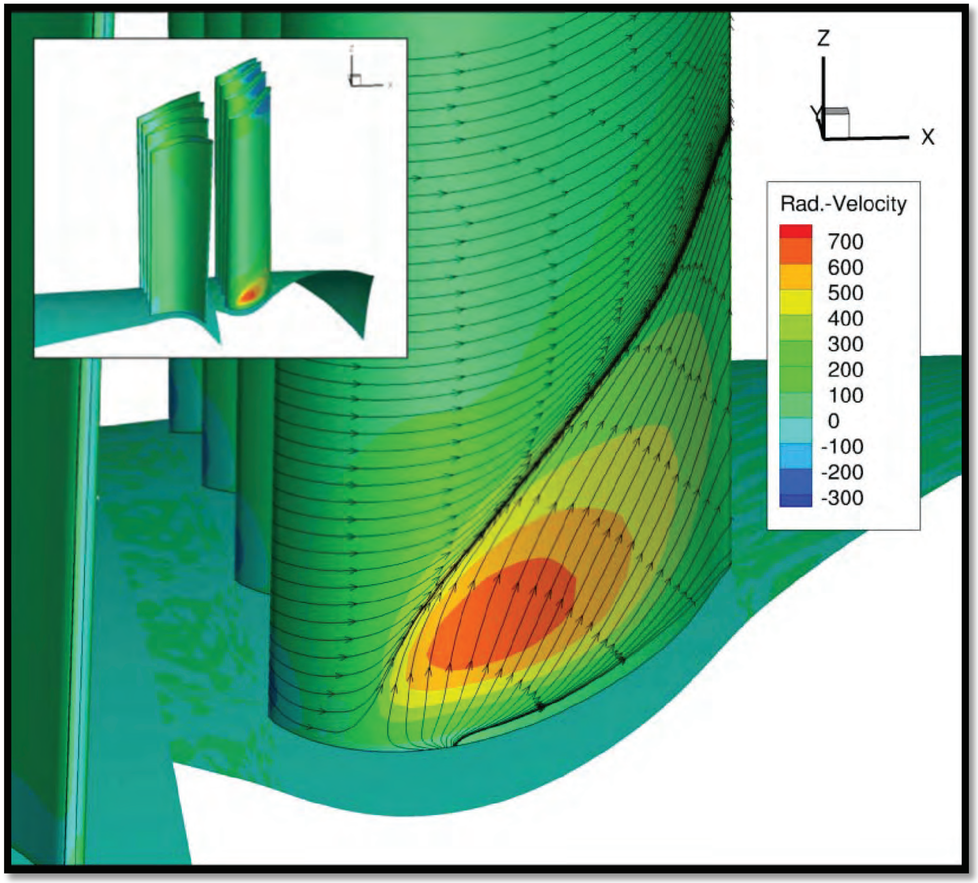
ND-HiLT01 Measured and Predicted Design and Off-Design Stage Efficiency Characteristics



Exit Swirl Comparison



Endwall Flows



Summary

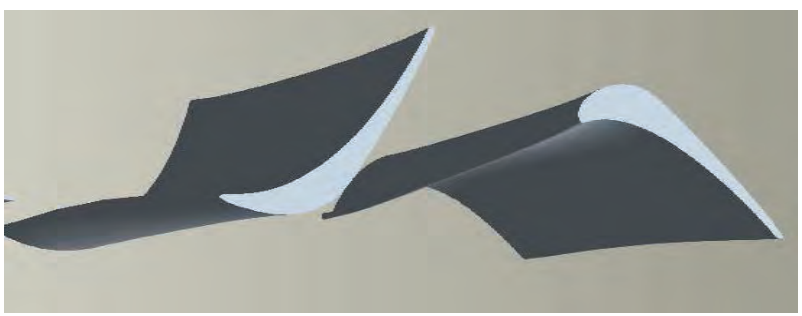
- The Notre Dame Turbine Facility is fully operational
  – The facility provides engine relevant conditions for many important parameters
  – The facility provides unique experimental capabilities
- Successfully validated AFRL high- lift, high-work LPT turbine stage design
- Currently projects include applied and academic problems in several LPT/HPT test articles

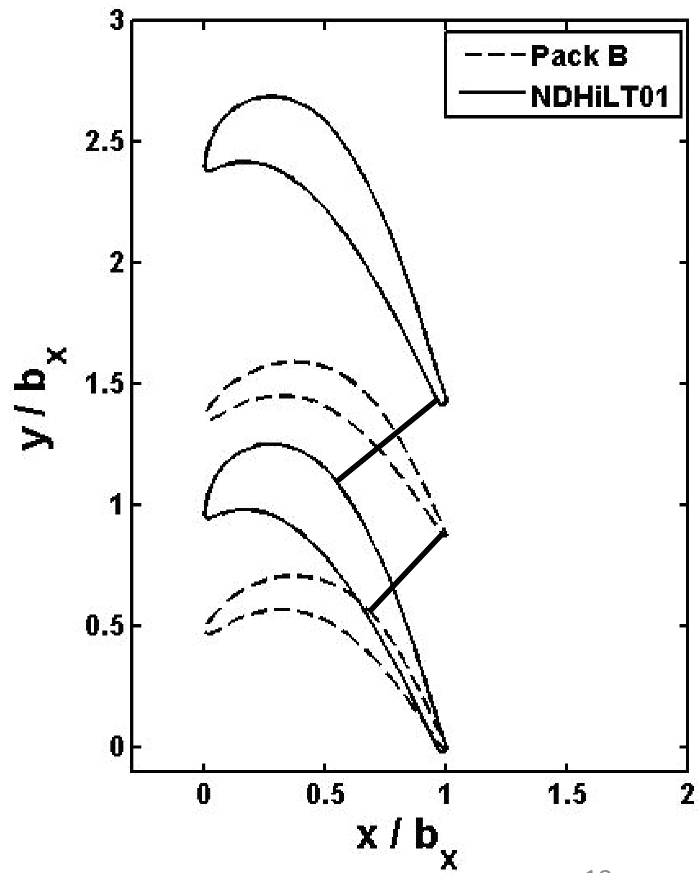
ND-HiLT01 LPT Stage

Highly Loaded
LPT Stage Parameters

Power: 238 kW / 319 hp
Mass flow rate: 4.9 kg/s / 10.9 lb/s
Rotor blade height: 68.6 mm
Rotor diameter: 0.5 m
Axial chord: 67.8 mm
RPM: 6280
Efficiency: 90.5% (predicted)
Number of Blades: 70
Overall Rotor Turning: 127 deg

Work coefficient: 2.76
Zweifel coefficient: 1.35
Flow coefficient: 0.78
Pressure ratio: 1.75





Experimental Uncertainty

- Instrumentation
  - Torque: ± 0.1%
  - Speed: ± 0.04%
  - Temperature: ± 0.5 K
  - Pressure: ± 0.1%
- Repeatability
  - Efficiency
  - Torque: ± 0.1 - 0.25%
  - Thermocouples: ± 0.25 – 0.5%
- Calculated Quantities
  - Mass Flow
    - Venturi: ± 0.3%
- Efficiency
  - Torque: ± 0.4 - 1.5%
    - Bias: ± 0.1 - 0.15%
  - Adiabatic: ± 0.4 - 1.4%
    - Bias: ± 1.0 - 4.0%

NASA/CP—2020-220327

Description of the NASA Glenn Single-Spool Turbine Facility

Fundamental Aeronautics
Subsonic Fixed Wing Project
Aerothermodynamics Discipline

Dr. Paul W. Giel, ASRC Aerospace / RTT
NASA Glenn Research Center

August 10, 2010

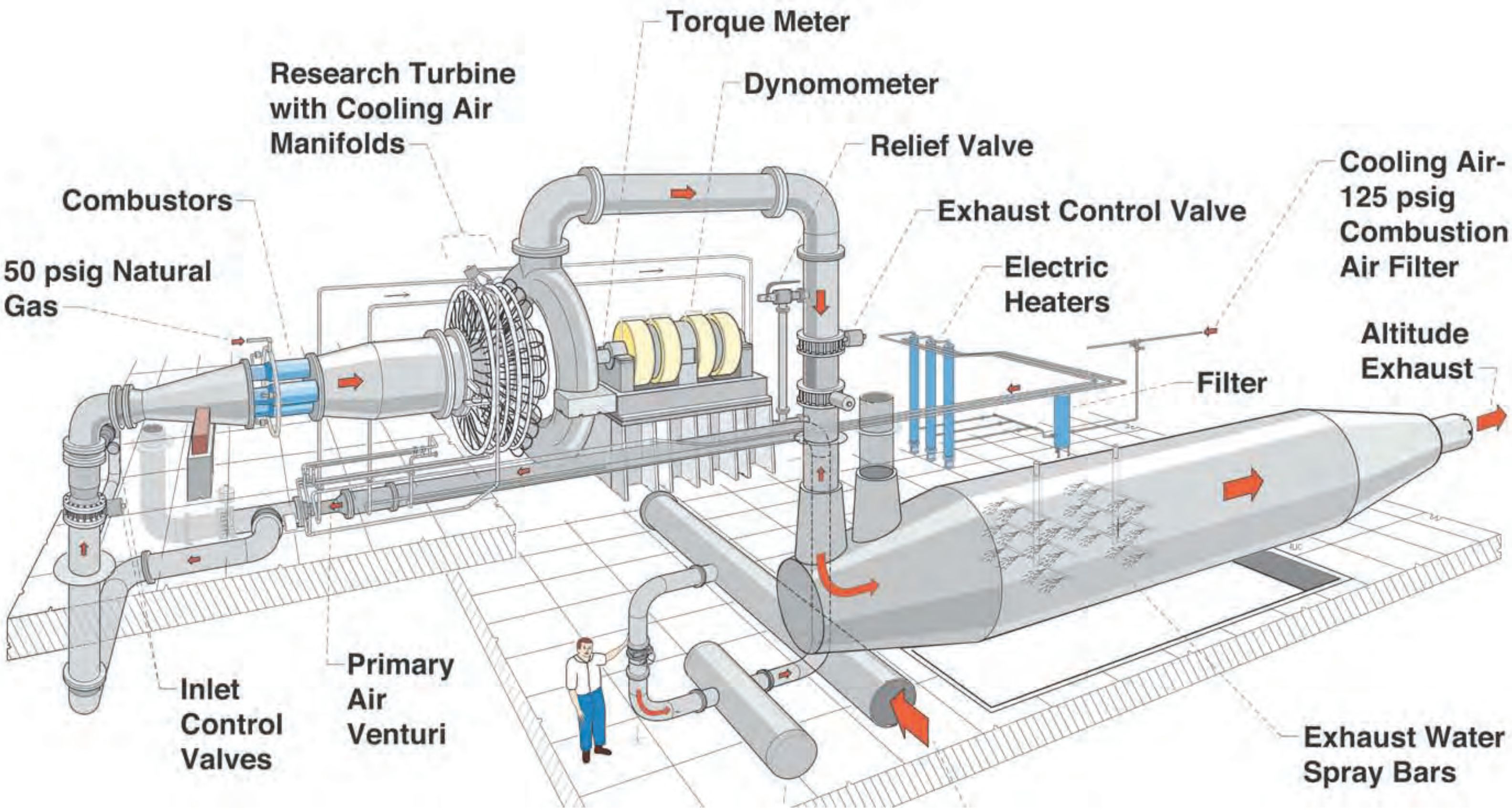
Single Spool Turbine Facility

This facility will provide the following research capabilities:

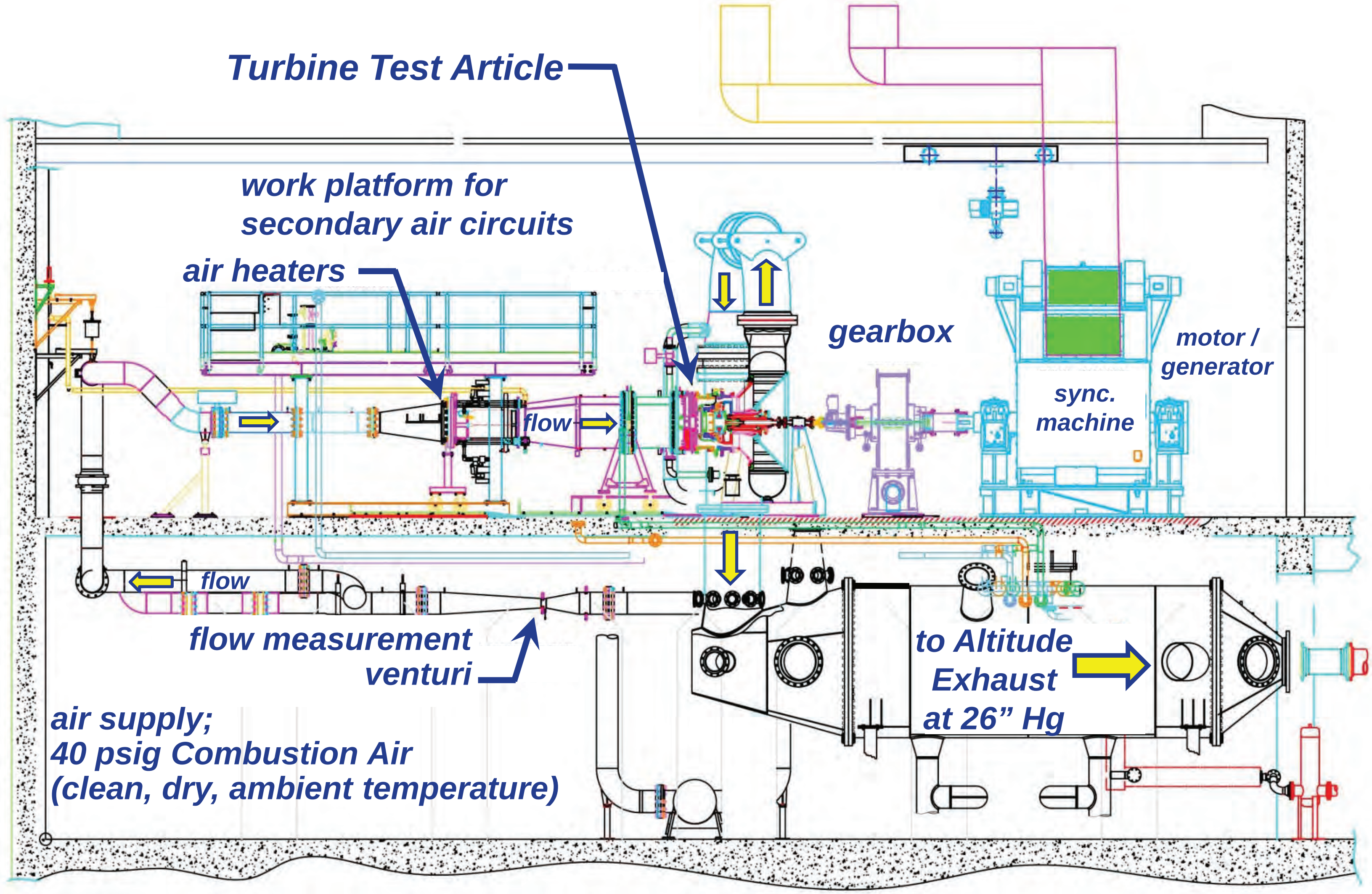
- **HPT / LPT Interaction losses up to LPT Vane 1**
- **Aggressive transition duct with integral vane/frame**
- **High lift blading**
- **Endwall contouring**
- **LPT with active / passive flow control**
- **Turbine Rear Frame (TRF) with flow control**
- **Reynolds number sensitivity reduction**
- **Ultra highly loaded HPT with 3-D blade design and reduced shock technologies**
- **New high response instrumentation**
- **Clearance Control Technologies**
- **Core Noise Reduction; rotor/stator interactions, turbine acoustical transmission loss.**

50 - 80% of the HPT/LPT aero interaction could be captured with this facility

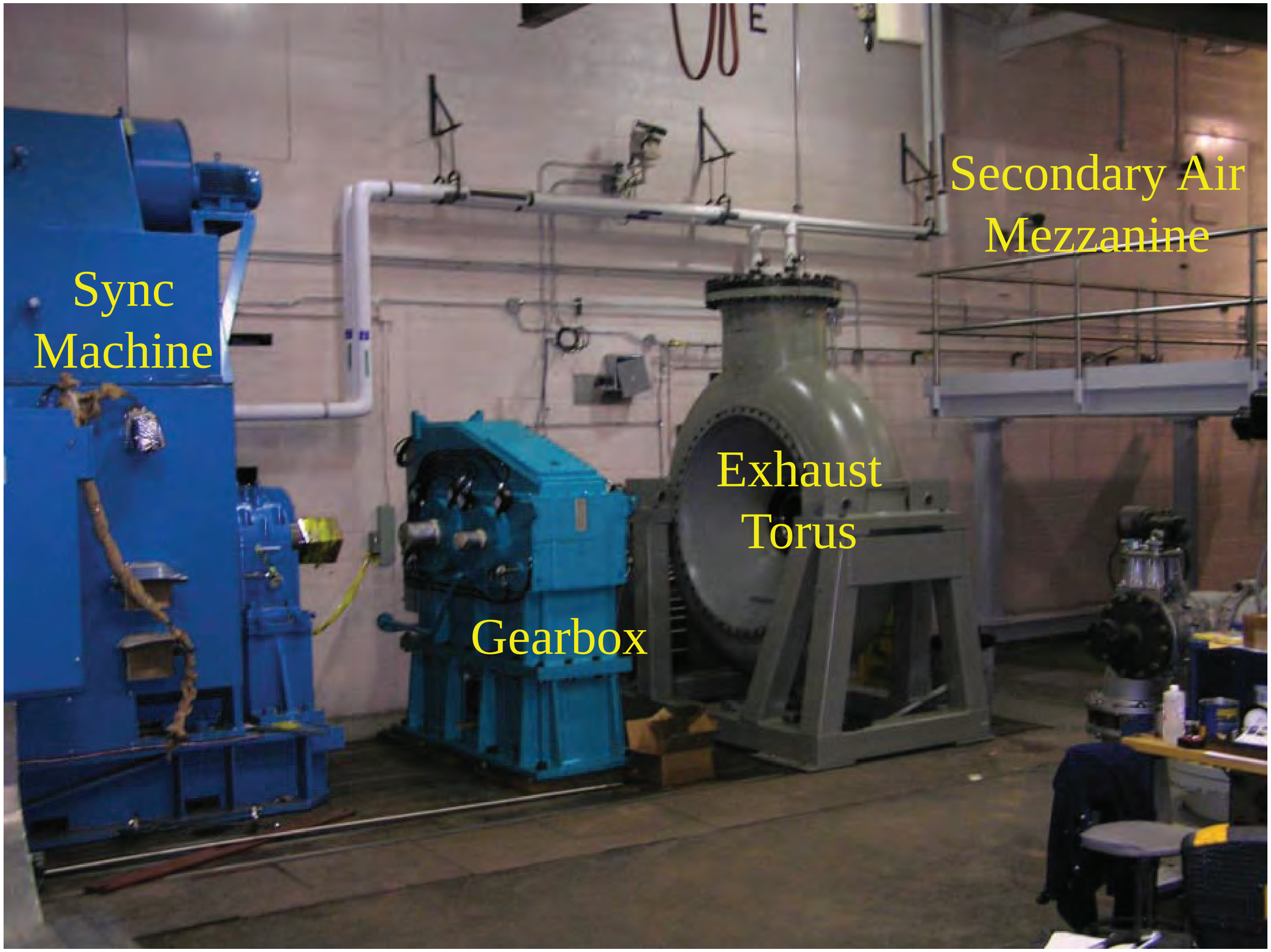
Previous W-6A Warm Core Turbine Facility



New Single Spool Turbine Facility Layout



Current Facility View



Facility Capabilities

- Maximum Turbine Inlet Pressure 50 psia
- Minimum Exhaust Pressure 2 psia
- Maximum Inlet Air Temperature 940 F
  (from in-line vitiated natural gas combustors)
- Maximum Primary Air Flow Rate 27 pps
- Secondary Air (150 psig supply):
  - » 2 Legs – 1.5 pps each up to 550ºF
  - » 4 Legs – 0.08 to 1.19 pps each up to 250ºF
  - » 6 Legs – at 70ºF
- Maximum Turbine Rotational Speed 14,000 rpm
  (with maximum Gear Ratio, G.R., of 7.87)
- Maximum Turbine Torque 36,217 $ft \cdot lb_f$/G.R.
- Minimum Gear Ratio, G.R. = 1.51
  (N_{max}= 2,718 rpm; $Torque_{max}$= 24,000 $ft \cdot lb_f$)
- Maximum Test Article Diameter 52 inch

Facility Renovation Status

- Sync machine, gearbox, and modified exhaust torus delivered.
- Driveline alignment completed.
- High voltage cabling and controls completed.
- Driveline checkout commencing;
  Sync machine, gearbox, dummy rotor.
- Work platform installation completed.
- Inlet and exhaust piping installation underway.
- Secondary Air / Natural Gas piping design complete.
- Facility instrumentation and control development underway.
- Flow checkout hardware nearly complete.
- Modifications to test article nearly complete.
- Integrated Systems Review completed.
- Driveline check-out Safety Permit issued.
- Estimated start of research testing: October 2011

Back-up slides

Current and Future Test Articles

- Two-stage E^3 HPT (*c*. 1980).

- GE-UEET single-stage HPT:
  - ultra-high pressure ratio = 5.98 (rig corrected)
  - film-cooled for aero simulation only
  - GE completed performance testing
  - some steady and unsteady surveys
  - NASA owned.

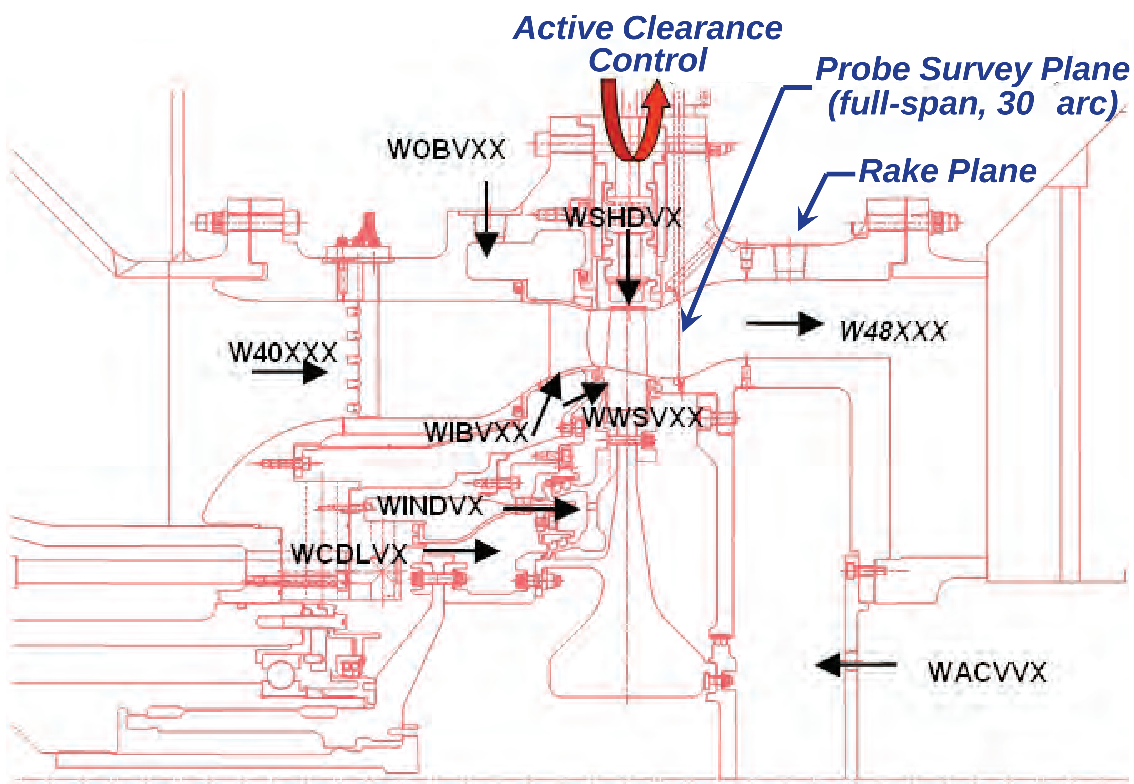
- GE-UEET single-stage HPT with t-duct and TVF
  - 'TVF' = Turbine Vane Frame; LPT Vane 1 & Strut
  - TVF design and fabrication complete
  - hardware delivered.

- GE-UEET four-stage LPT:
  - aerodynamic engine design completed
  - detailed rig design completed; no hardware fabricated
  - de-staged tests only (1+2 or 3+4+TRF)
  - flow control TRF (Turbine Rear Frame) design completed
  - endwall contouring throughout.

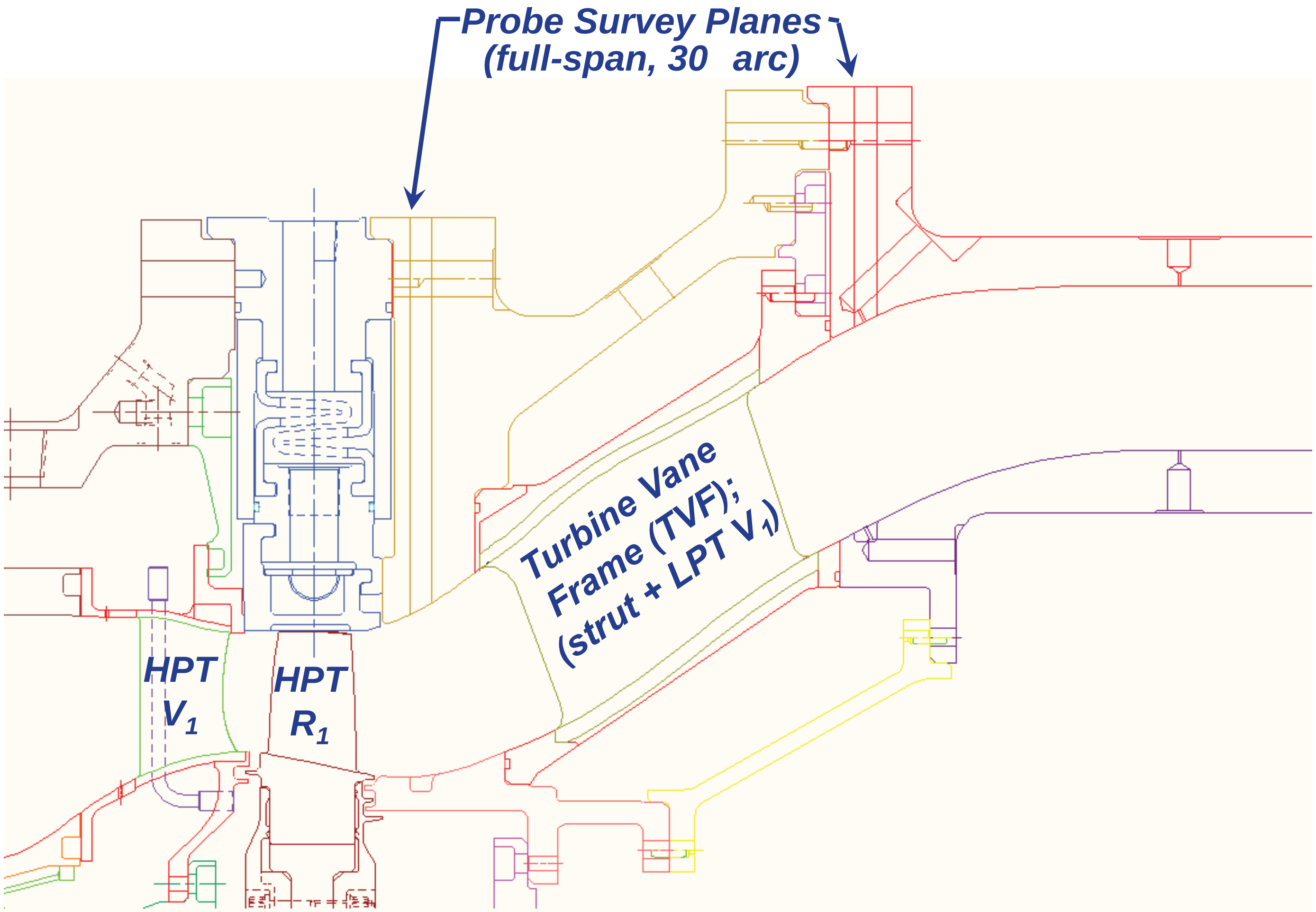
GE-UEET Single-Stage HPT

Goal/Purpose:

- To verify that relatively high efficiency can be maintained for a single stage turbine operating at an equivalent two stage work extraction level.
- To validate the reduced shock design concept at high stage pressure ratio.



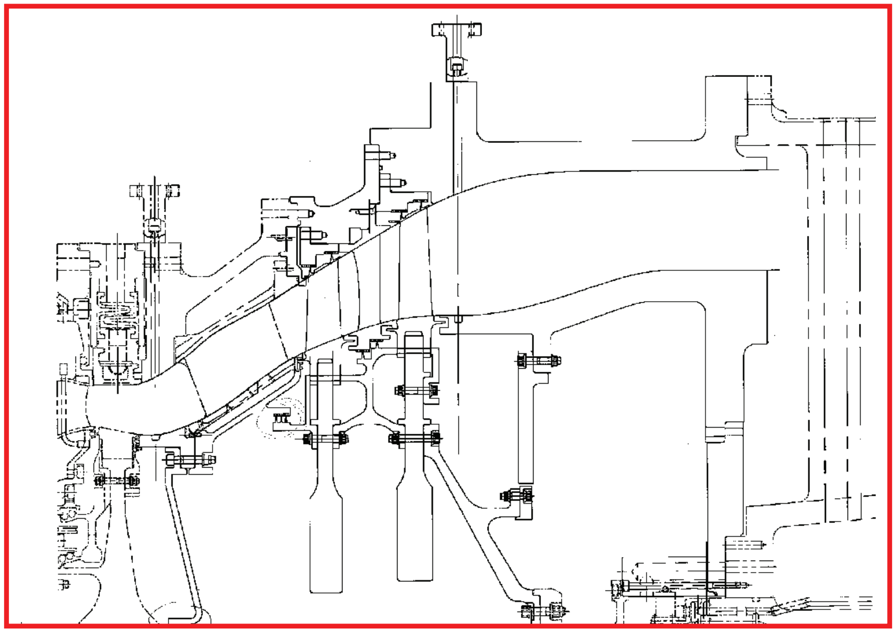
GE-UEET Single-Stage HPT with TVF



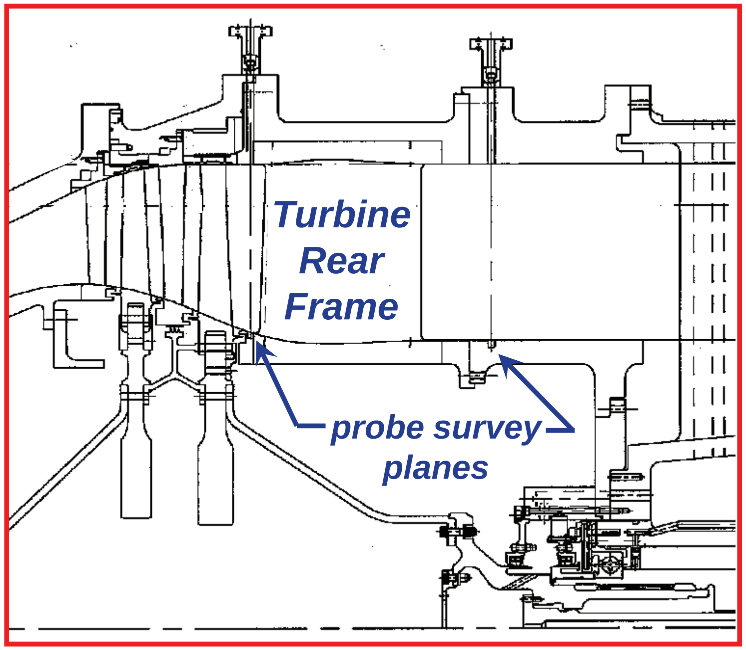
GE-UEET 4-Stage LPT

- Counter-rotation
- TVF (same as HPT)
- Low-solidity blading
- Fully optimized airfoils and passages with EWC
- TRF with fluidics; allows higher loading of aft stages; eliminates 5th stage
- Discrete passive fluidic jets on TRF

TVF with LPT stages 1 & 2; scale = 1.34



LPT stages 3 & 4 + TRF; scale = 1.00



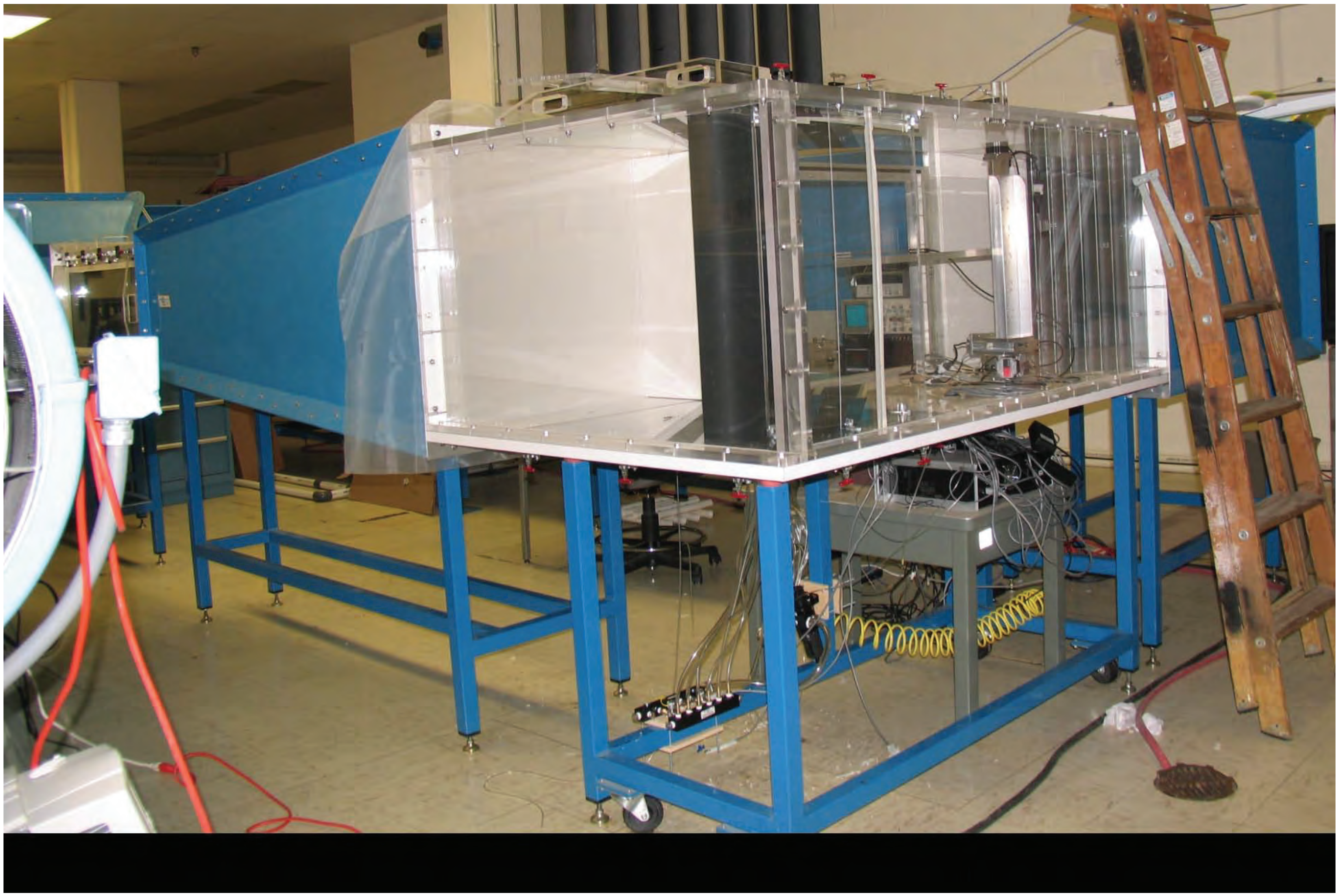
NASA/CP—2020-220327

U.S. Naval Academy Low Speed LPT Cascade With Wake Generator and Vortex Generator Jets

Ralph J. Volino
United States Naval Academy
Annapolis, MD

Sponsor:

Facility: Low Speed Wind Tunnel with Corner Cascade Test Section

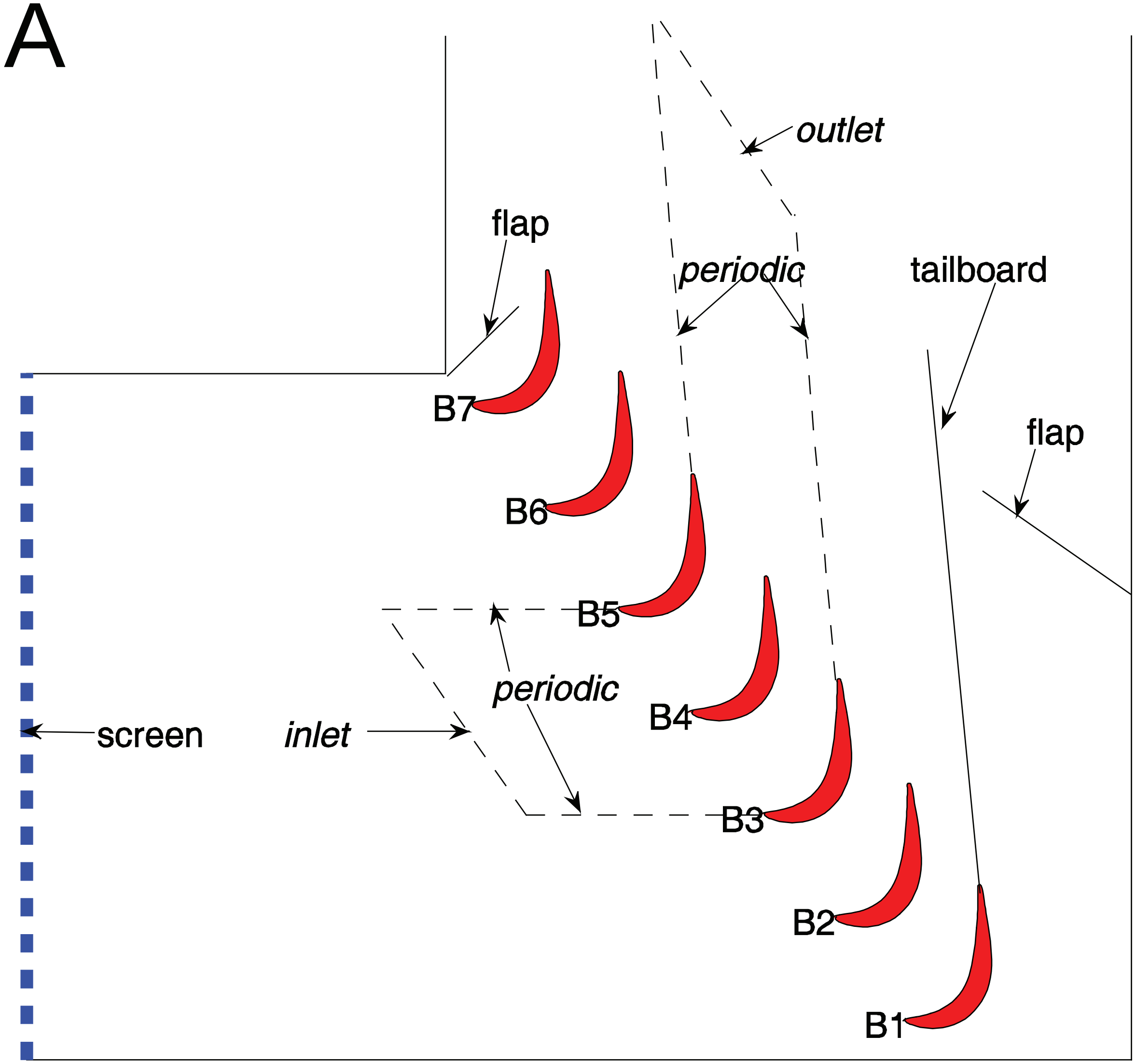


Linear L1A cascade 7 blades

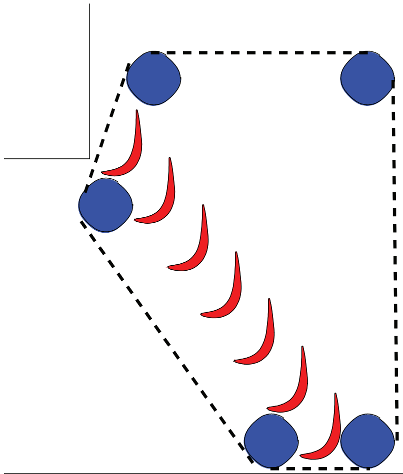
AFRL design (John Clark)

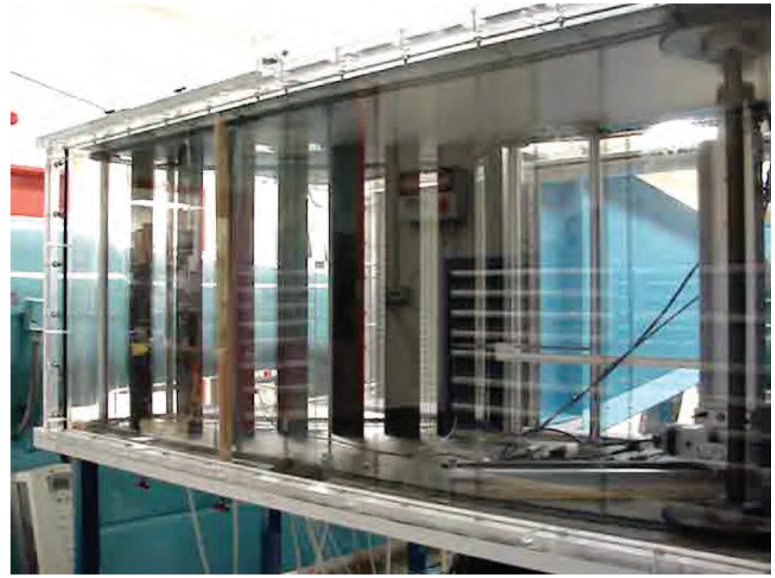
Aft loaded

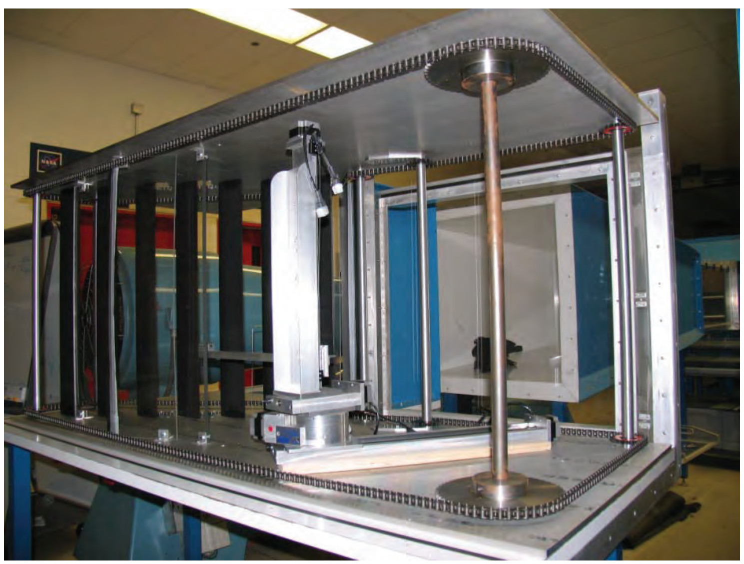
17% higher Zweifel than Pack B, same as L1M

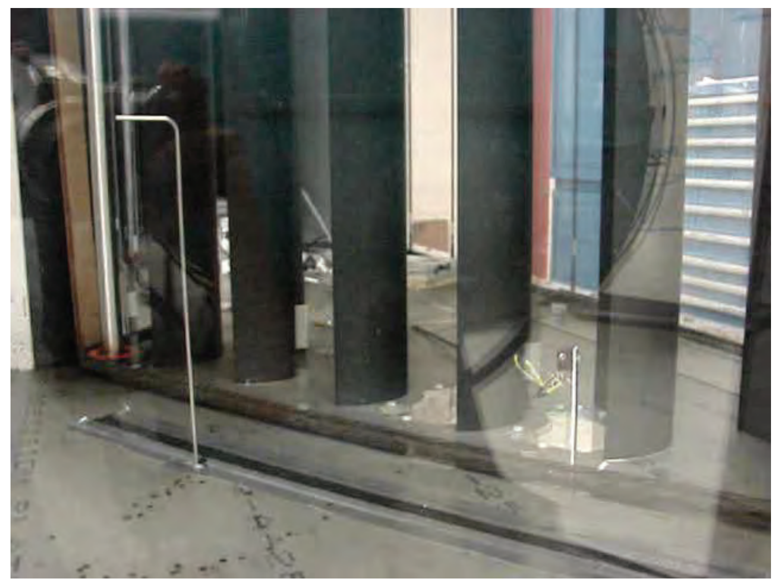


Wake Generator

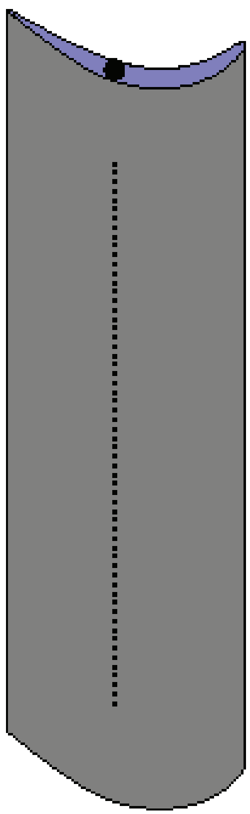


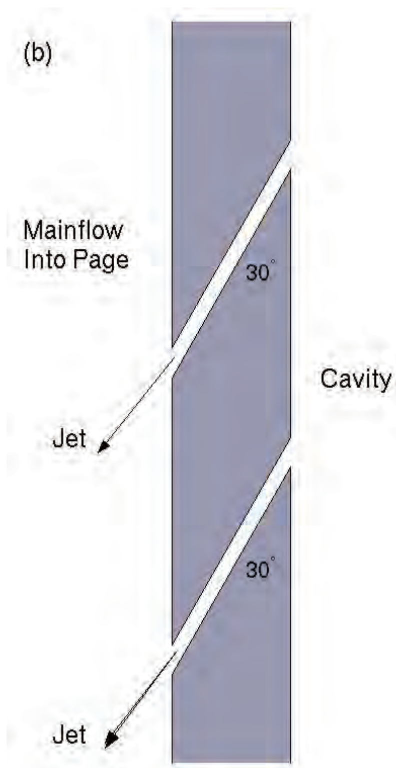




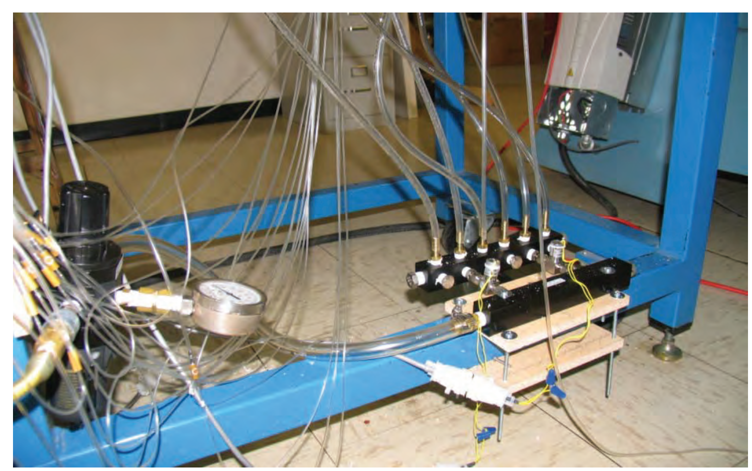


VGJs





- On all blades in cascade
- Located at suction peak
- 0.0059 C_x diameter
- Spacing = 10.7D
- Compound Angle
  - 30 to surface
  - 90 to main flow
- Supplied from cavity in blade
- Solenoid valves for pulsing



Conditions

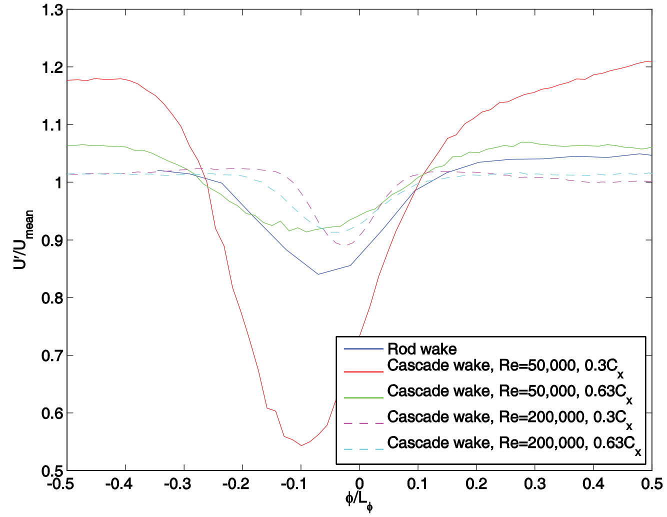
- $Re = U_e L_s / \nu$ = 25,000; 50,000
- Freestream turbulence: TI=0.5%, 4%
- Rod diameter: 4 mm = 0.02 C_x
- Rod spacing: 1, 1.6, 2 L_ϕ
- Flow coefficient: $\zeta = U_{axial} / U_{rod}$=0.35, 0.7, 1.4
- Wake passing frequency: $F = f L_{j\text{-}te} / U_{ave}$= 0.14, 0.22, 0.28, 0.45, 0.56

NASA/CP—2020-220327

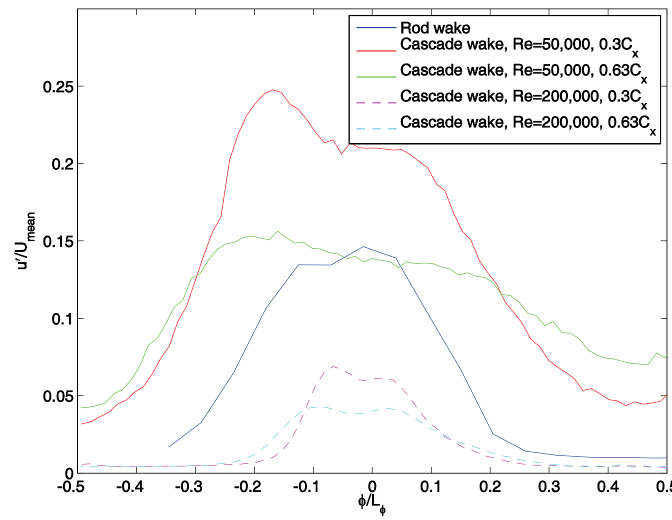
Conditions

- $Re=U_e L_s/\nu$ = 25,000; 50,000
- Freestream turbulence: 4%
- Jet blowing ratio: B=0.25, 0.5, 0.75 1.0, 1.5, 2.0, 2.5, 3.0
- Pulsing frequency: f=0, 3, 6, 12, 24 Hz; $F=fL_{j\text{-}te}/U_{ave}$=0, 0.14, 0.28, 0.56, 1.12
- Jet duty cycle: D=10%, 50%

Wake characteristics

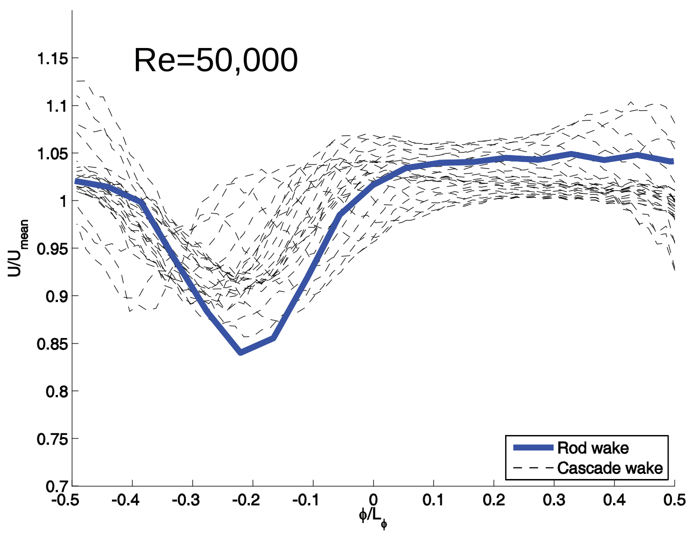


Rod wake at cascade inlet and airfoil wakes downstream of cascade w/o VGJs

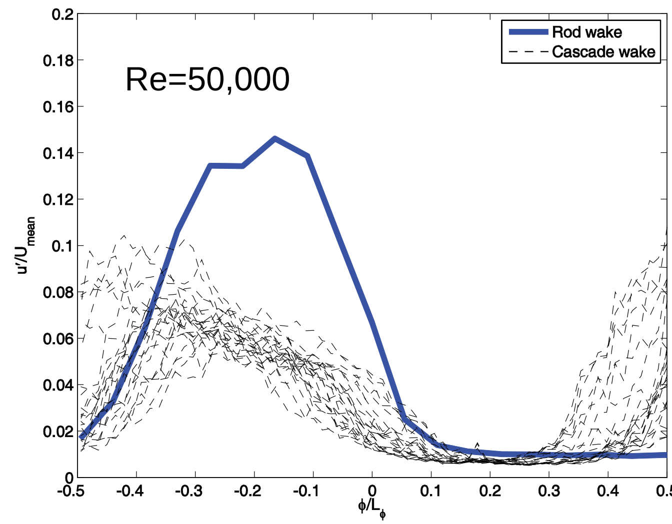


Mean Velocity

RMS streamwise velocity

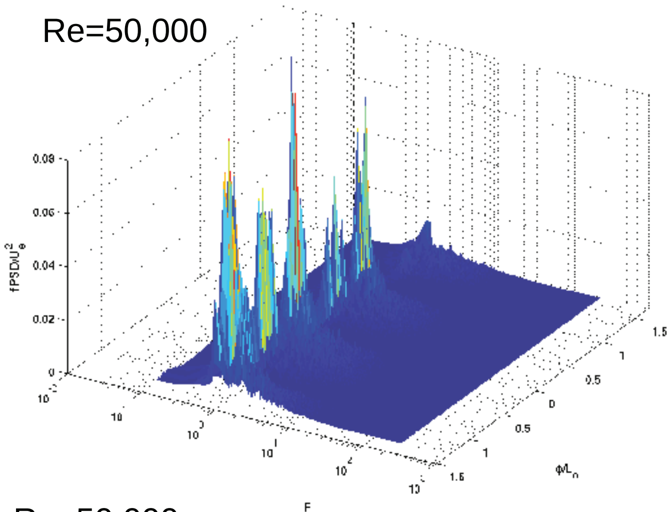


Rod wake at cascade inlet and phase averaged airfoil wakes downstream of cascade with VGJ flow control



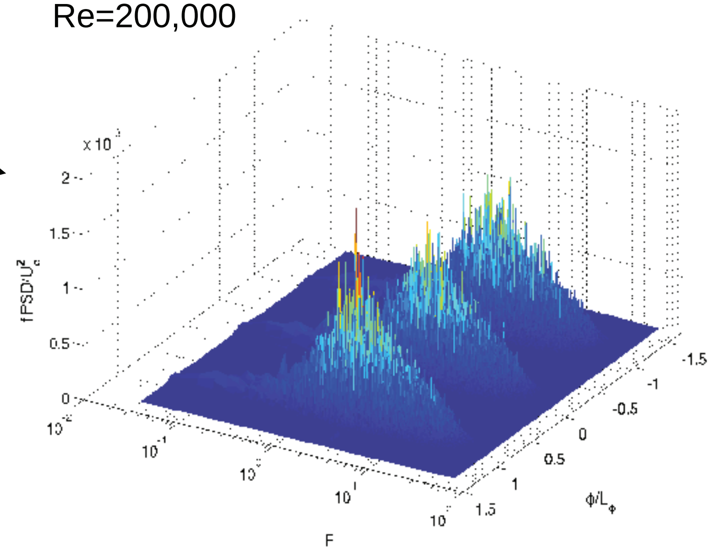
Wake spectra

Re=50,000

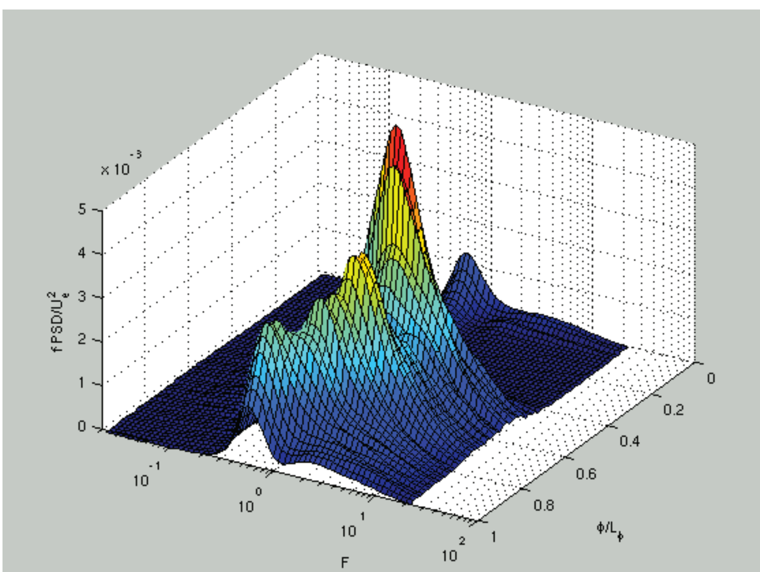


Cascade wake w/o VGJs

Re=200,000

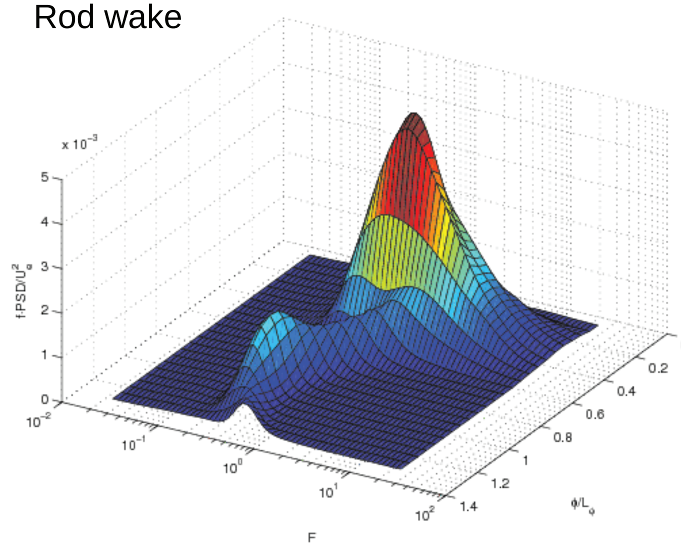


Re=50,000



Cascade wake with VGJ flow control

Rod wake



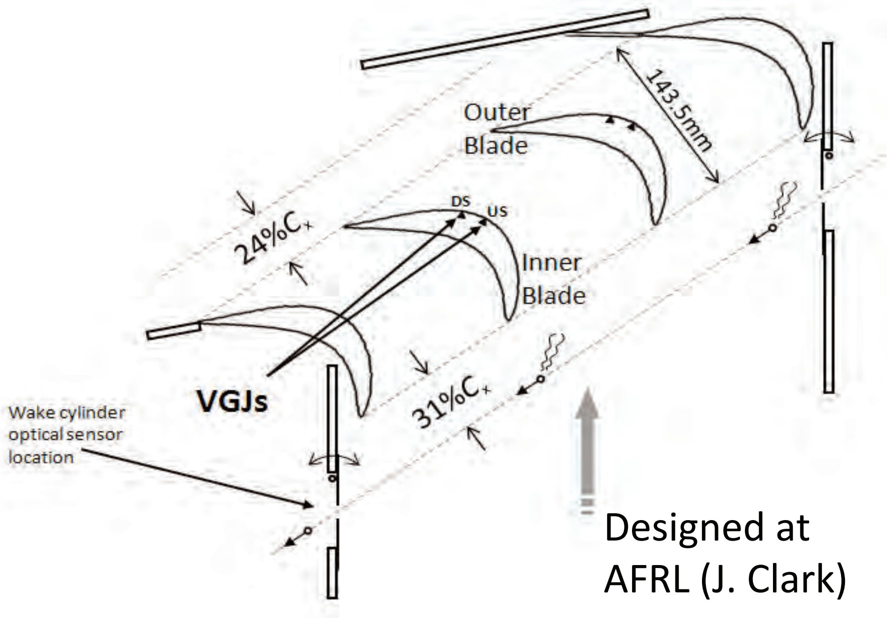
NASA/CP—2020-220327

Low-Speed L1A LPT Cascade

Kyle Gompertz
Dr. Jeffrey Bons
Ohio State University
Dept. of Mechanical & Aerospace Engineering

Sponsored by AFOSR/NASA

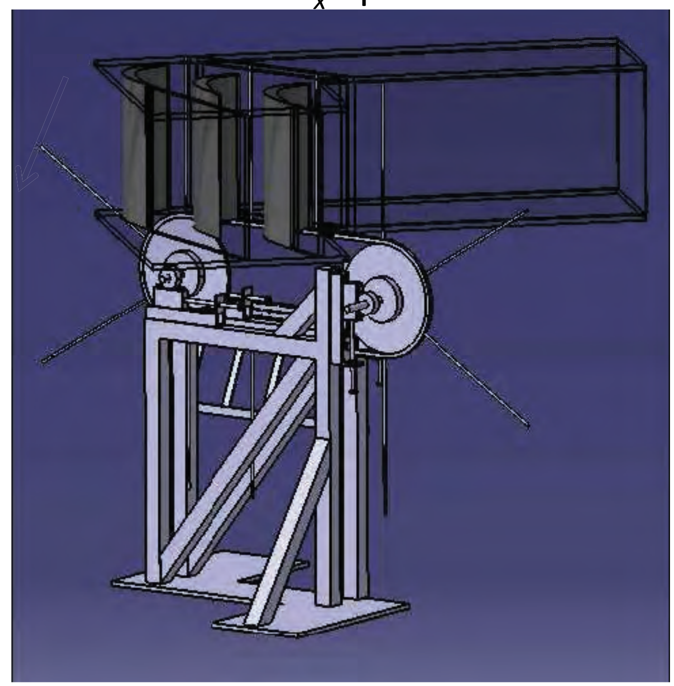
L1A Cascade Facility



Designed at
AFRL (J. Clark)

Wake Generator

- 4mm diameter rods
- Flow coefficient: $\Phi = U_{in,ax}/U_{rod} = 0.91$
- $F_{red} = f \times c/U_{exit} = 0.41$
- $T_{wake} = 115$ms
- Rod spacing = 1.57 × blade pitch
- Located 31%C_x upstream



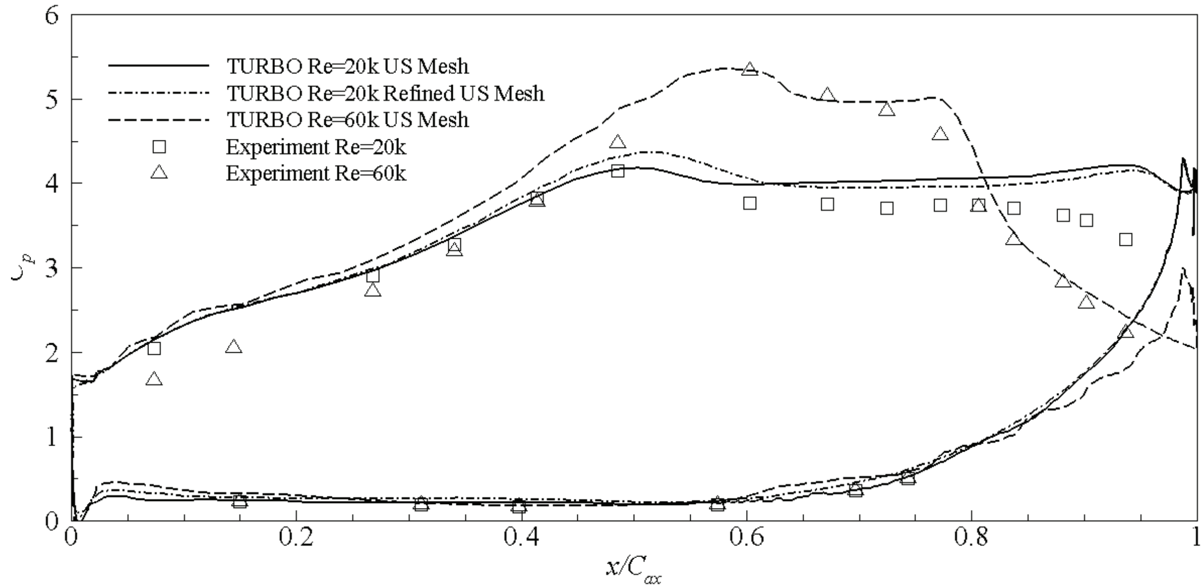
4-blade (3 passage) low speed cascade:

- 3% inlet freestream turbulence
- static pressure taps $\rightarrow c_p$
- $Re_{cx} = U_{in} \times c_x / \nu = 20{,}000$
- $Re_c = U_{ex} \times c / \nu = 34{,}000$
- $Re_{ssl} = U_{ex} \times SSL / \nu = 50{,}000$

Steady CFD Capability

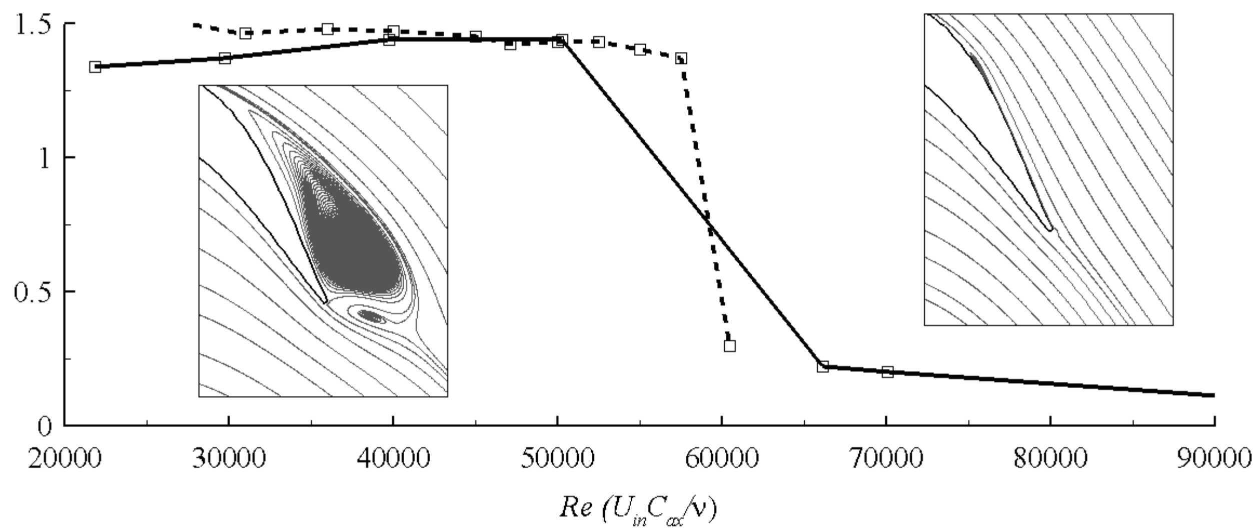
-TURBO numerical solver, 5 million cells.

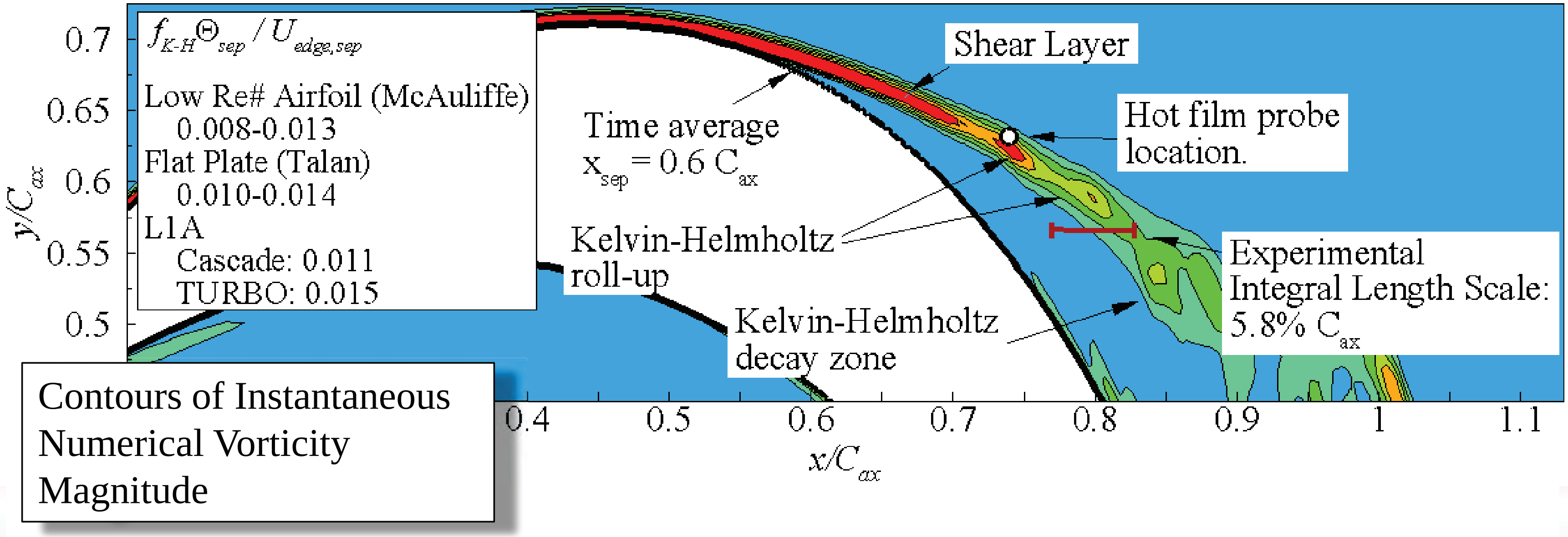
- C_p distributions show agreement with experimental separation location and separation zone strength.



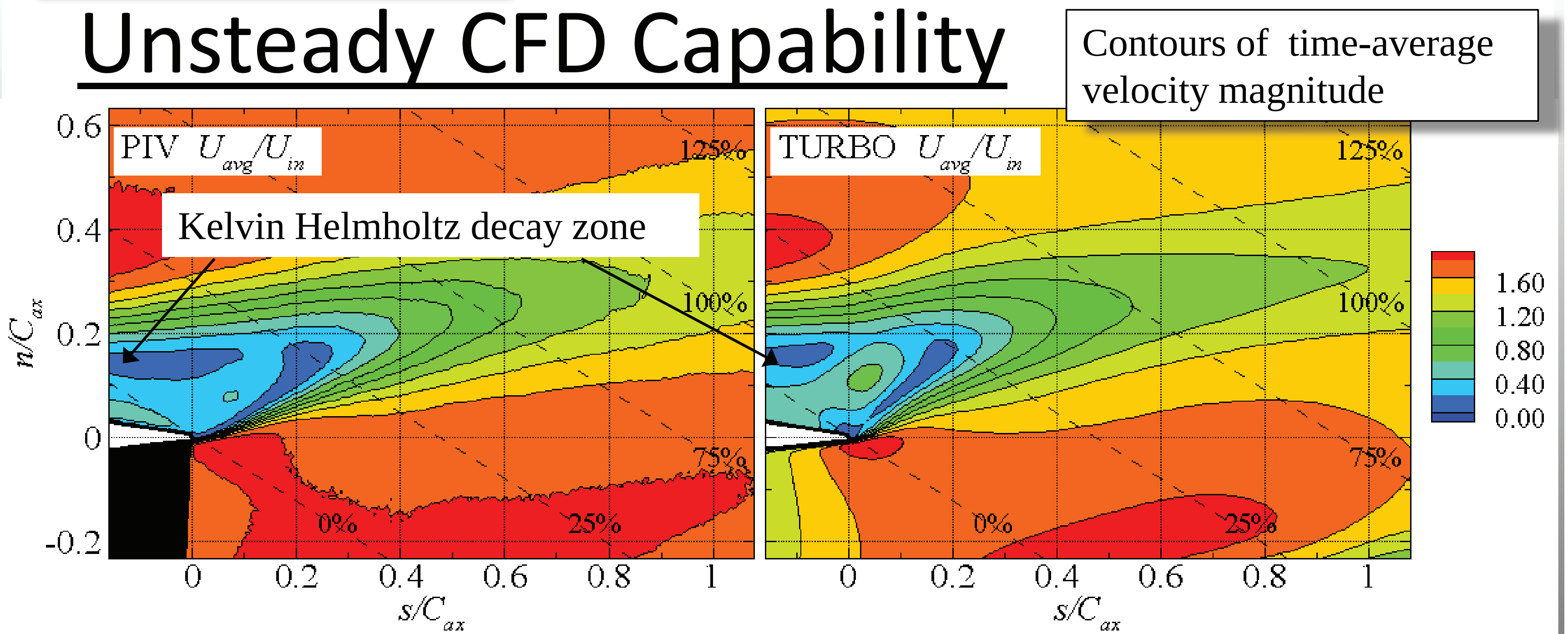
- Integrated wake loss vs. Re # agrees w/ experimental (solid: TURBO, dashed: cascade.

$$\gamma = \frac{1}{s}\int_{-s/2}^{s/2} \frac{P_{o,in} - P_{o,ex}}{P_{o,in} - P_{s,in}} ds$$

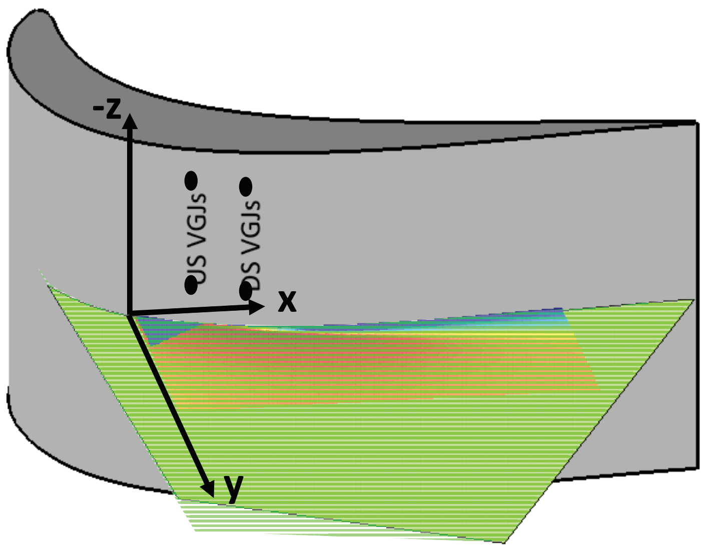


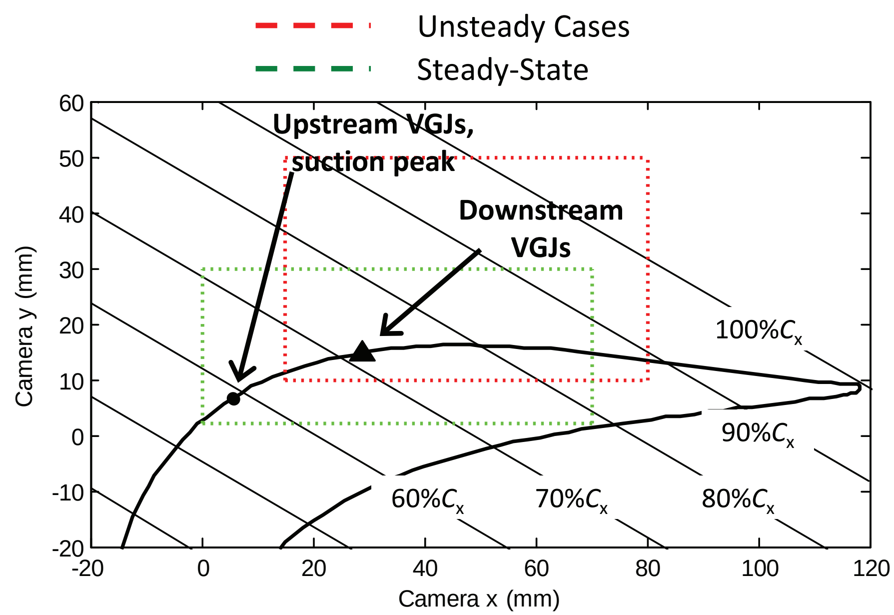


Unsteady CFD Capability



Phase-Locked PIV Data with Wakes



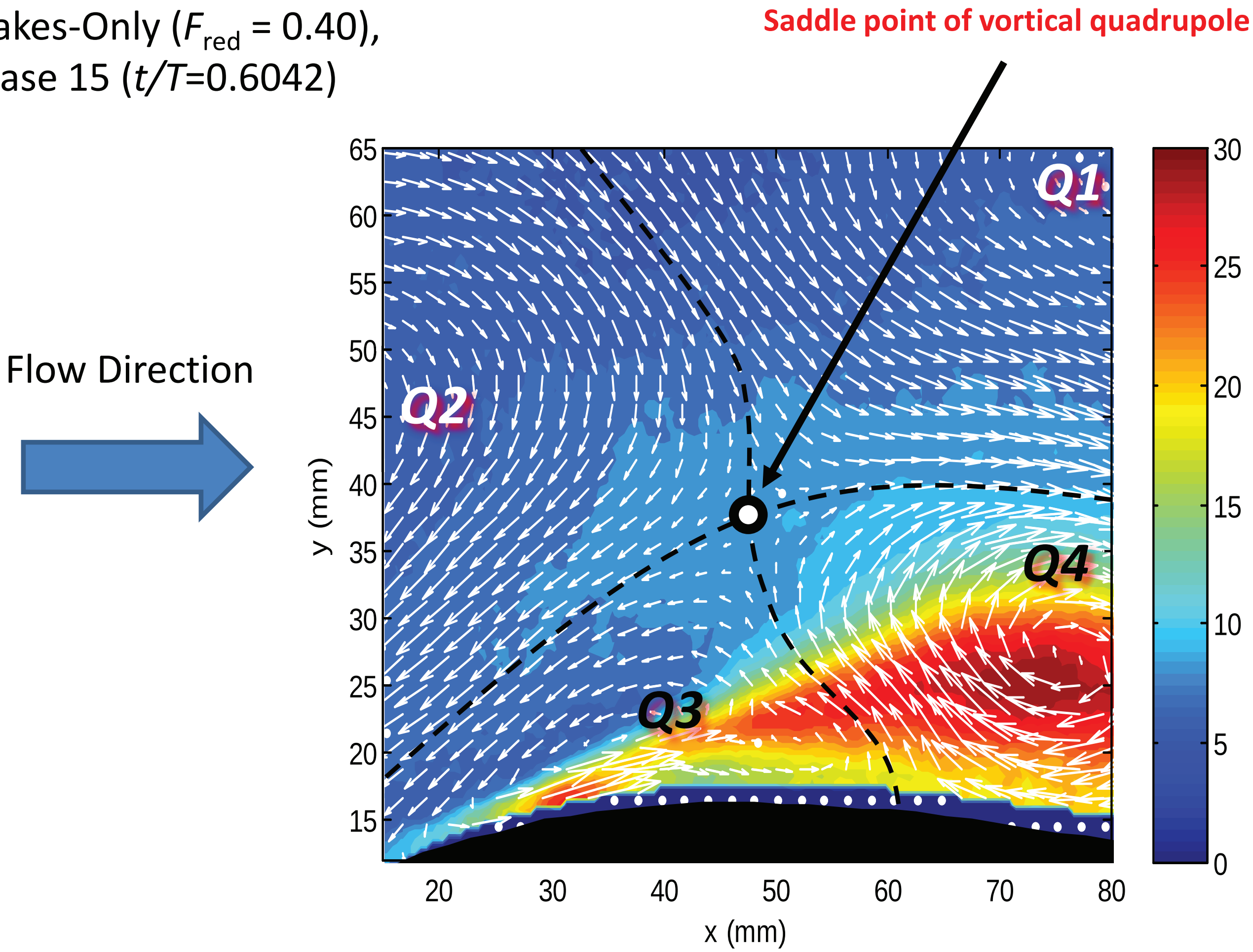


The coordinate system and PIV data windows used to present the data. Also included are the axial chord lines of the L1A.

- LaVision PIV system
- Nd:YAG laser, olive oil seed
- Two 1mm-thick laser sheets, Δt = 100µs
- Velocity uncertainty ±0.08m/s
- Phase-locked DAQ
  - triggered by wake cylinder optical sensor (t = 0)
  - T_{wake} divided into 24 meas. phases
  - 800 images per meas. phase

Naming Convention for Spanwise (2D) Vortices

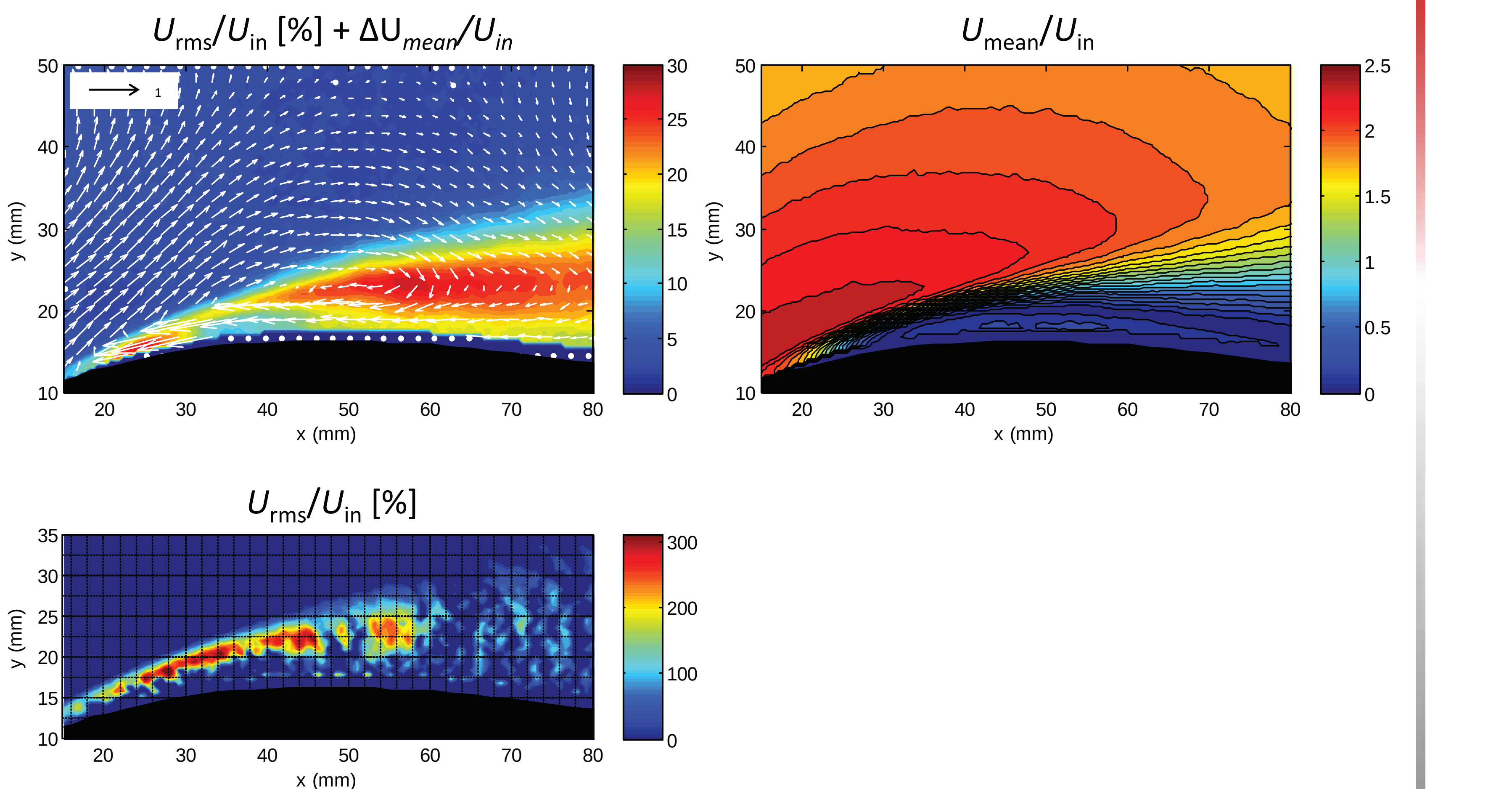
Wakes-Only (F_{red} = 0.40),
Phase 15 (t/T=0.6042)



Phase #10

t/*T* = 0.3958

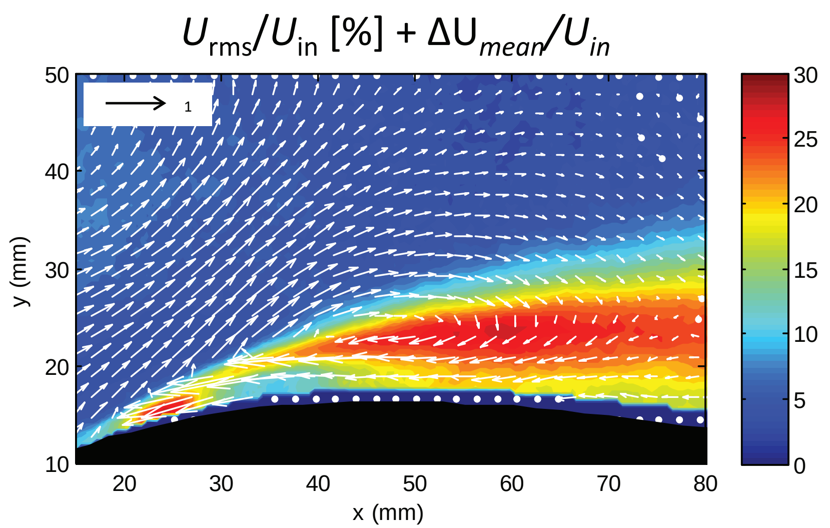
Phase-Locked PIV Data with Wakes

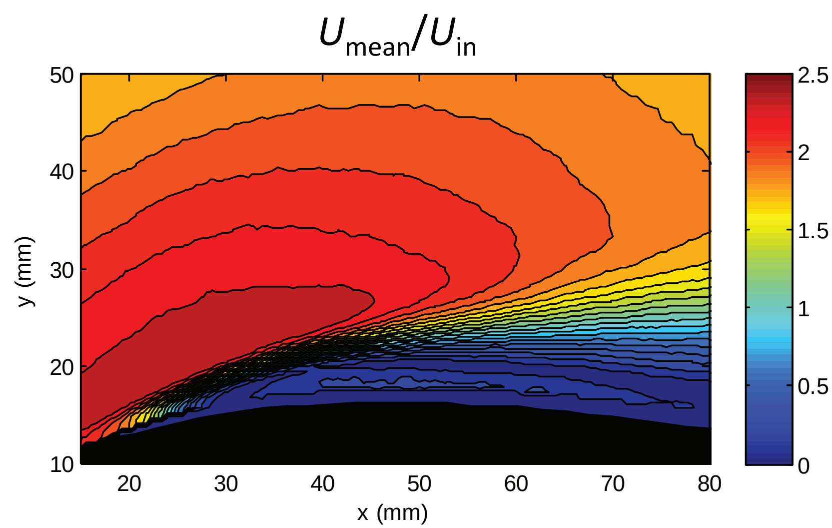


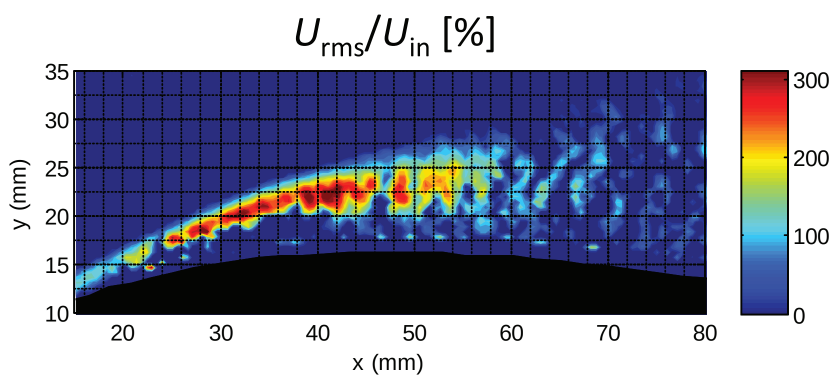
Phase #11

t/*T* = 0.4375

Phase-Locked PIV Data with Wakes





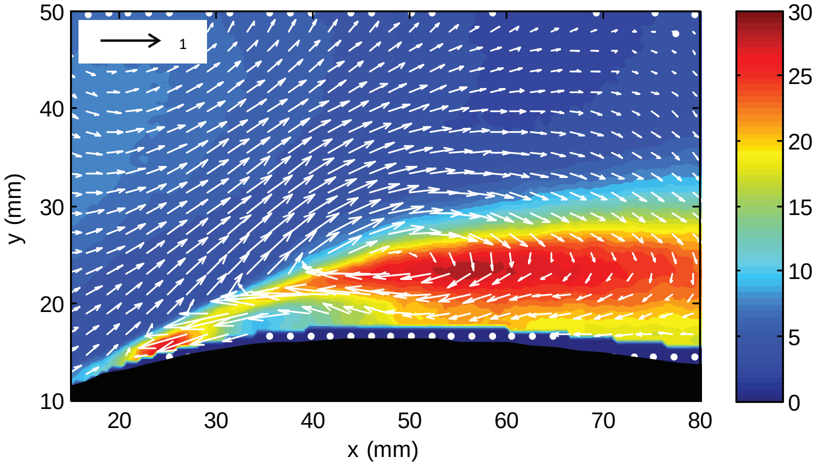


Phase #12

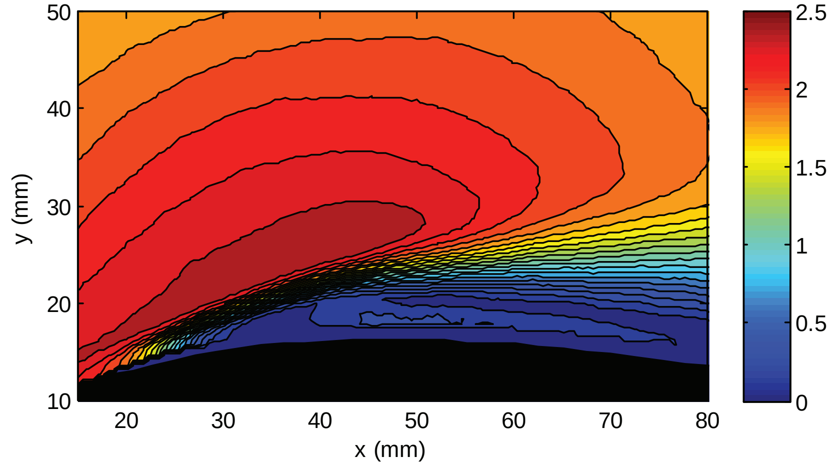
t/*T* = 0.4792

Phase-Locked PIV Data with Wakes

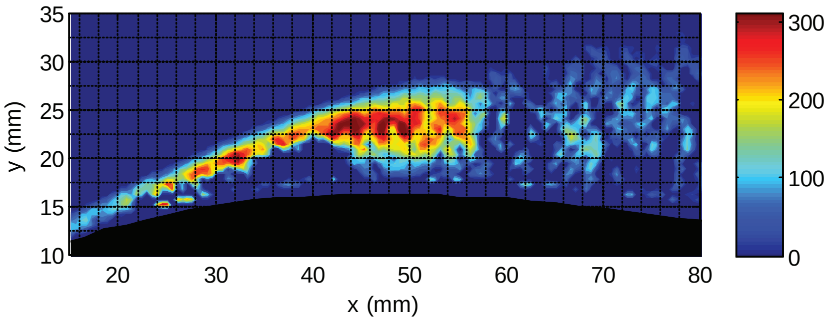
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}

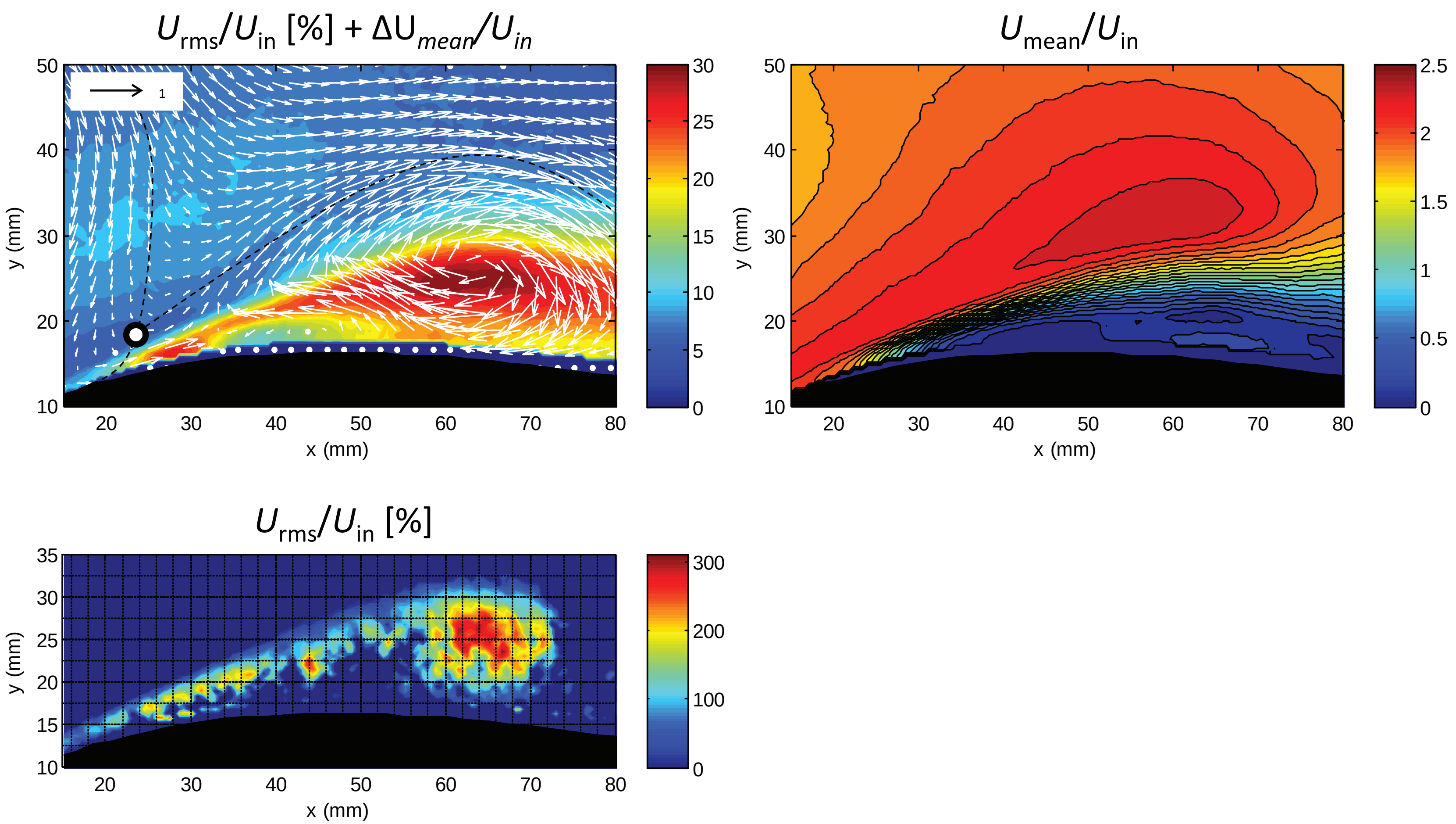


U_{rms}/U_{in} [%]



Phase #13 t/*T* = 0.5208

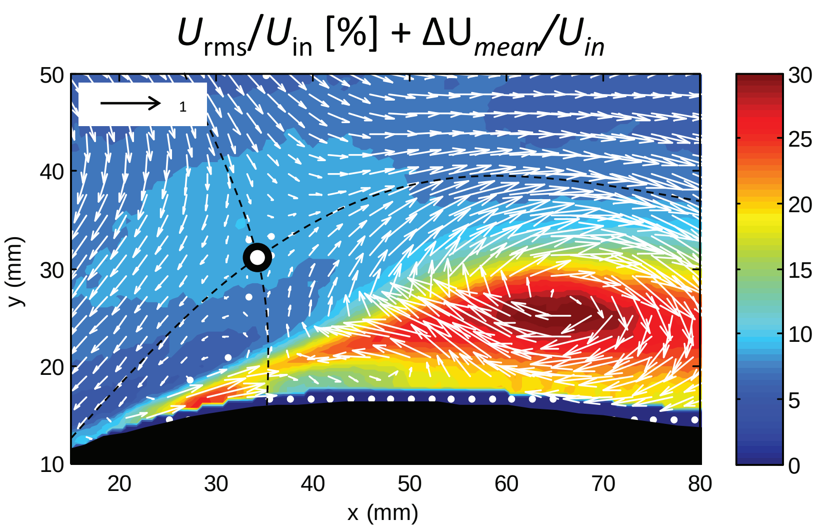
Phase-Locked PIV Data with Wakes

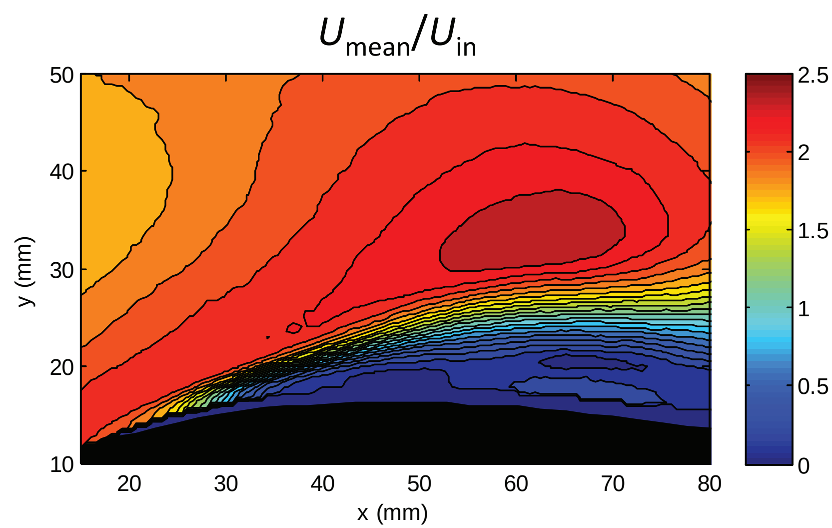


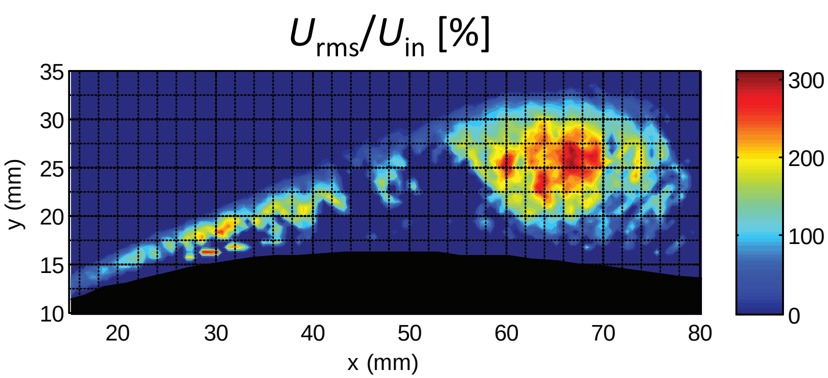
Phase #14

t/*T* = 0.5625

Phase-Locked PIV Data with Wakes







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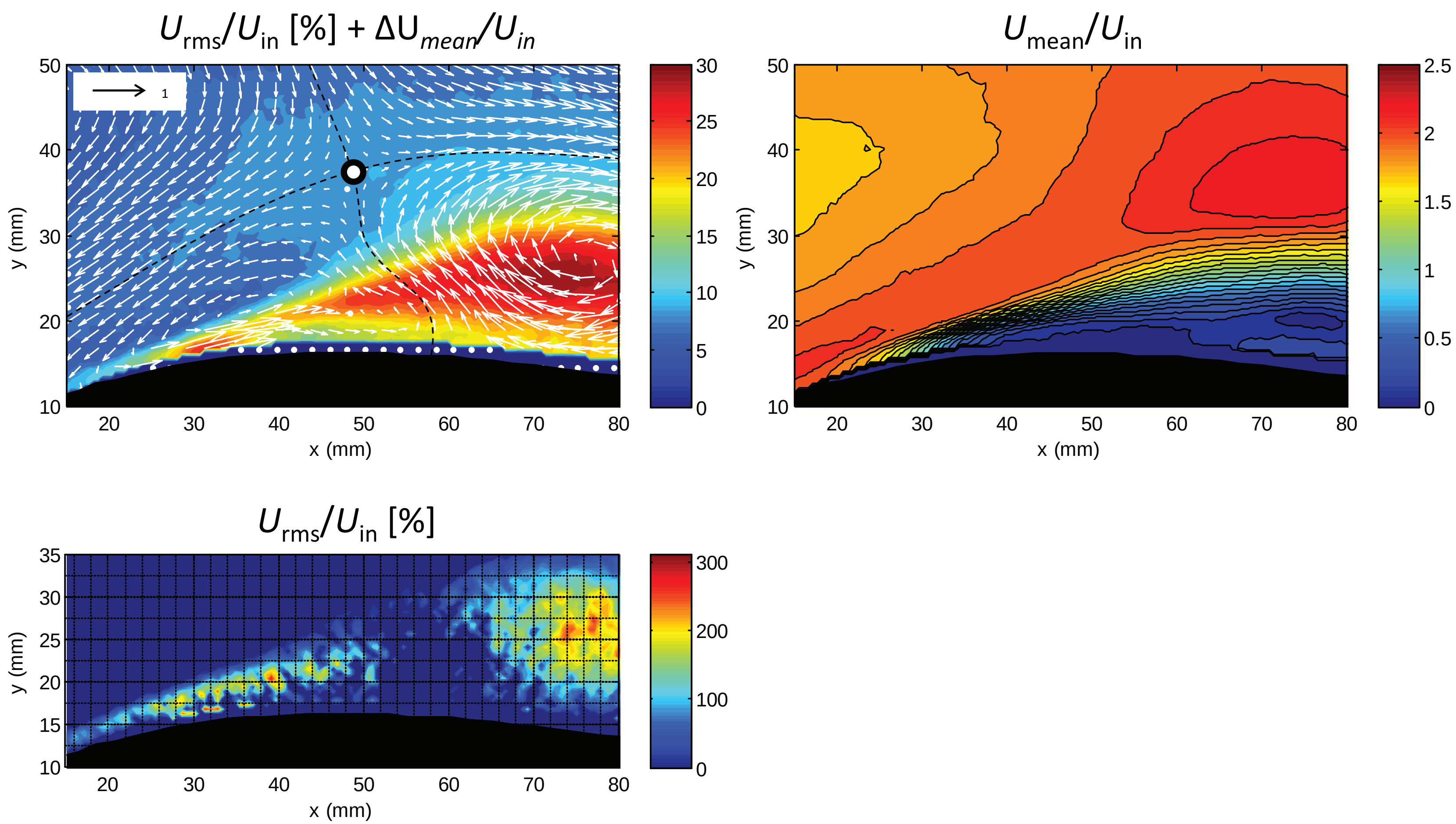
Phase #15

t/T = 0.6042

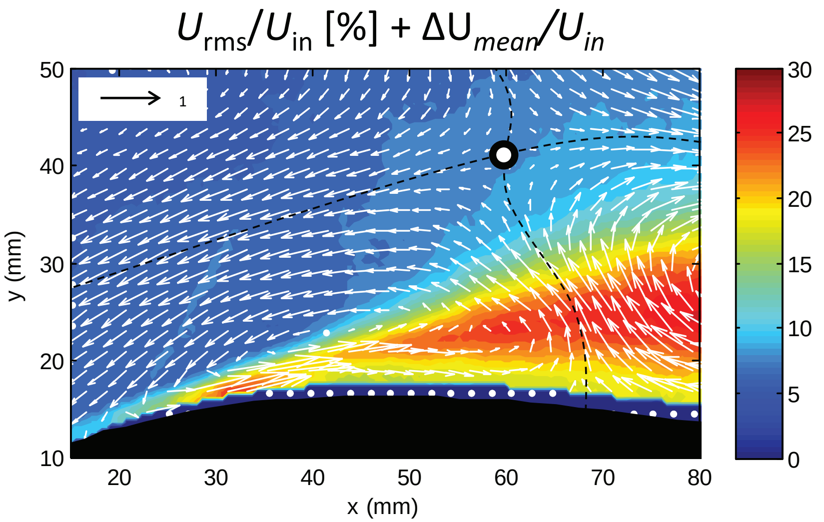
Phase-Locked PIV Data with Wakes

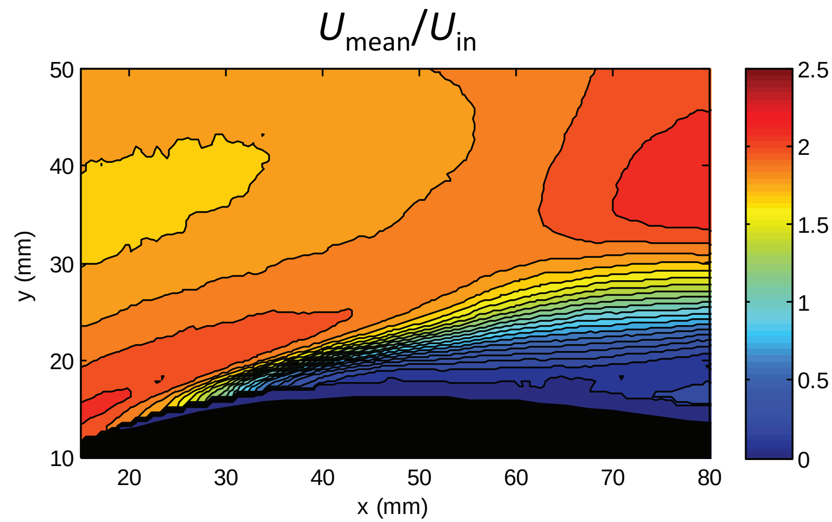


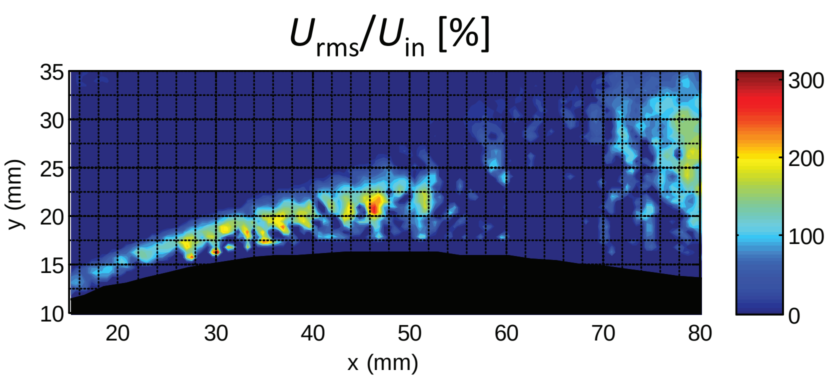
Phase #16

t/T = 0.6458

Phase-Locked PIV Data with Wakes



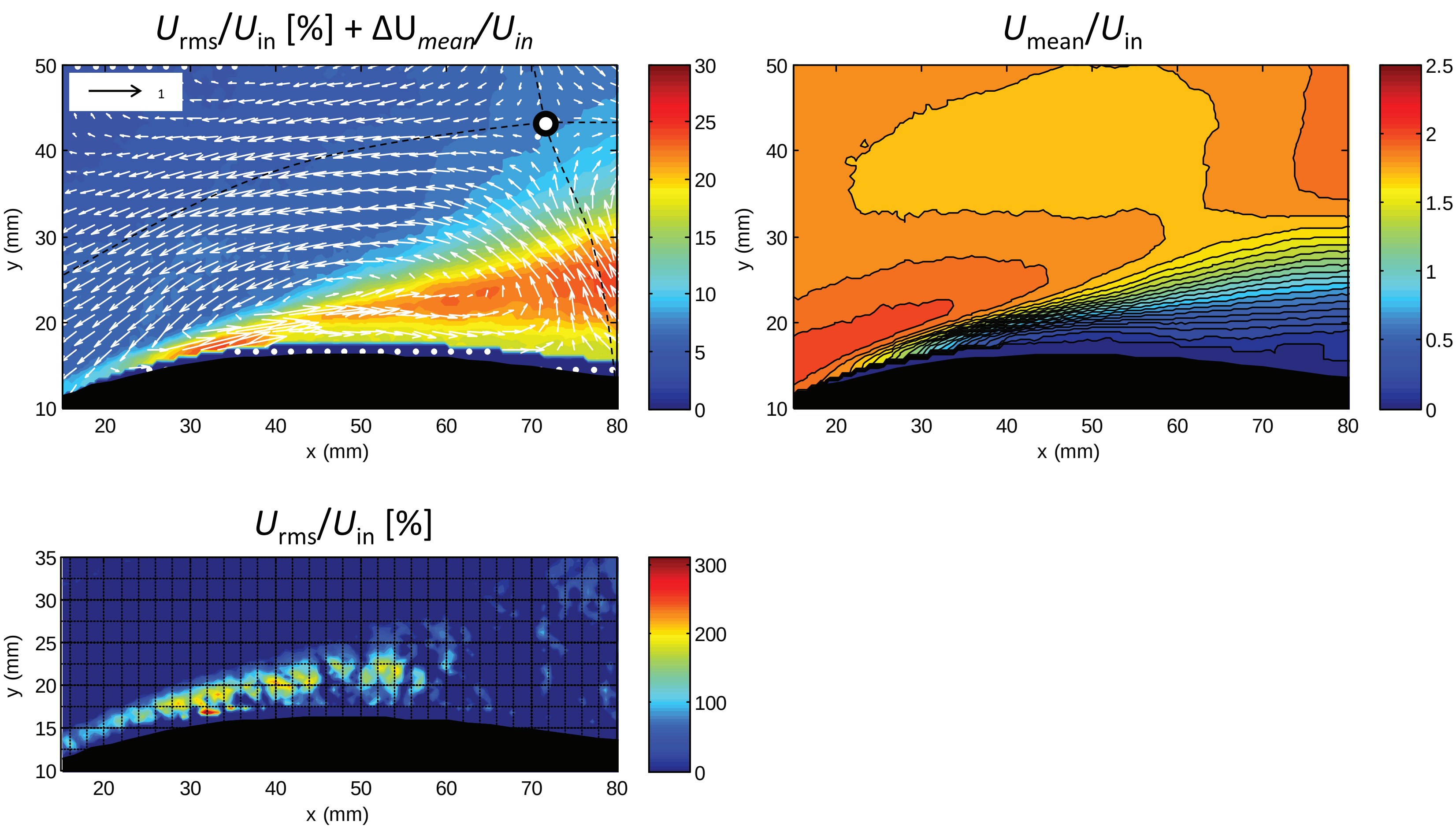




Phase #17

t/*T* = 0.6875

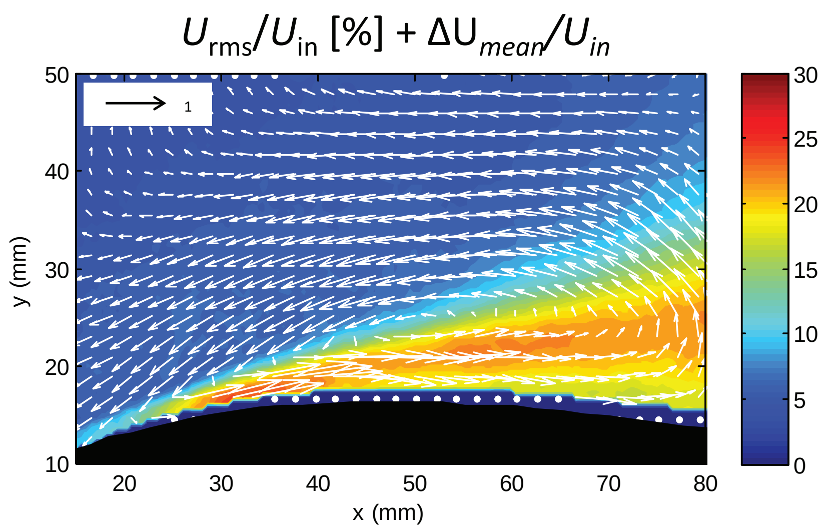
Phase-Locked PIV Data with Wakes

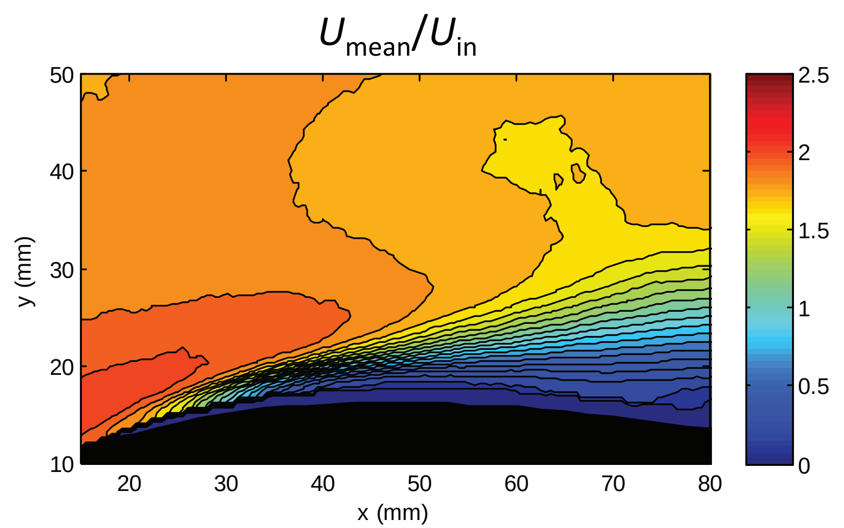


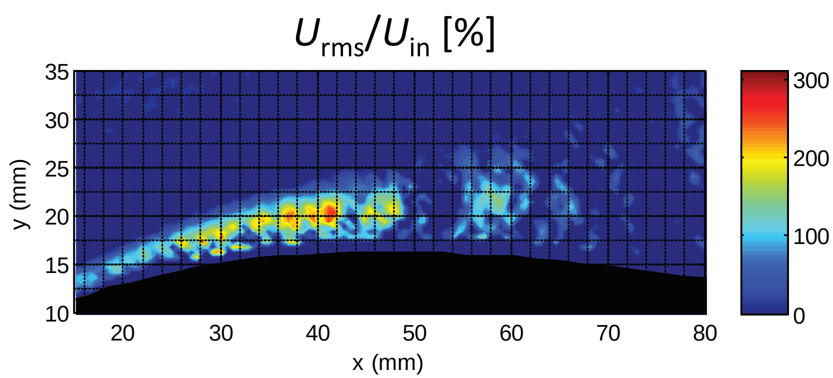
Phase #18

t/*T* = 0.7292

Phase-Locked PIV Data with Wakes





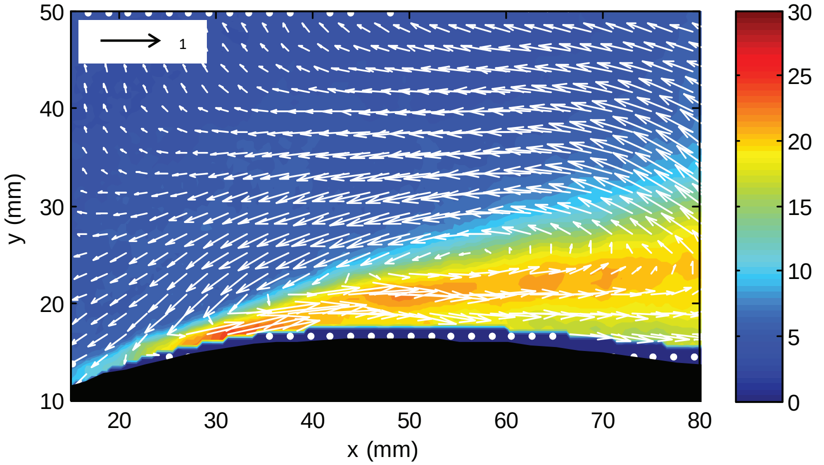


Phase #19

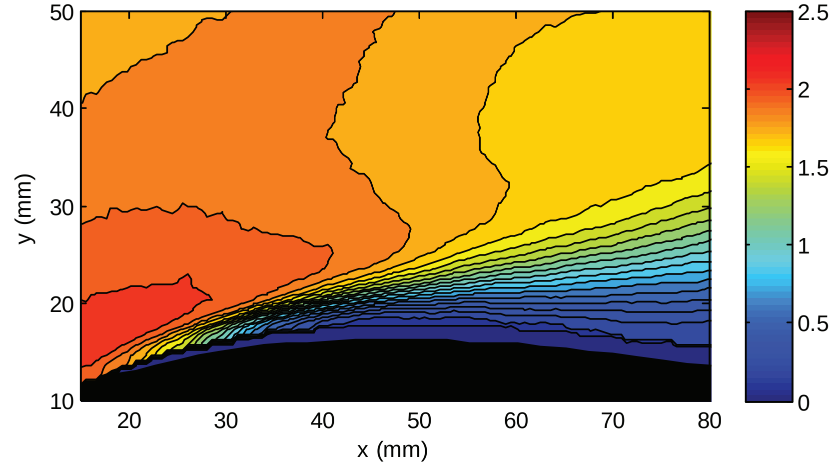
t/*T* = 0.7708

Phase-Locked PIV Data with Wakes

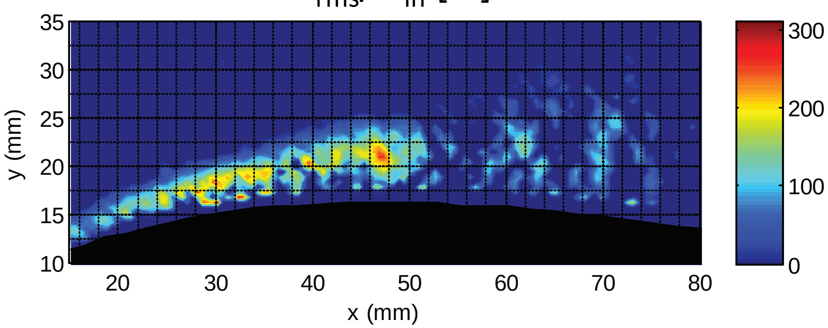
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}



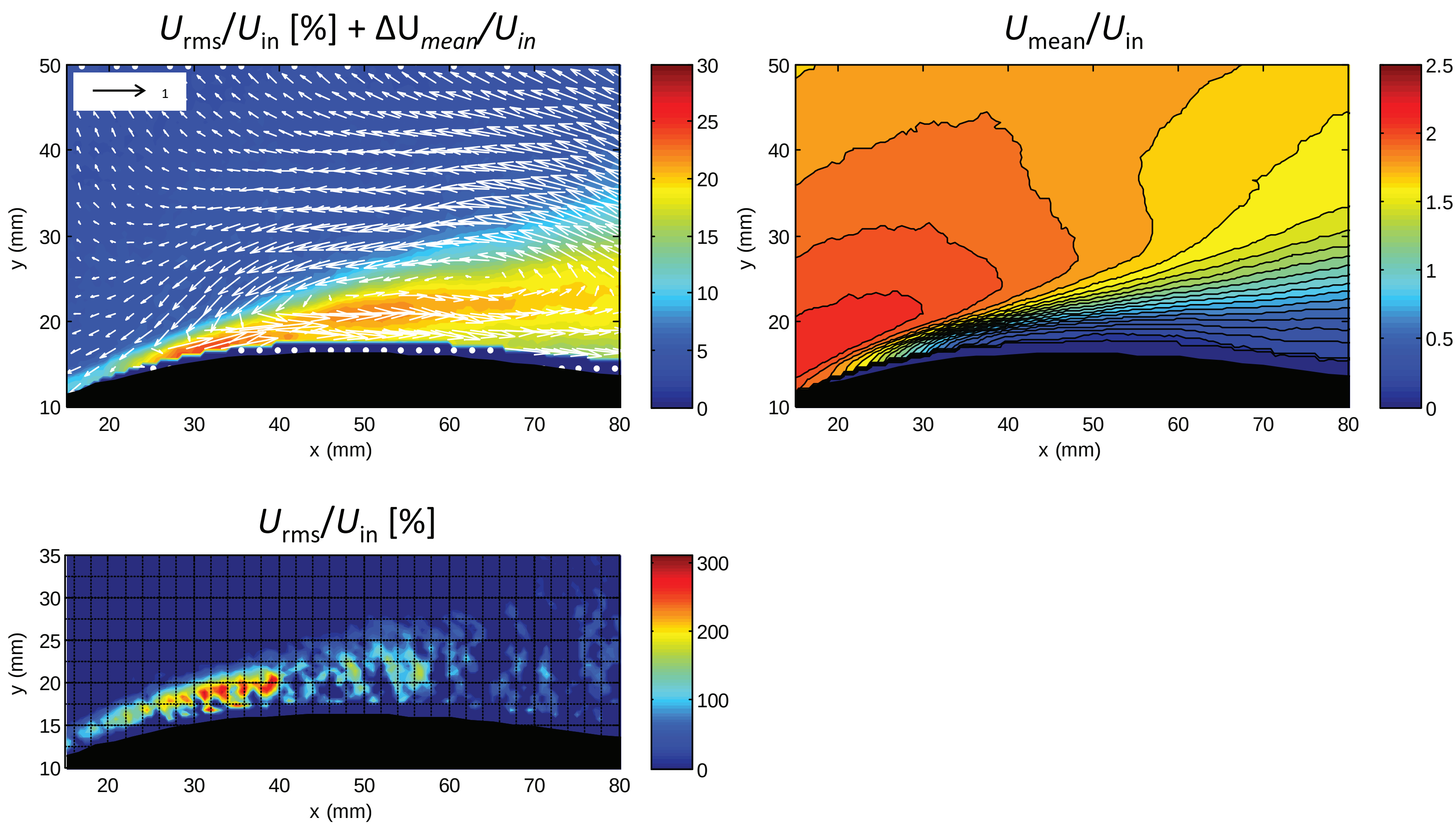
U_{rms}/U_{in} [%]



Phase #20

t/T = 0.8125

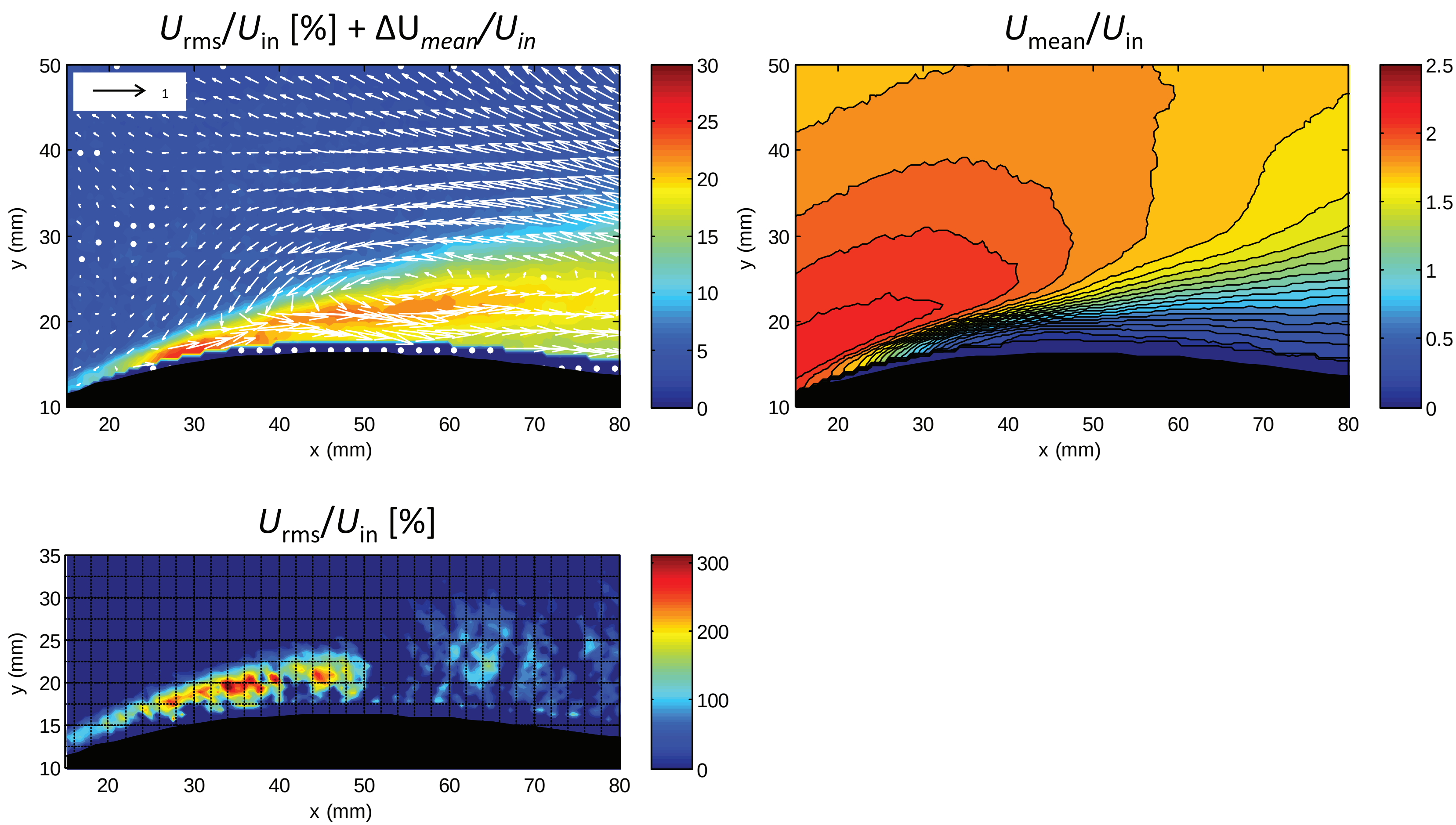
Phase-Locked PIV Data with Wakes



Phase #21

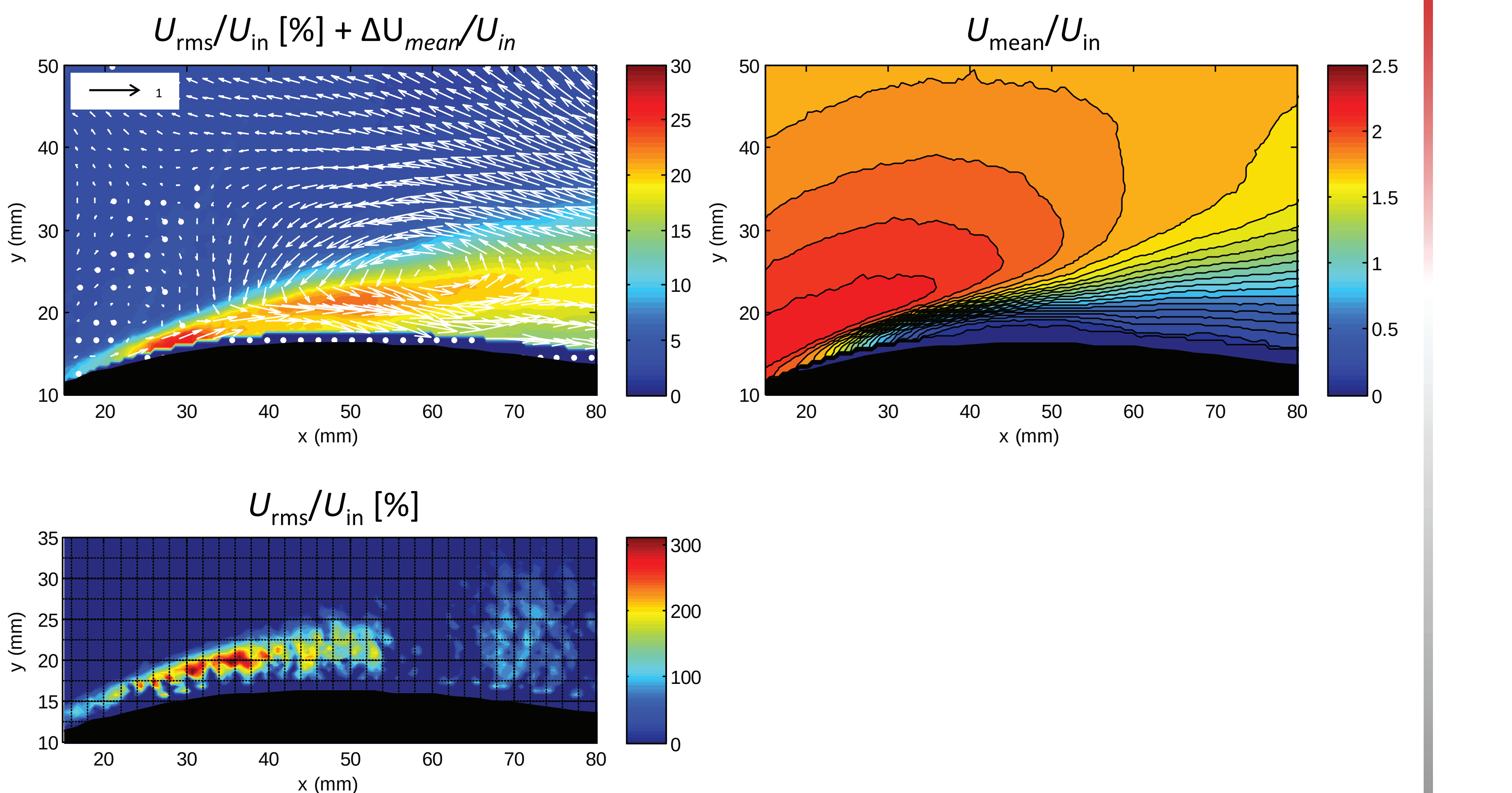
t/T = 0.8542

Phase-Locked PIV Data with Wakes



Phase #22 t/T = 0.8958

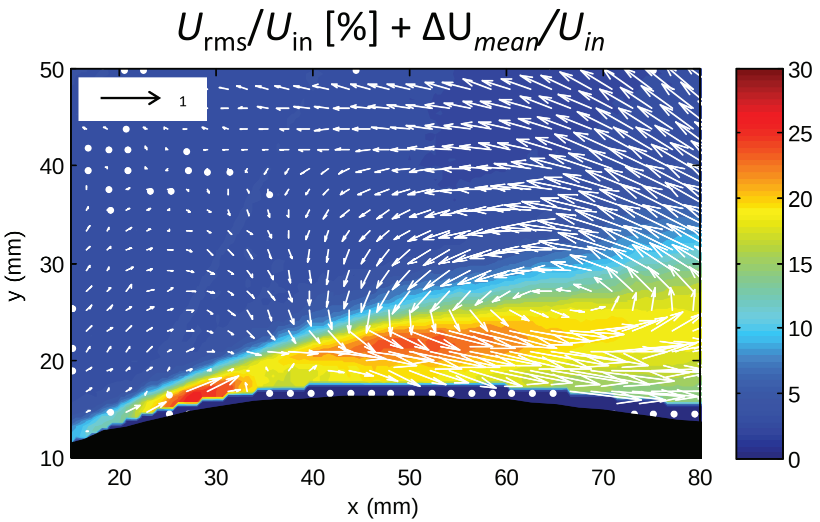
Phase-Locked PIV Data with Wakes

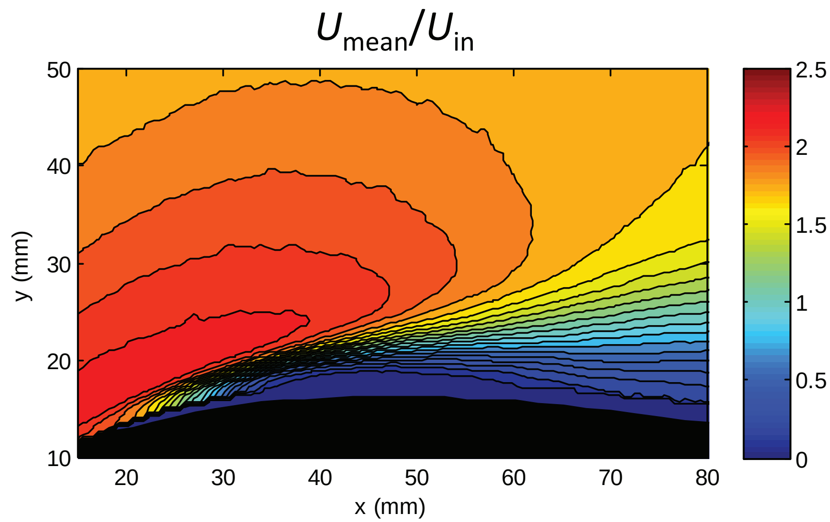


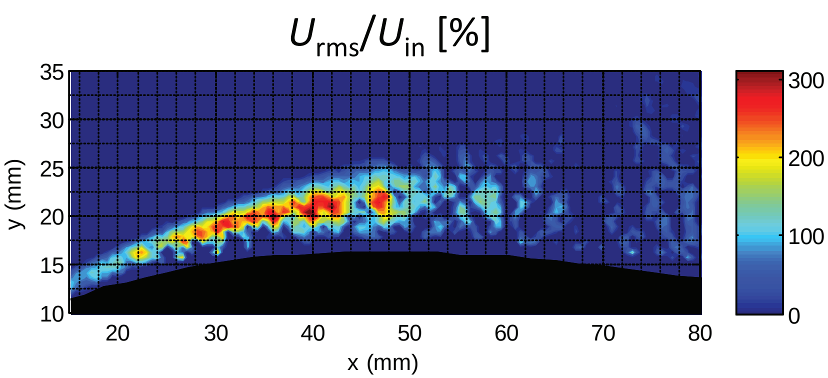
Phase #23

t/*T* = 0.9375

Phase-Locked PIV Data with Wakes



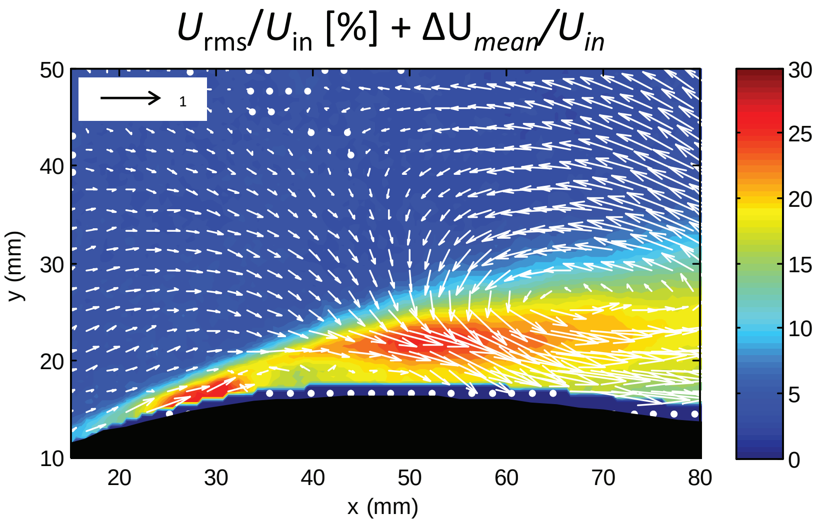


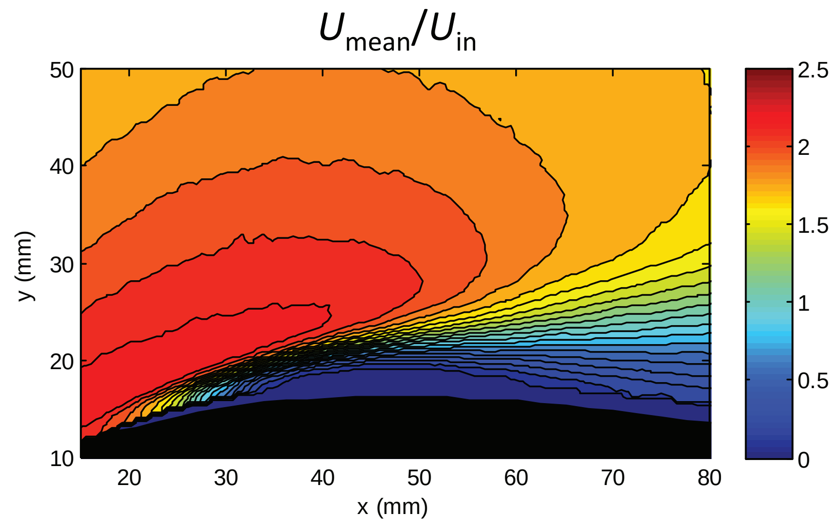


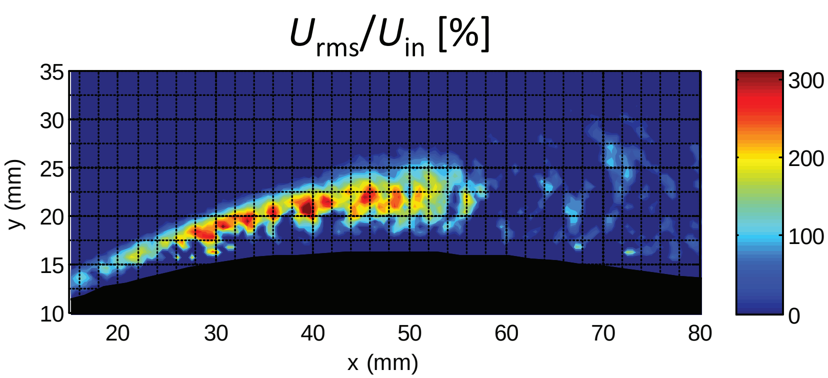
Phase #24

t/T = 0.9792

Phase-Locked PIV Data with Wakes



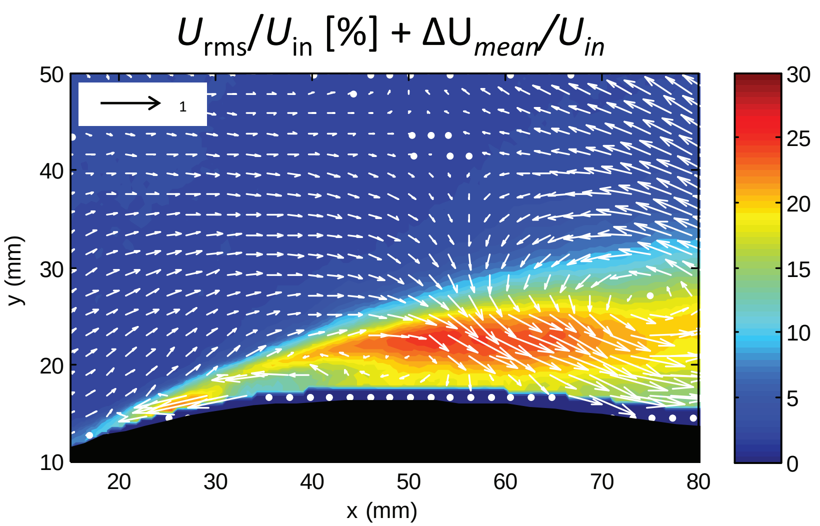


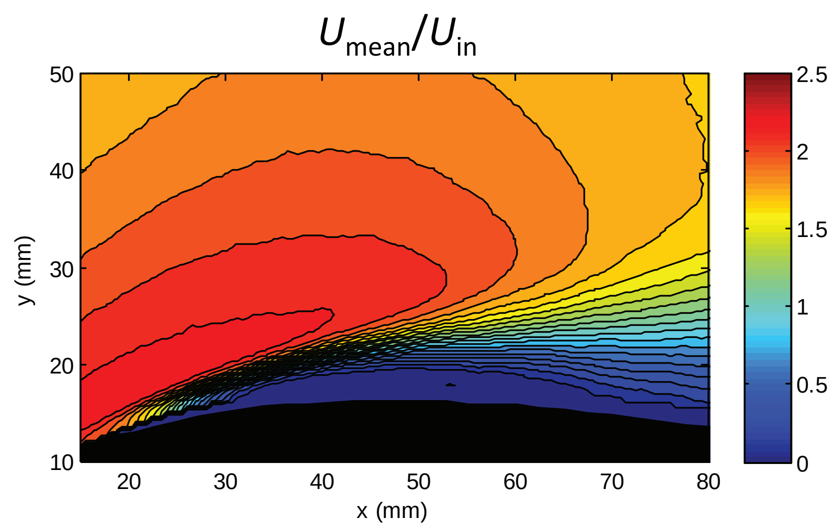


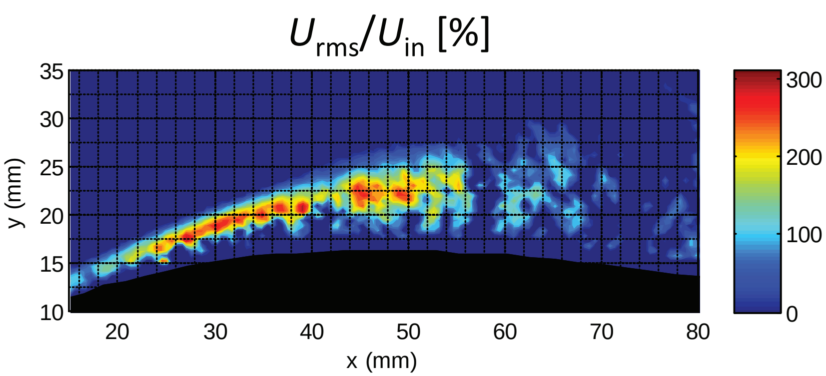
Phase #1

t/*T* = 0.0208

Phase-Locked PIV Data with Wakes





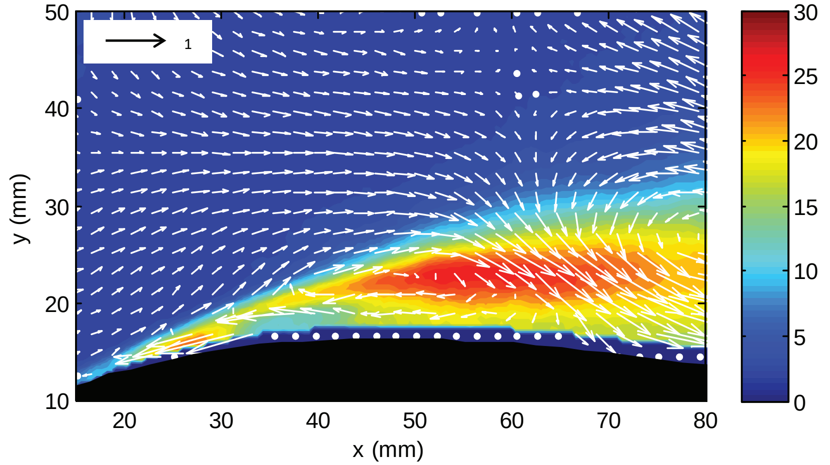


Phase #2

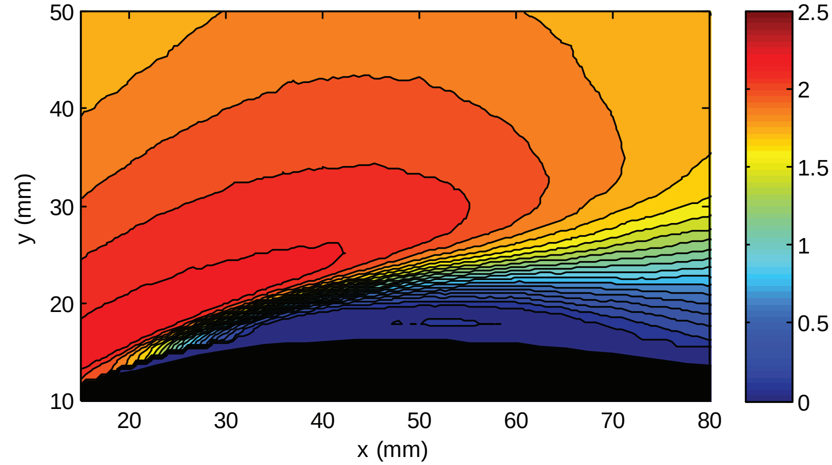
t/*T* = 0.0625

Phase-Locked PIV Data with Wakes

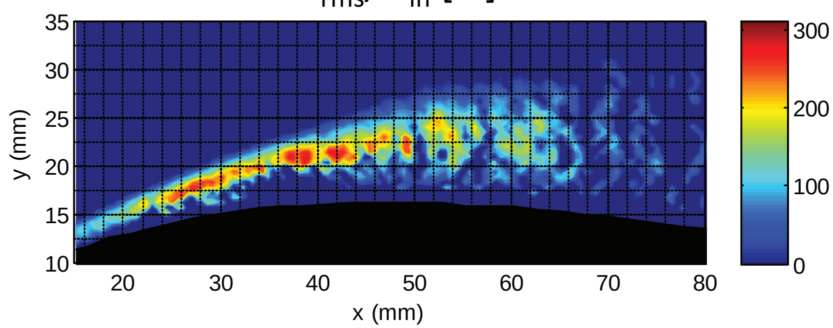
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}



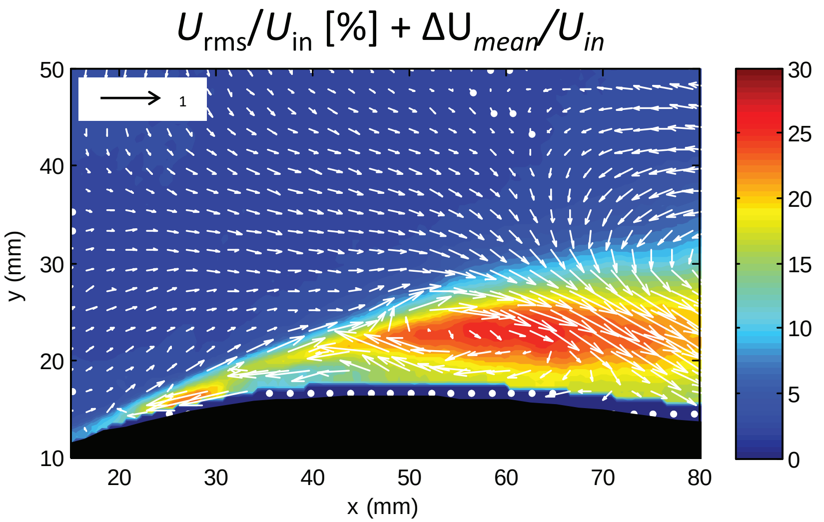
U_{rms}/U_{in} [%]

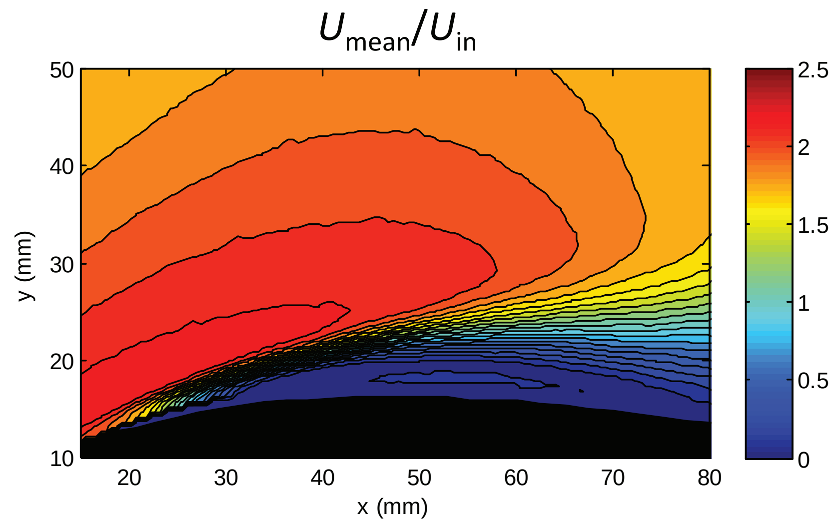


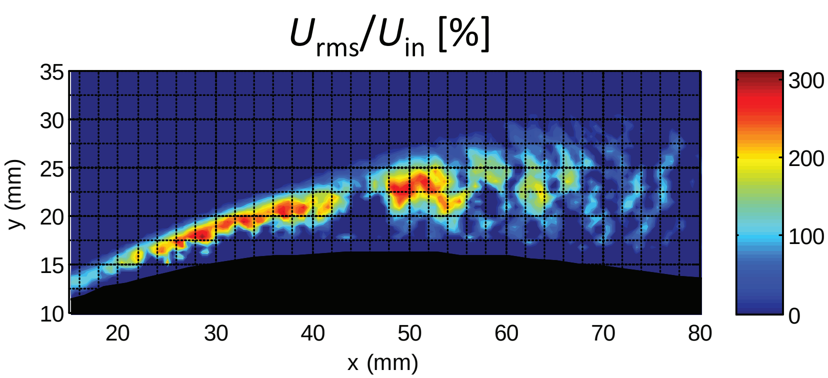
Phase #3

t/*T* = 0.1042

Phase-Locked PIV Data with Wakes



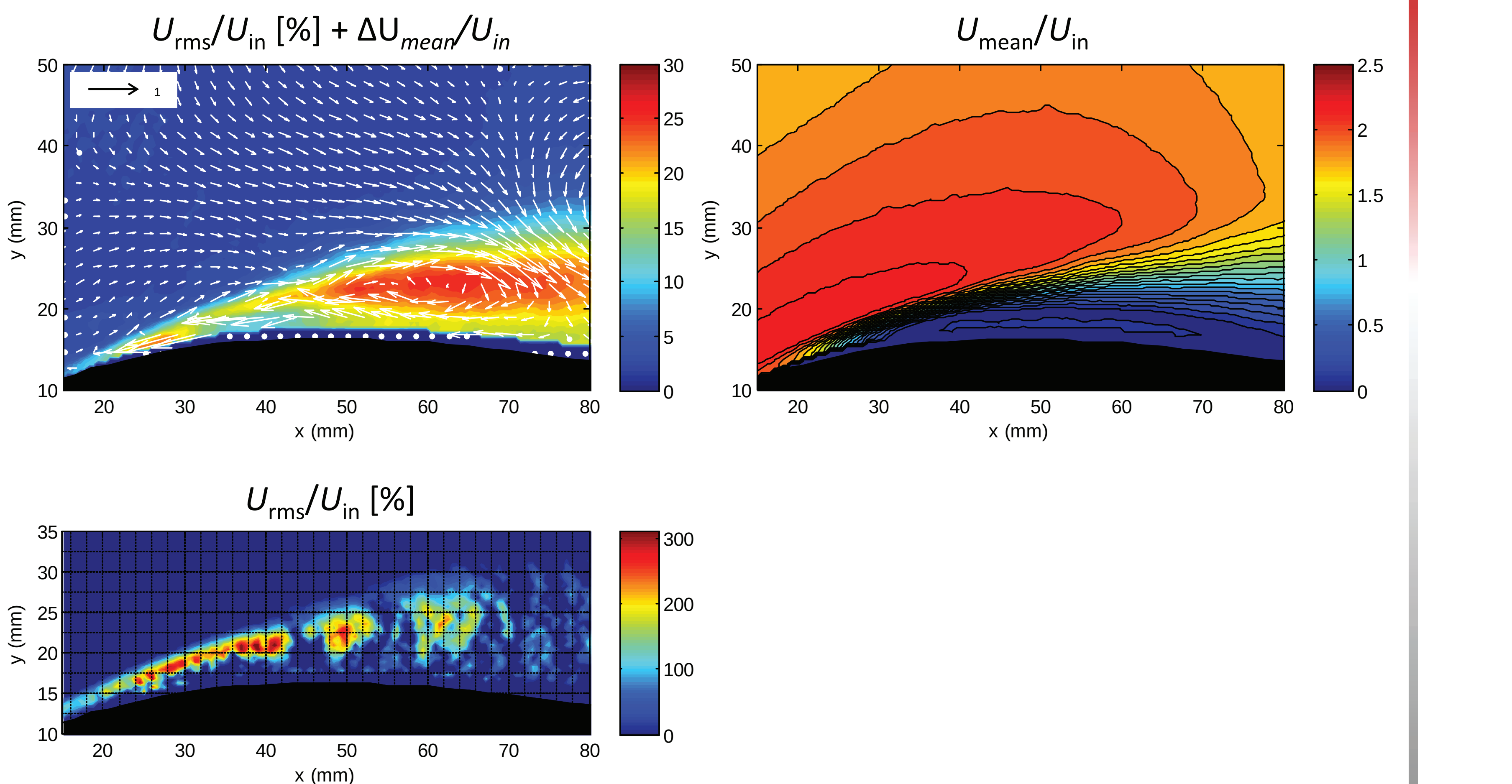




Phase #4

t/*T* = 0.1458

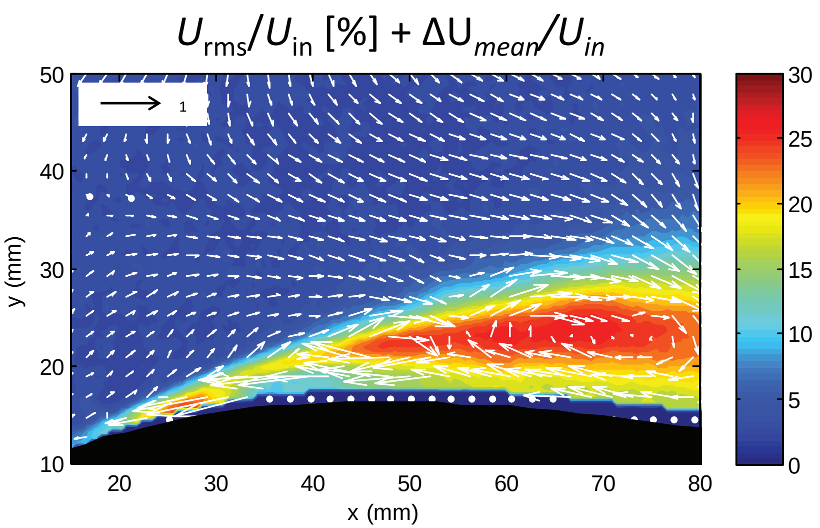
Phase-Locked PIV Data with Wakes

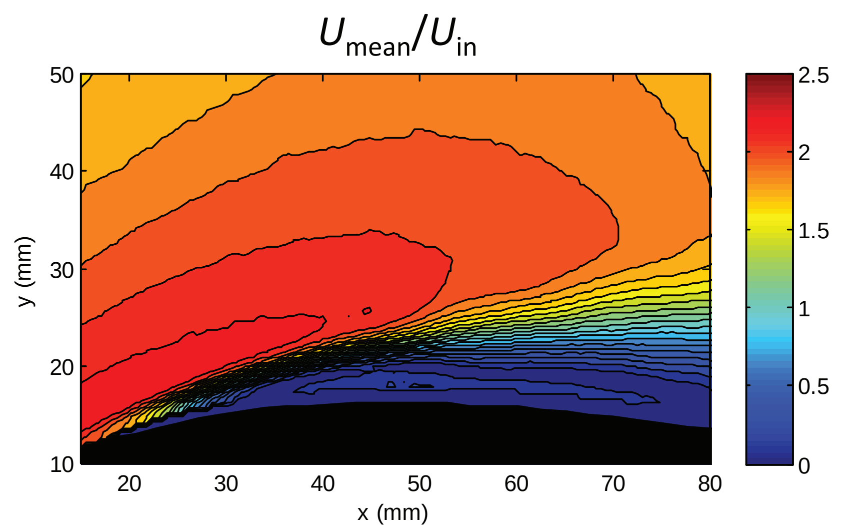


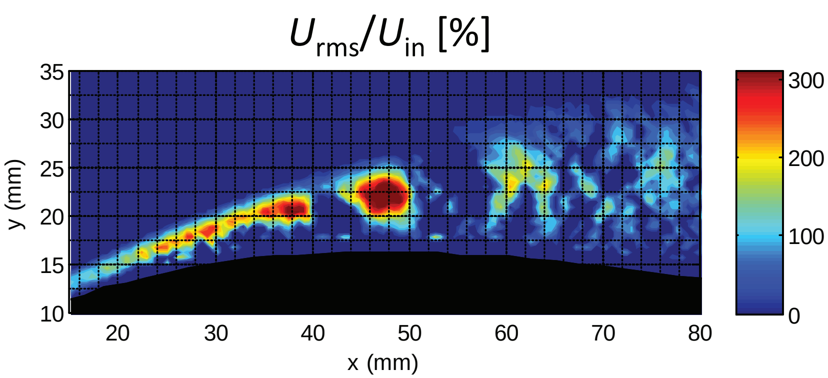
Phase #5

t/*T* = 0.1875

Phase-Locked PIV Data with Wakes



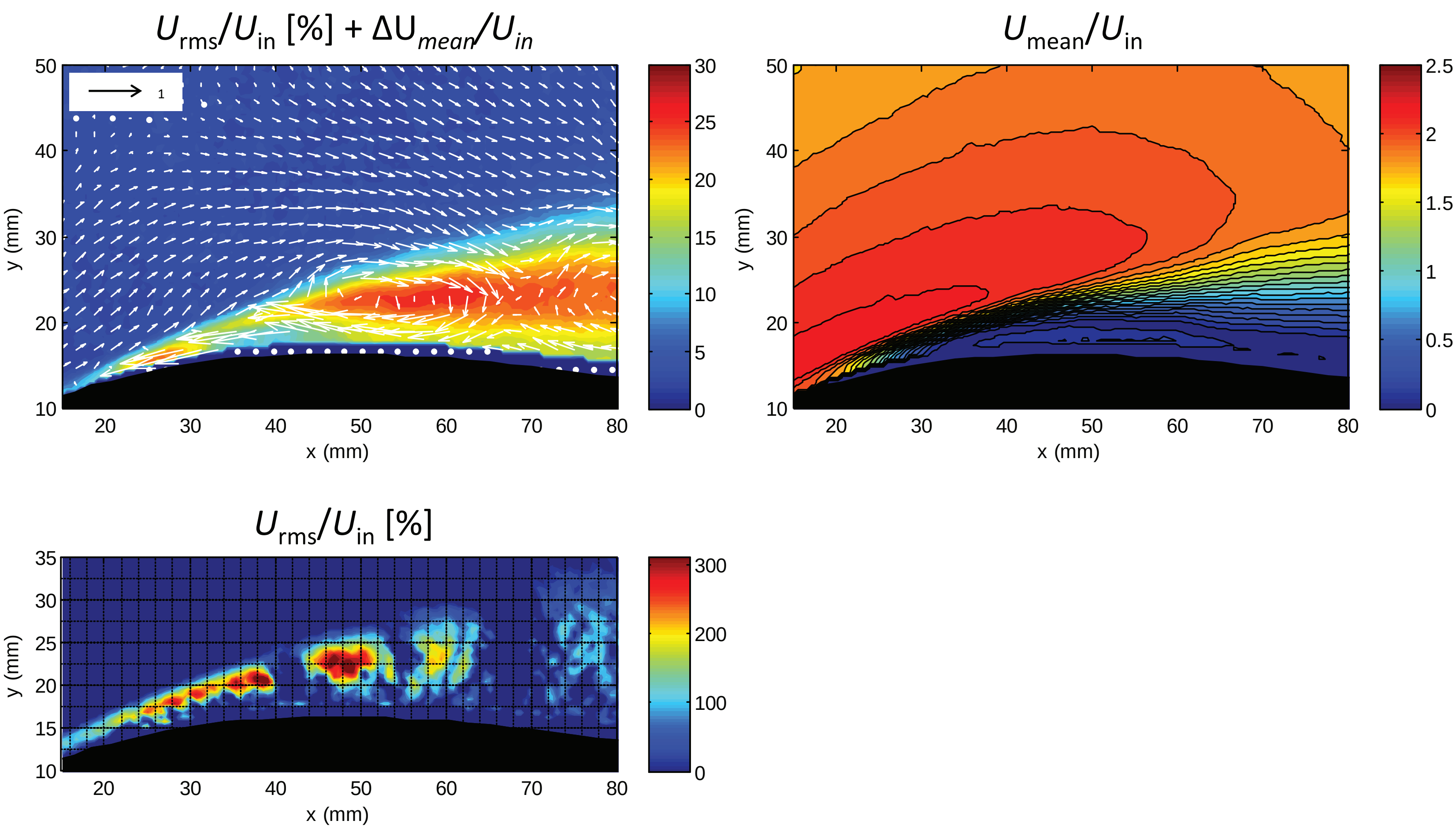




Phase #6

t/T = 0.2292

Phase-Locked PIV Data with Wakes

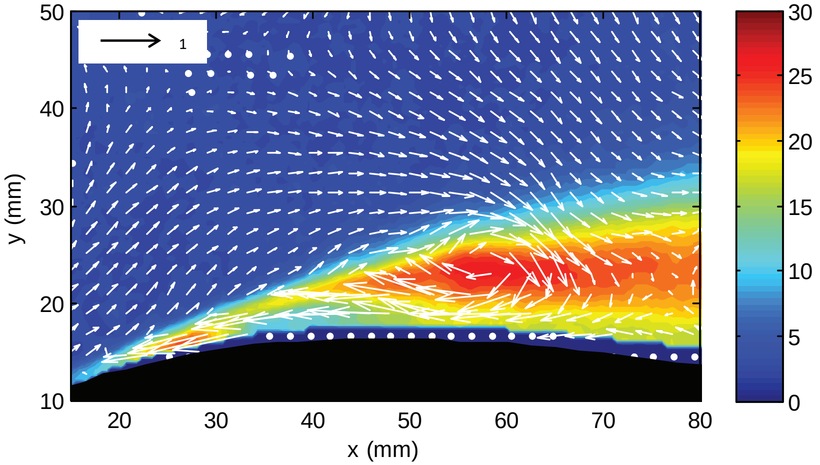


Phase #7

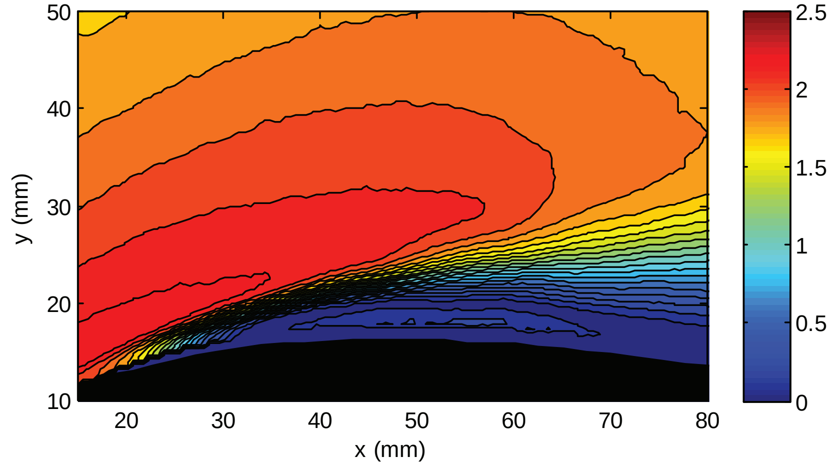
t/*T* = 0.2708

Phase-Locked PIV Data with Wakes

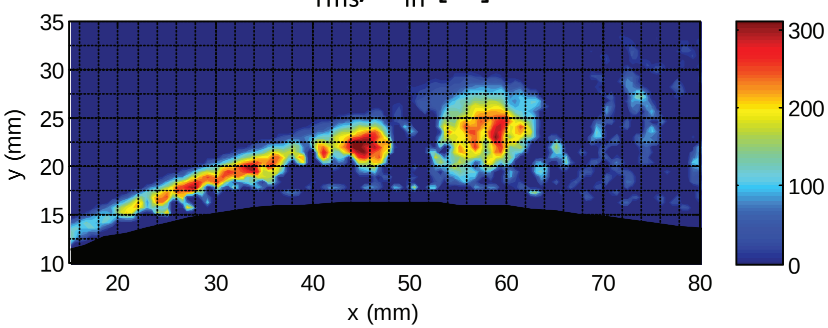
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}



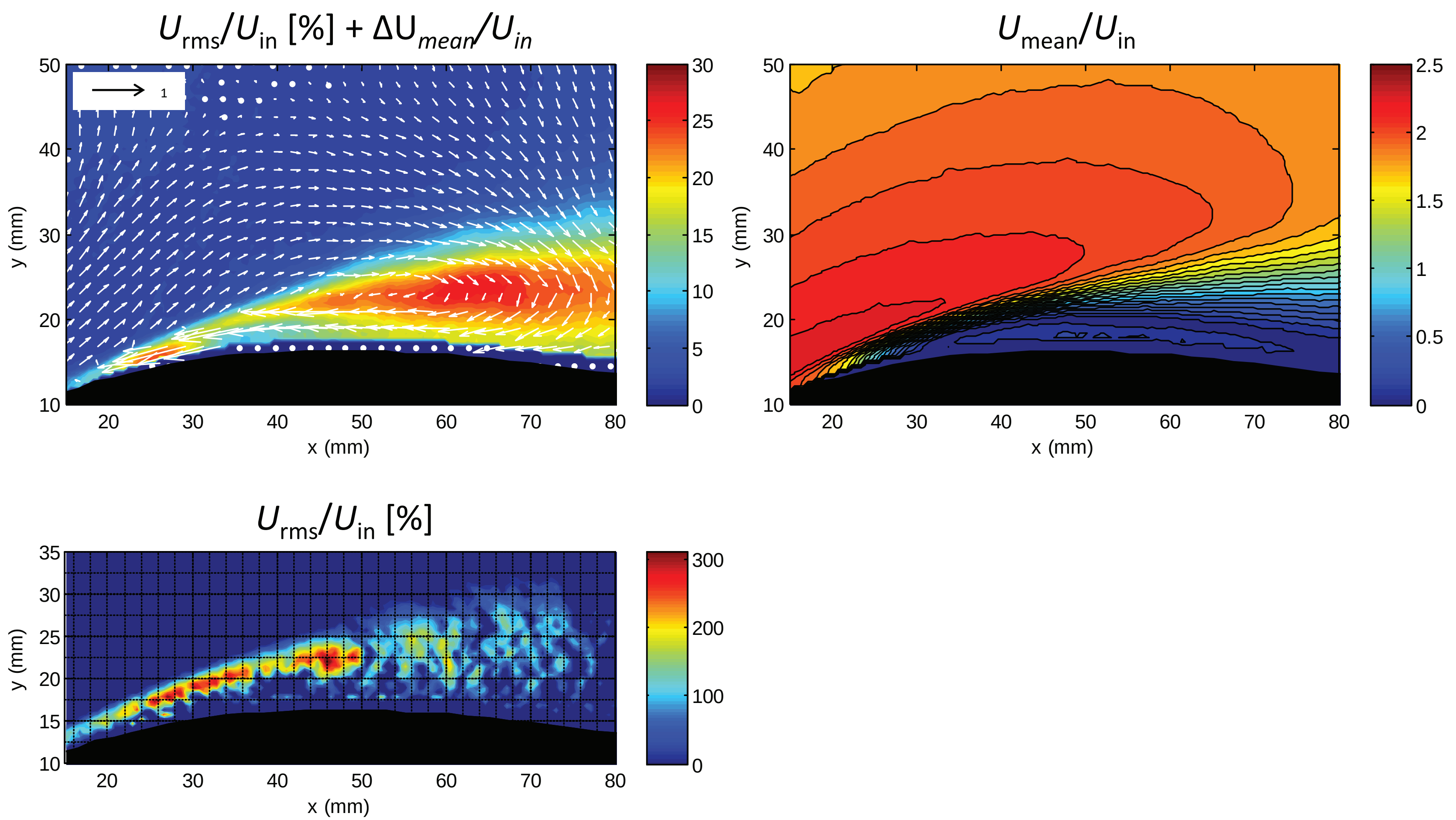
U_{rms}/U_{in} [%]



Phase #8

t/T = 0.3125

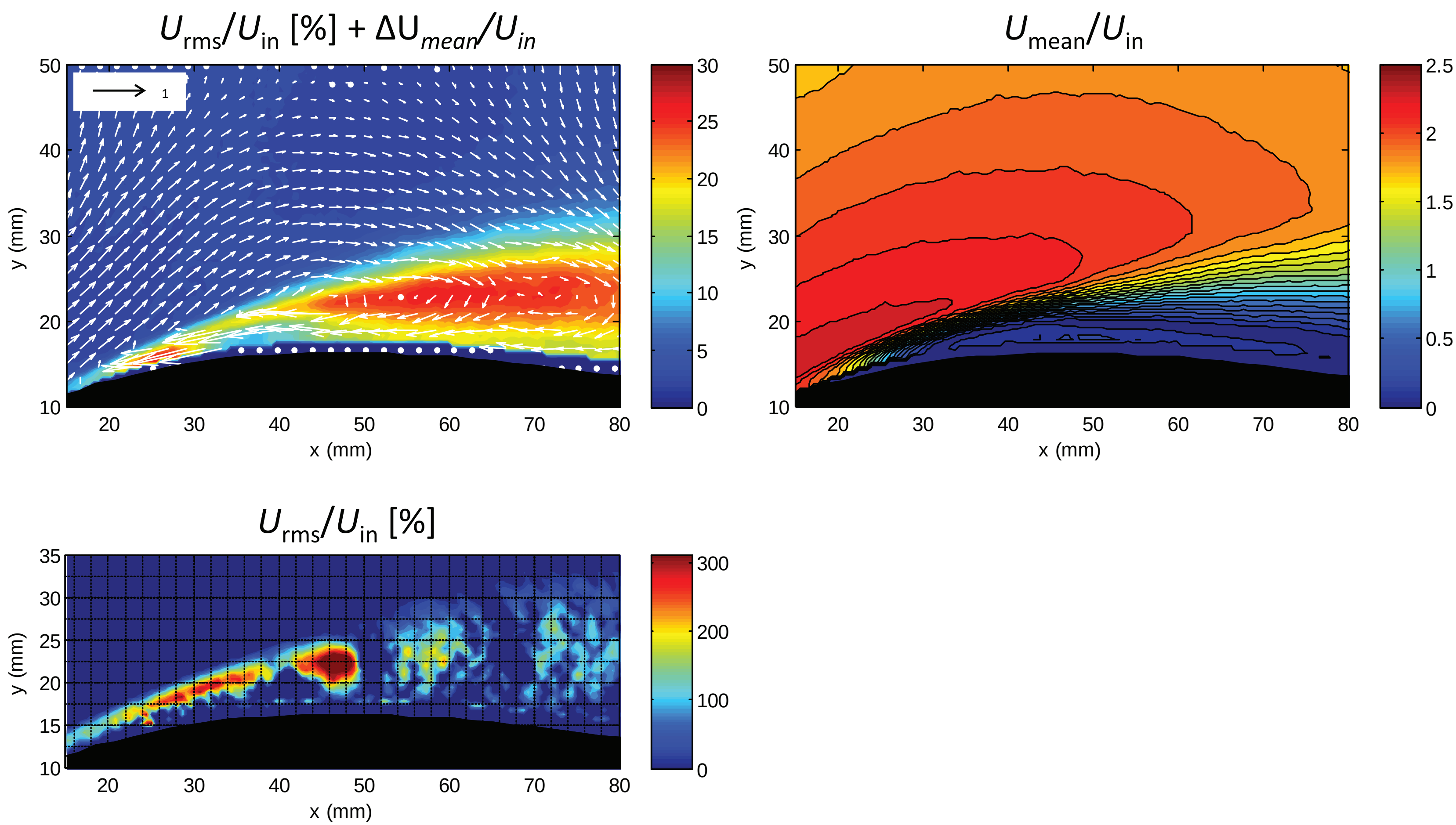
Phase-Locked PIV Data with Wakes



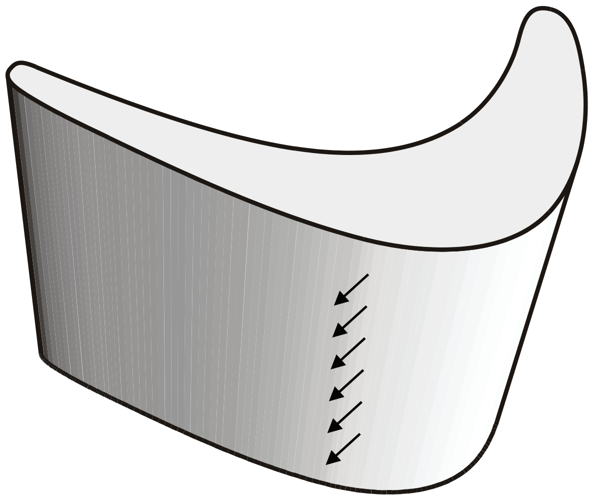
Phase #9

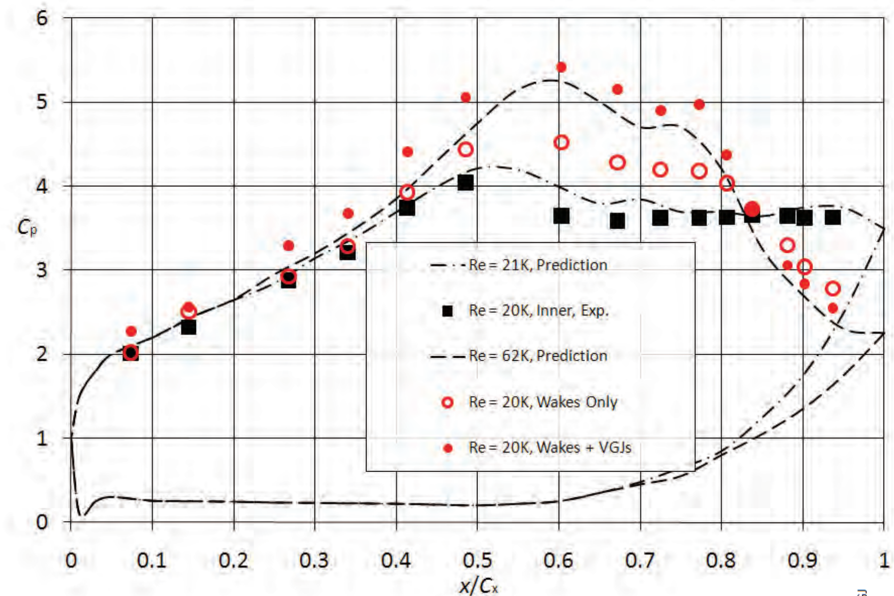
t/*T* = 0.3542

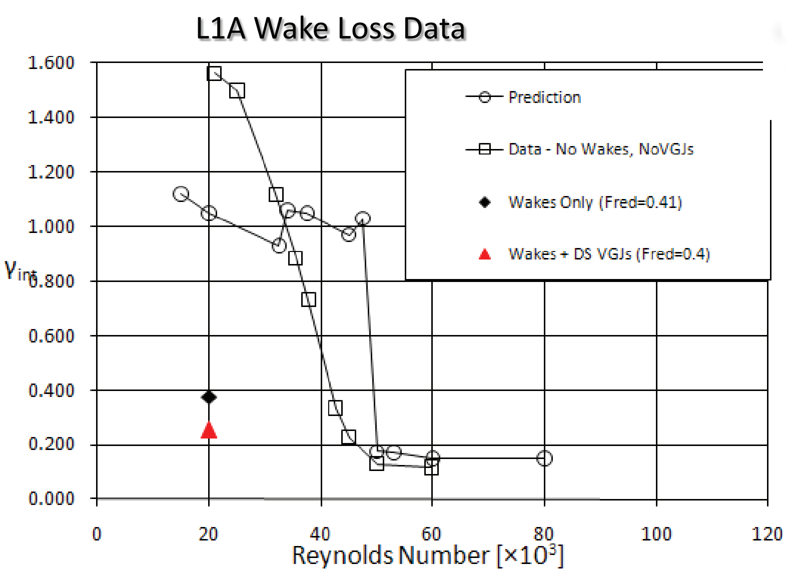
Phase-Locked PIV Data with Wakes

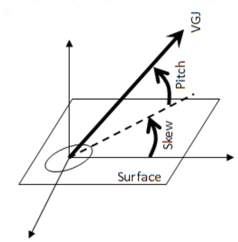


L1A Cascade Results – Wakes with Pulsed VGJs





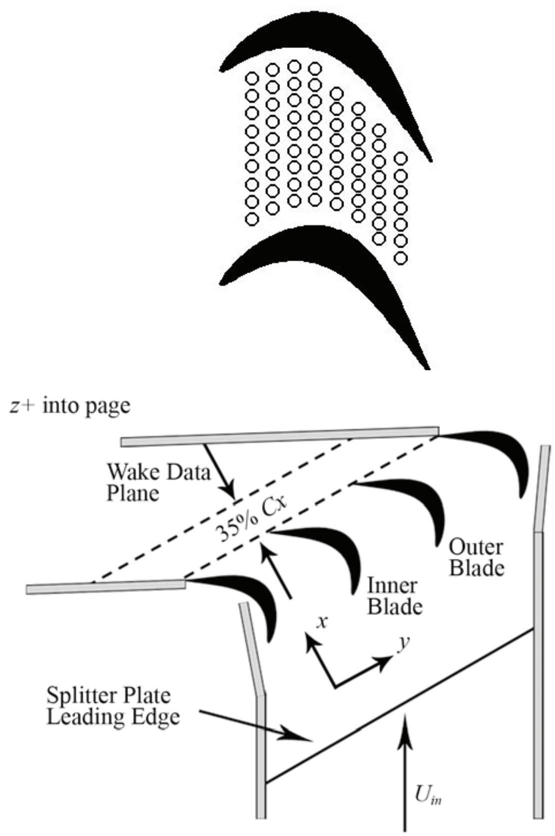




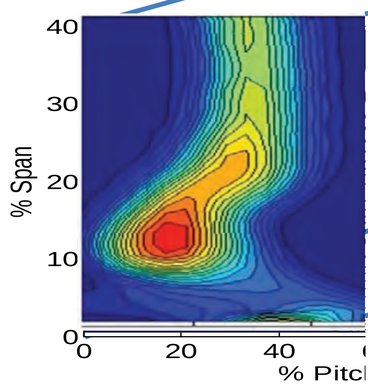
- VGJs at x/C_x=0.72
- 25% duty cycle
- Avg blowing ratio (B) = 2.0
- Pulsed actuation between wakes
- 35% loss reduction even with wakes

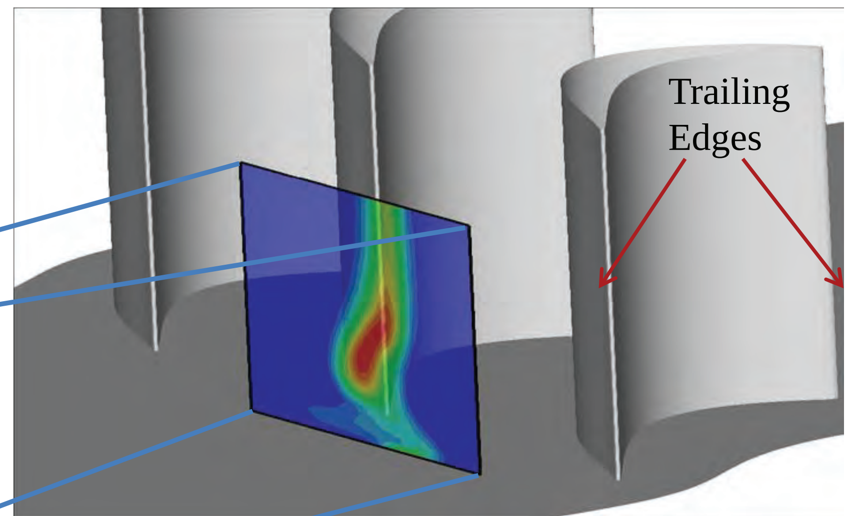
Splitter Plate for Endwall Flow Control

A splitter plate was created on the floor of the L1A linear cascade for endwall loss studies.
The splitter plate incorporates an array of suction holes for control of the passage vortex system.



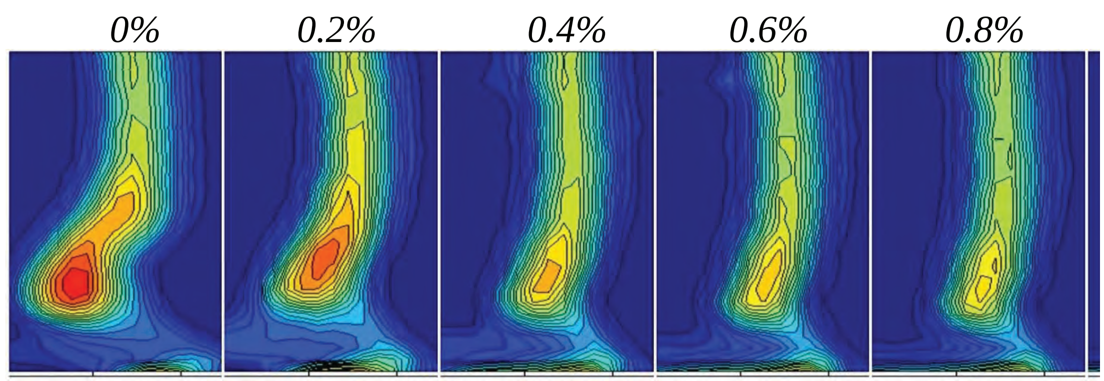
Endwall Loss Reduction with Suction





P_T Loss Contours at Re_{Cx}=50000
Increasing suction levels (% of passage flow)

(Use fluid removed from endwall to supply midspan VGJs!)



Thank You

(Now we can go home!)

Backup Slides

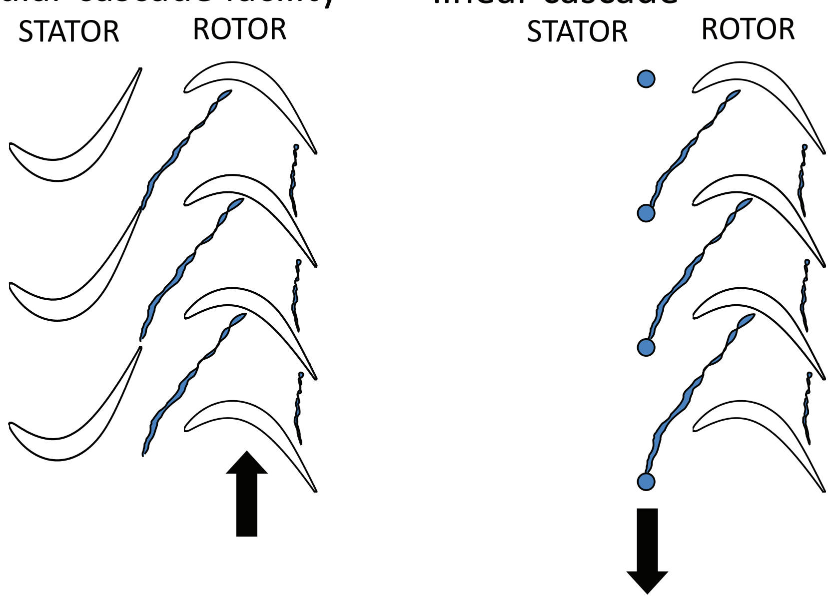
Wake Generator

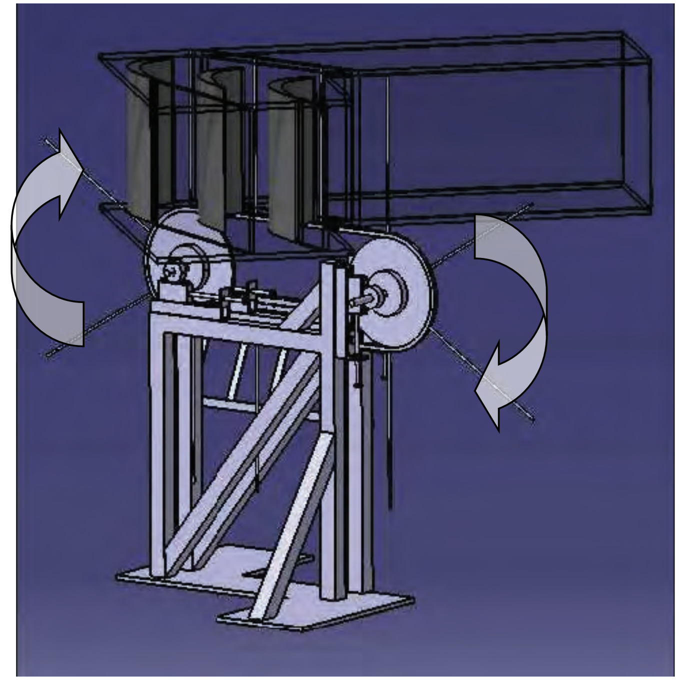
Flow control applications MUST consider unsteady turbomachinery flowfield.

Potential opportunities for synchronization of pulsed flow control.

Exact wake simulation is only possible in a full annular cascade facility

Use moving cylinders to simulate stators for finite linear cascade

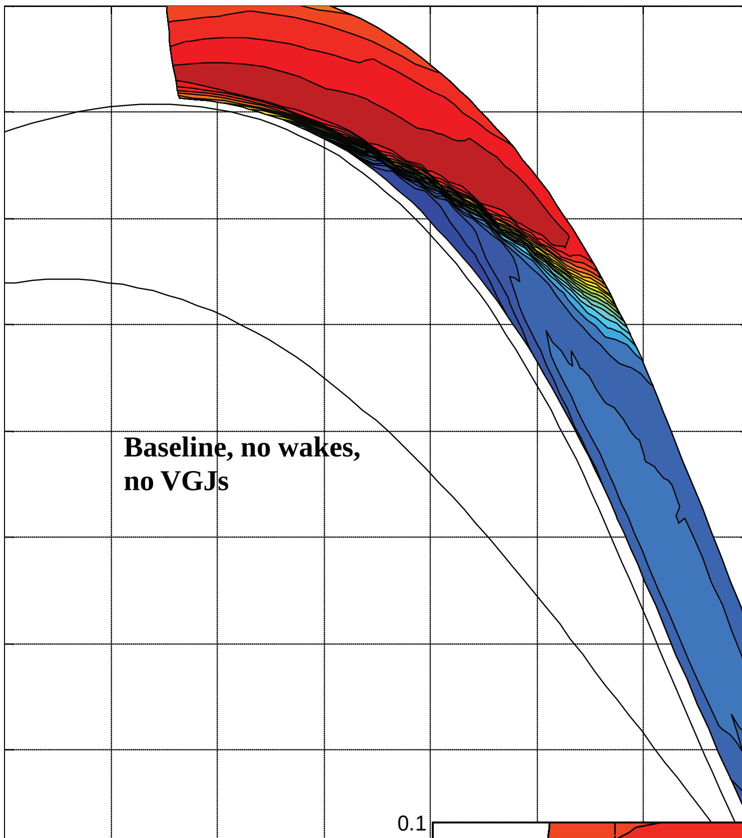




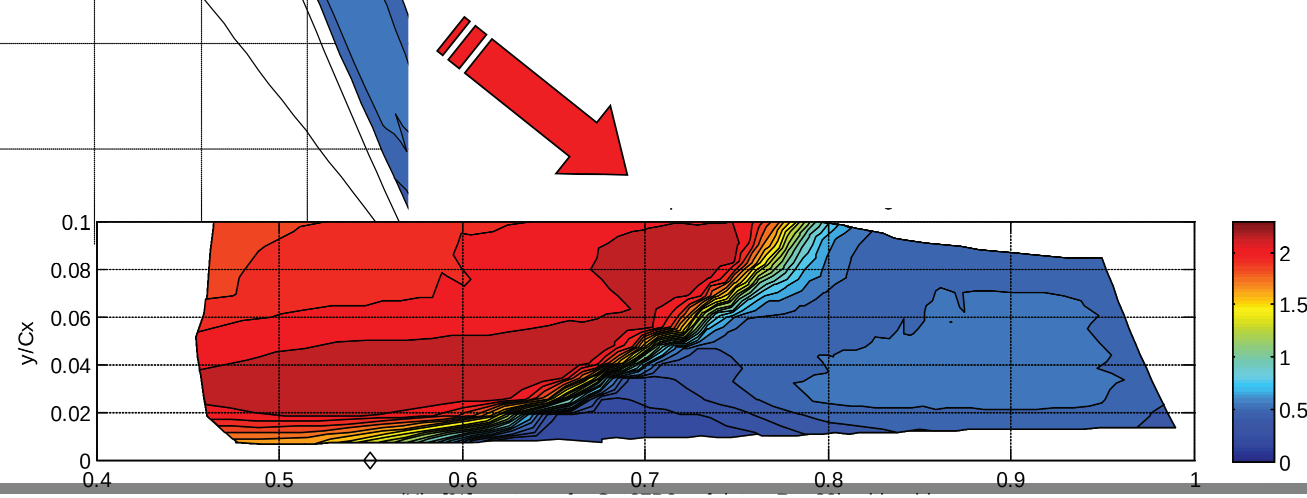
- 4mm diameter rods
- Flow coefficient: $\Phi = U_{in,ax}/U_{rod} = 0.91$
- $F_{red} = f \times c/U_{exit} = 0.41$
- $F^{+} = f \times SSLJ/U_{avg} = 0.20$
- T_{wake} = 115ms
- Rod spacing = 1.57 × blade pitch
- Located 31%C_x upstream

L1A Cascade Hot Film Results – u_{mean}/U_{in}

TIME-AVERAGED MEAN VELOCITY DATA

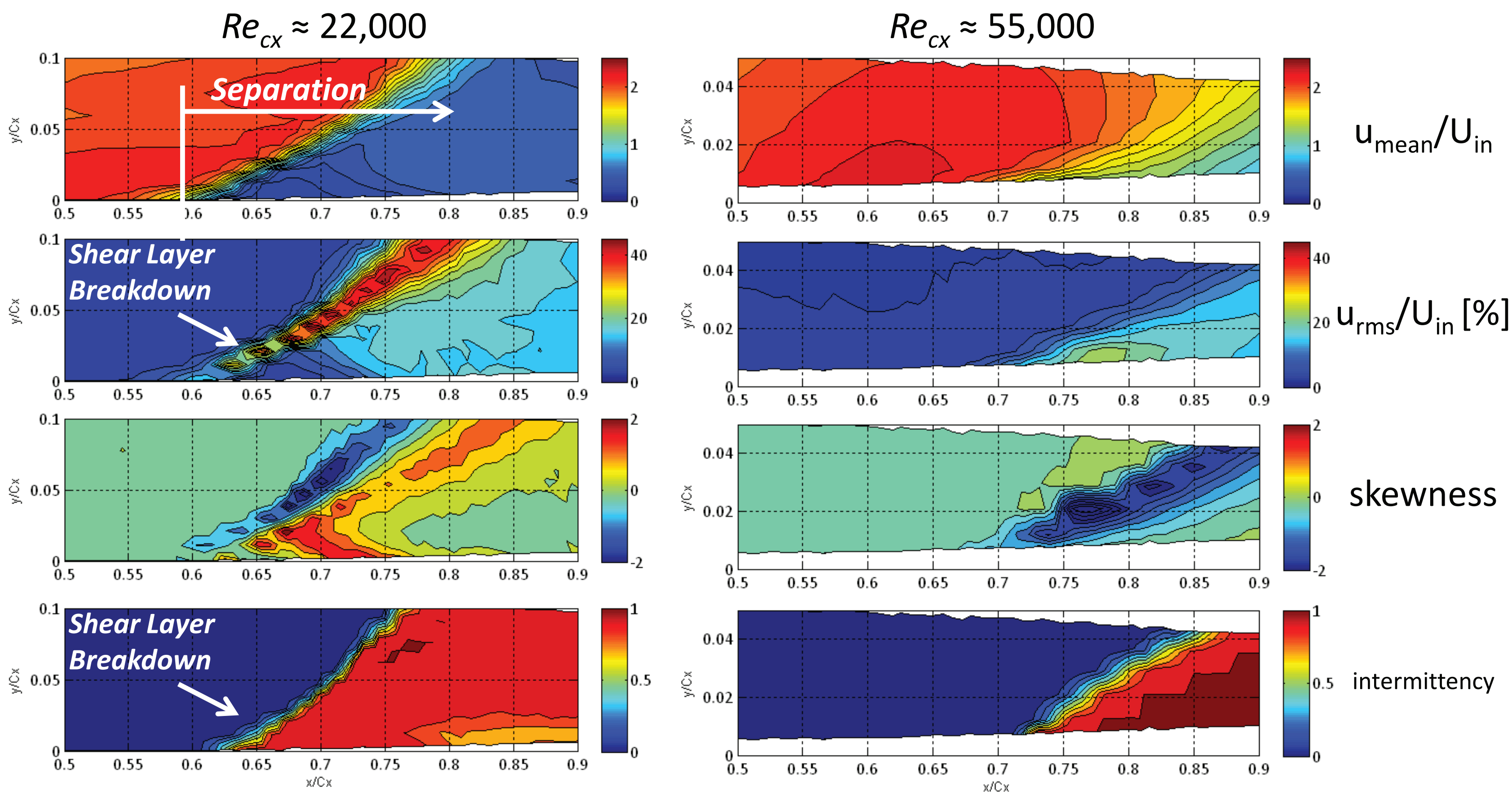


Transformed Coordinate Axes - % Axial Chord



Steady State L1A: No Control

Data acquired with a hot-film mounted on blade surface-follower device

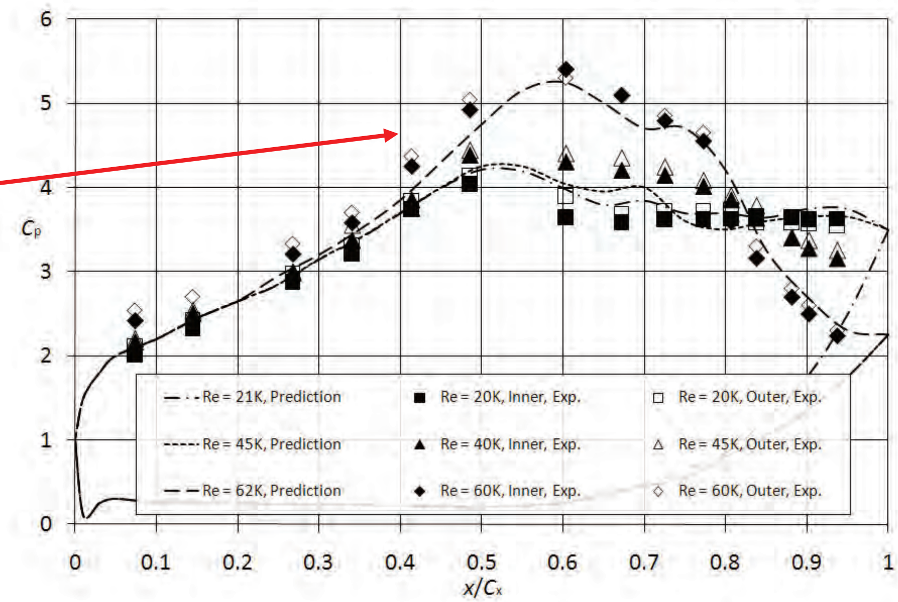


L1A is an excellent candidate for flow control due to large, non-reattaching suction surface separation at low Re.

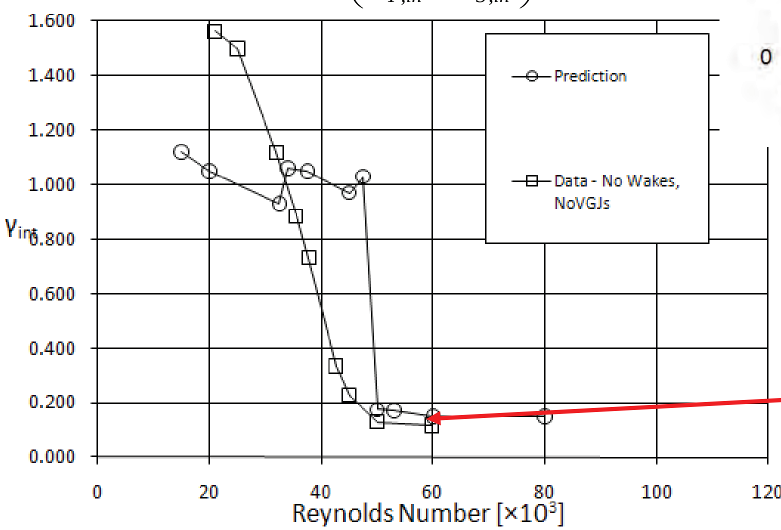
L1A Cascade Results - Pressures

(Steady State, no wakes, no VGJs)

Peripheral inlet bleeds used to match prediction



$$\gamma_{int} = \frac{1}{S}\int_{-S/2}^{S/2}\left(\frac{P_{T,in} - P_{T,ex}}{P_{T,in} - P_{S,in}}\right)ds$$



($Re_{c,ex}$ = 1.7×$Re_{cx,in}$)

Integrated wake total pressure loss exhibits low Reynolds loss comparable to AFRL calculation (*Re* ~ 52k).

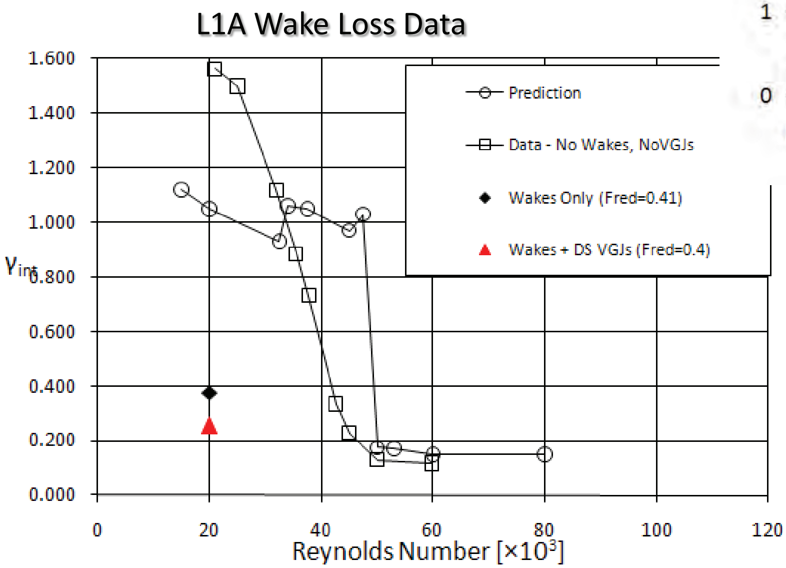
L1A Cascade Results – Wakes with Pulsed VGJs

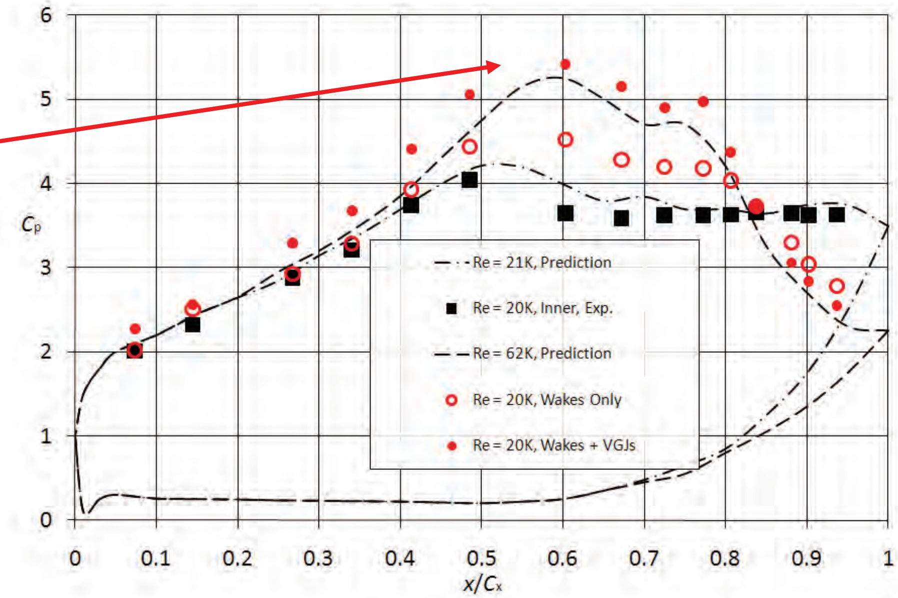
(Upstream Wakes, VGJs at 72%C_x)

DS VGJs located near average incipient separation with unsteady wakes only

DS VGJs also effectively reduce separation P_T loss, emulating flow diffusion at high Re

Pressure plateau 0.7 < x/C_x < 0.8

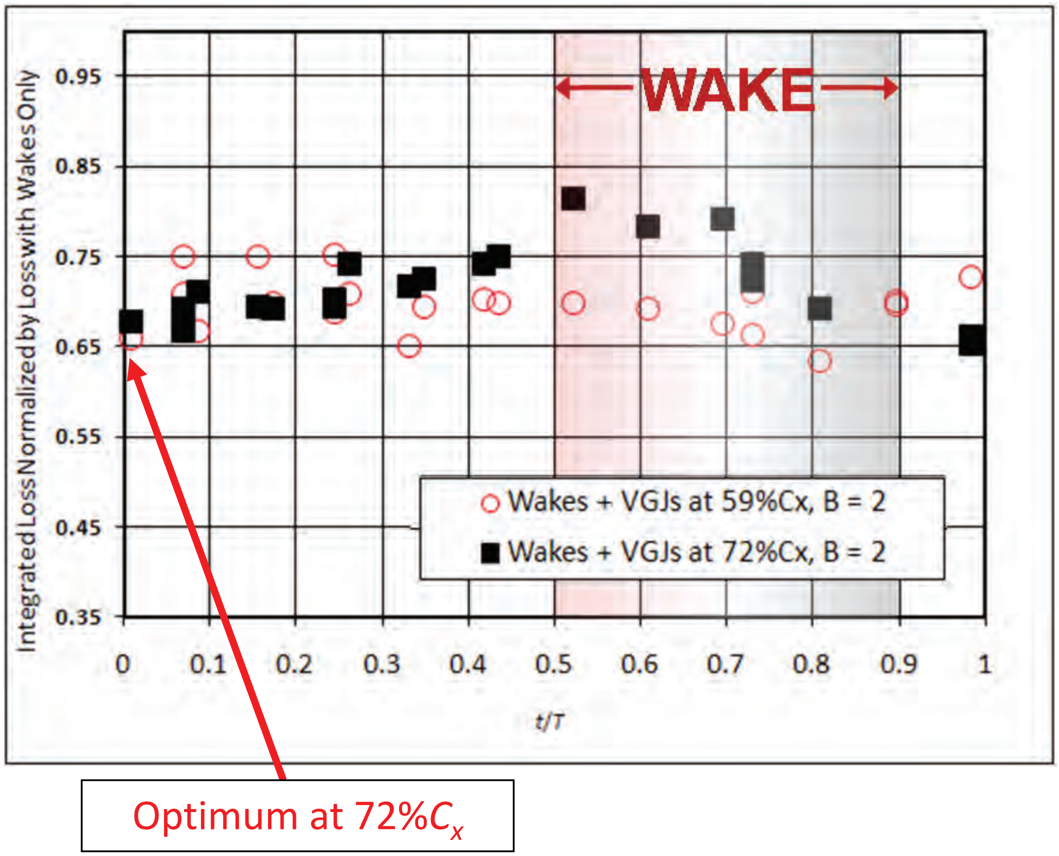




- VGJs at x/C_x=0.72
- 25% duty cycle
- Avg blowing ratio (B) = 2.0
- Pulsed actuation between wakes

Synchronization Study with the L1A

Optimal actuation with DS VGJs just after wake passing, before boundary layer recovery



Varying phase of actuation during wake passing period (*t*/*T*=0 : Signal from wake rod optical sensor)

- Fixed duty cycle (25%*T*)
- Fixed blowing ratio (*B* ≈ 2)

No optimum identified for actuation at 59%C_x (US)

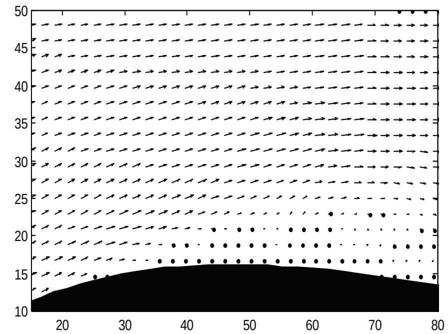
Actuation US yields similar performance with or without wakes

Optimal phase synchronization actuating at 72%C_x (DS) ~ *t*/*T*=0

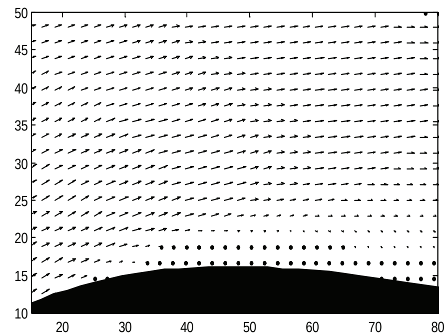
PIV Data Processing: Perturbation Velocity Field (ΔU_{mean})

Perturbation Velocity Vector Field:

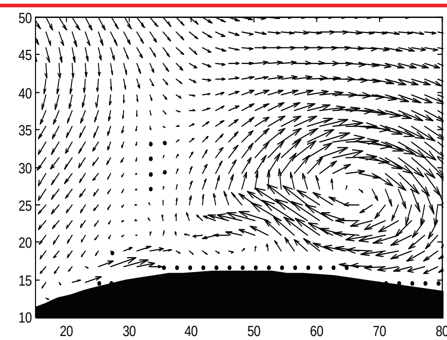
– Subtract the time-mean (or *cycle-avg'd*) vector field from the ensemble-avg'd flow field at each phase



Ensemble-avg'd flow field phase 14, wake-only case U_{mean}/U_{in}



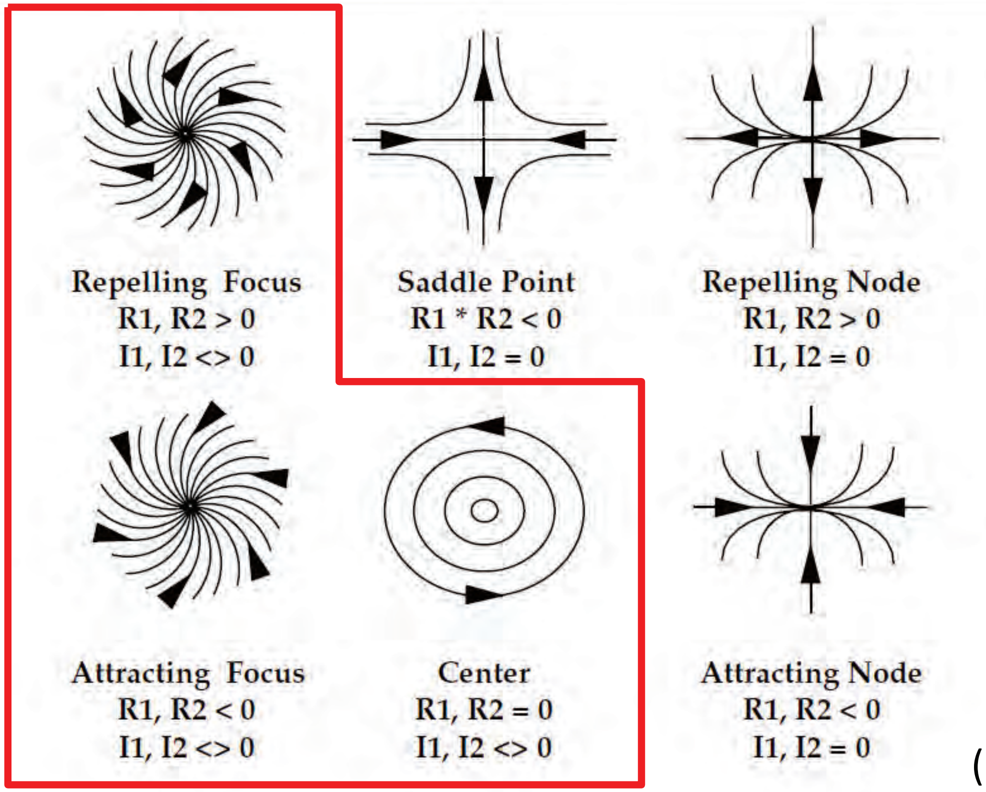
Cycle-avg'd U_{mean}/U_{in}



Normalized Perturbation Velocity $\Delta U_{mean}/U_{in}$

PIV Data Processing: Swirl Strength Parameter (*Sw*)

- Vortex Identification
  - Eigen analysis of the velocity gradient tensor
  - Non-zero Imaginary part of eigen values indicates swirling flow

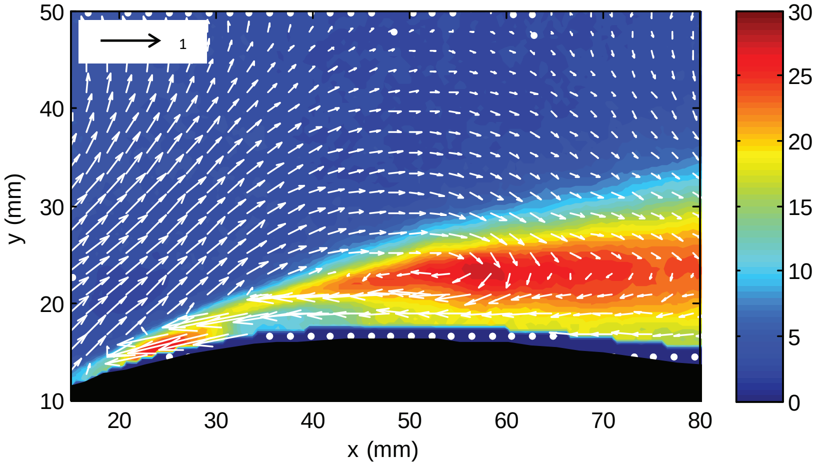


(Post et al., 2003)

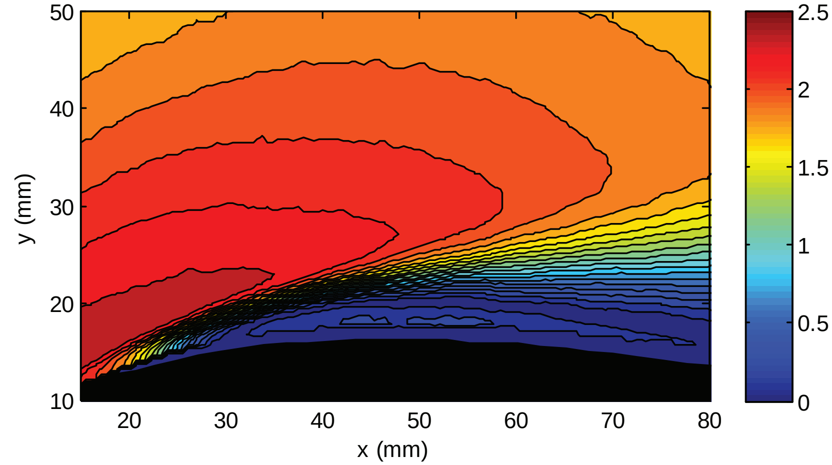
Phase #10

t/*T* = 0.3958

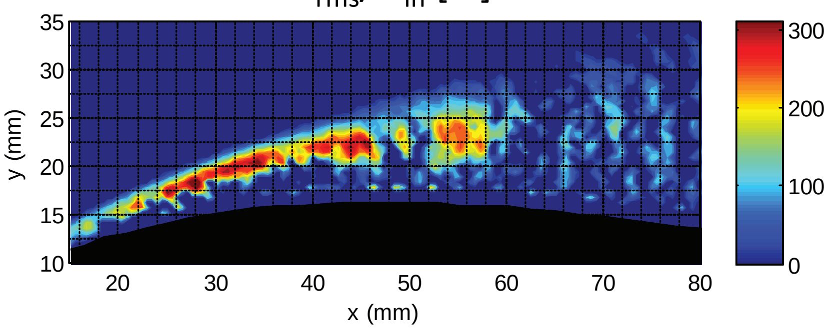
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}

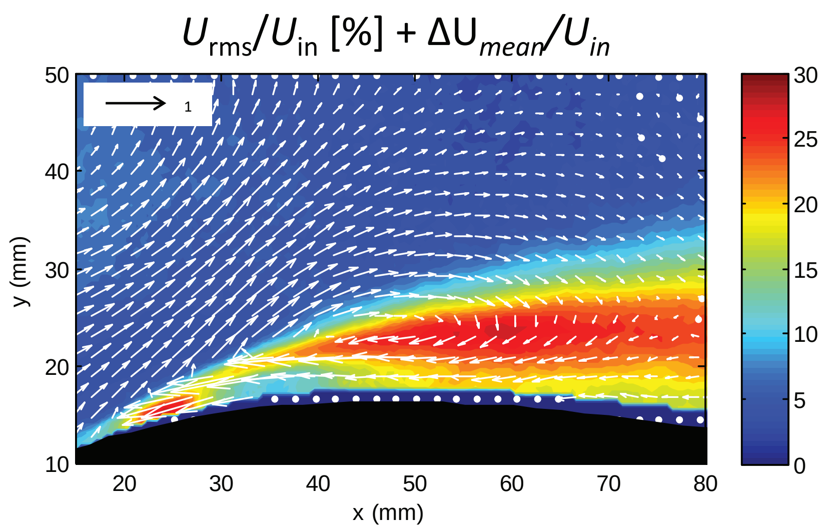


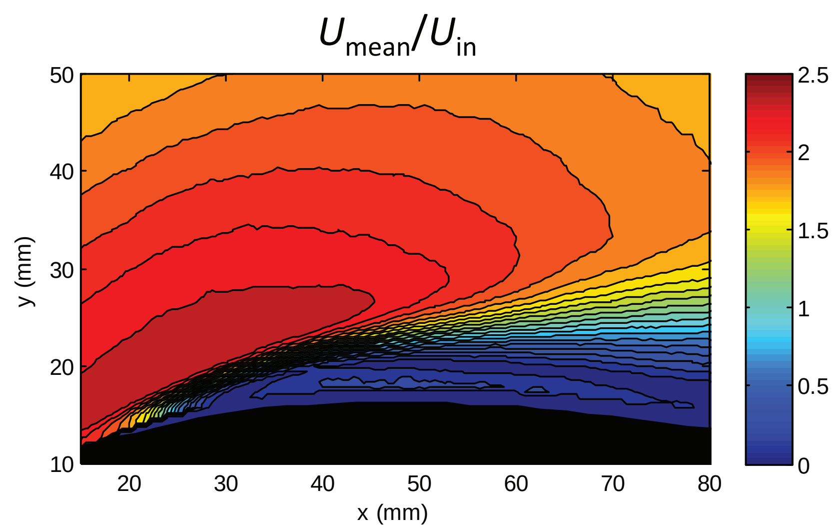
U_{rms}/U_{in} [%]

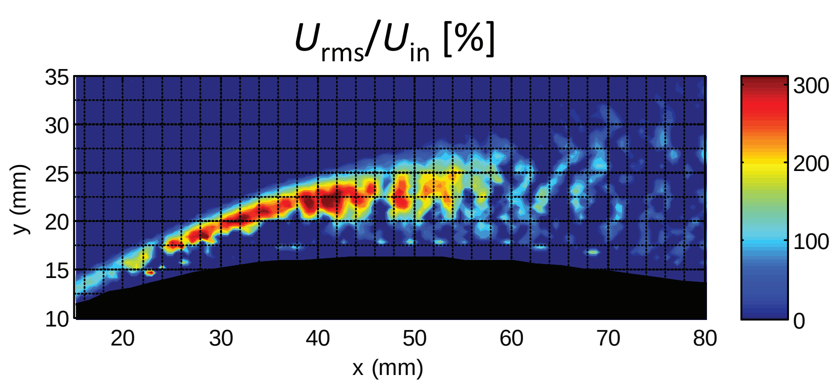


Phase #11

t/*T* = 0.4375

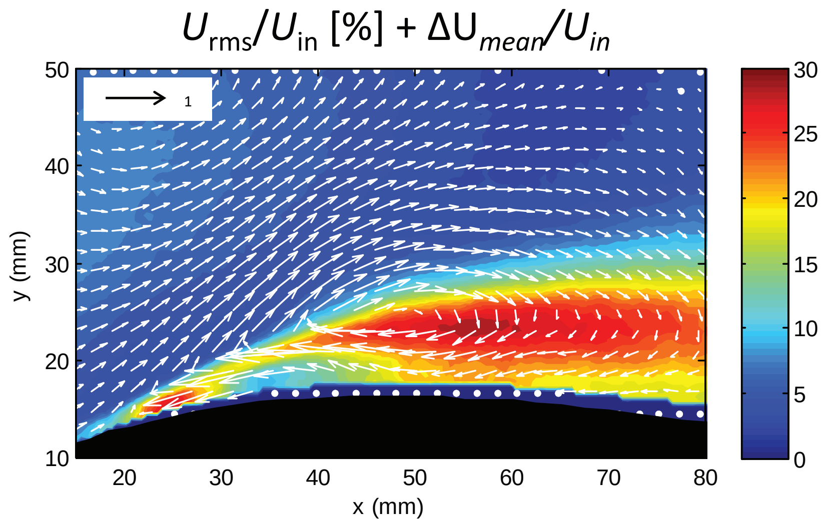


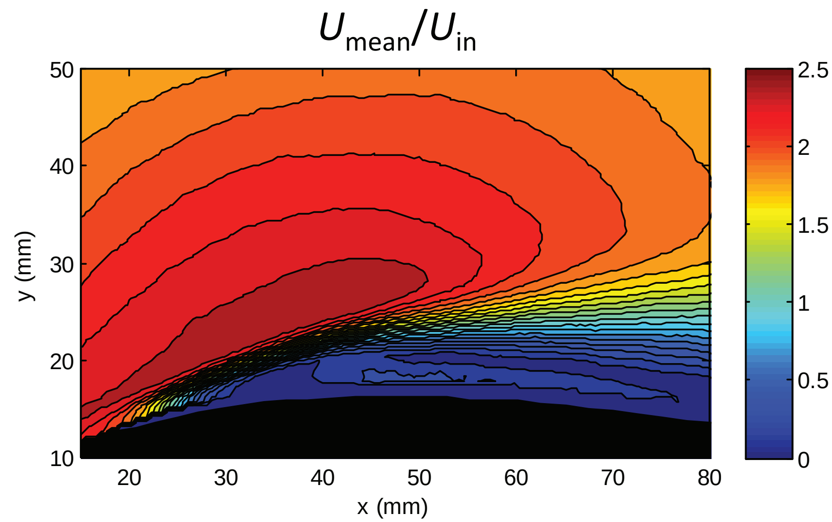


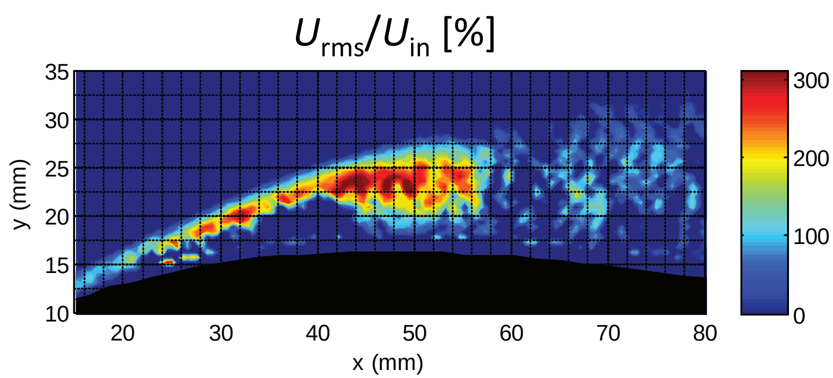


Phase #12

t/*T* = 0.4792

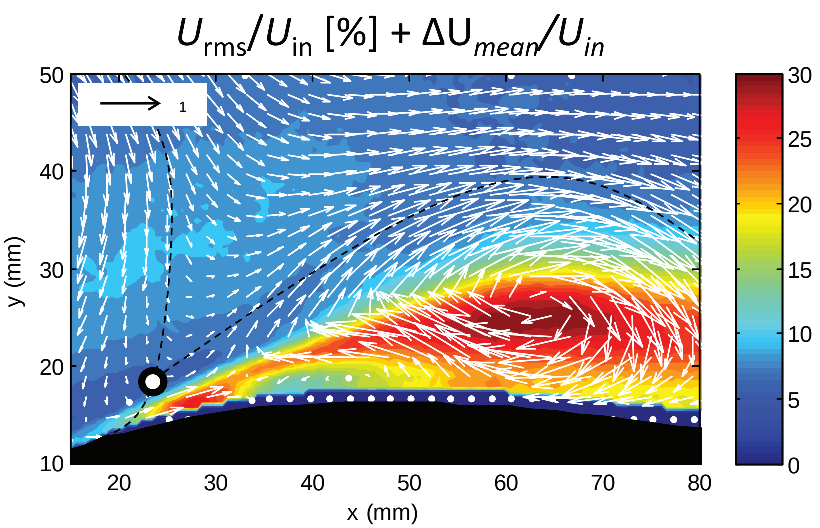


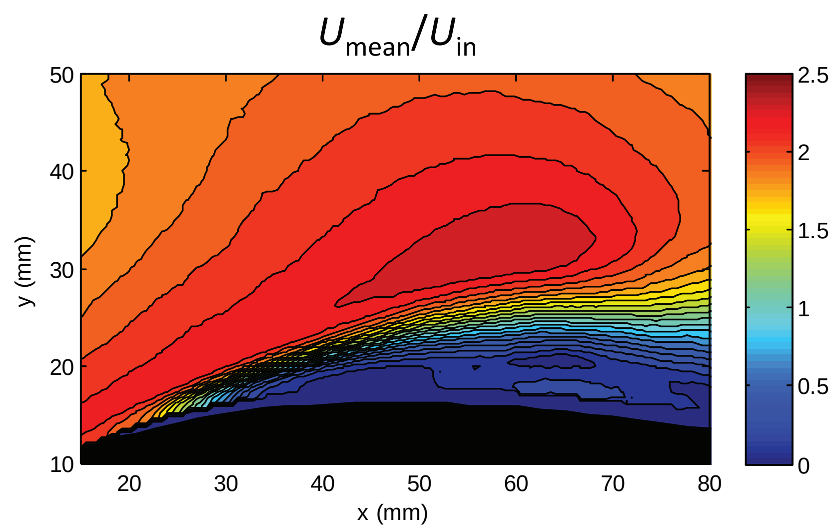


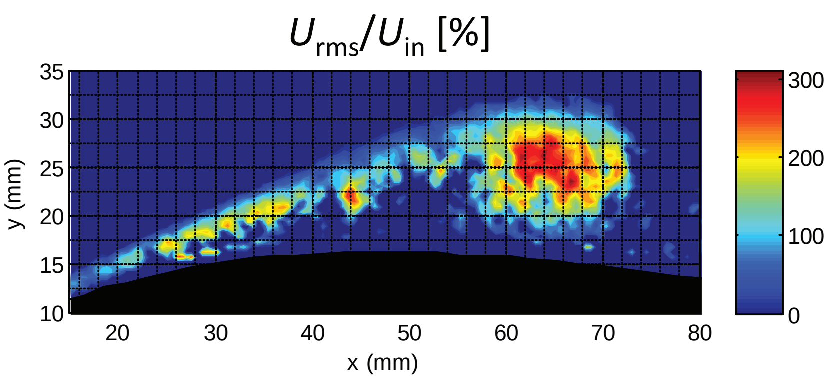


Phase #13

t/*T* = 0.5208







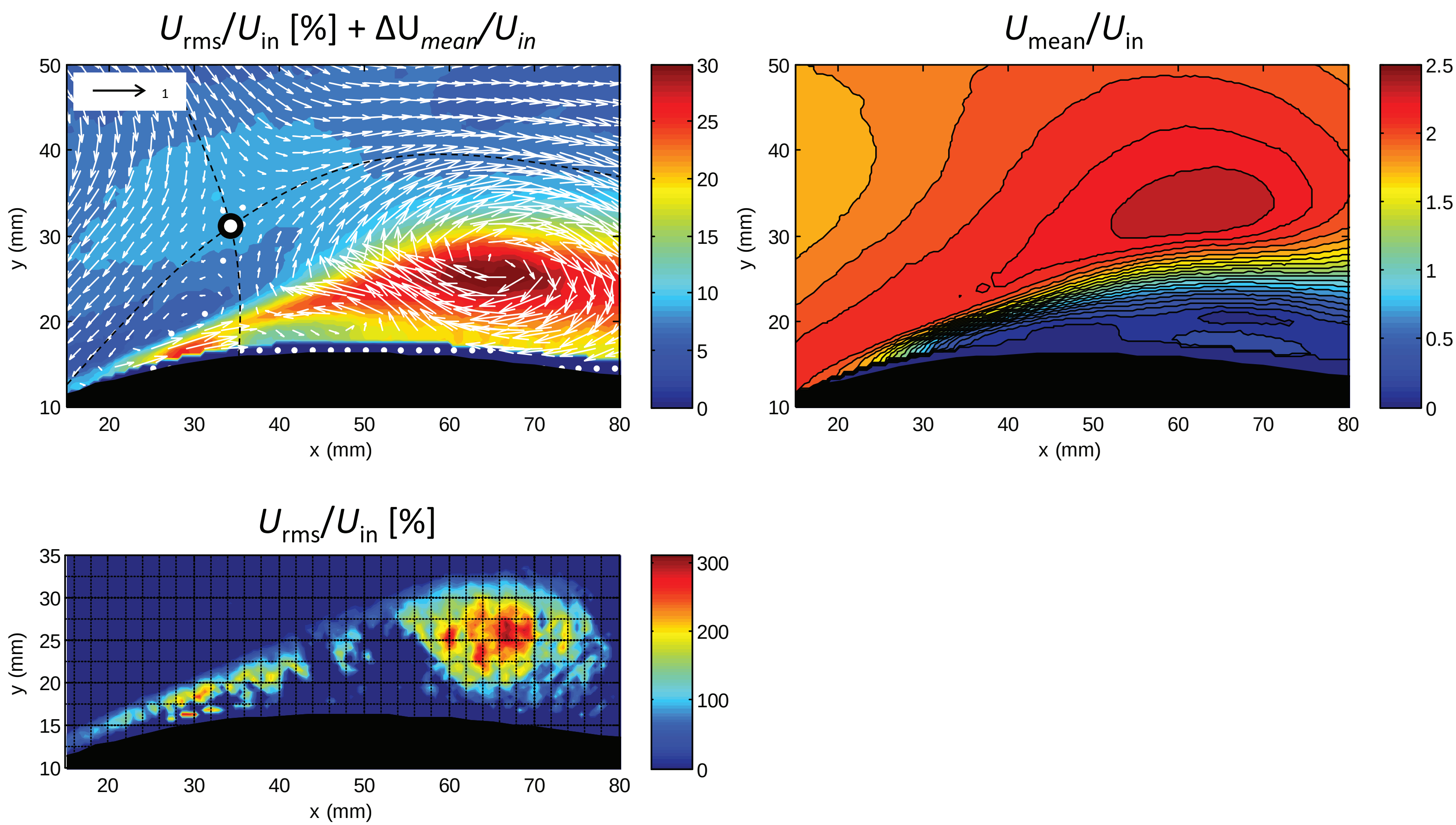
Peak $\Delta U_{mean}/U_{in} \approx 0.6$

Q1 enhances wall-bound vorticity, initiates the rollup of Q4 – forced inviscid K-H mechanism (Uzol et al., Steiger et al., etc)

Core of Q4 coincides with peak unsteadiness (U_{rms})

Phase #14

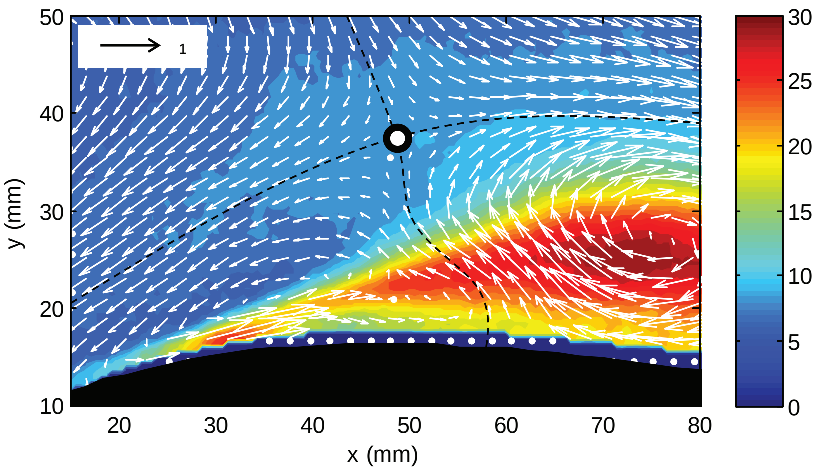
t/T = 0.5625



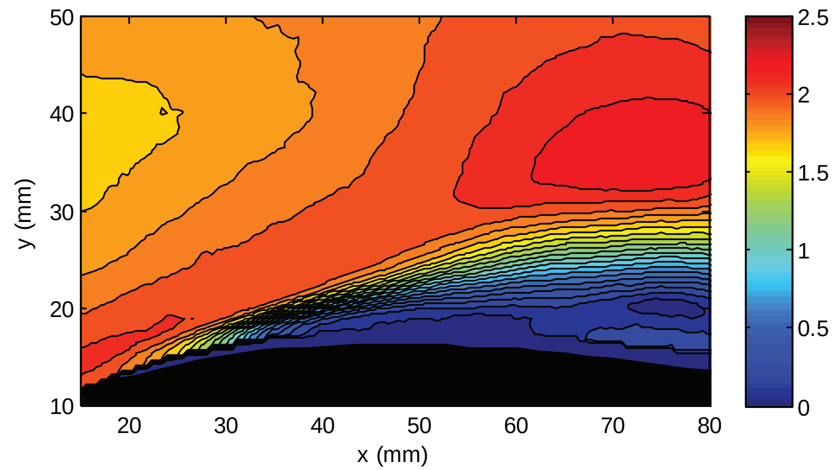
Phase #15

$t/T = 0.6042$

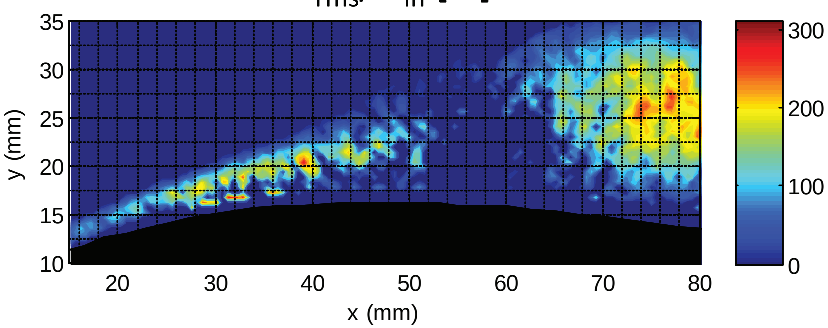
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}



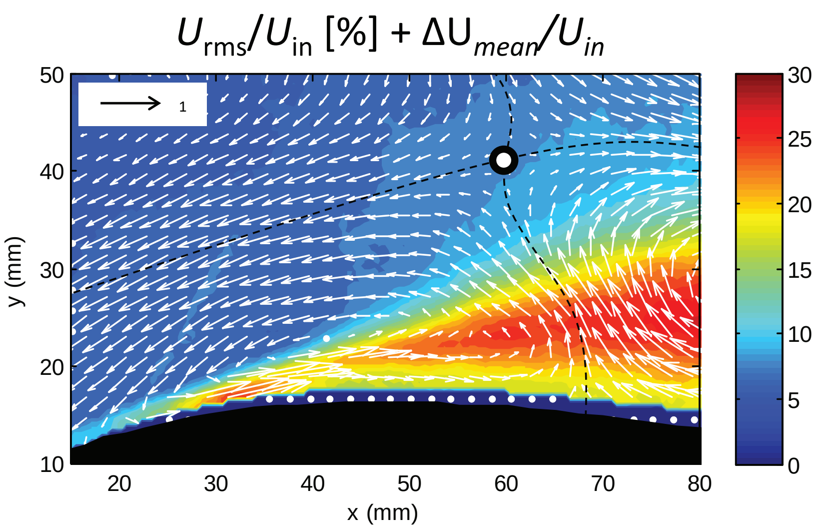
U_{rms}/U_{in} [%]

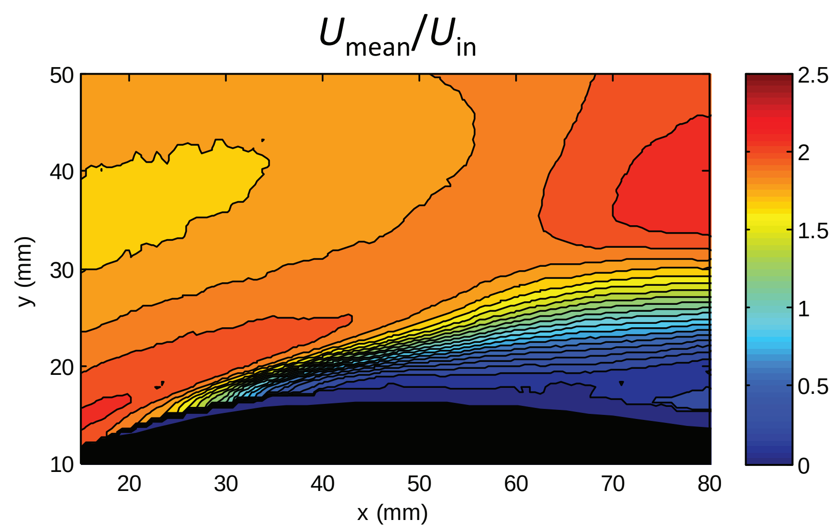


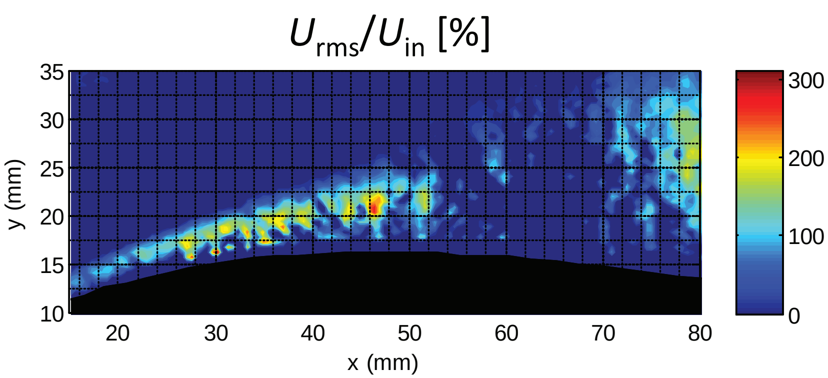
Saddle point away from the wall

Phase #16

t/*T* = 0.6458



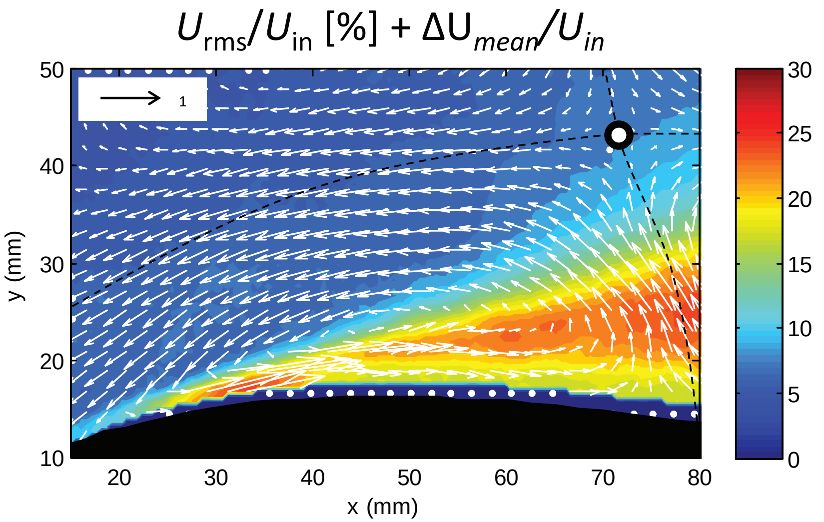


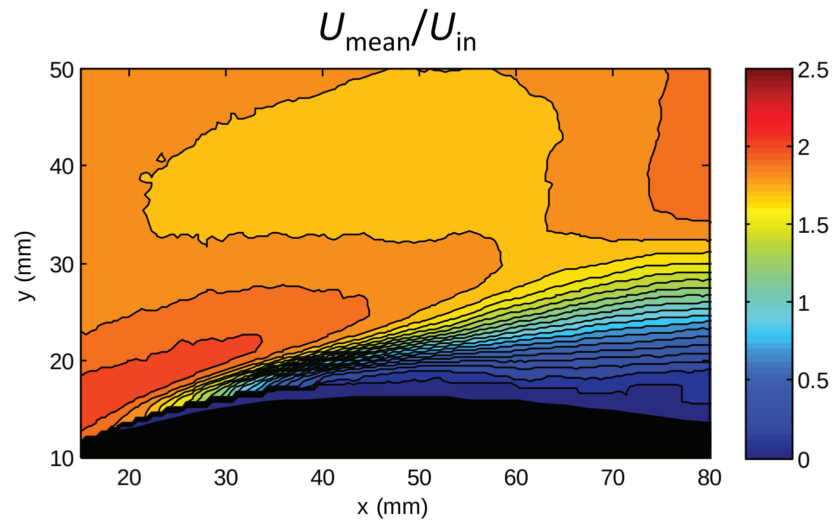


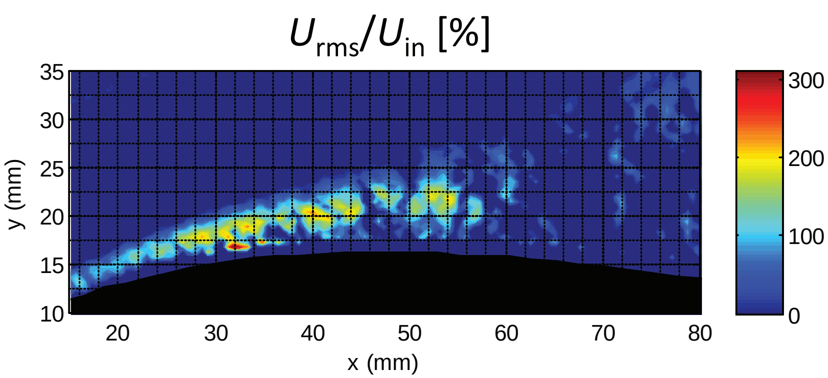
High reverse flow levels, and wall-normal distance to saddle point results in formation of Q3.

Phase #17

$t/T = 0.6875$

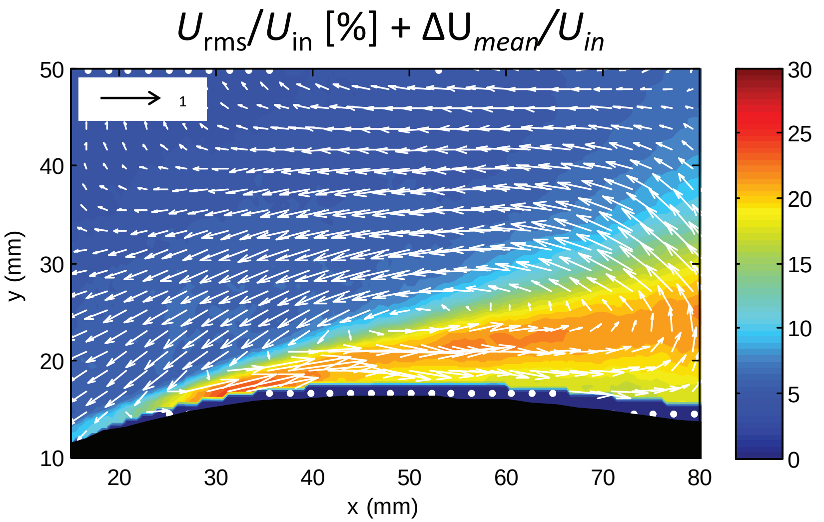


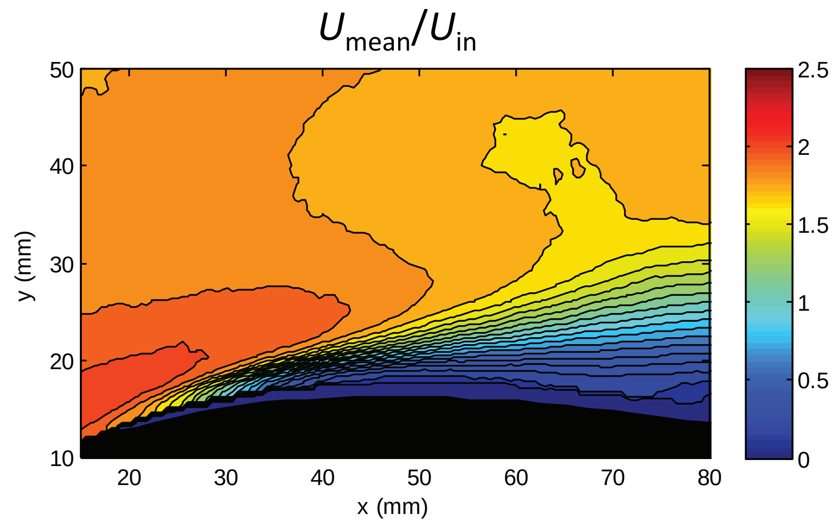


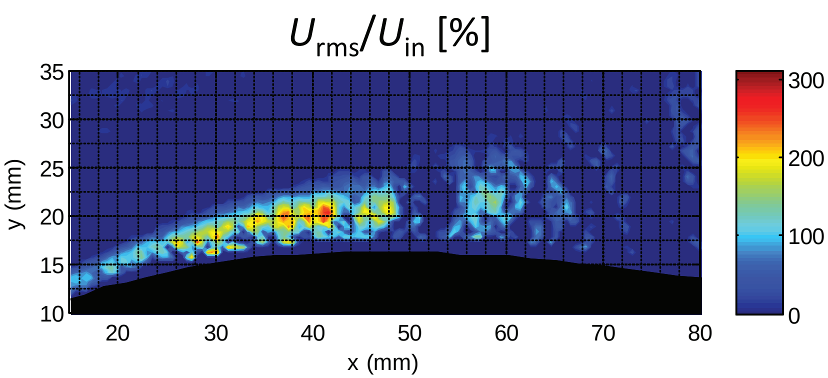


Phase #18

t/*T* = 0.7292



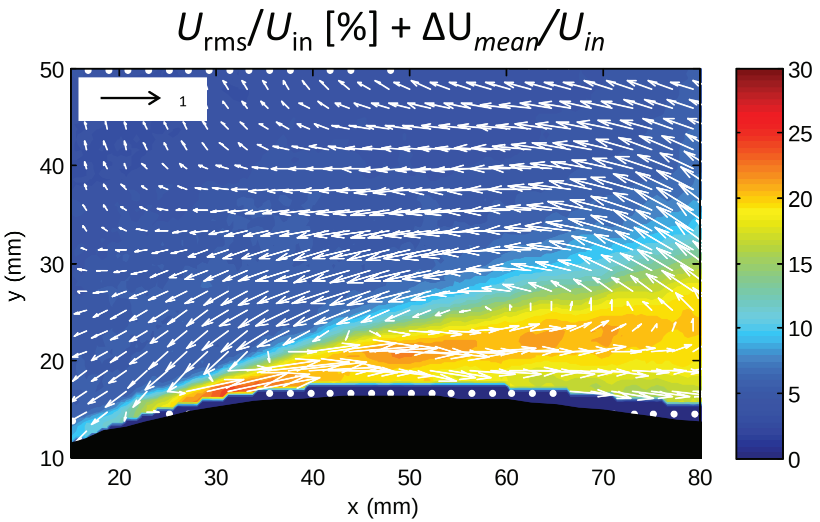


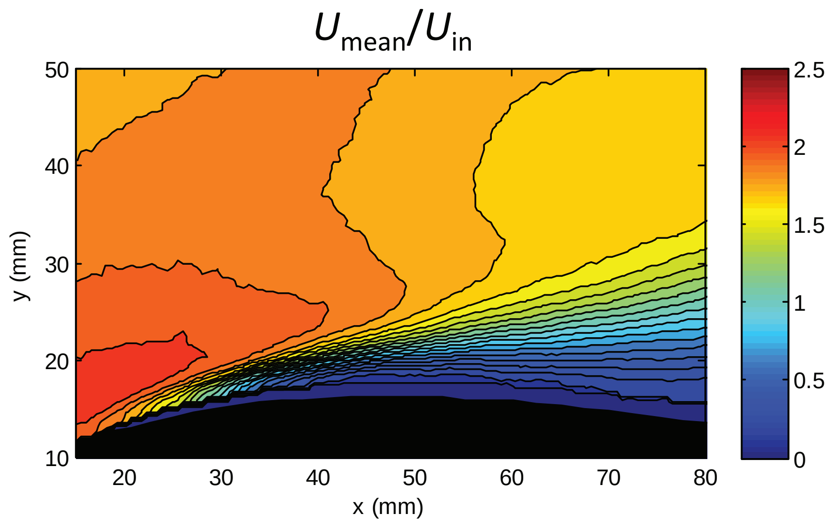


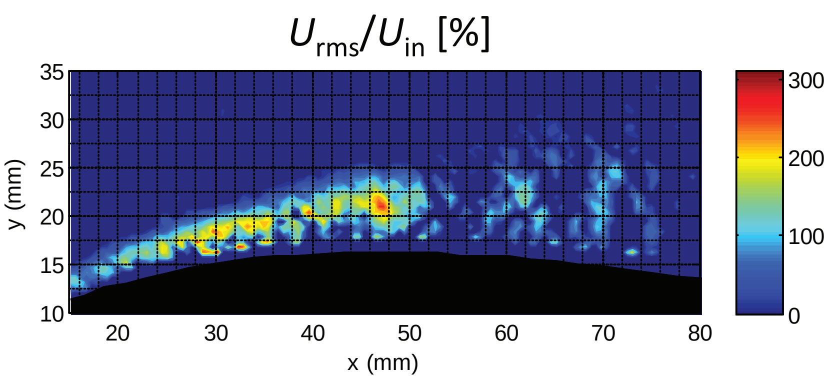
Wake-induced *calmed zone*.

Phase #19

t/*T* = 0.7708



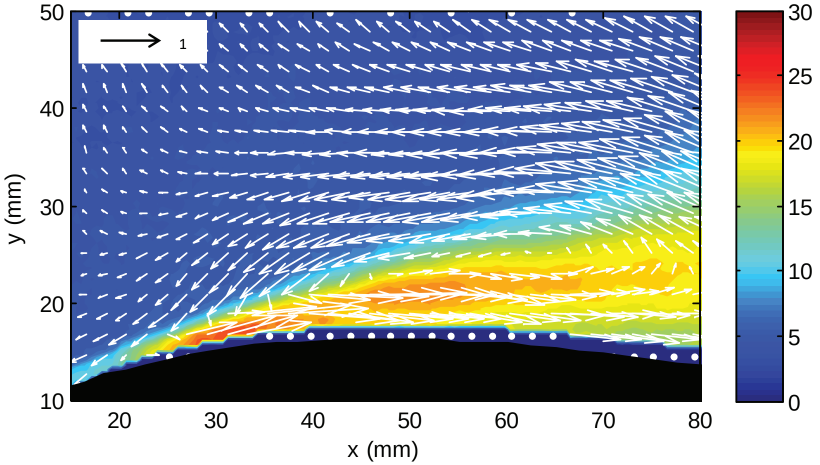




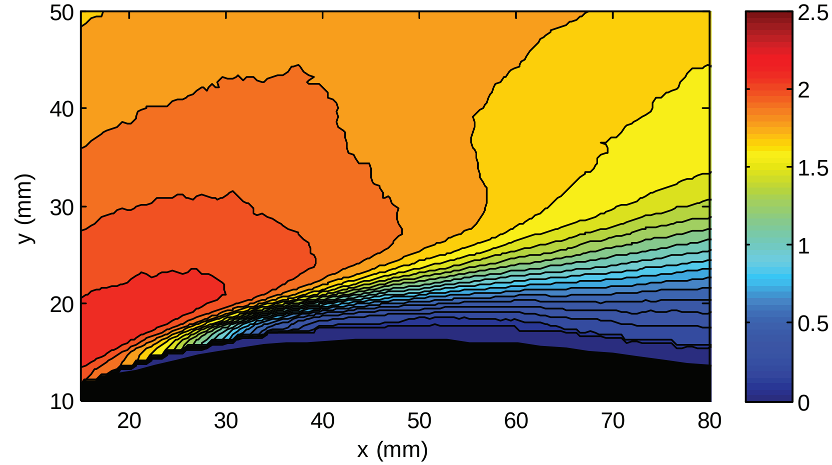
Phase #20

t/T = 0.8125

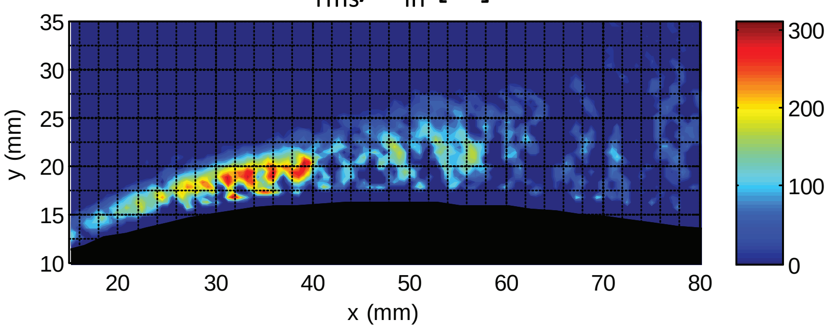
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}



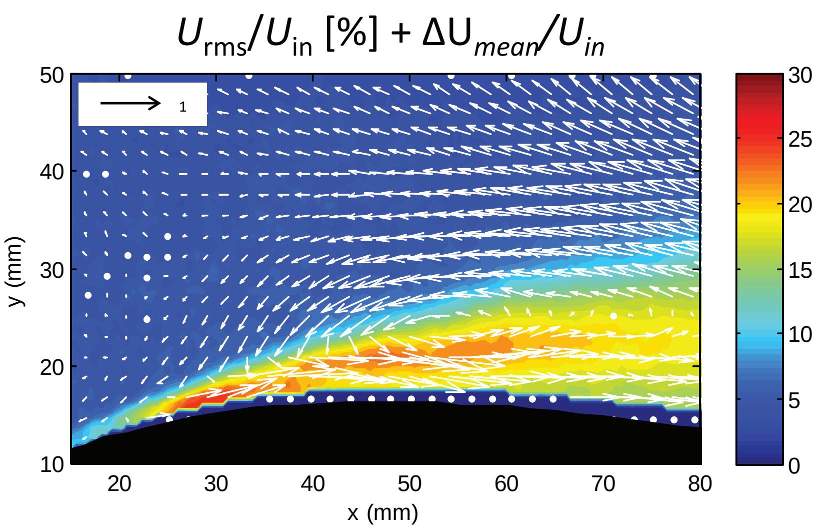
U_{rms}/U_{in} [%]

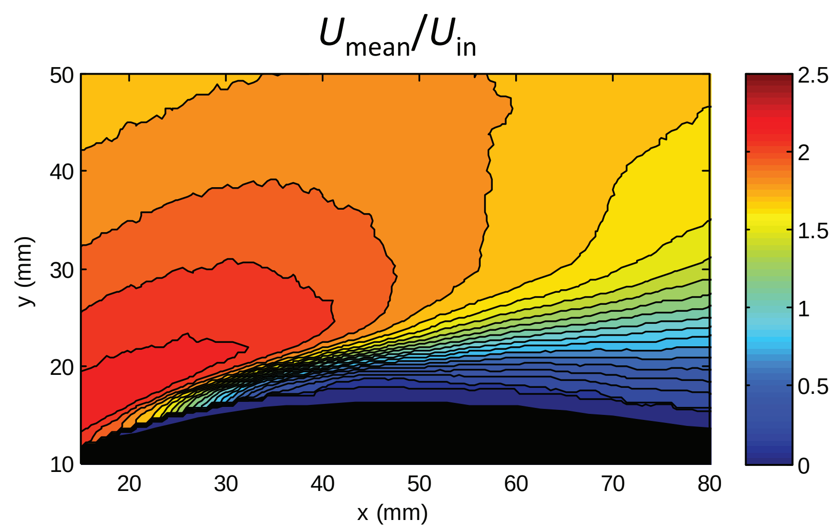


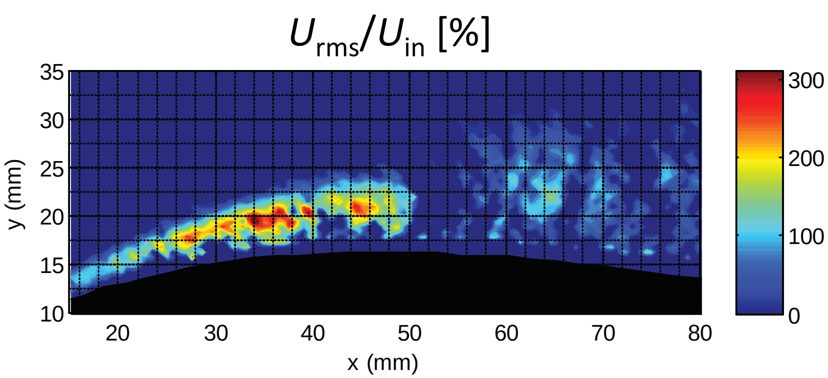
Still evidence of vorticity shedding, though weaker *Sw* values.

Phase #21

t/*T* = 0.8542



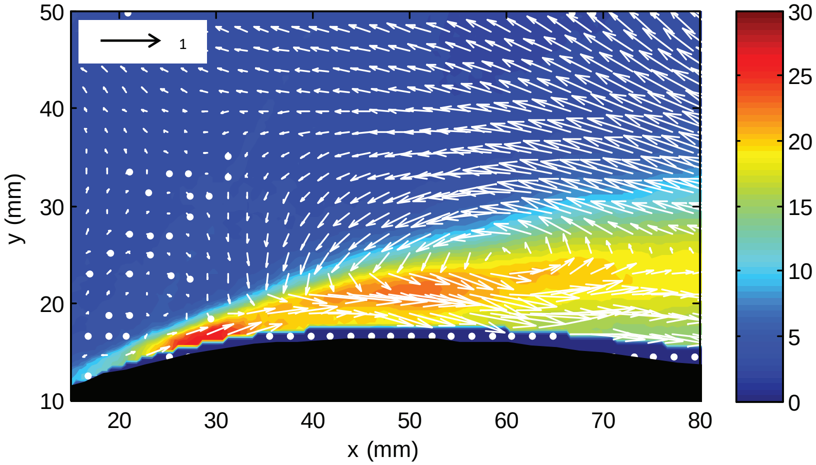




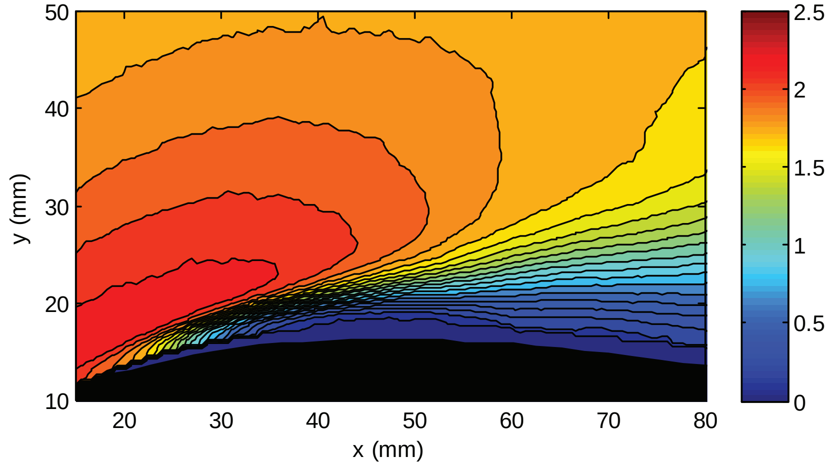
Phase #22

t/T = 0.8958

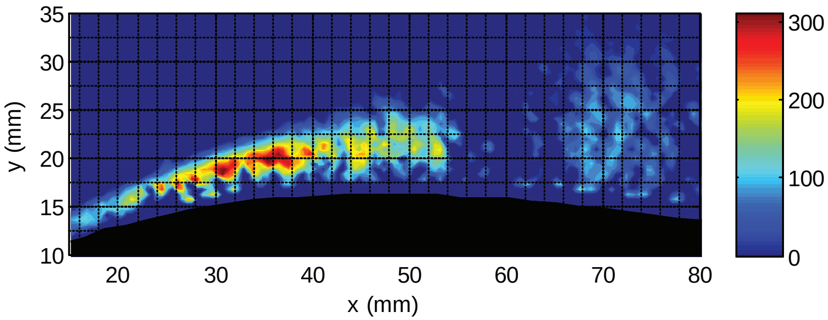
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}

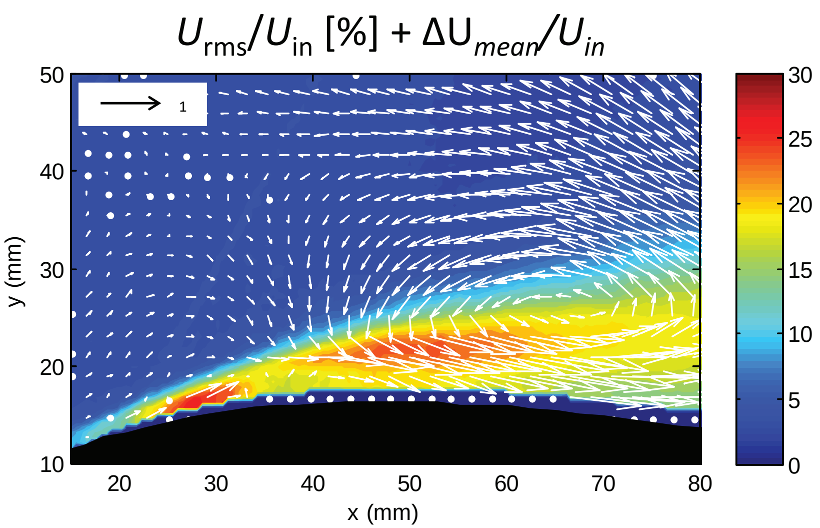


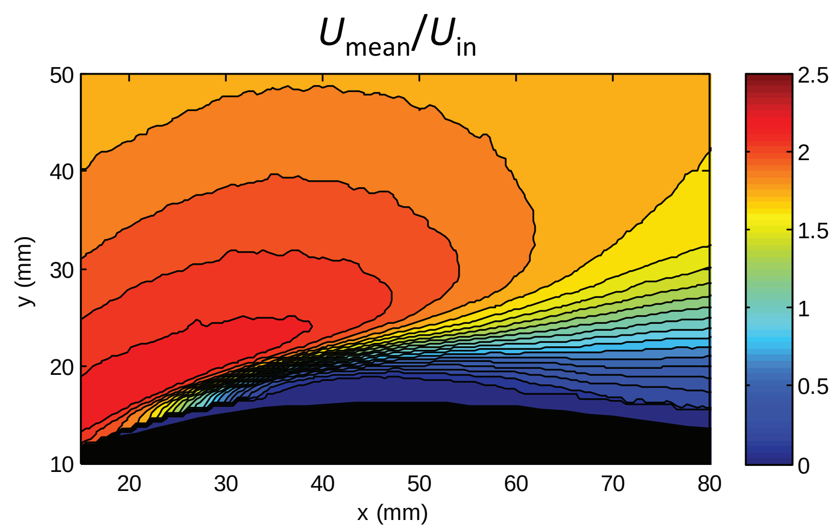
U_{rms}/U_{in} [%]

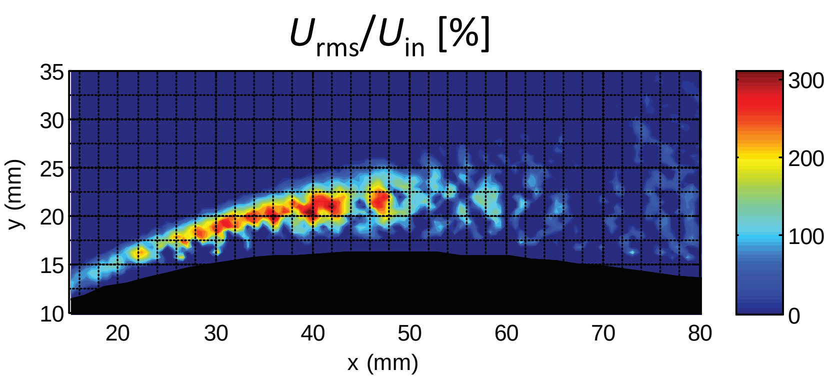


Phase #23

t/T = 0.9375



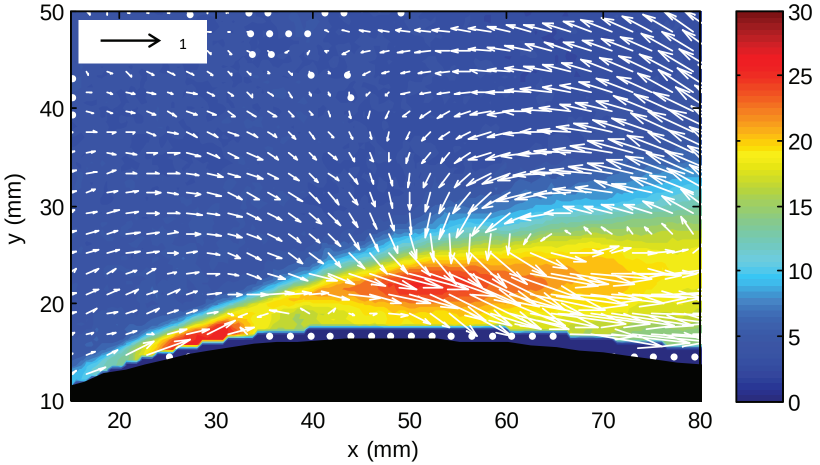




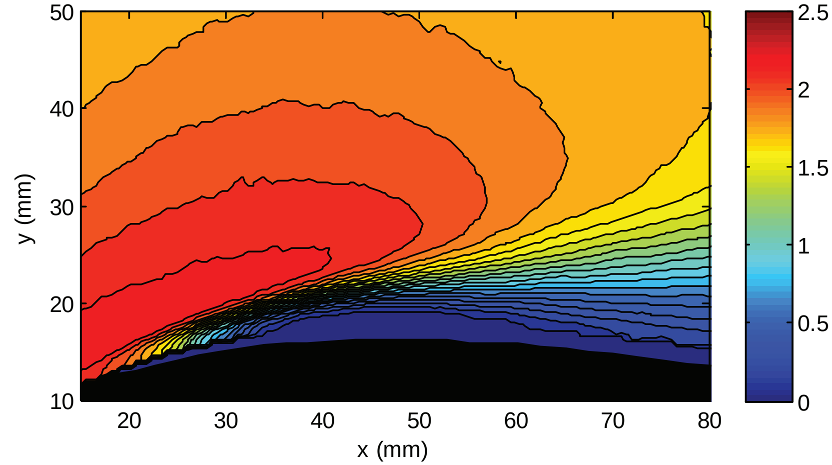
Phase #24

t/*T* = 0.9792

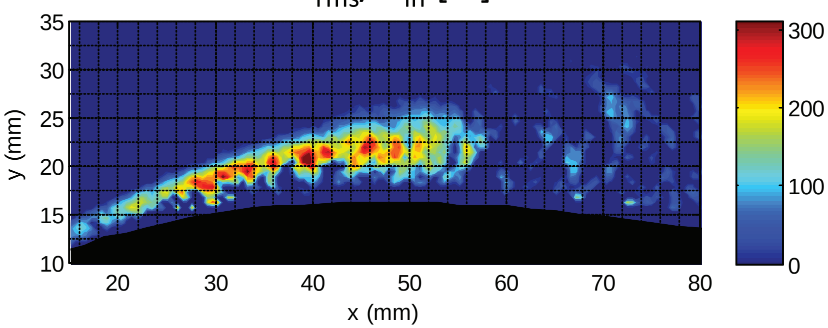
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}

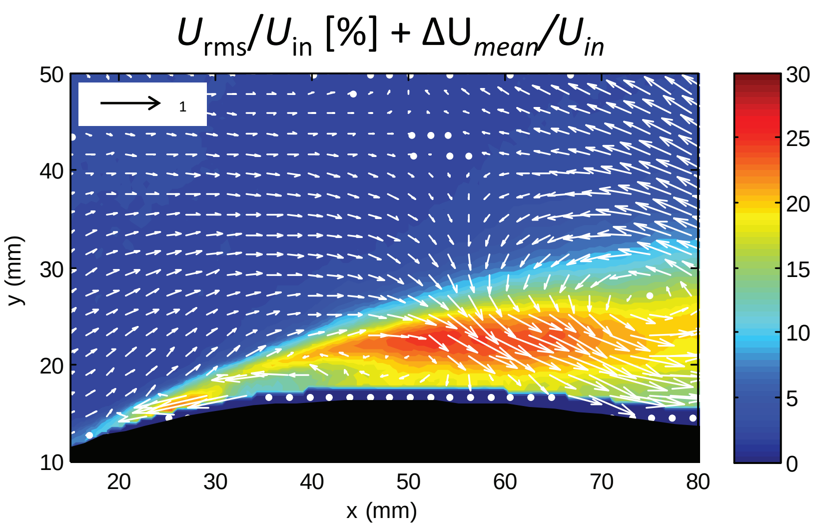


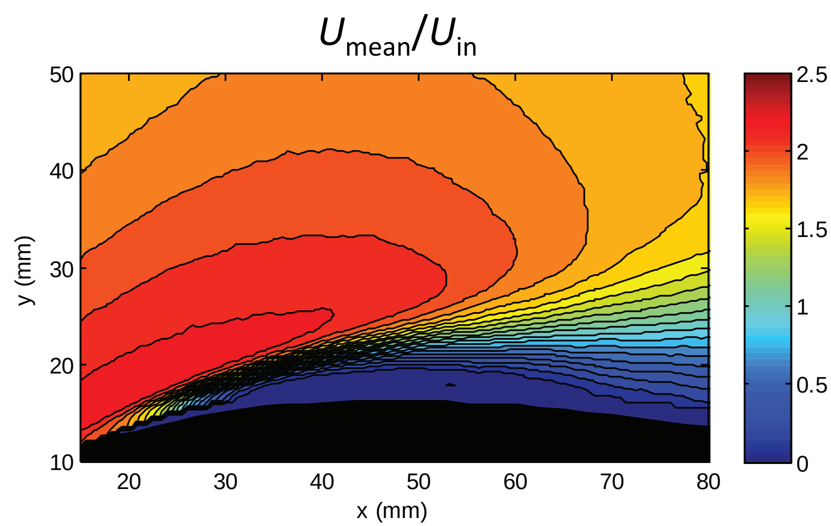
U_{rms}/U_{in} [%]

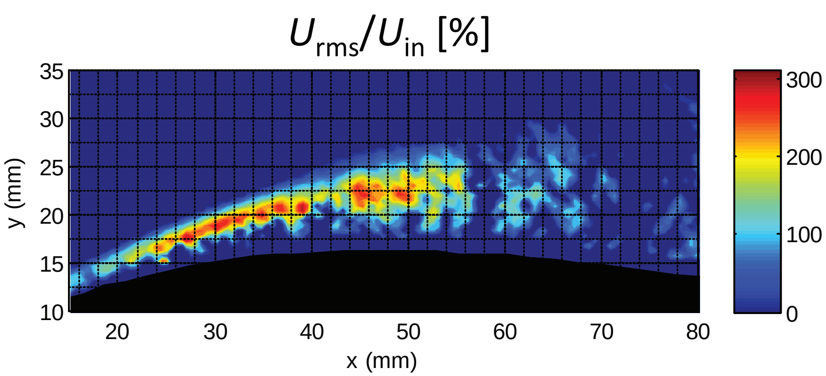


Phase #1

$t/T = 0.0208$



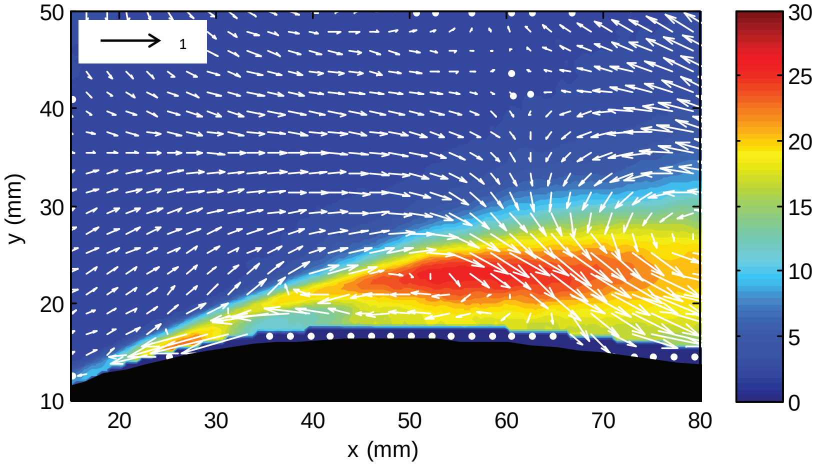




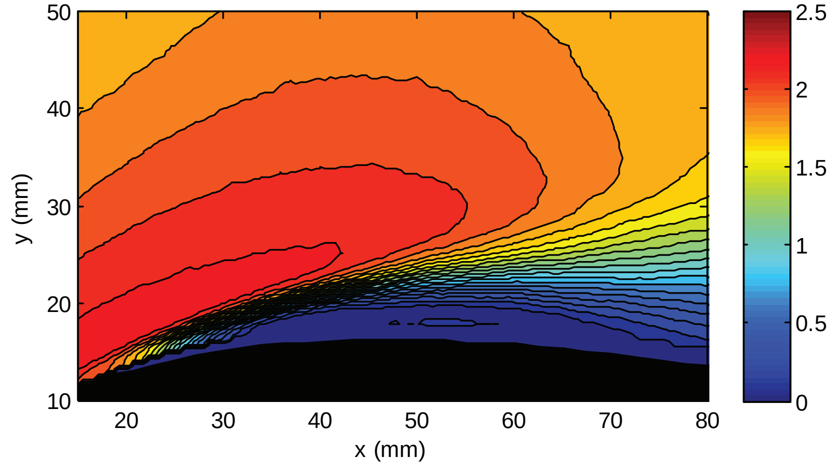
Phase #2

t/*T* = 0.0625

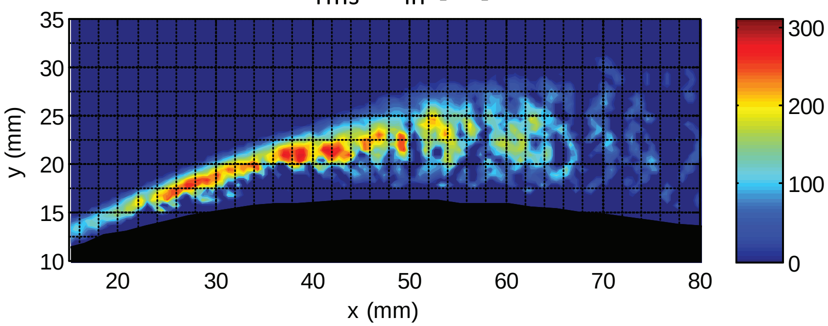
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}

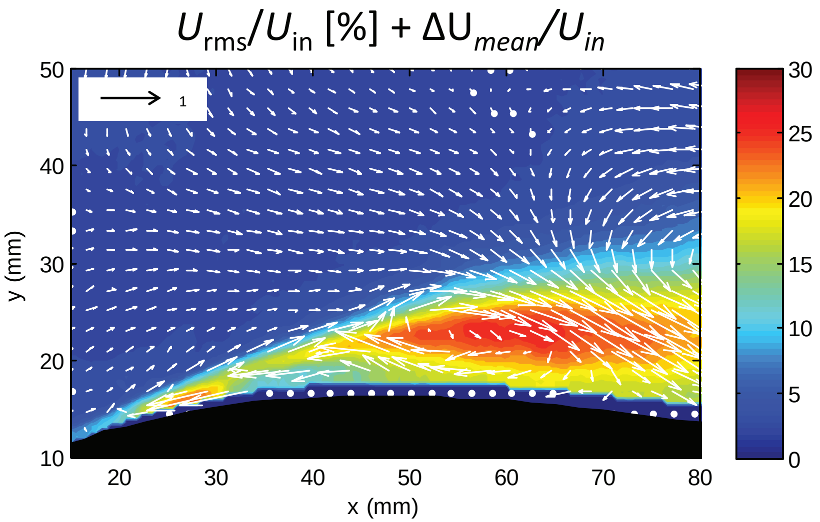


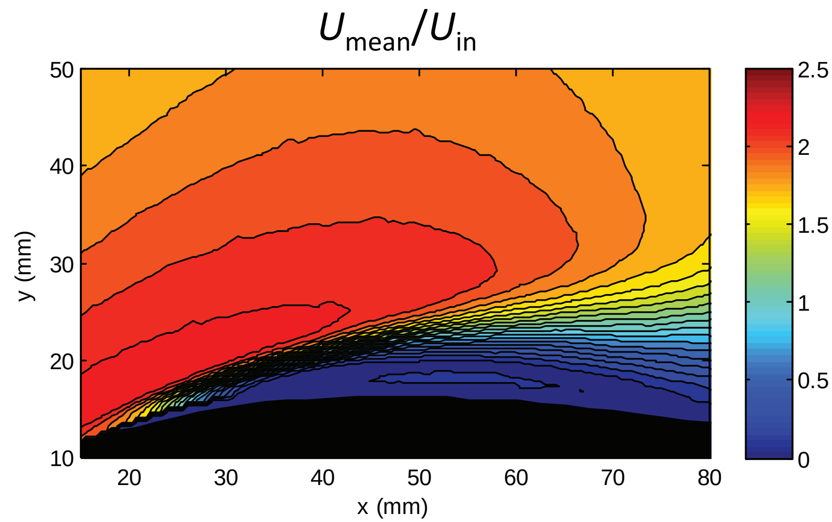
U_{rms}/U_{in} [%]

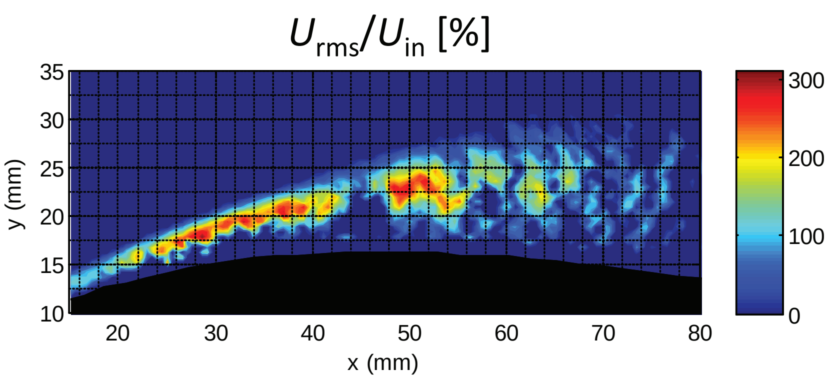


Phase #3

t/*T* = 0.1042



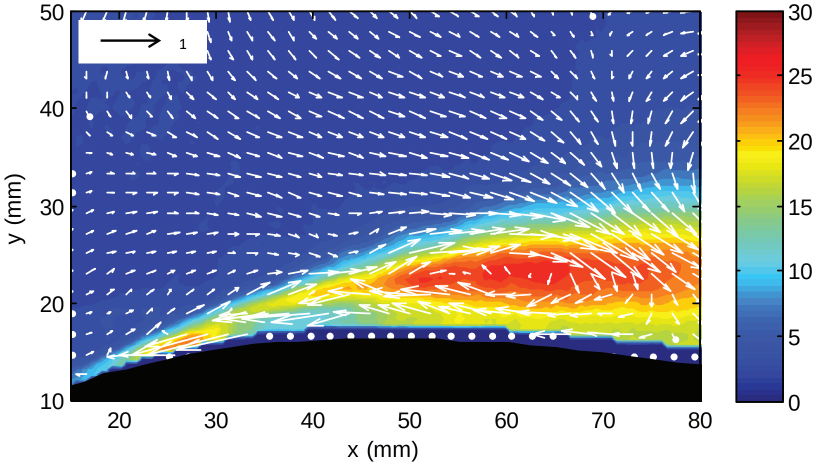




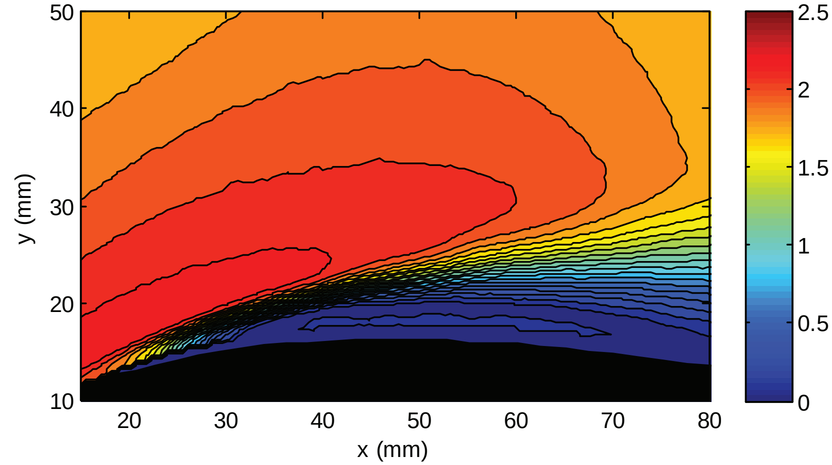
Phase #4

t/T = 0.1458

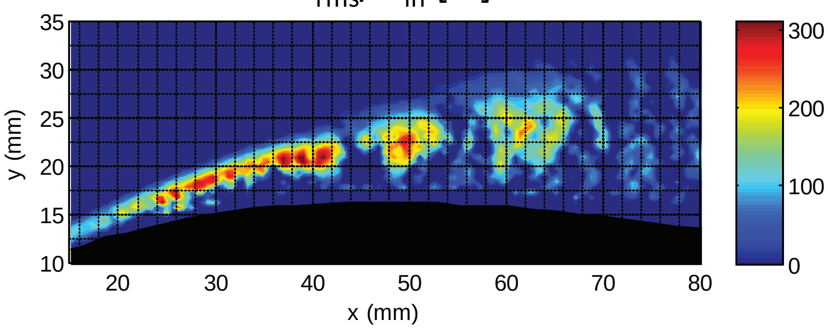
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}

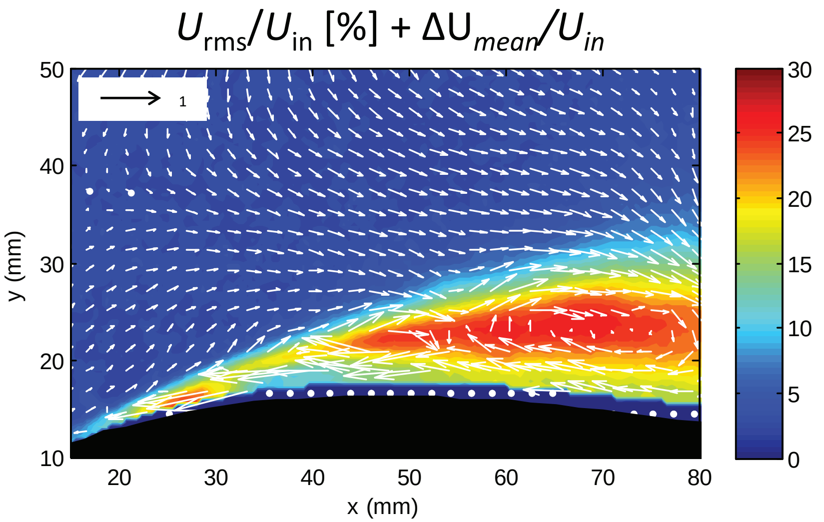


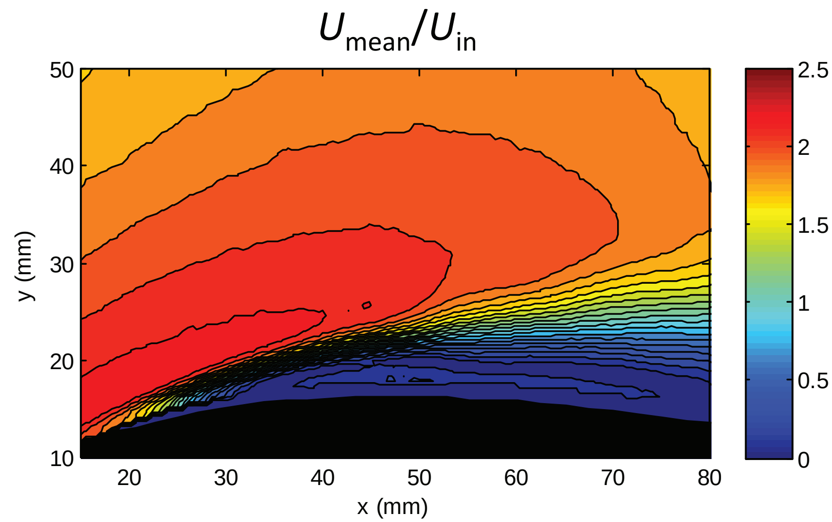
U_{rms}/U_{in} [%]

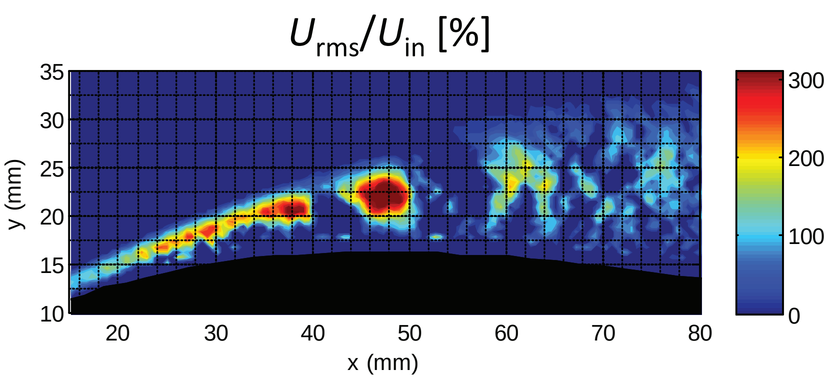


Phase #5

t/T = 0.1875

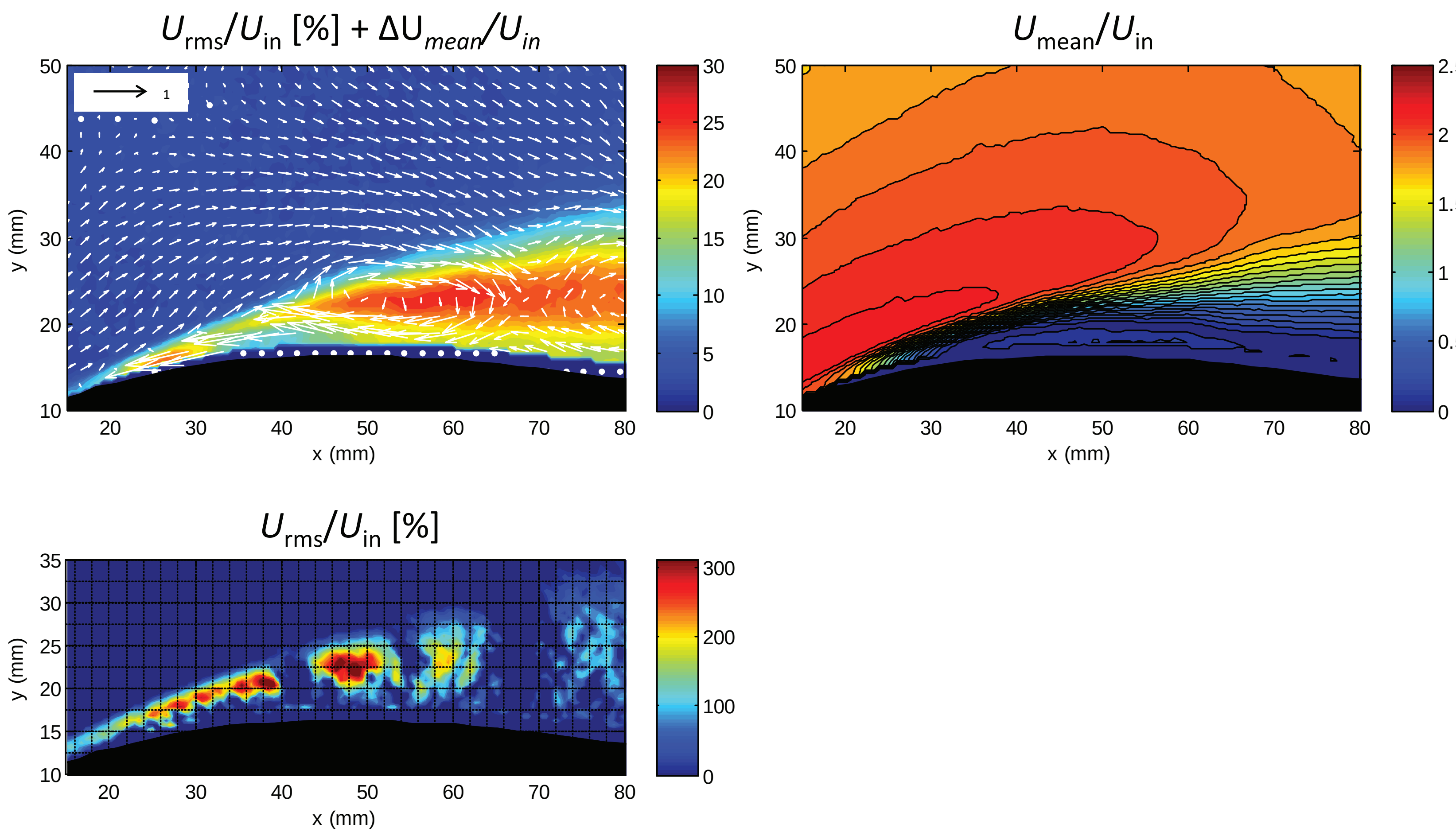






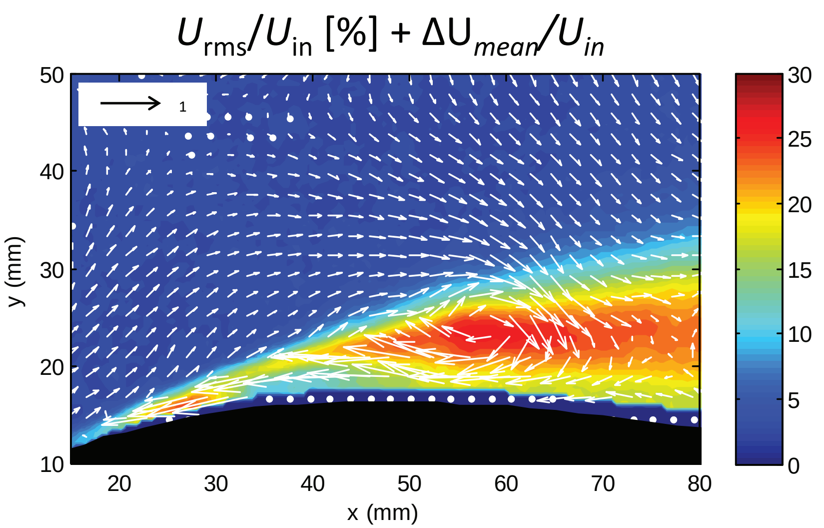
Phase #6

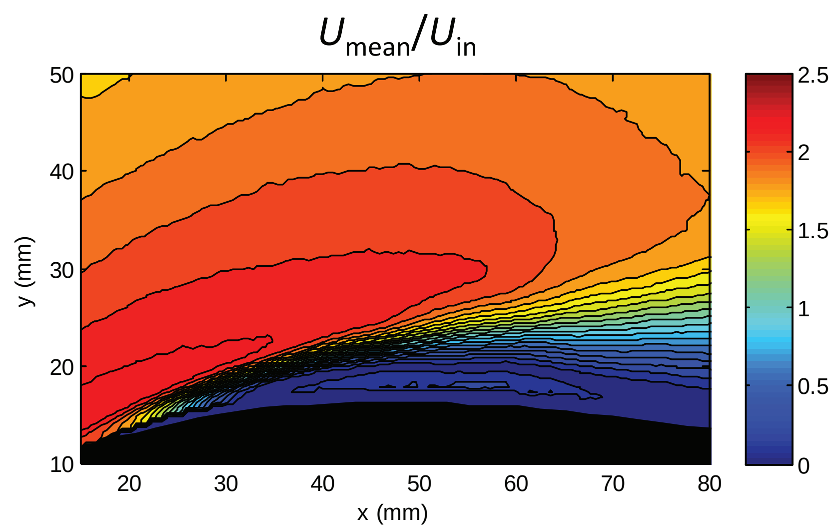
t/*T* = 0.2292

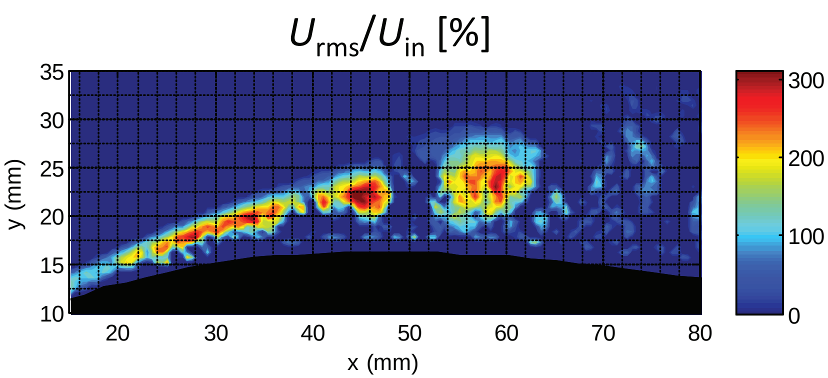


Phase #7

t/T = 0.2708





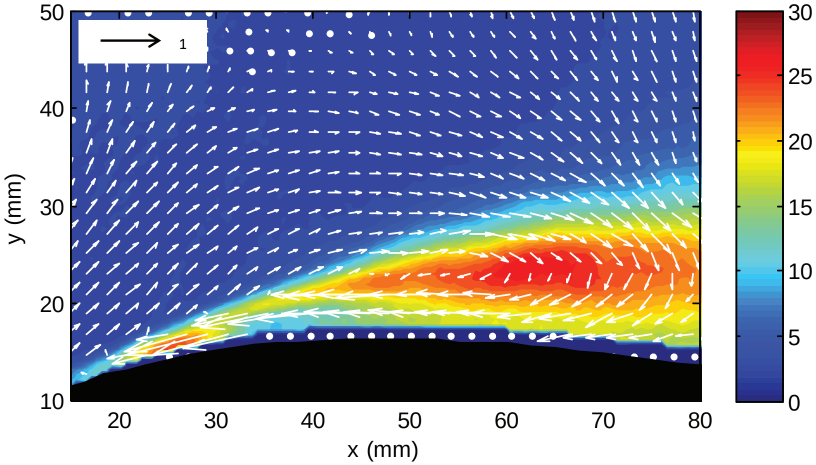


Dense regions of high Sw indicative of vorticity shedding from within the BL

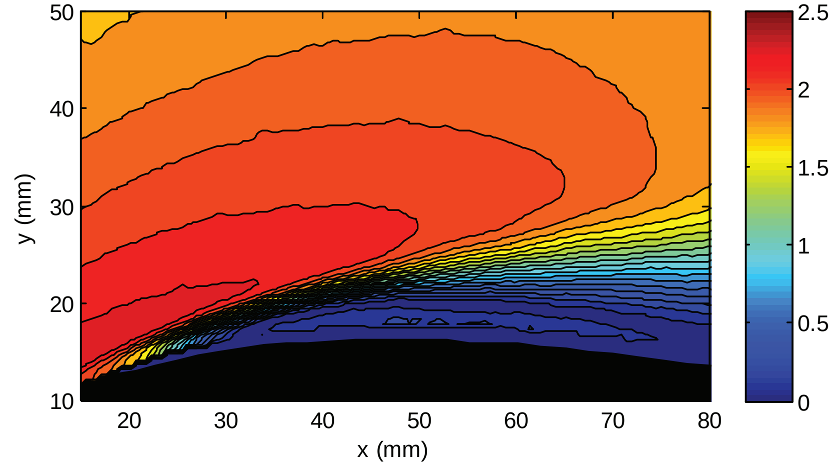
Phase #8

t/*T* = 0.3125

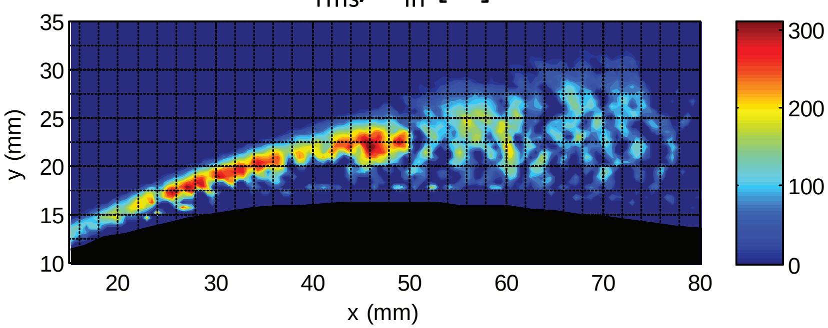
U_{rms}/U_{in} [%] + $\Delta U_{mean}/U_{in}$



U_{mean}/U_{in}

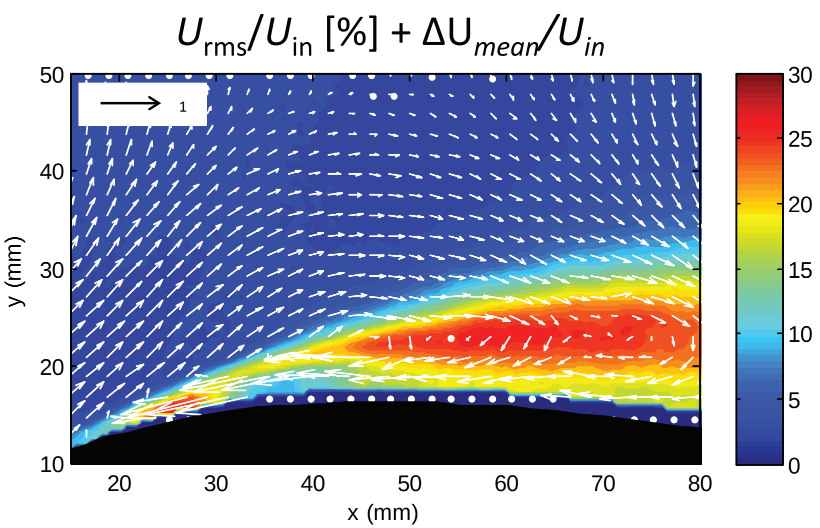


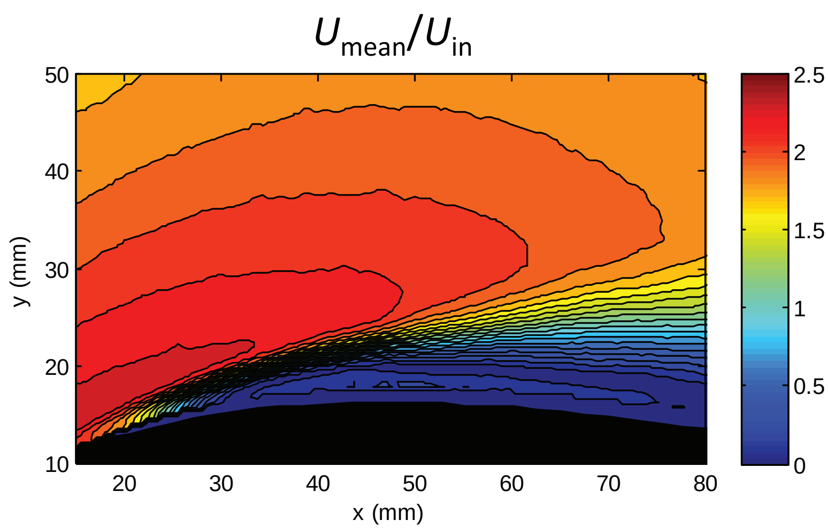
U_{rms}/U_{in} [%]

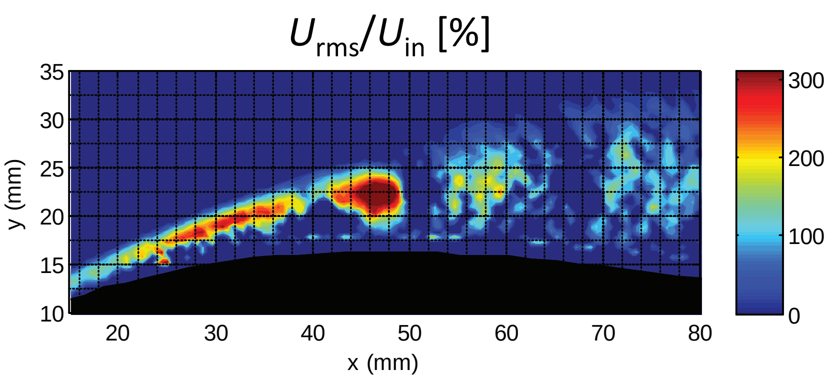


Phase #9

t/*T* = 0.3542

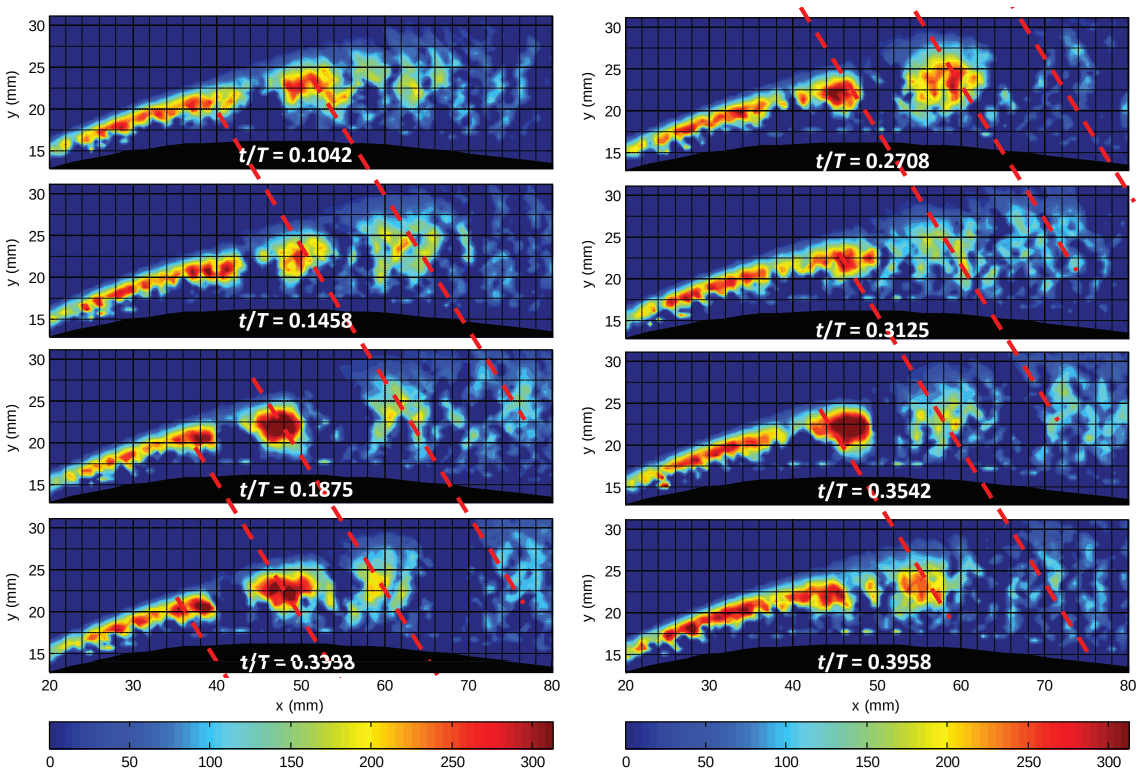






Large-scales structures breaking down into smaller scales as they convect downstream

Vortex Shedding – Wake Forcing



Recall that these are contours of Sw for the ensemble-averaged flow field. For each phase shown, 800 image pairs were processed.

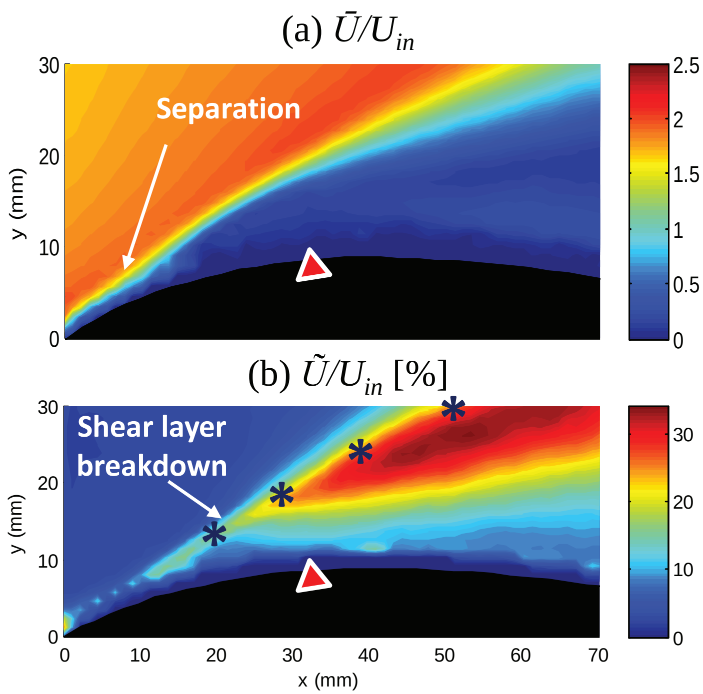
Since these features have survived the averaging process, can surmise that the structures are real.

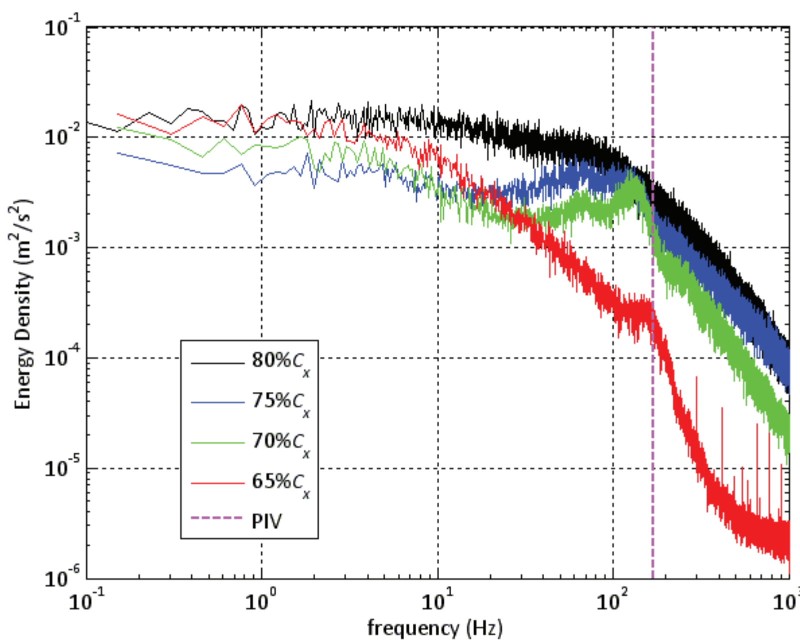
Vortex shedding from within the BL seems to lock into the wake forcing, even though the shedding frequency is an order of magnitude higher.

Use spacing between vortices (wavelength) and vortex convection speed to estimate the shedding frequency → 195Hz

Vortex Shedding – Wake Forcing

Revisit the steady-state case and collect measurements of power spectra at the wall-normal location of peak skewness

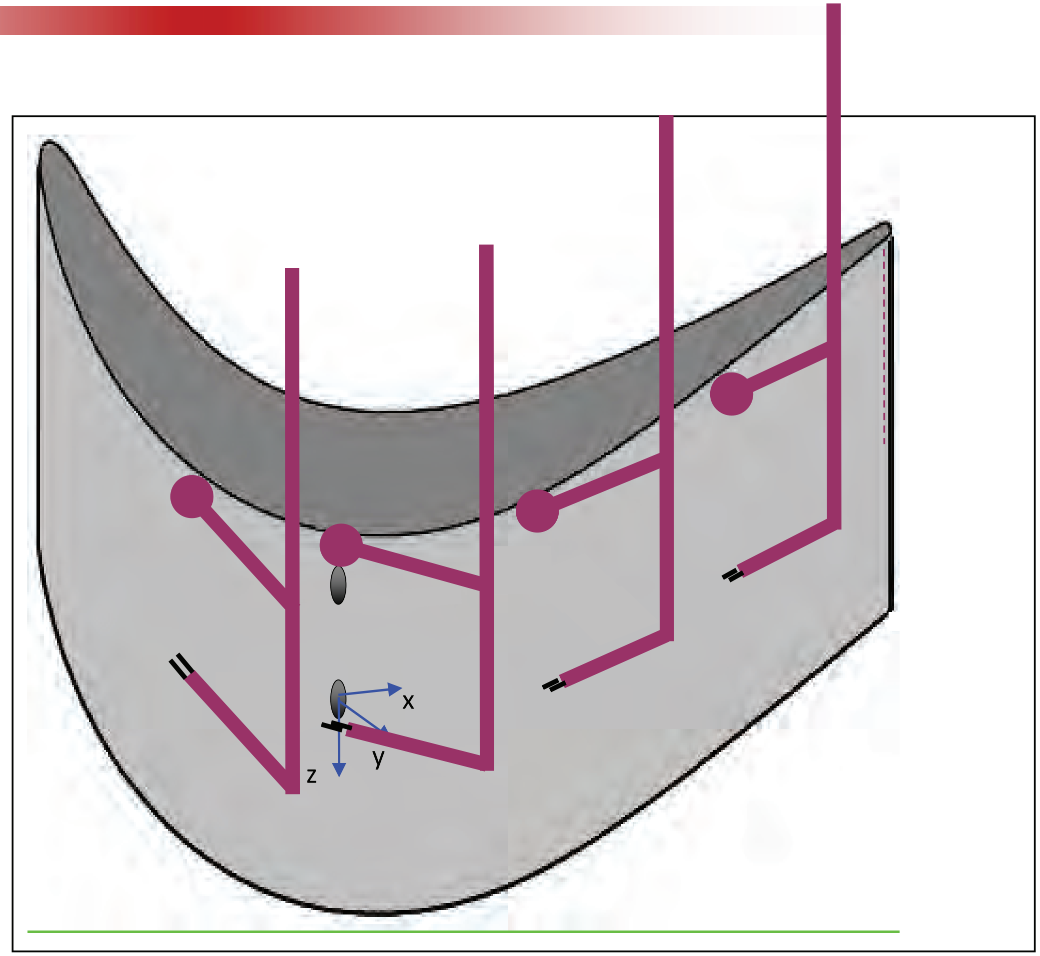




The estimated frequency from contours of *Sw* (wake-only PIV data) is very near to the significant frequency in steady-state conditions.

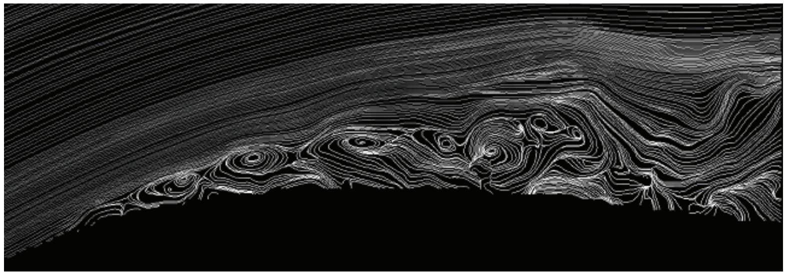
Blade Follower for Time-Resolved Hot-Film Measurements

- Single element hot-film for turbulence statistics.
- Blade-follower used to take data in streamwise direction at 14 fixed wall distances over curved blade surface.
- Data rate:10kHz for 20 seconds (200 ksamples)
- Calculate:
  - rms fluctuation
  - intermittency
  - others…

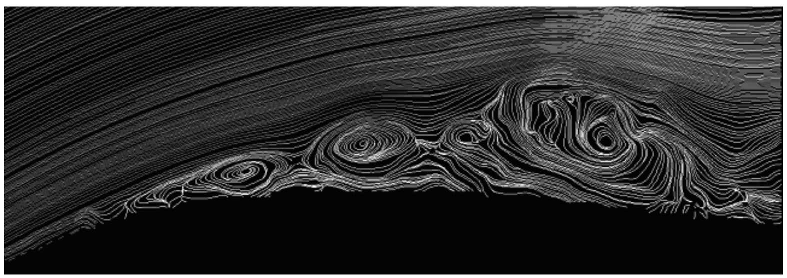


Representative Snapshots during Wake-Passing Period: Wakes-Only (F_{red} = 0.40)

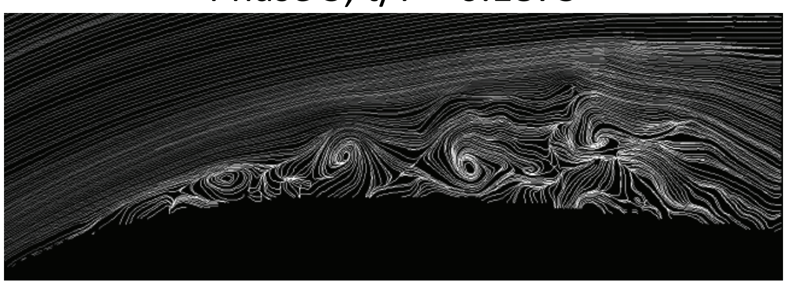
Phase 3, t/*T* = 0.1042



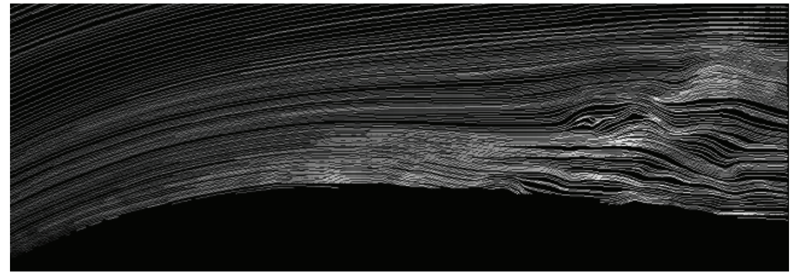
Phase 4, t/*T* = 0.1458



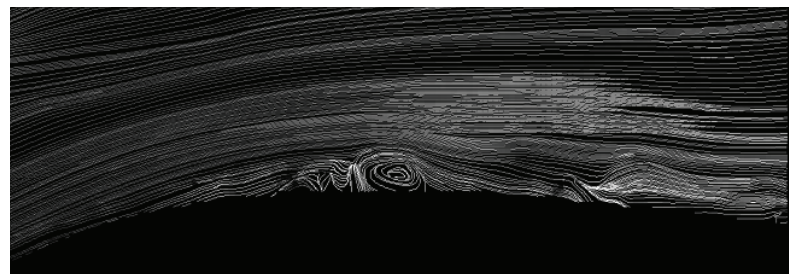
Phase 5, t/*T* = 0.1875



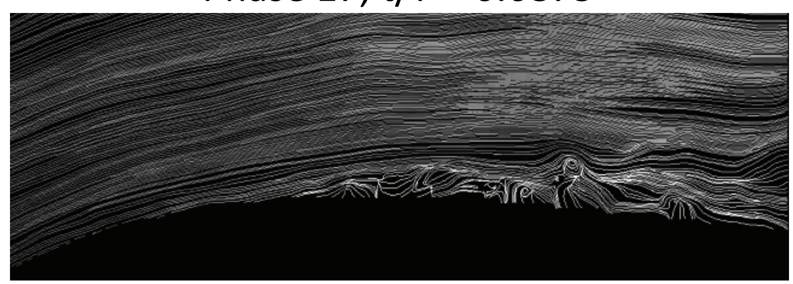
Phase 10, t/*T* = 0.3958



Phase 12, t/*T* = 0.4792



Phase 17, t/*T* = 0.6875



Session 7
Keynote Presentations

NASA/CP—2020-220327

LP Turbine Research Issues: Physical Phenomena & Performance Modelling

John Coull
Howard Hodson

Whittle Laboratory, University of Cambridge

Whittle Laboratory

Outline

- Physical Problems (HPH)
  - Freestream disturbance environment
  - Multi-modal unsteady transition
  - Endwall boundary layers
- Modelling Performance (JDC)
  - Profile Loss:
    - Key parameters
    - Preliminary Design Method
  - Mean-line Case Study:
    - Smith Chart design space
    - Lift Coefficient
    - Secondary Loss Models
    - Increasing blade lift

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LP Turbine Disturbance Environment

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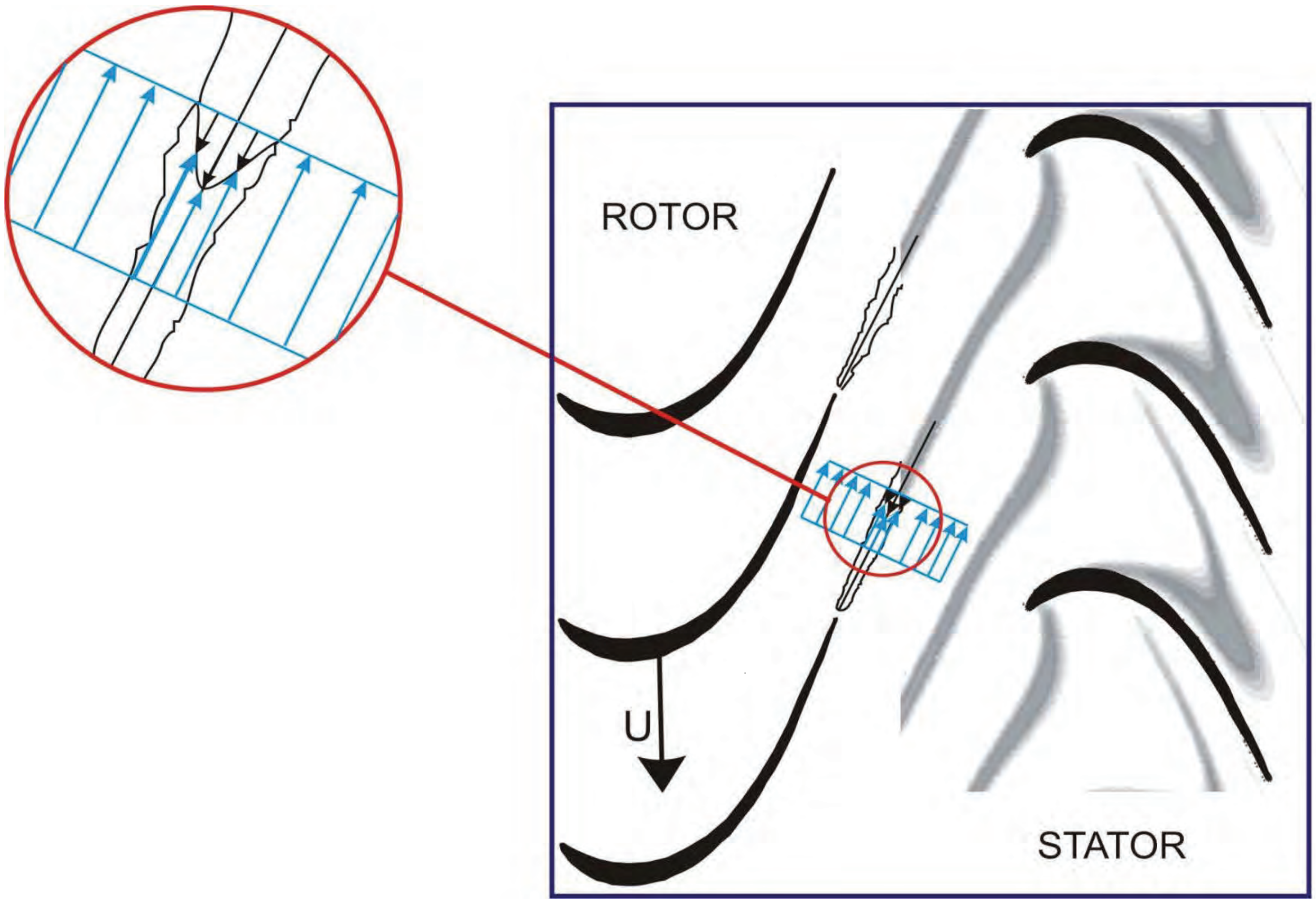
Unsteady wakes: Meyer's Negative Jet



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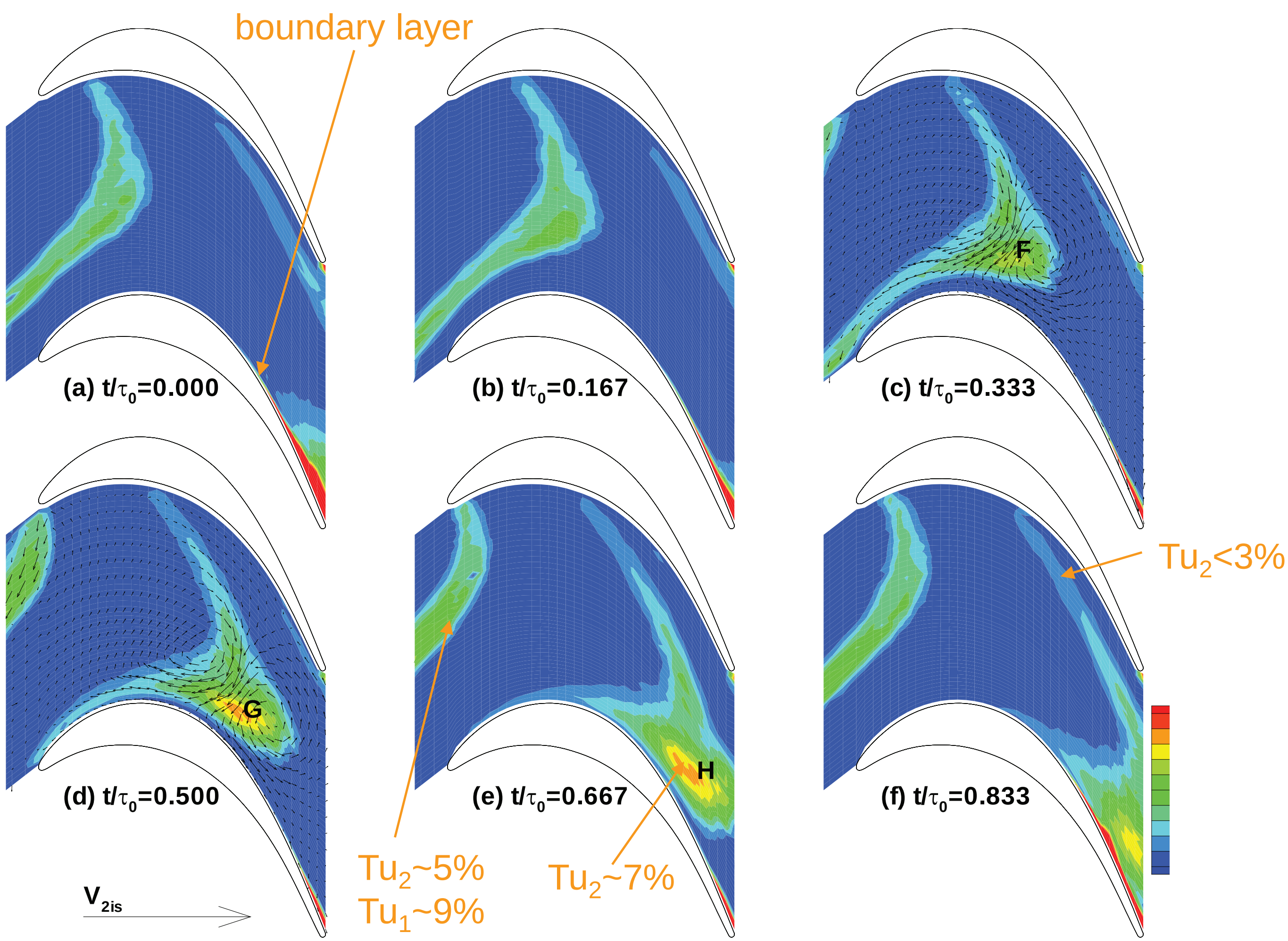
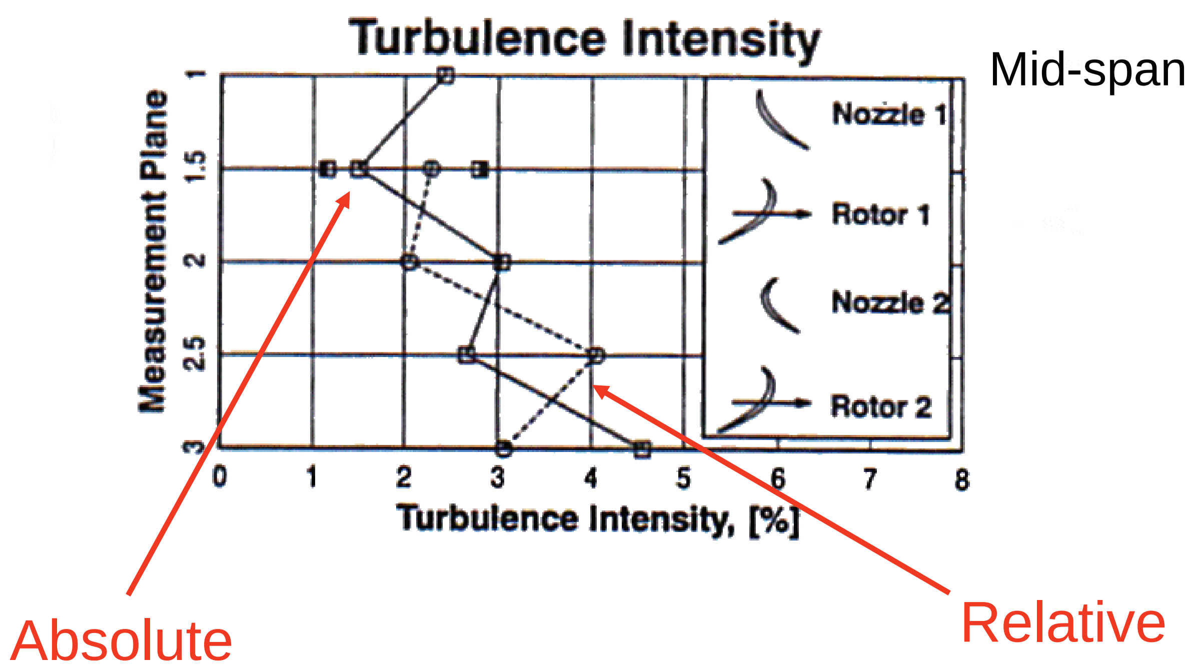
Unsteady Wake Convecting in Blade Passage



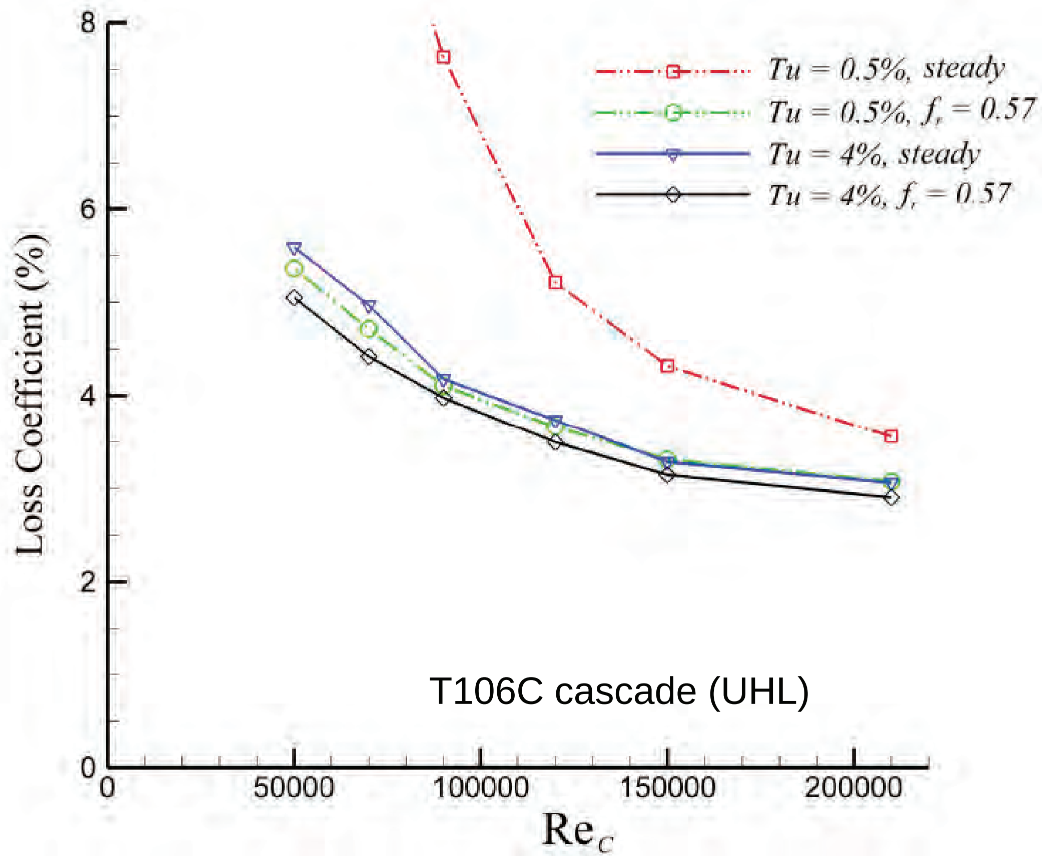
Stieger & Hodson (2004)

Pitchwise averaged time-mean Tu



Halstead

Profile losses with/without incoming wakes (UHL)



Himmel 2010

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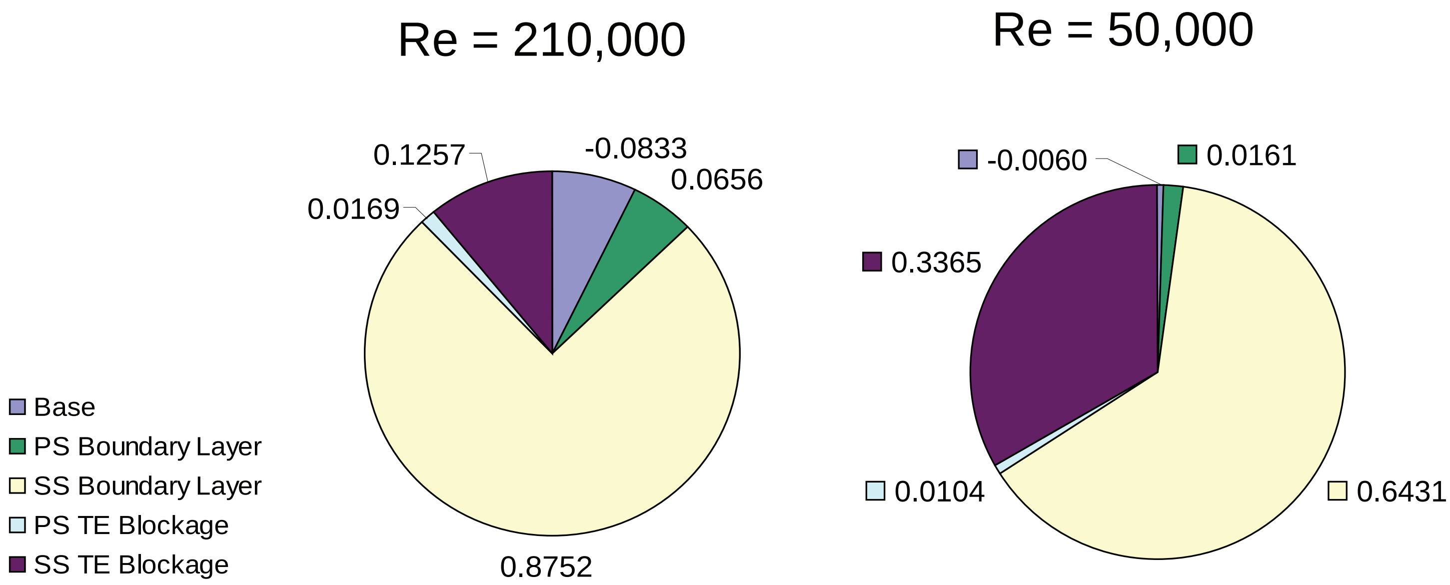
Contributions to Profile Loss



- Far higher suction side loss at lower Reynolds No.s due to bubble
- Suction side loss much higher on higher lift blades at low Reynolds No.s

Himmel

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Wake Induced Transition

Attached Flow
Low Freestream Turbulence

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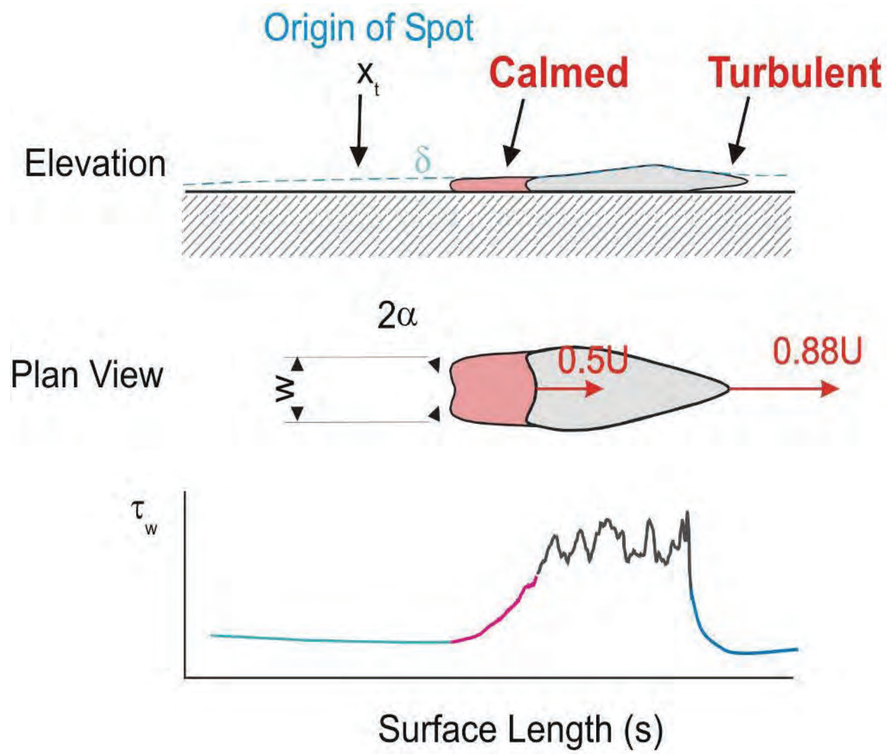
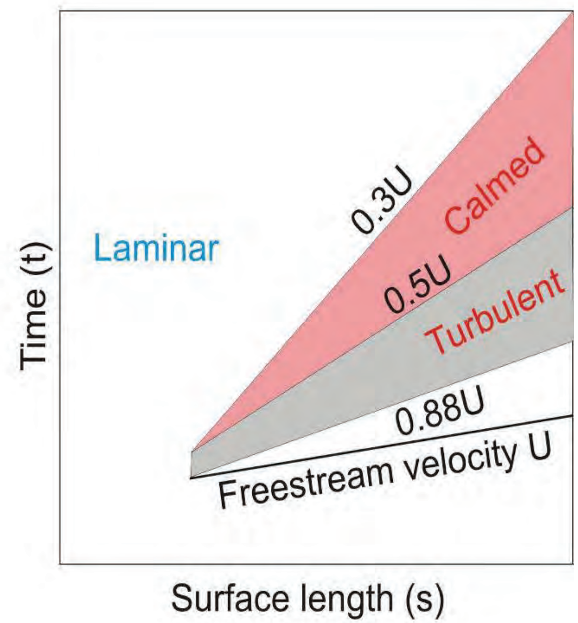
Anatomy of a Turbulent Spot





Calmed Region:

- Lower turbulence ⇒ Lower loss
- Fuller profile ⇒ More resistant to transition and separation

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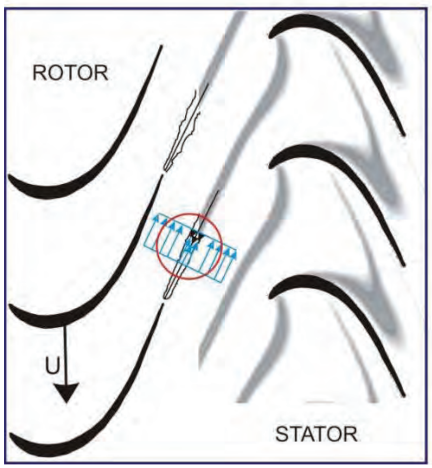
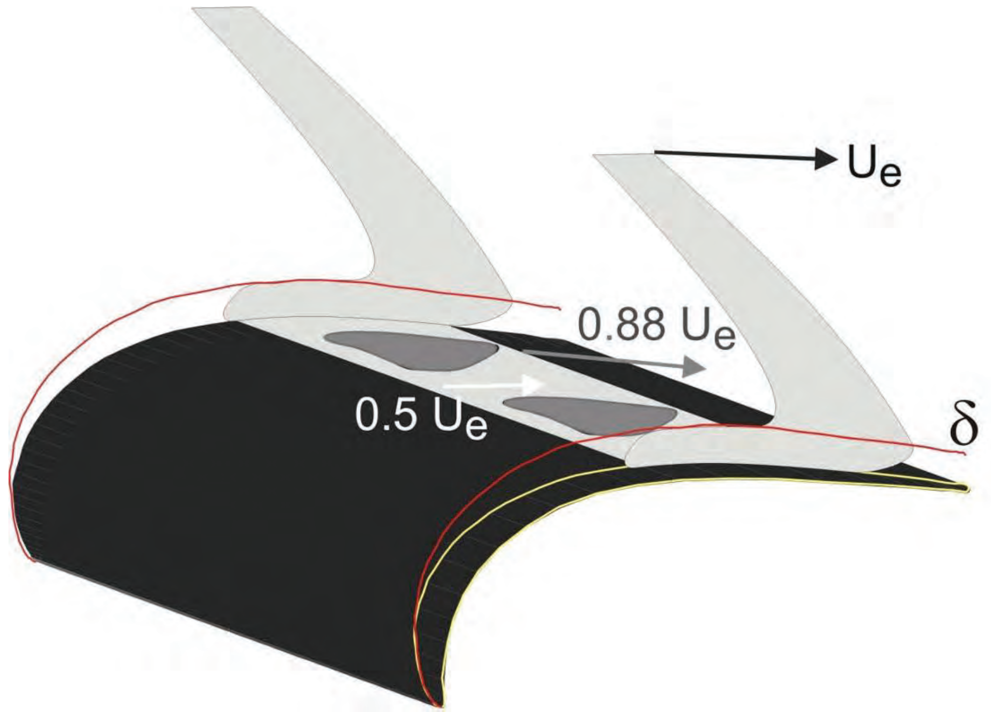
Schematic of wake-induced transition strip





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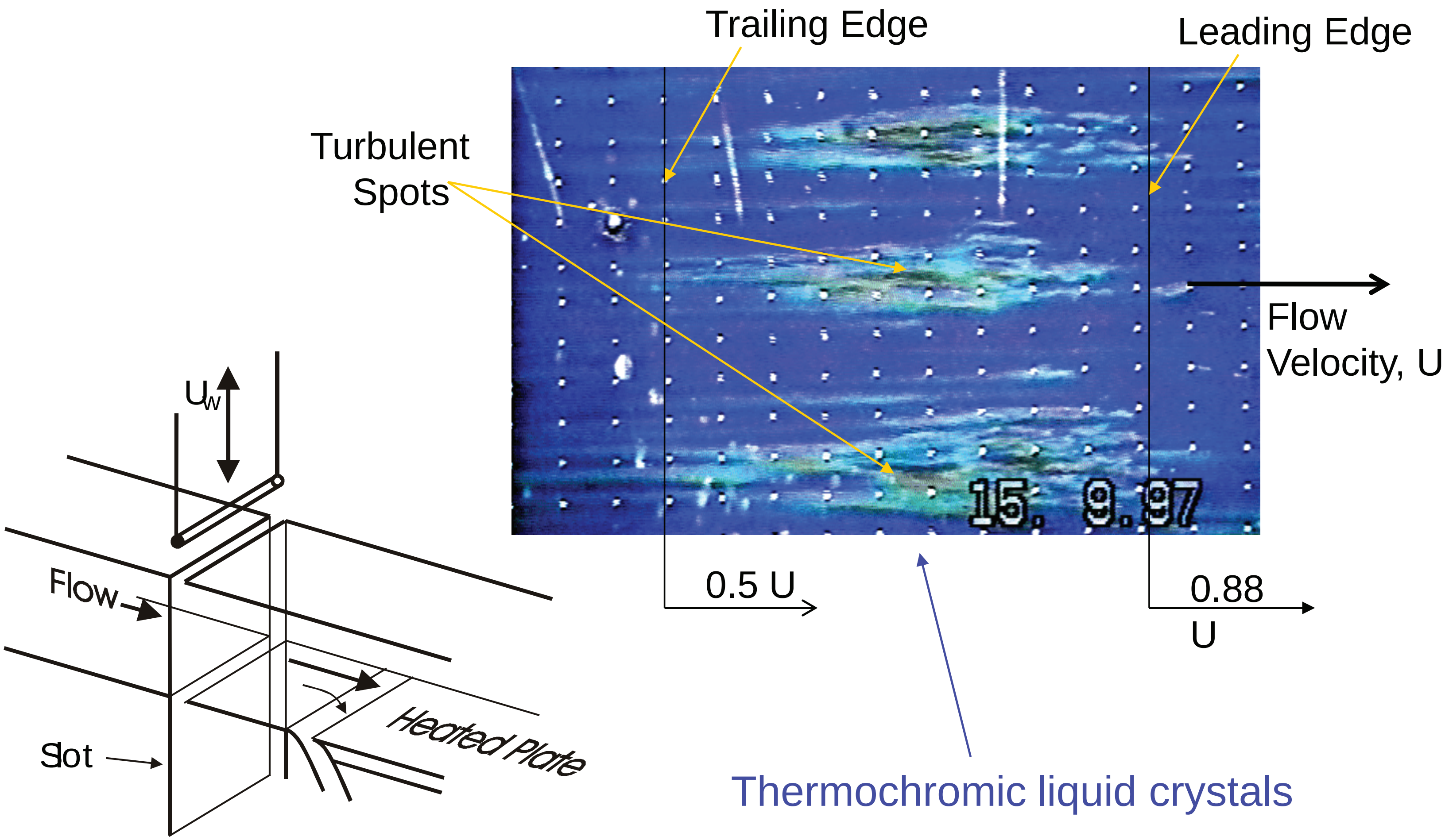
Visualisation of *attached* wake-induced transition



Zhong et al (2000)

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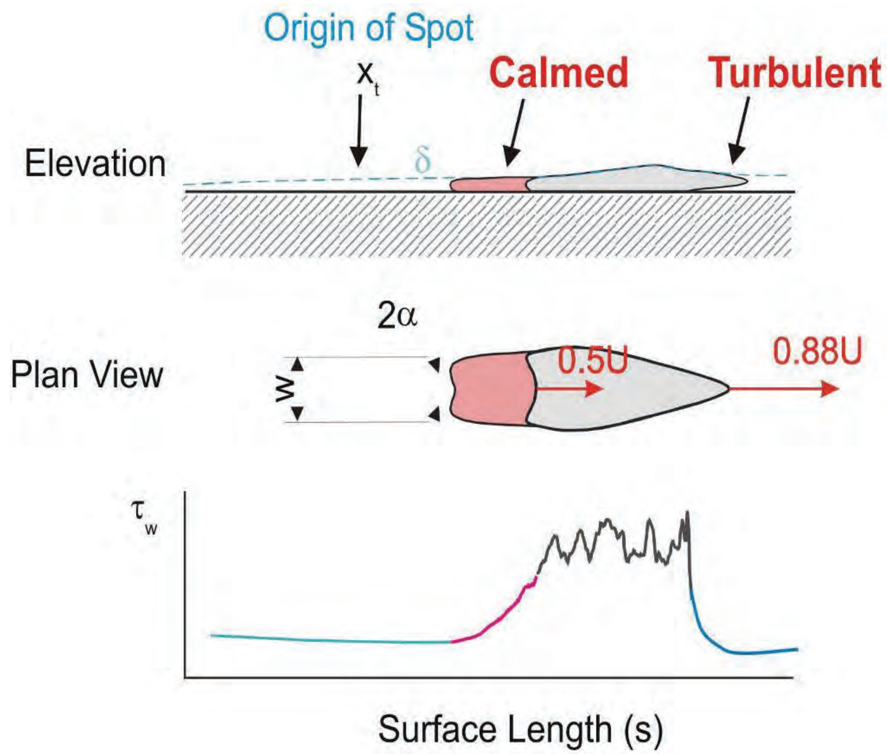
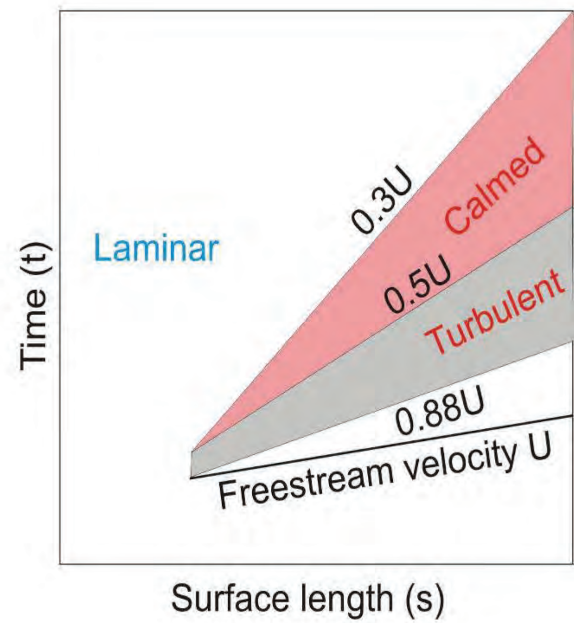
Anatomy of a Turbulent Spot





Calmed Region:

- Lower turbulence ⇒ Lower loss
- Fuller profile ⇒ More resistant to transition and separation

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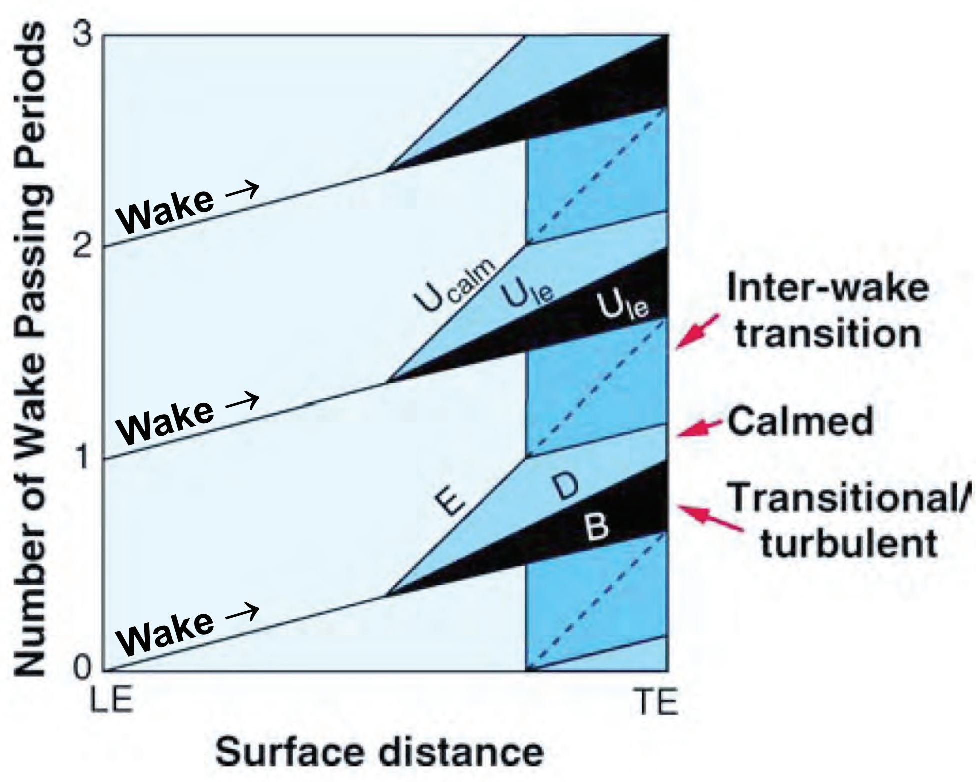
Classical Space Time Description



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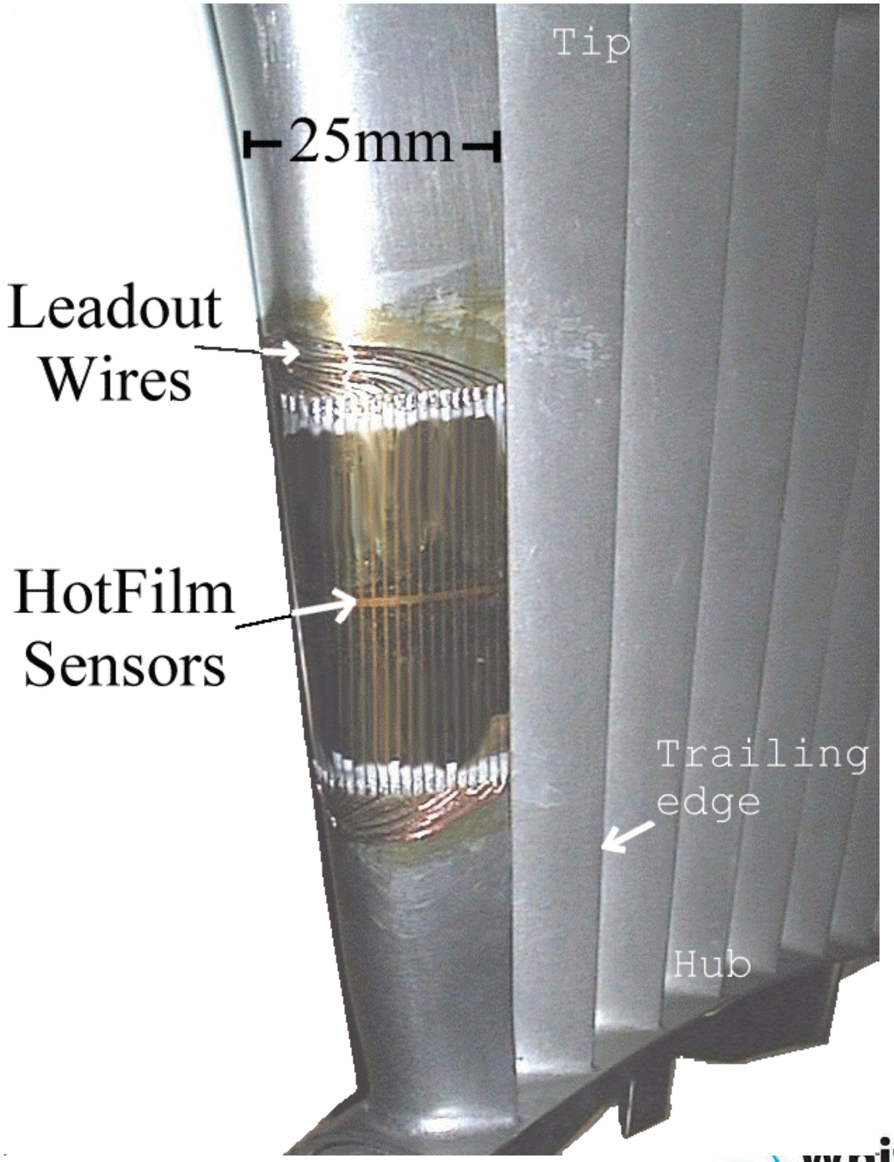
Surface hot film anemometers on 3rd stator of BR715 LP Turbine



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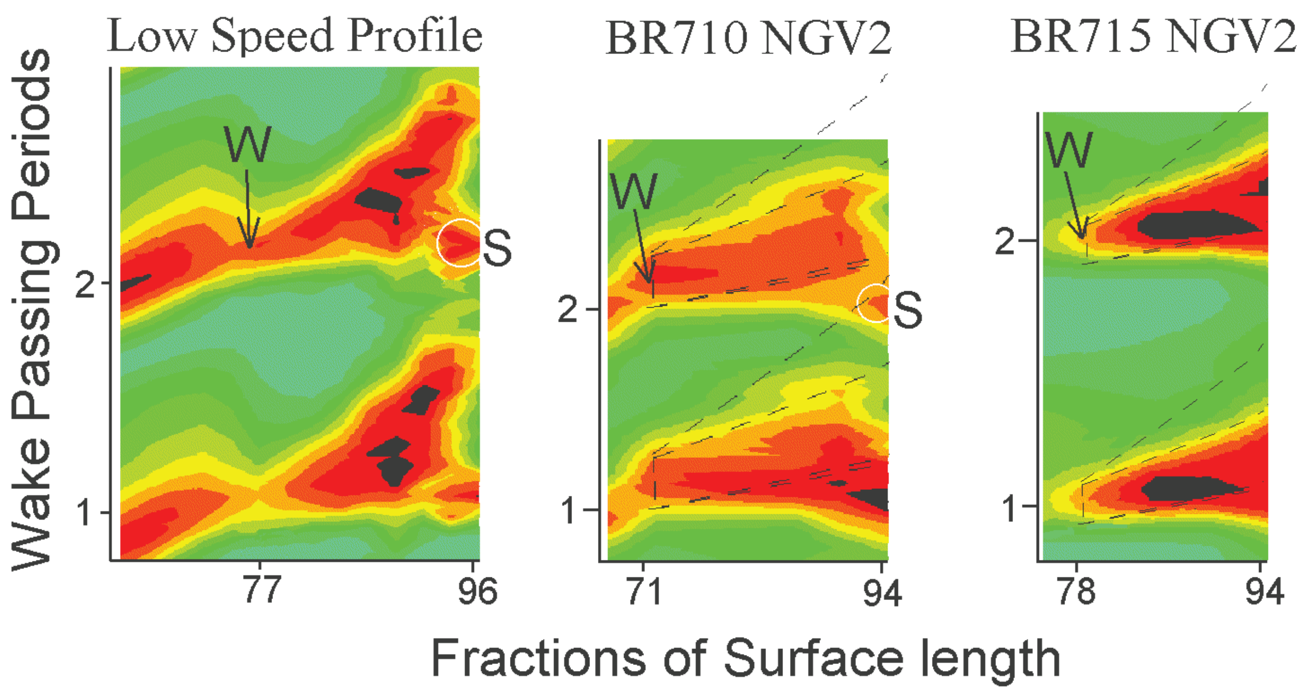
Unsteady Boundary Layers in Cascades & LPT Rigs

$$\tau_{ND} = \frac{\tau_w - \tau_{w_{min}}}{\tau_{w_{max}} - \tau_{w_{min}}}$$



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Wake Induced Transition

Separated Flow
Low Freestream Turbulence

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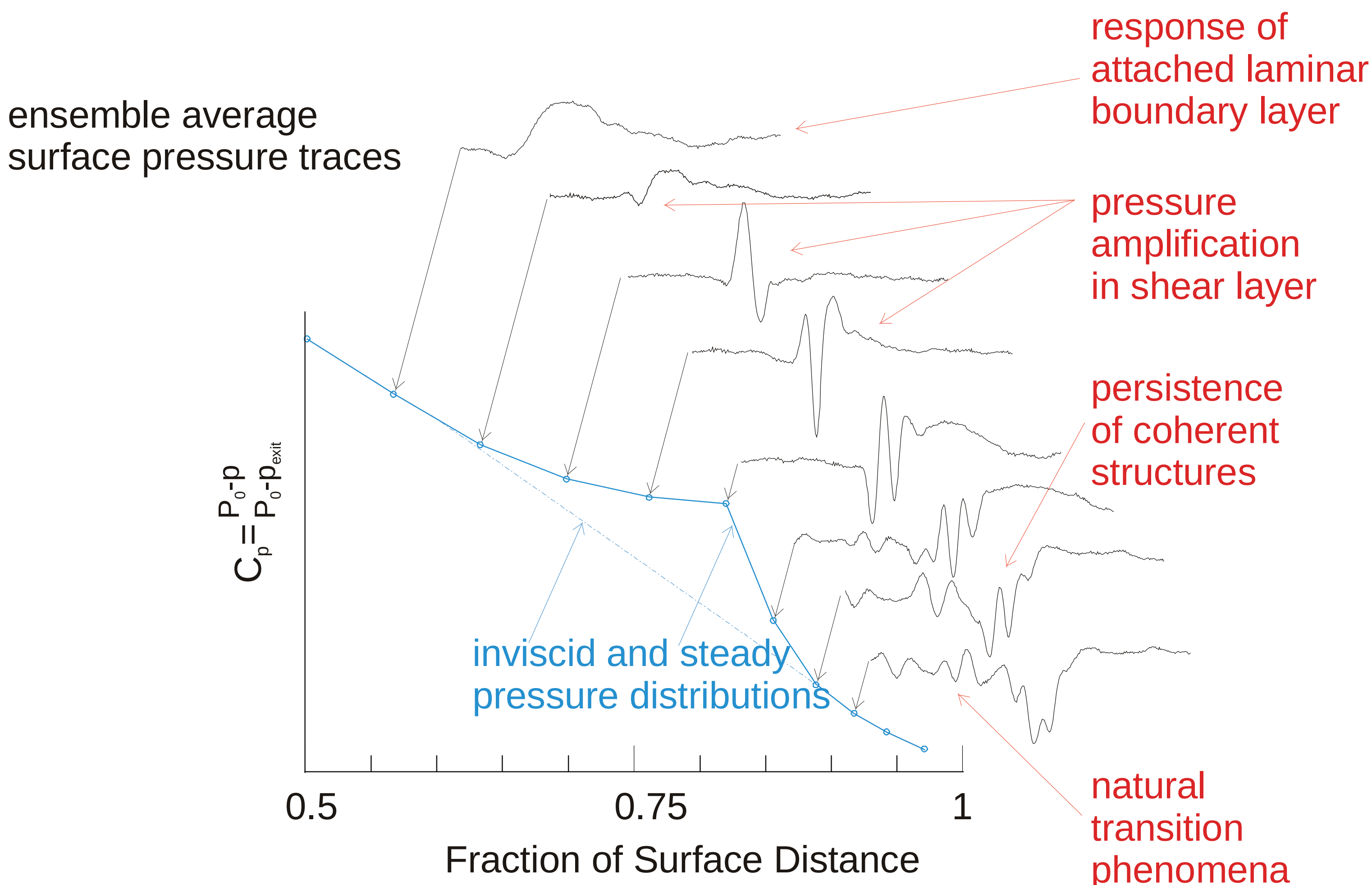
Pressure wiggles due to wake-bubble interaction



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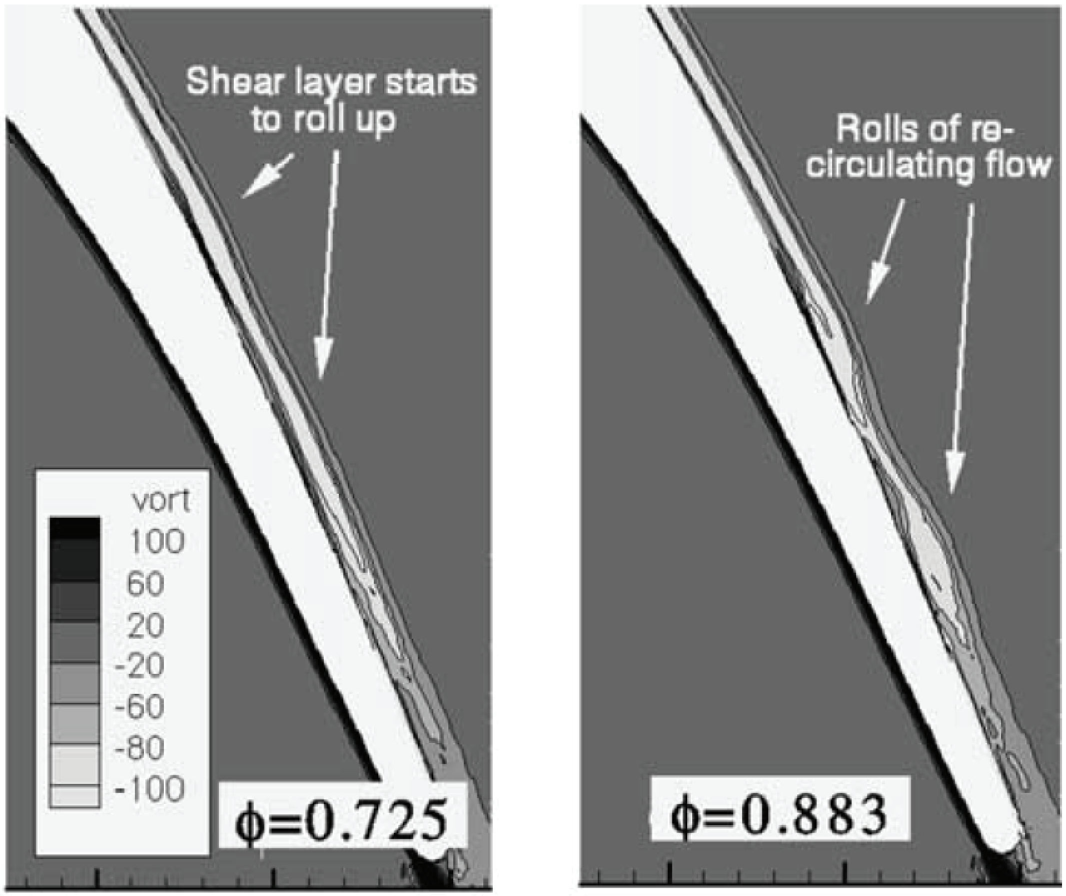
DNS predicts KH Roll-Up Mechanism



Wissink 2003 (DNS)

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Wake Induced Transition

Attached & Separated Flow
High Freestream Turbulence

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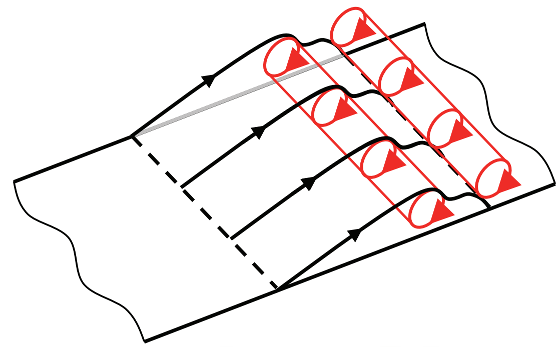
KH Excitation for High vs. Low Freestream Turbulence

Low Freestream Turbulence:

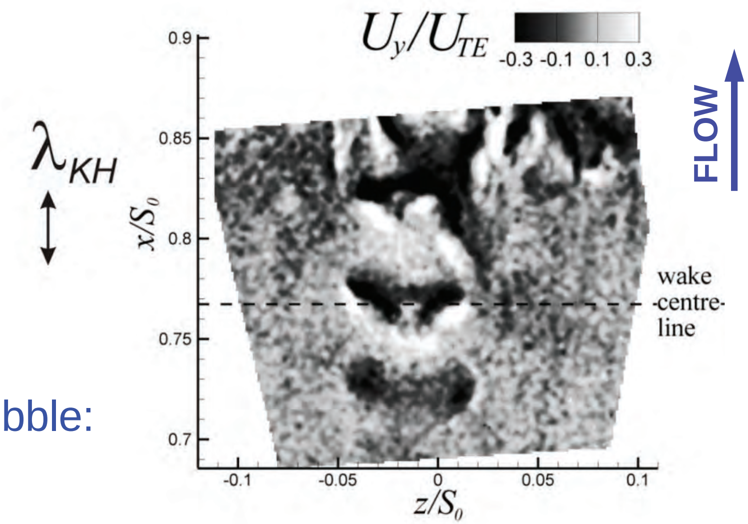
• Full-Span Coherent Structures induced by velocity perturbation of wakes



High Freestream Turbulence:

• Shear Layer distorted by Klebanoff modes
• Localised instabilities excited by Wake
• Short-Span KH structures generated

Instantaneous PIV looking down on bubble:



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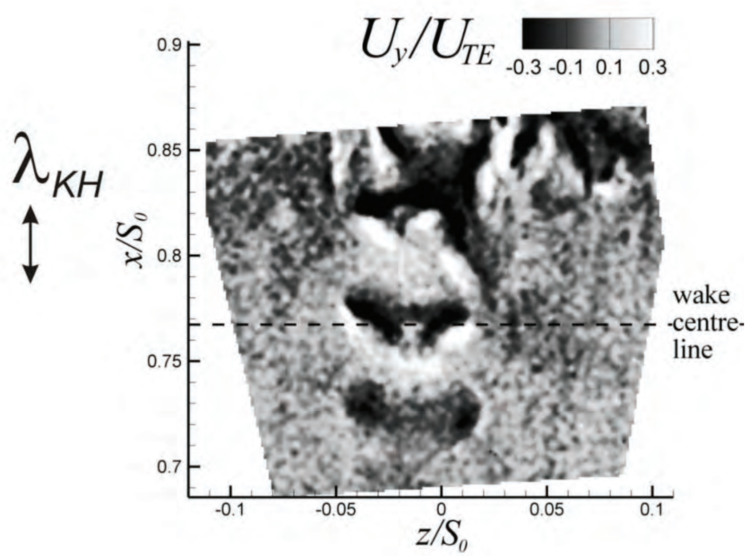
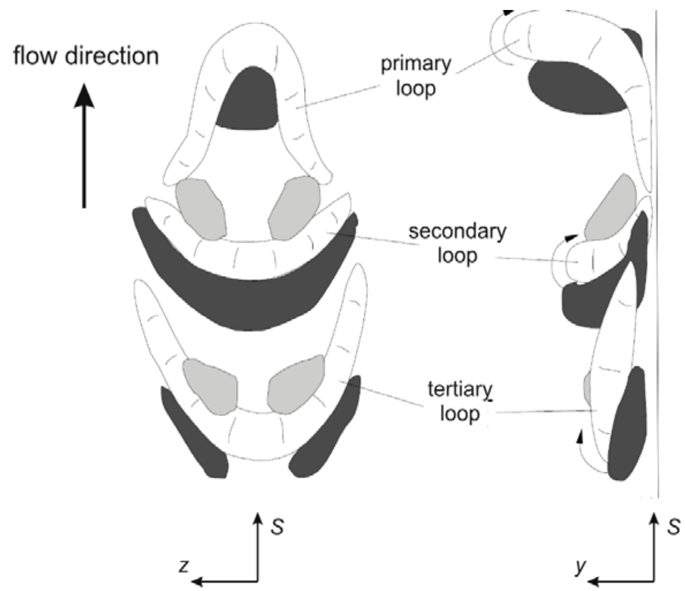
Short-Span KH Structures





McAuliffe and Yaras 2010:
"Typical Young Spot"
(DNS, no wakes, high Tu)

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NASA/CP—2020-220327

Breakdown of Wake-Induced Klebanoff Streaks

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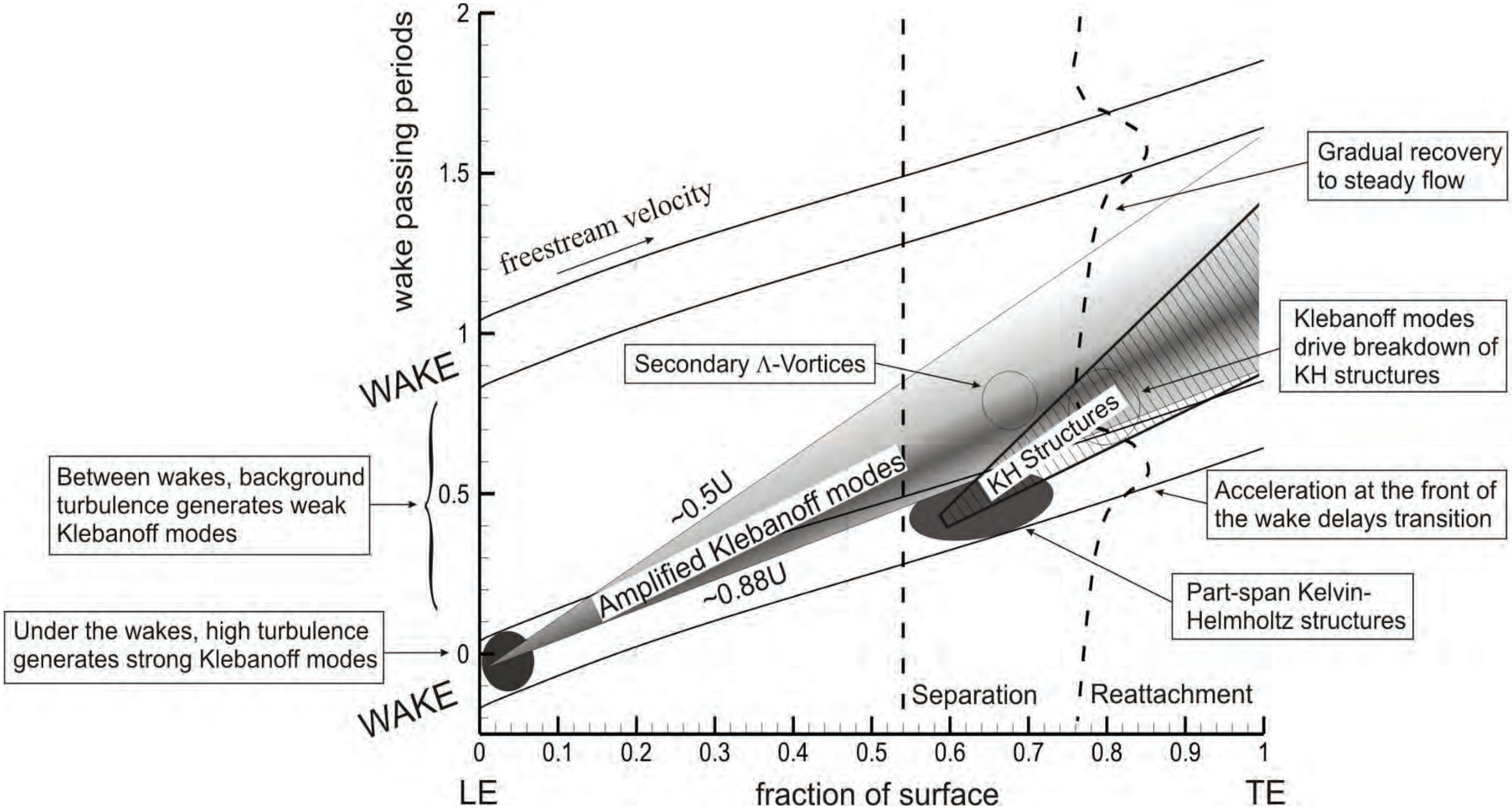
Updated Space-Time Description



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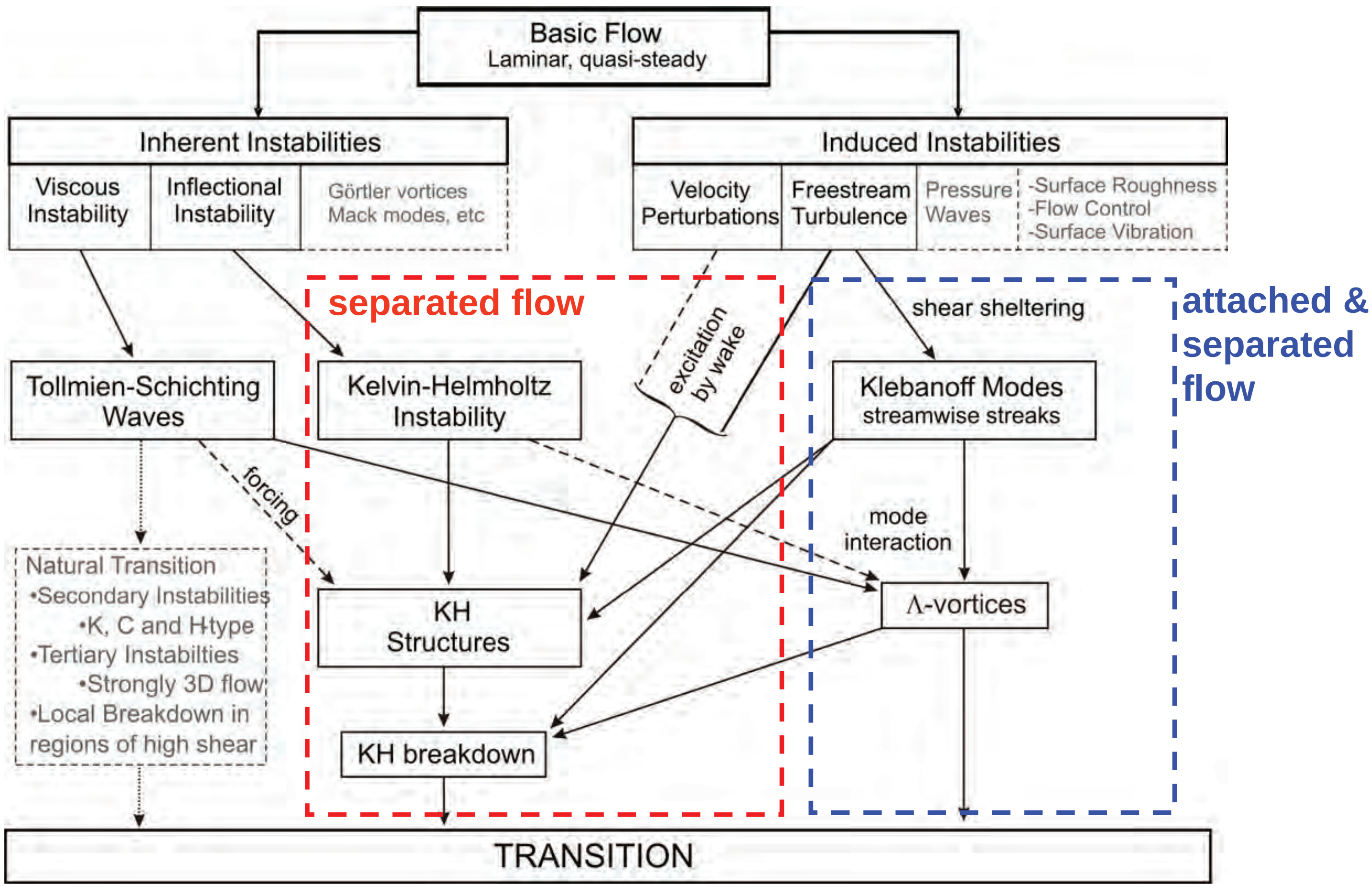
Roadmap: Boundary Layer Transition in LPTs



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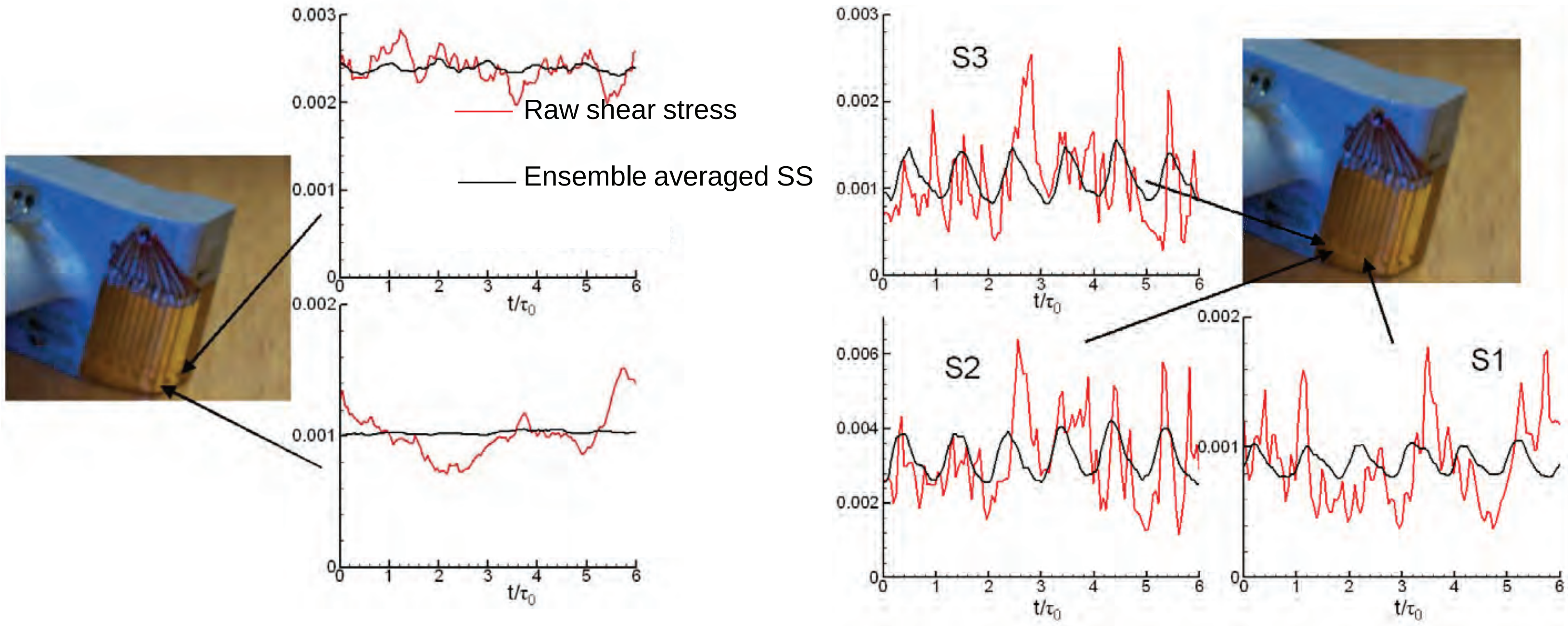
Endwall Boundary Layers in 4th stage of LPT rig



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Conclusions: Physical Problem

- **Unsteady boundary layer transition:**
  - Highly complex and multi-modal models needed
  - Freestream Turbulence and Wakes must be modelled
  - Wakes generate
    - Klebanoff modes
    - Short-span Kelvin-Helmholtz structures
  - Disturbances/Transitional flow is moving (approx $0.7U_{fs}$)
    - Cannot use steady models
- **Endwall boundary layers:**
  - Affected by blade passing
  - Transitional, not turbulent
  - More prone to separation

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Outline

- Physical Problems (HPH)
  - Freestream disturbance environment
  - Multi-modal unsteady transition
  - Endwall boundary layers

- Modelling Performance (JDC)
  - Profile Loss:
    - Key parameters
    - Preliminary Design Method
  - Mean-line Case Study:
    - Smith Chart design space
    - Lift Coefficient
    - Secondary Loss Models
    - Increasing blade lift

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Growth of the Suction Surface Boundary Layer

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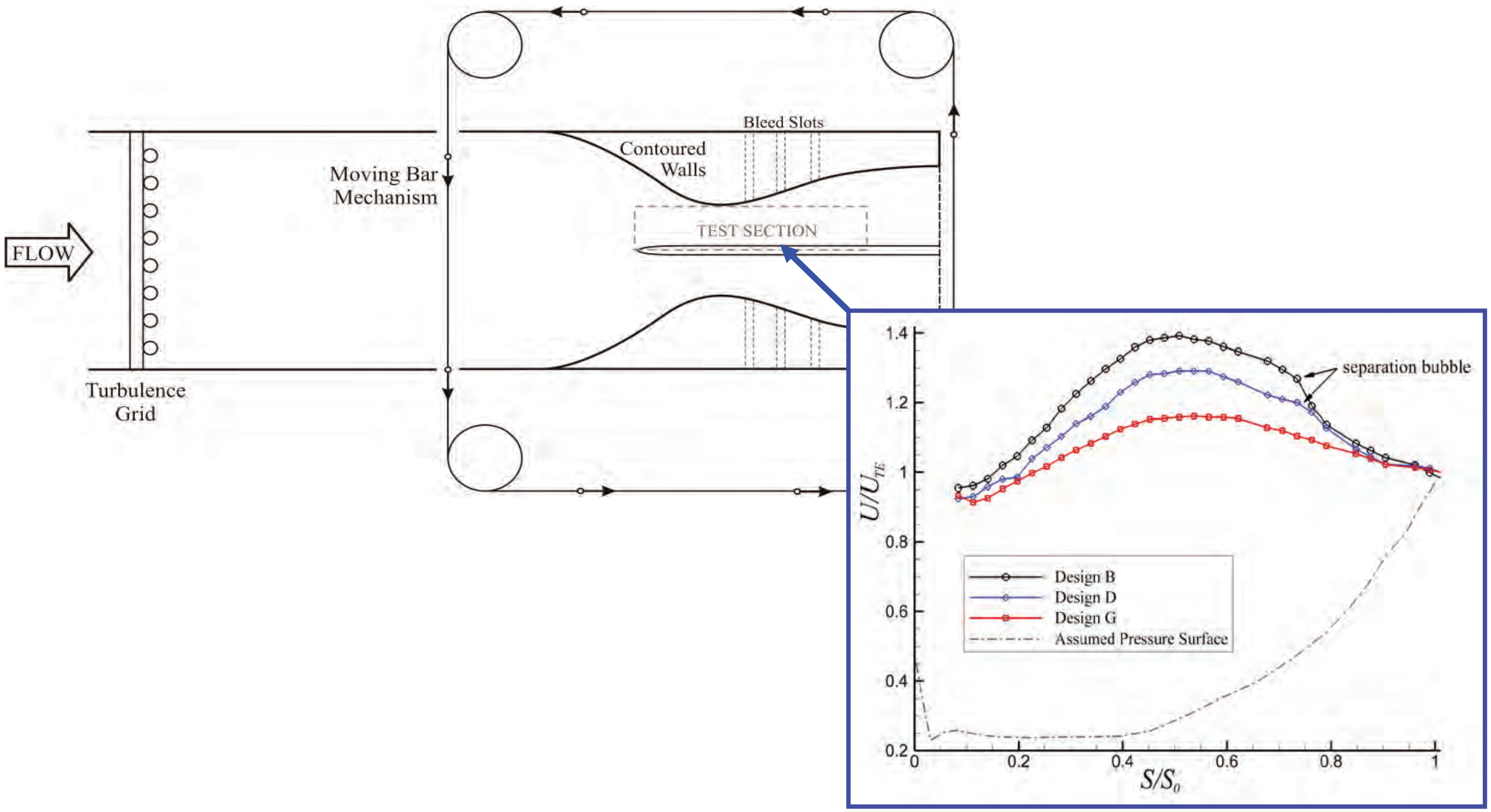
Flat Plate Study of High-Lift Designs



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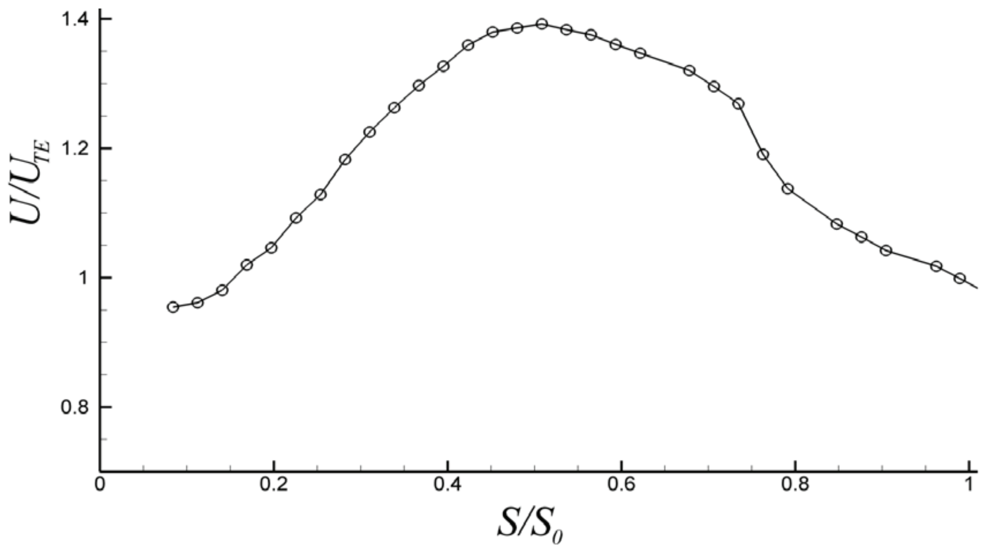
What Controls Growth of Suction Surface Boundary Layer?



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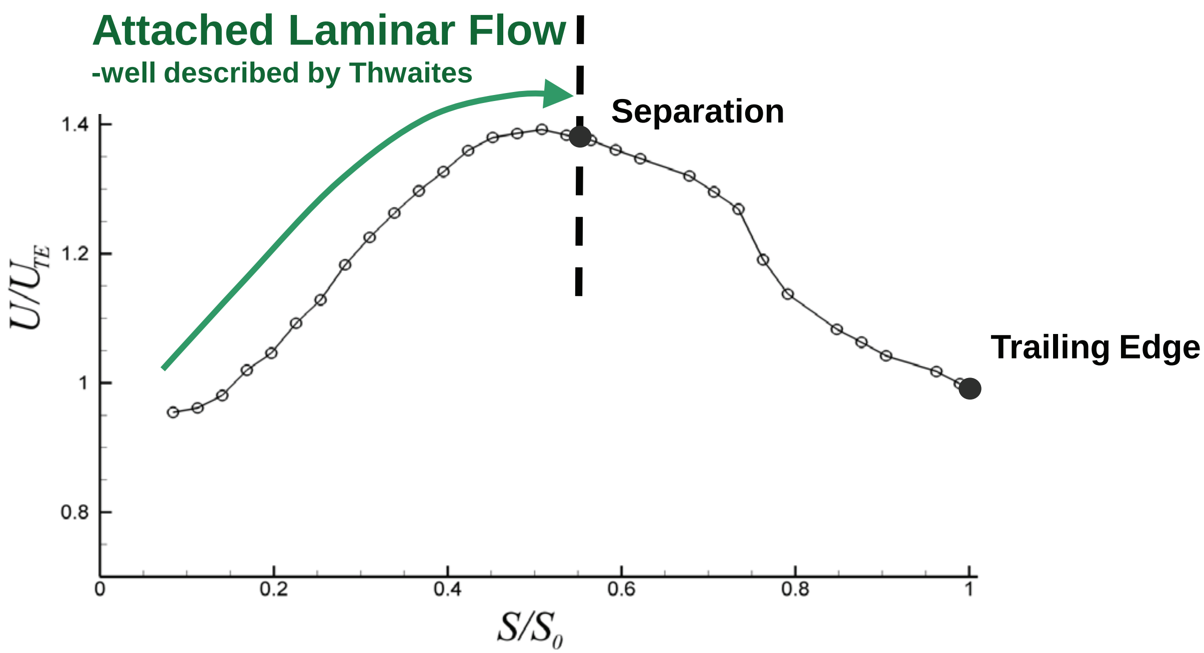
What Controls Growth of Suction Surface Boundary Layer?



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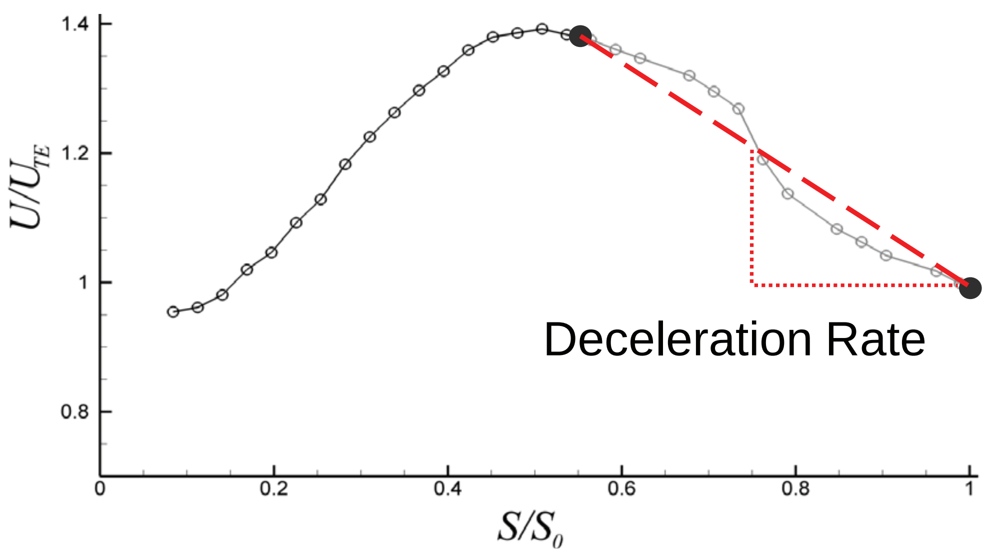
Deceleration Rate

Boundary layer Momentum Integral Eq. →

$$\frac{\mathrm{d}\theta/\theta}{\mathrm{d}S/S} \approx (H+2)\left(-\frac{\mathrm{d}U/U}{\mathrm{d}S/S}\right)$$



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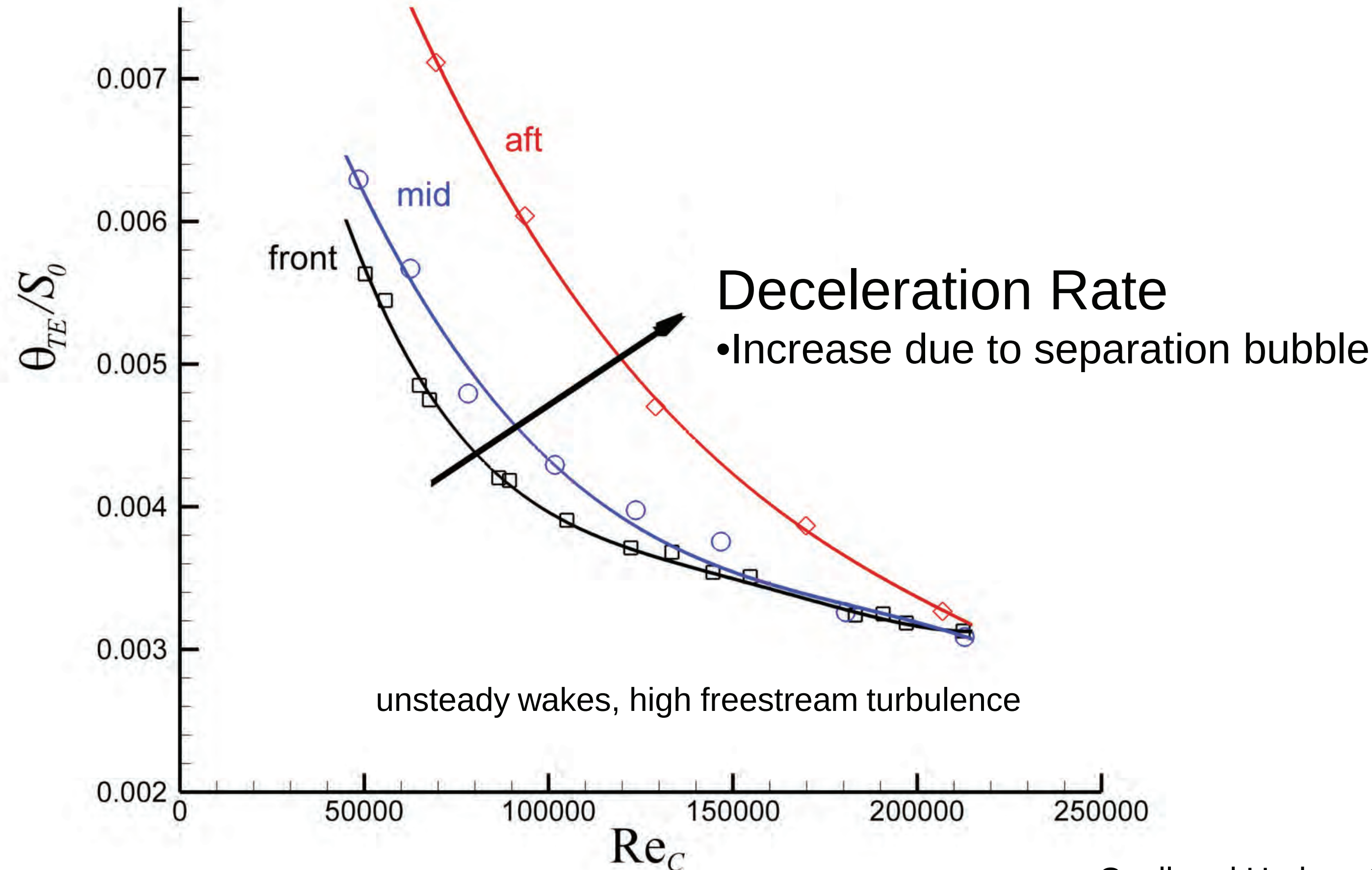
Influence of Deceleration Rate



Coull and Hodson 2010

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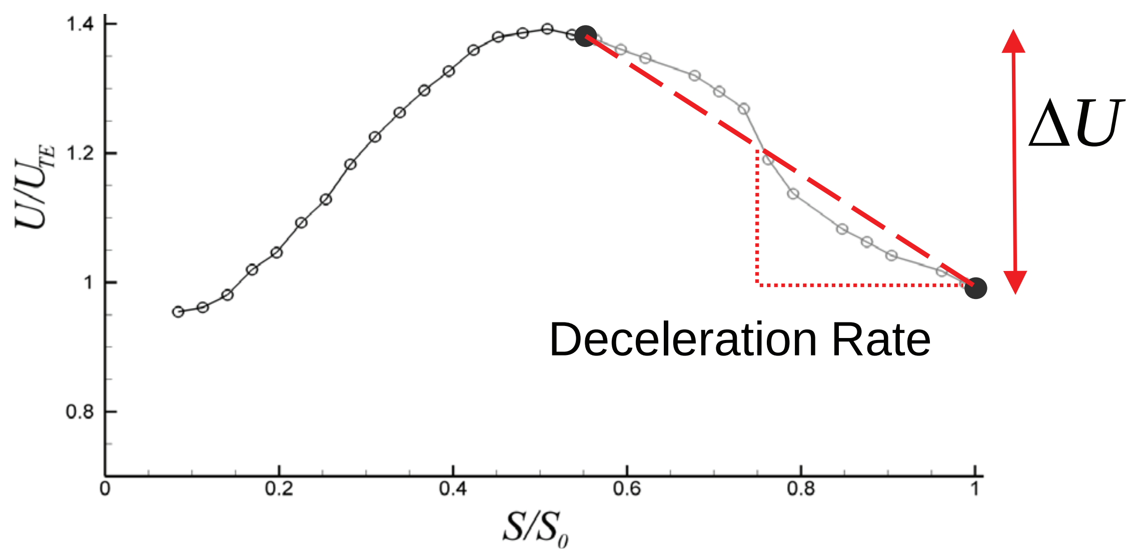
Diffusion Factor

$$\frac{\mathrm{d}\theta/\theta}{\mathrm{d}S/S} \approx (H+2)\left(-\frac{\mathrm{d}U/U}{\mathrm{d}S/S}\right) \longrightarrow \ln\left(\frac{\theta_{TE}}{\theta_{sep}}\right) \approx -\int_{U_{sep}}^{U_{TE}} \frac{(2+H)}{U}\,\mathrm{d}U$$



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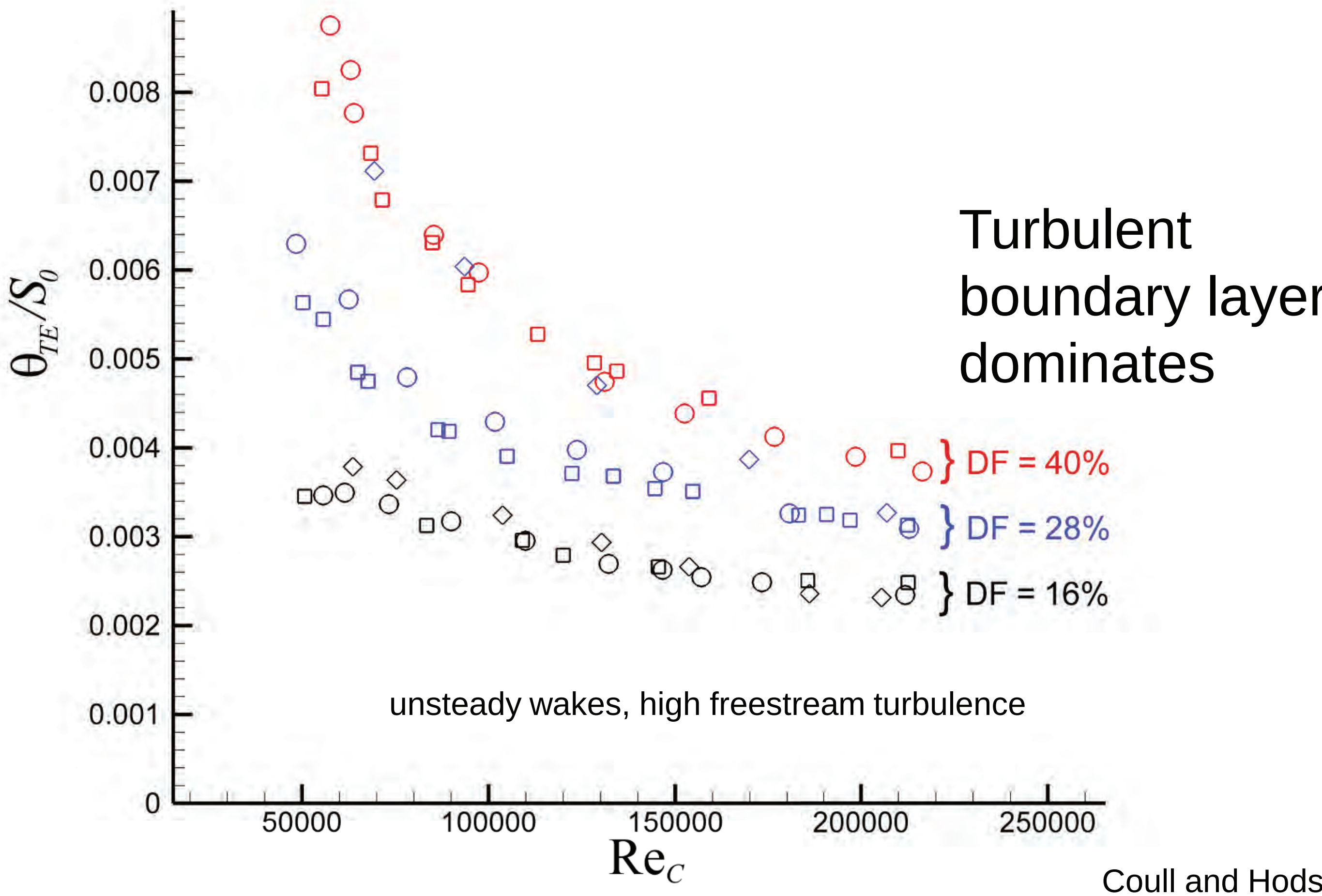
Influence of Diffusion Factor



Coull and Hodson 2010

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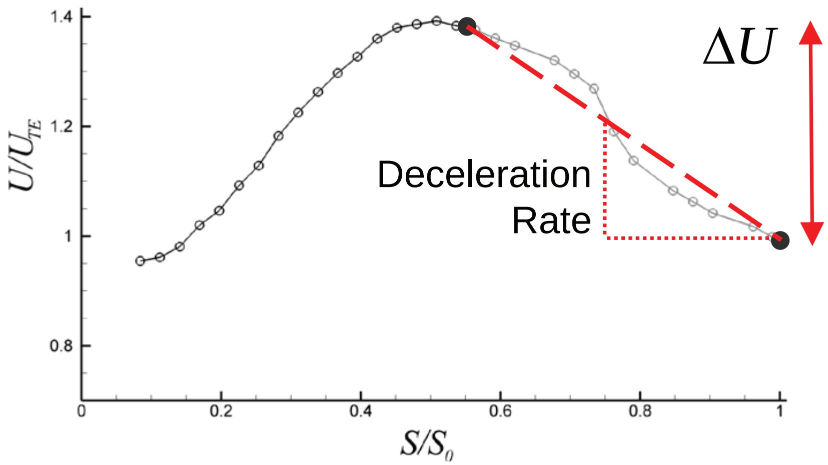
Modelling Loss

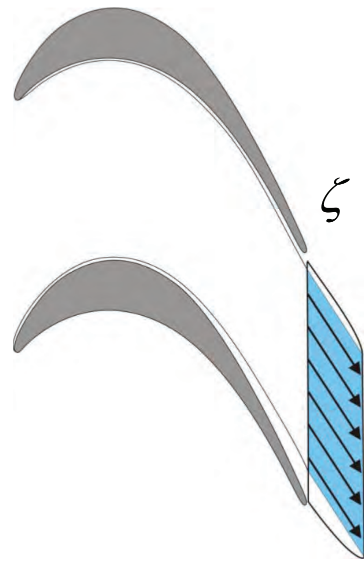
Profile Loss Model for High-Lift Blades (GT2010-22675)

1) Empirical method for momentum thickness:



$$\theta = f\left(\Delta U, \text{ deceleration rate }, \mathrm{Re}_{\theta sep}, f_r\right)$$

2) Relate to Profile Loss:



$$\zeta \approx \left(\frac{2\theta}{s\cos(\alpha_2)}\right)$$

(also accounts for pressure surface and blockage)

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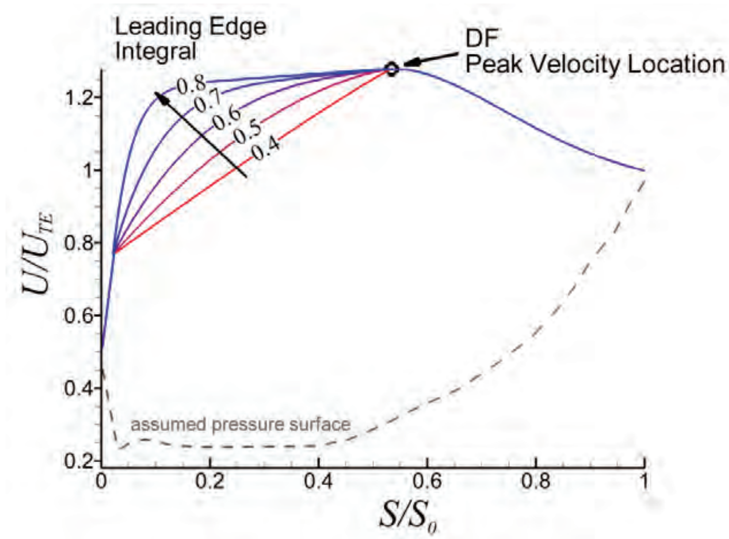
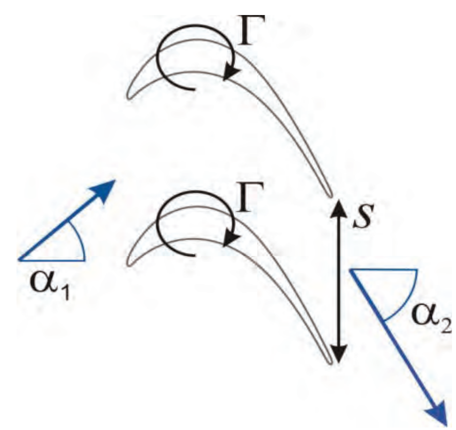
Preliminary Design Method

1) Parameterise Velocity Distribution:



2) Relate Pitch to Circulation:



3) Predict θ and hence Profile Loss:

$$\begin{bmatrix} \textit{profile loss} \\ \textit{pitch} \end{bmatrix} = f\left(\mathrm{DF}, \begin{pmatrix} \textit{peak} \\ \textit{velocity} \\ \textit{location} \end{pmatrix}, \begin{pmatrix} \textit{leading} \\ \textit{edge} \\ \textit{integral} \end{pmatrix}, \mathrm{Re}_{S_0}, \ f_r, \begin{pmatrix} \textit{flow} \\ \textit{angles} \end{pmatrix} \right)$$

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Mean-line Design Study:
Low Speed Single Stage LPT

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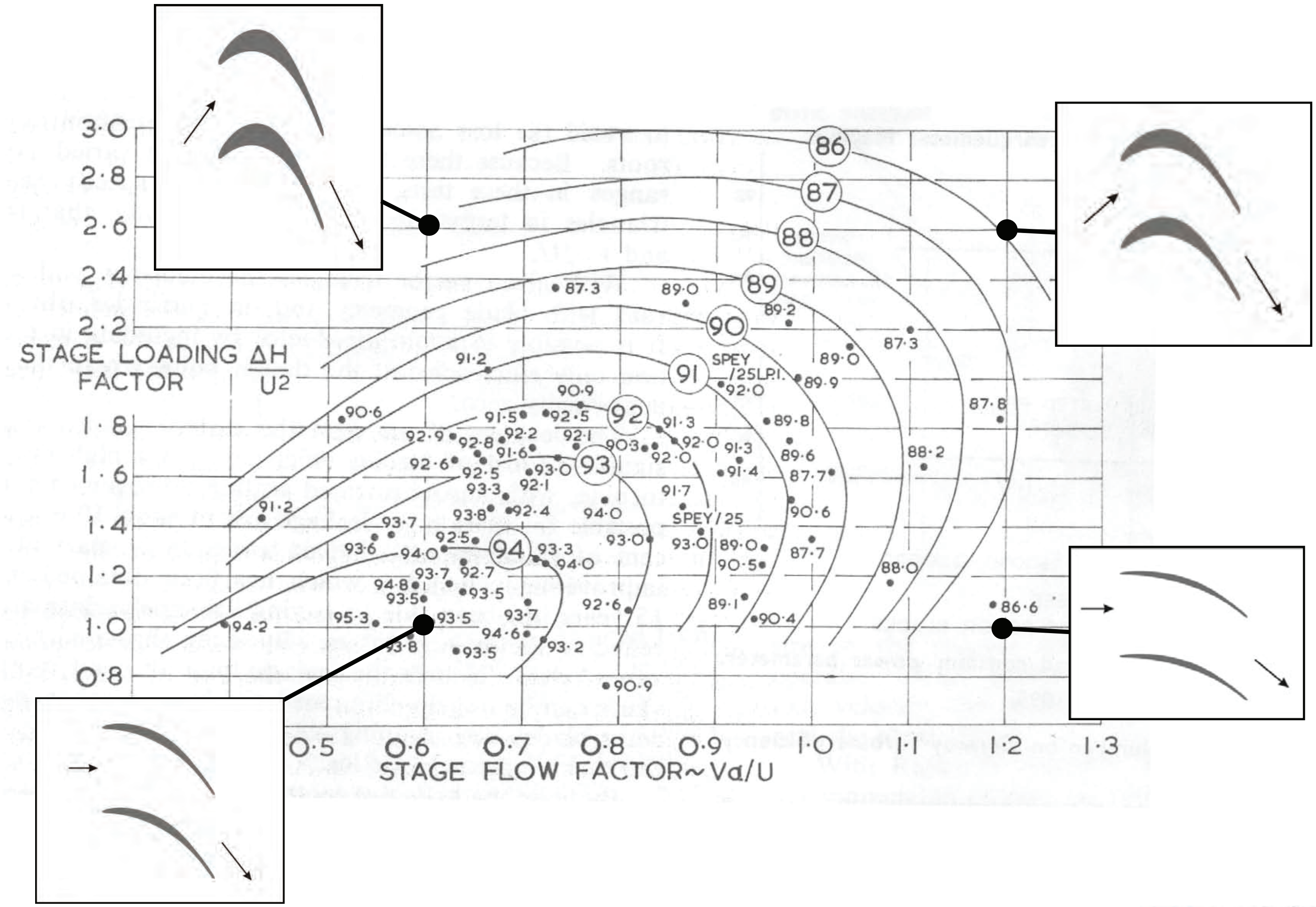
Motivation: Smith Chart (1965)



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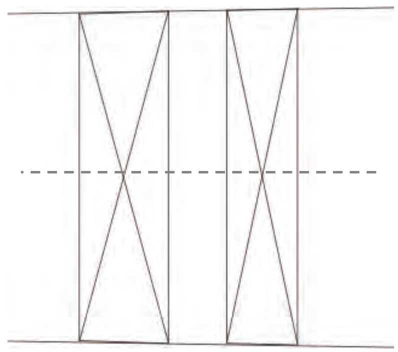
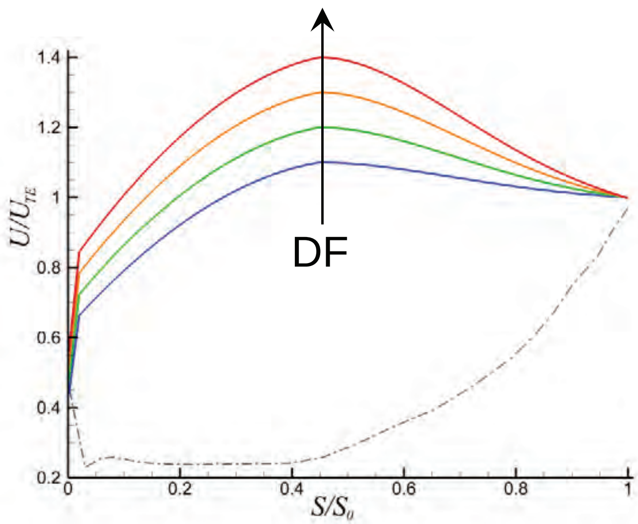
Mean-line Design Study: Low Speed Single Stage LPT

- **Specified Requirements:**
  - Power, Mass Flow, Shaft RPM, Inlet P_0 T_0
  - (Aspect ratios, small tip gap, no flare, etc)
- **Flow Angles:**
  - Fixed Reaction (50%)
  - Vary: ϕ and ψ
- **Velocity Distributions:**
  - Fixed Peak Suction (45%)
  - Fixed Leading Edge Loading (50%)
  - Vary DF (to achieve Lift Coefficient)
- **Efficiency Prediction:**
  - Preliminary design method (Profile)
  - Craig and Cox 1970 (Secondary & Tip)





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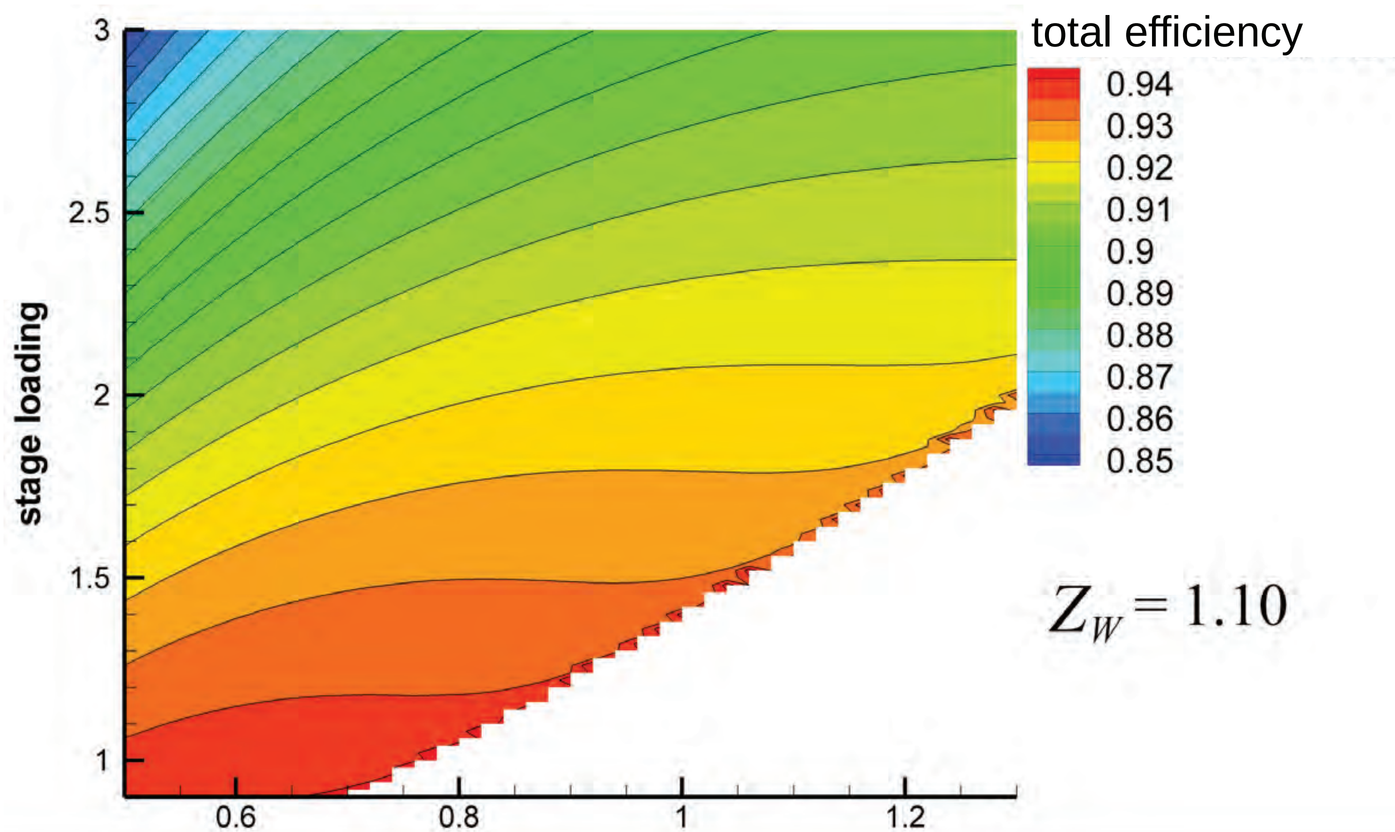
Efficiency for constant Z_w = 1.10



[redacted]

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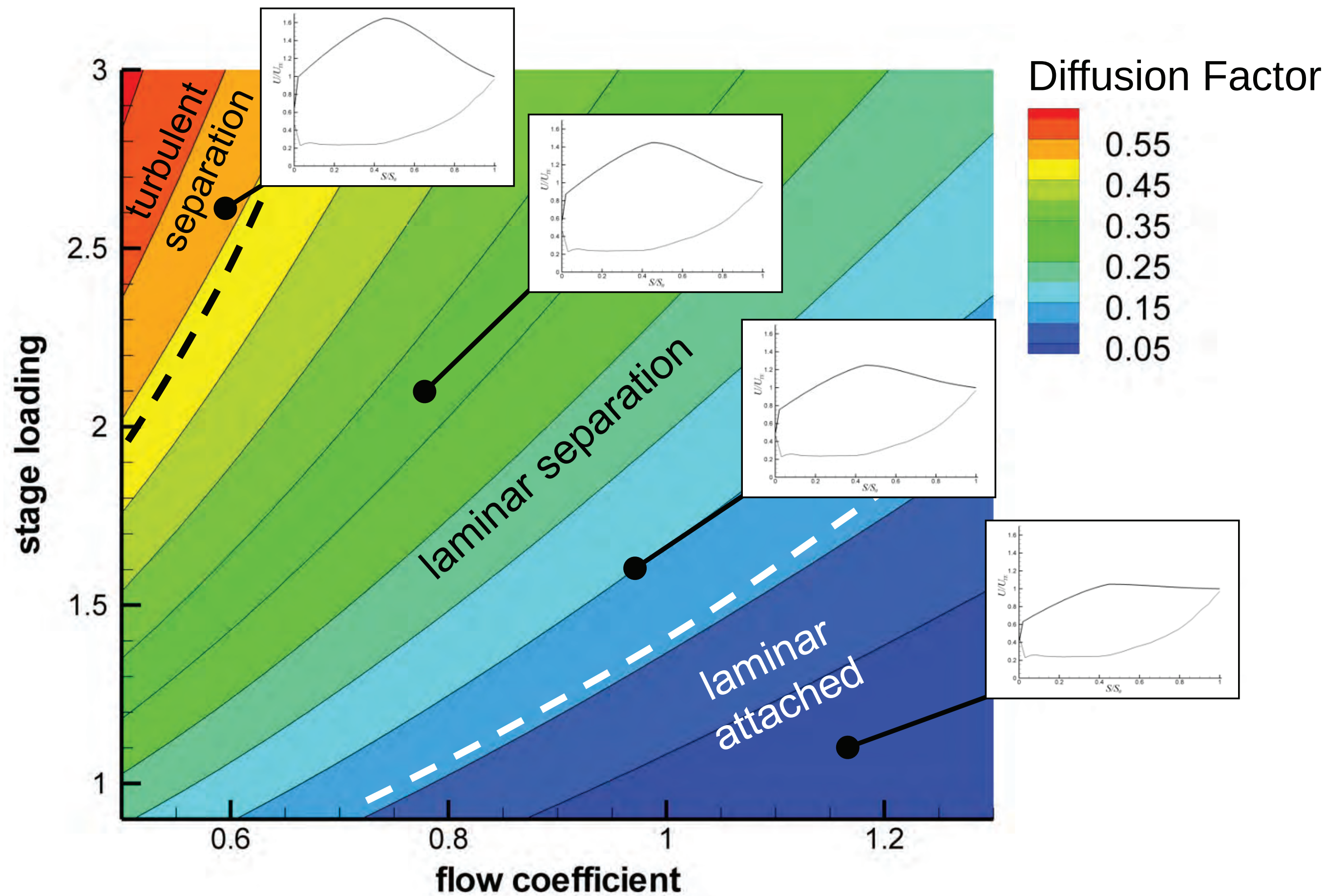
Diffusion Factor for constant Z_w = 1.10



Zw simultaneously describes laminar attached and turbulent separated designs!

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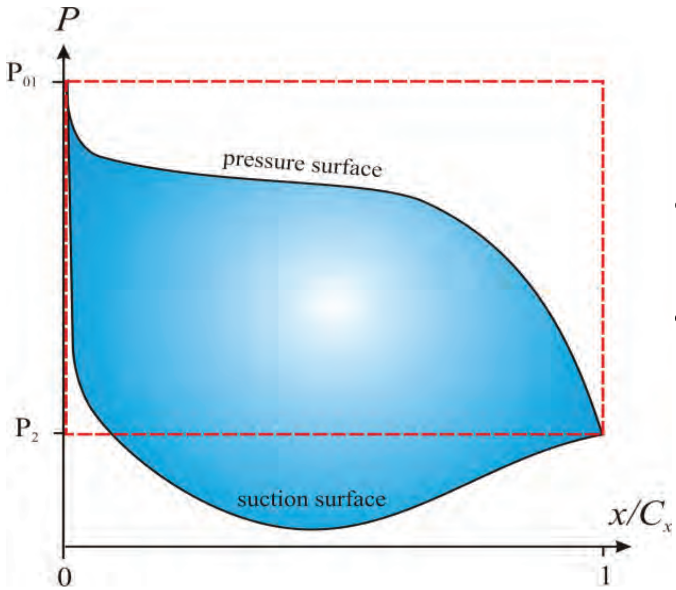
What's wrong with Zweifel?

$$Z_w = \frac{Actual\ Tangental\ \ Force}{Ideal\ Tangental\ \ Force} = \frac{\oint P \mathrm{d}x}{(\mathrm{P}_{01} - P_2) C_x} = \frac{s}{C_x}\left(\frac{\tan\alpha_1 - \tan\alpha_2}{0.5\sec^2\alpha_2}\right)$$



If angles are fixed:

- measure of pitch:axial chord

If angles vary:

- Circulation must increase with $|\alpha_2|$ to maintain Z_w:

$$\Gamma = \frac{V_2 C_x}{2\cos\alpha_2} Z_w$$

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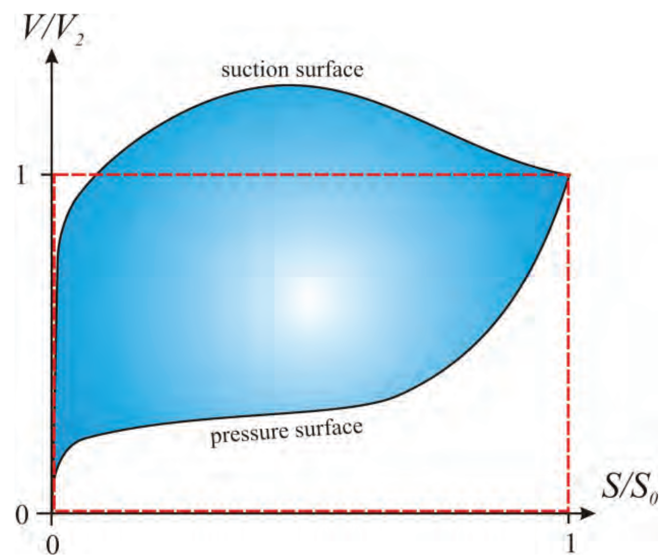
Circulation Coefficient C_0

$$C_0 = \frac{Actual\ Circulation}{Ideal\ Circulation} = \frac{\oint V dS}{V_2 S_0} = \frac{s}{S_0}\left(\frac{\tan\alpha_1 - \tan\alpha_2}{\sec\alpha_2}\right)$$



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Zweifel vs. Circulation Coefficient

$$Z_w = \frac{Actual\ Tangental\ Force}{Ideal\ Tangental\ Force} = \frac{s}{C_x}\left(\frac{\tan\alpha_1 - \tan\alpha_2}{0.5\sec^2\alpha_2}\right)$$

$$C_0 = \frac{Actual\ Circulation}{Ideal\ Circulation} = \frac{s}{S_0}\left(\frac{\tan\alpha_1 - \tan\alpha_2}{\sec\alpha_2}\right)$$

$$C_0 = Z_w\underbrace{\left(\frac{0.5\,C_x}{S_0\cos\alpha_2}\right)}$$

Geometry Parameter
=0.5 for inclined flat plate
=0.8 for very high camber

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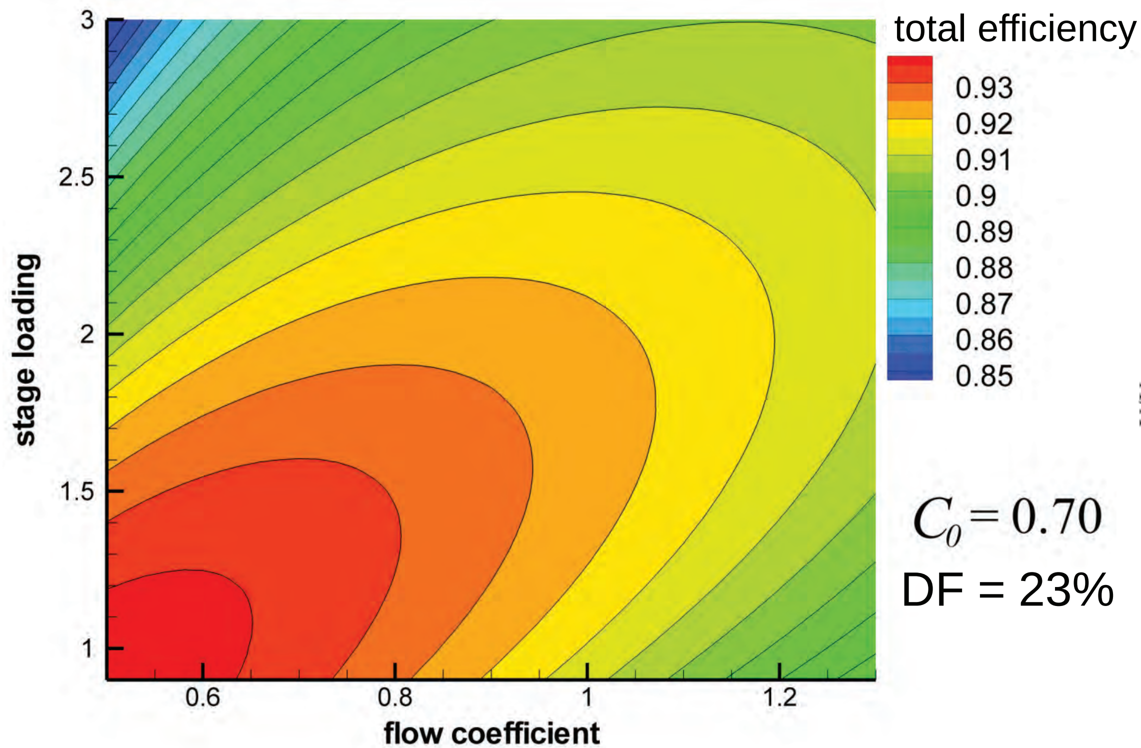
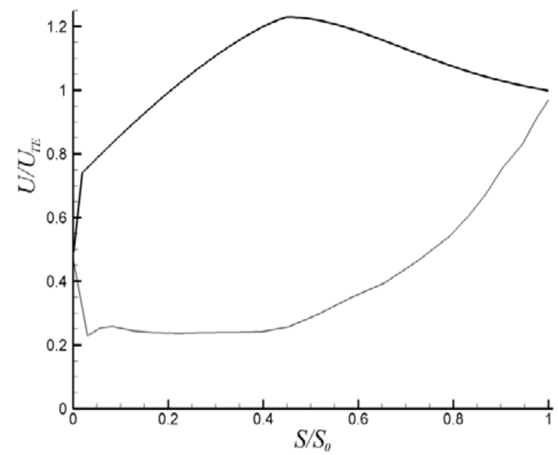
Efficiency for Constant Circulation Coefficient C_0



$C_0 = 0.70$

DF = 23%



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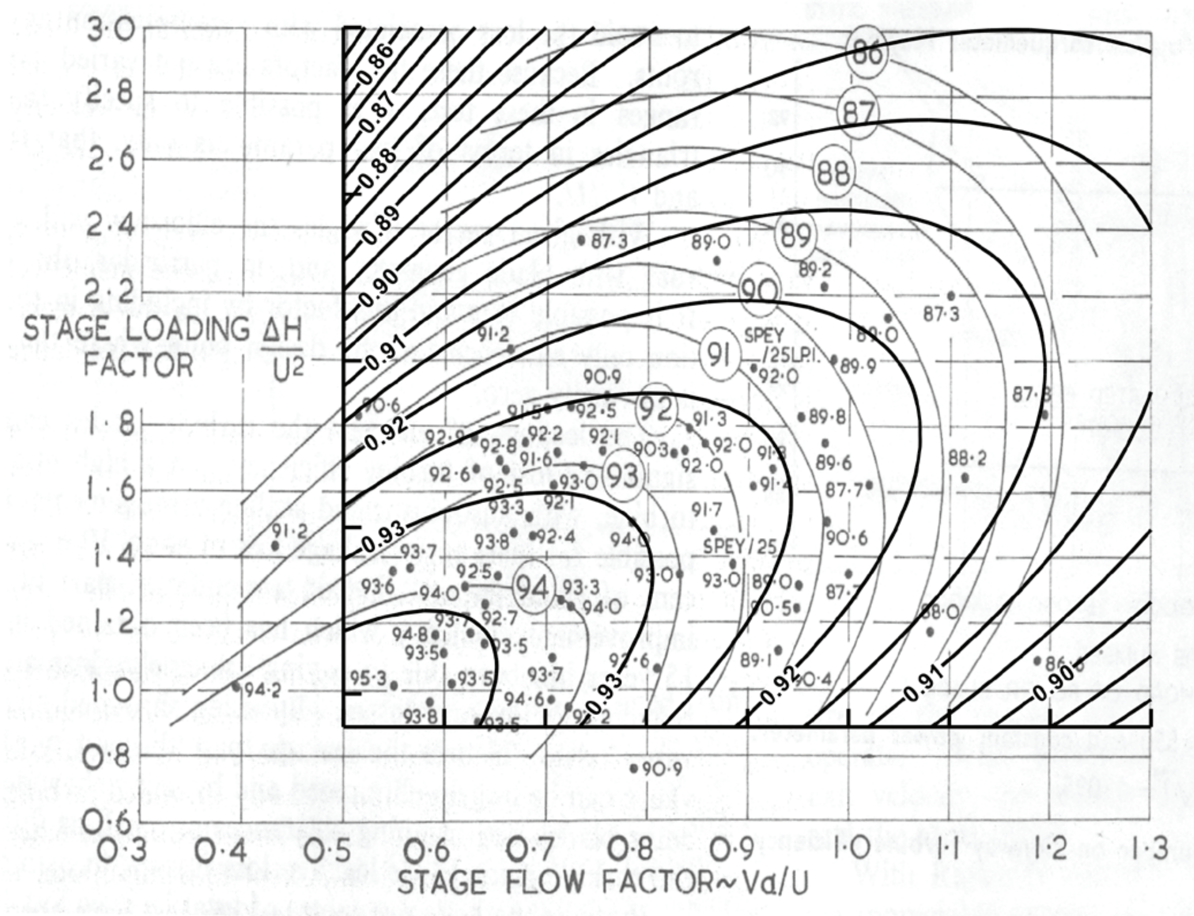
Constant Circulation Coefficient C_0



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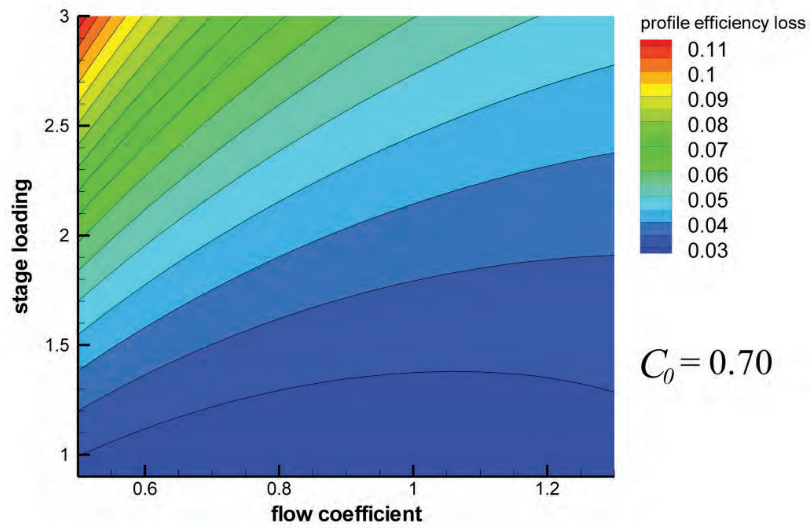
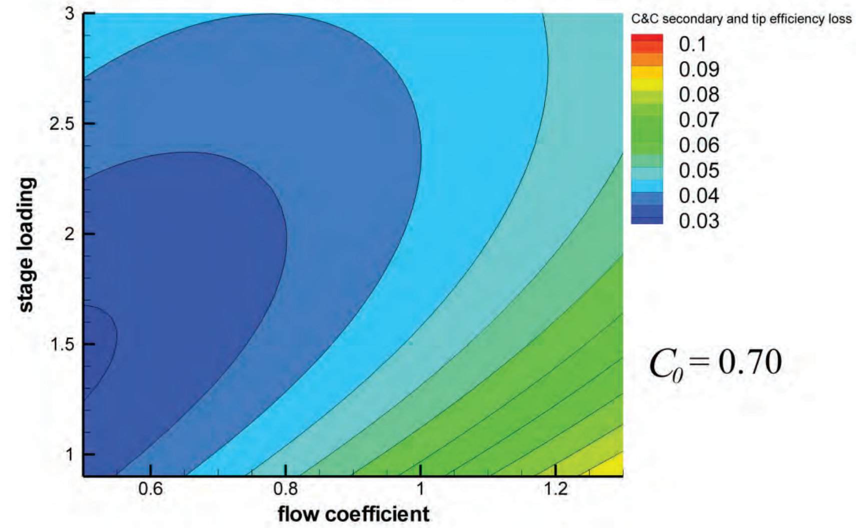
Profile vs. Secondary Losses



Profile Losses



Craig and Cox Secondary Flows

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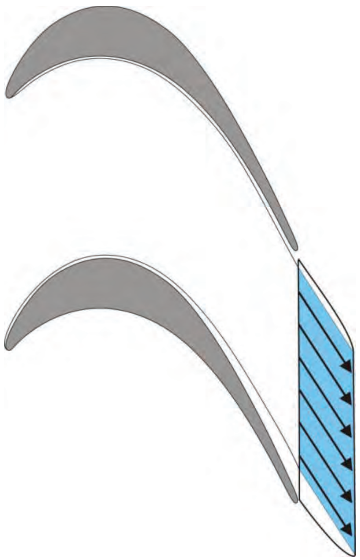
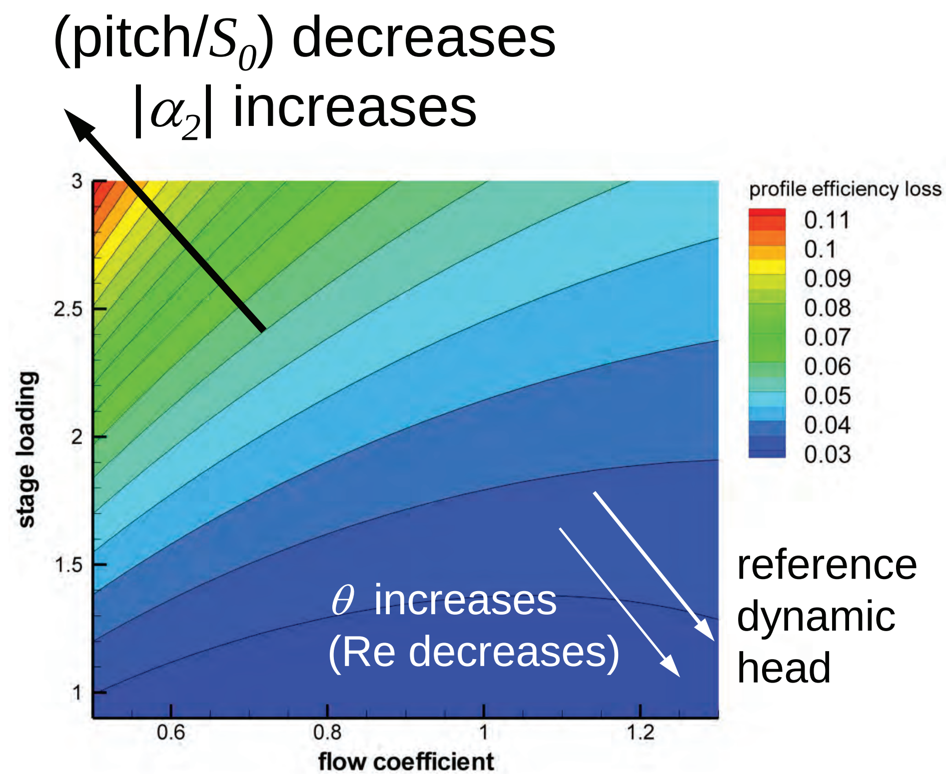
Profile Loss

$$\zeta \approx \left(\frac{2\theta}{s\cos(\alpha_2)} \right)$$





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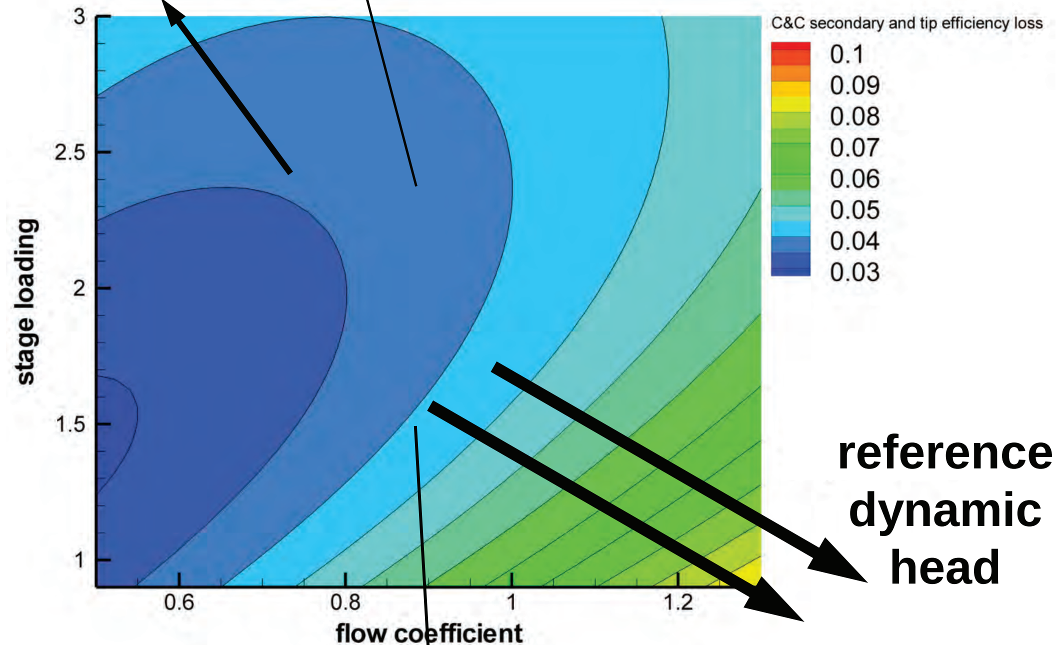
Craig and Cox (1970) Secondary Loss

decreasing
aspect ratio
(span/camber)

turning



reference dynamic head

increasing pitch

low velocity ratio

V_1/V_2

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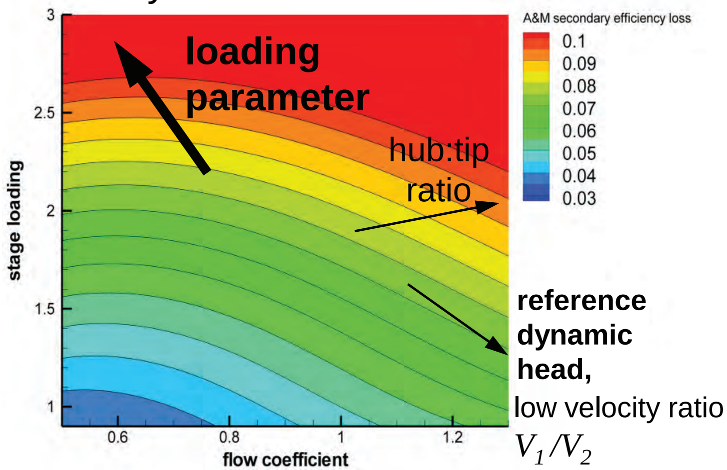
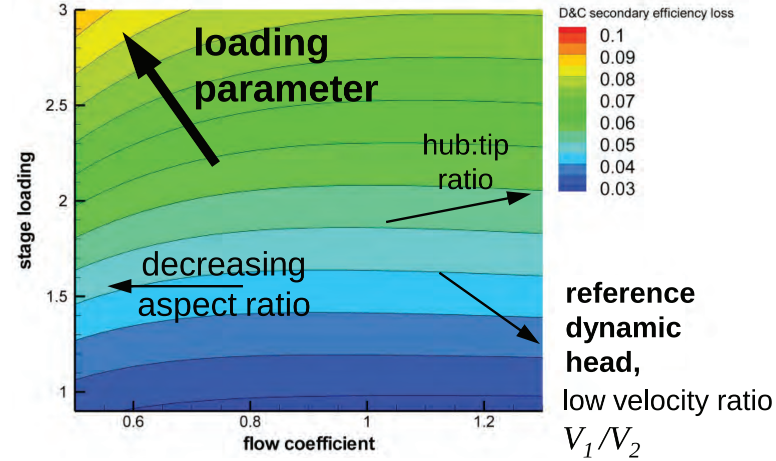
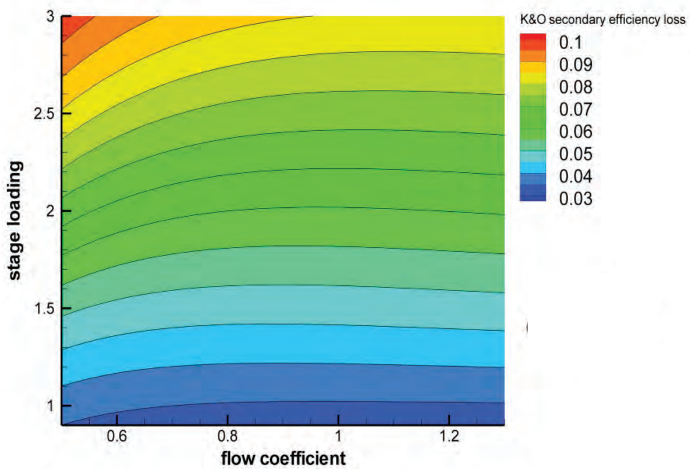
Other Secondary Loss Models

Ainley and Mathieson 1957

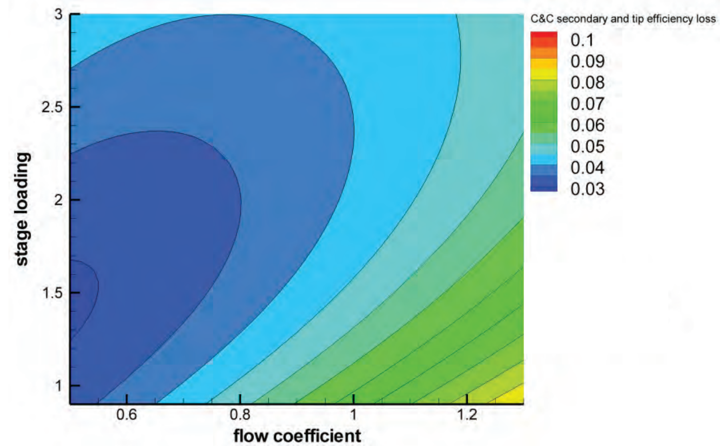


Dunham and Came 1970





Kacker and Okapuu 1982



Craig and Cox 1970

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Variation of Lift Coefficient C_0

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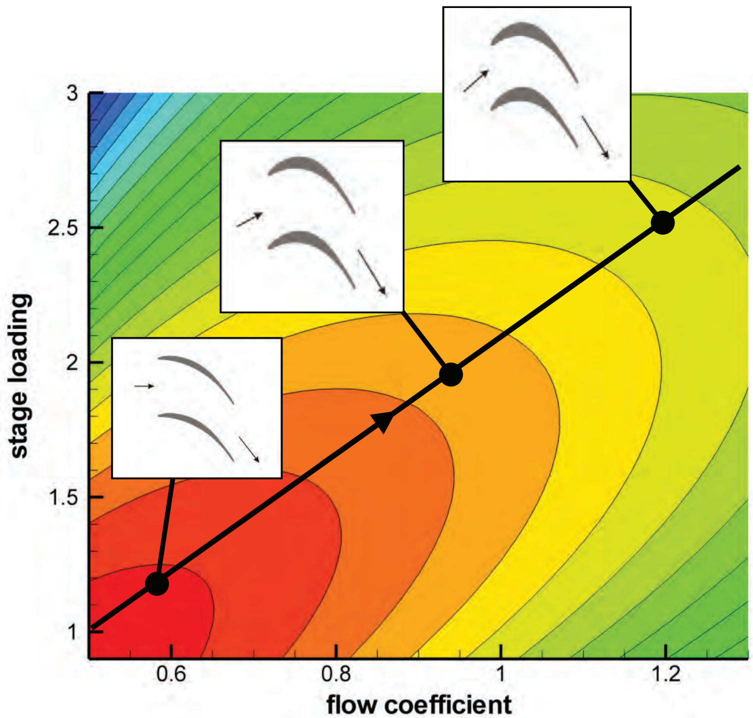
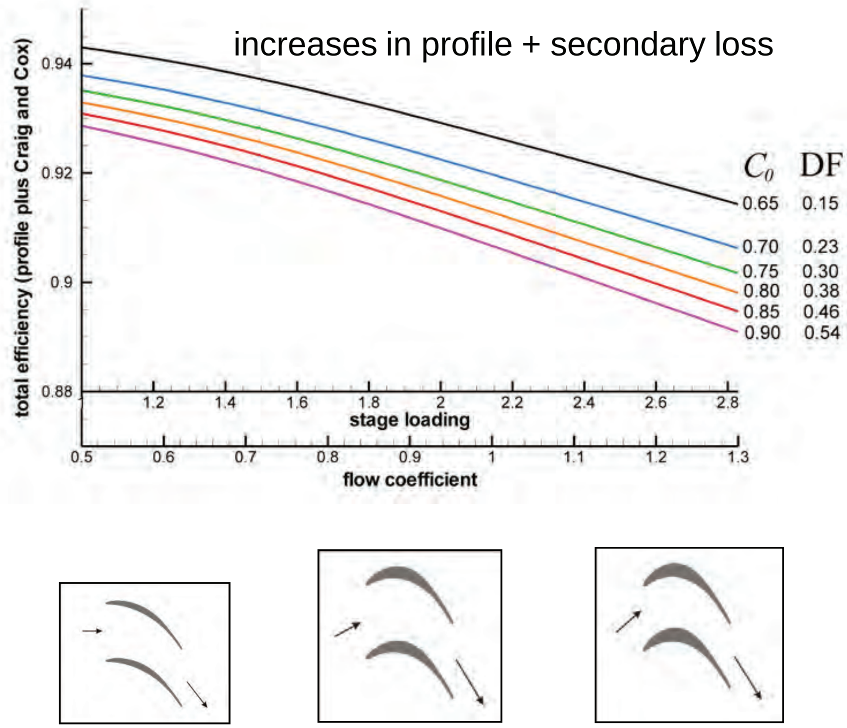
Efficiency Variation with Circulation Coefficient





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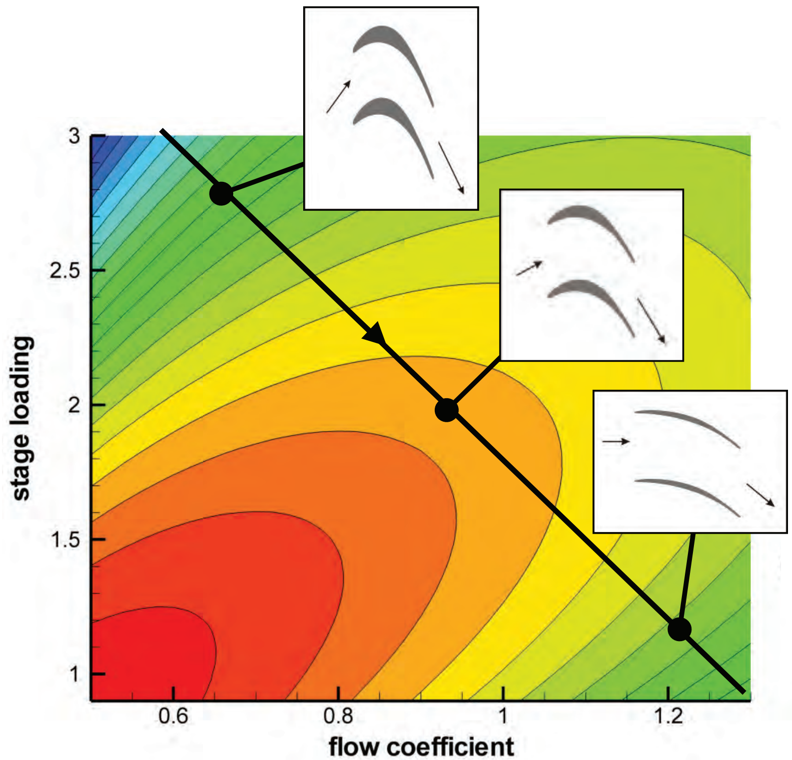
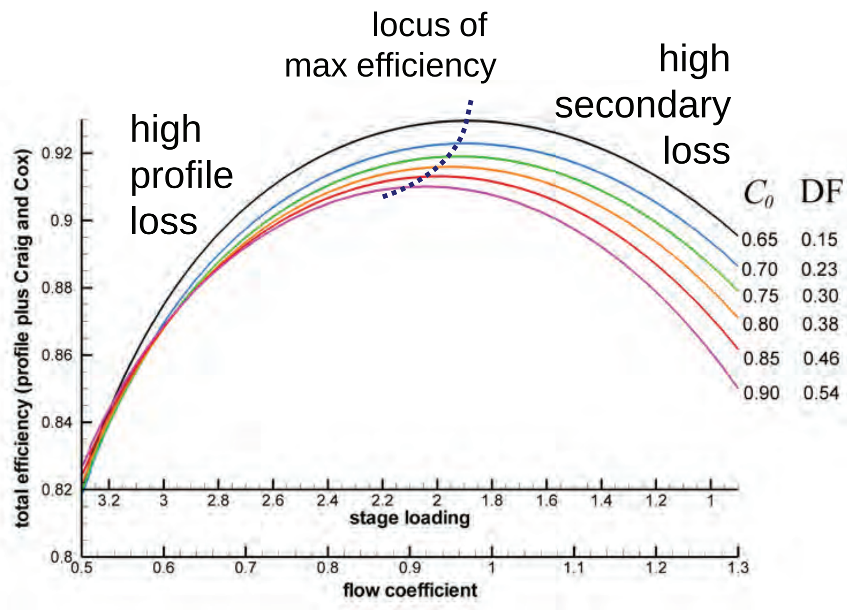
Efficiency Variation with Circulation Coefficient





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Conclusions: Modelling Performance

Modelling Profile Loss:

- Growth of suction surface boundary layer dominated by:
  - Deceleration Rate
  - Diffusion Factor

Design space study:

- Lift Coefficients:
  - Zweifel is not appropriate when angles change!
  - Circulation Coefficient C_0 :
    - direct measure of boundary layer loading
    - reproduces Smith Chart
- Secondary flow models:
  - Craig and Cox works best
  - Need further investigation & updating
- Model captures efficiency drop-off with increased lift

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Challenges and New Directions for Flow Prediction in Low Pressure Turbines

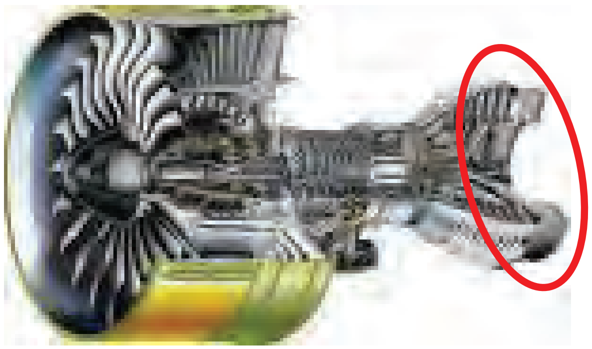
Prof. Roger L. Davis
University of California, Davis

NASA Glenn LPT Workshop
August 10-11, 2010

Introduction

- **Background**
- **CFD challenge areas for LPT flow prediction**
  - Areas of Weakness in Flow Prediction
- **Review of current techniques**
  - Strengths and weaknesses
- **Directions for Future Prediction Techniques**
- **Summary**

Background



- **Low pressure turbine design is a challenge due to:**
  - – Relatively large airfoils lead to weight penalty
  - – Reduction of weight leads to high pressure loading
  - – High pressure loading and low Reynolds number transitional flow leads to premature separation
  - – Flow separation leads to engine aerodynamic and structural performance penalties

CFD Challenge

- **Low pressure turbine design is also a challenge for CFD due to:**
  - The low Reynolds number of flow leads to transition occurring in turbine passage and is a strong affect on aerodynamic performance prediction
    - Accurate, robust transition prediction needed
  - The existence or possibility of separated flow leads to self-excited unsteadiness that must be captured in order to accurately predict aerodynamic and structural performance
    - Fast, accurate, time-averaged, unsteady simulations needed

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Goals of this Presentation

- **The goals of this particular presentation are to:**
  - Discuss the two specific bottlenecks to fast, accurate CFD prediction of LPT flows
    - Accurate, robust transition prediction
    - Fast, accurate, time-averaged, unsteady simulations
  - Summarize the research that has been done in the last decade in those two bottleneck areas
  - Identify the technical papers that provide further information
  - Suggest directions for further research of CFD for LPT flows

Accurate, robust transition prediction needed

Review of Transition Prediction Approaches

- **Review of transition prediction techniques are provided in**
  - Cheng et al. (AIAA2009-1141)
  - Pasquale et al. (AIAA2009-3812)
  - Cutron et al. (GT2005-68330)
- **I have gone through much of the literature myself to obtain papers and understand the viable methods specifically for turbomachinery**
  - Hopefully, this is not a duplication of effort by others in this workshop
  - I apologize if I have missed a particular transition prediction method or CFD approach/reference

Transition Prediction Approaches(1)

- **Stability theory via e^N**
  - Weaknesses:
    - Not robust, not as meaningful for internal flows
- **Low-Re two-equation models**
  - Weaknesses:
    - Not robust, not physical
- **Algebraic correlations for transition in conjunction with turbulence models**
  - Strengths:
    - Based on turbomachinery experiments
    - Can be more easily tuned to specific turbomachinery problems
    - Affordable in terms of computational resources
  - Weaknesses:
    - Can be difficult to implement for multi-block unstructured or structured grids used in parallel computations and for 3D problems
    - Do not lend themselves to extension into wakes or multiple blade row turbomachinery (additional transport equations sometimes used for this)
    - Requires calculation of boundary layer length scales and boundary layer edge quantities that are difficult to accurately obtain for 3D flows
    - Not necessarily universal for all types of turbomachinery

Transition Prediction Approaches(2)

- **Intermittency equations in conjunction with turbulence models**
  - Strengths:
    - Turbomachinery correlations can be incorporated for onset of transition
  - Weaknesses:
    - Requires calculation of boundary layer length scales and boundary layer edge quantities that are difficult to accurately obtain for 3D flows
- **γ–$R_{\theta t}$ two-equation transport model for transition**
  - Strengths:
    - Turbomachinery correlations can be incorporated for onset of transition
    - Vorticity Reynolds number used rather than momentum thickness Reynolds number
  - Weaknesses:
    - Requires correlations that may be dependent on particular problem
    - Not clear what transport of vorticity Reynolds number means physically
- **3 Equation k_L-k_T-ω transition transport model**
  - Strengths:
    - Does not rely on correlations
  - Weaknesses:
    - Early in model development. Promising but needs more validations.

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Transition Prediction Approaches(3)

- **Detached-eddy simulation with transition model**
  - Strengths:
    - Outer-layer turbulence resolved and transported
  - Weaknesses:
    - Requires transition model since near-wall turbulent structures responsible for transition offset are not resolved
- **Large-eddy simulation**
  - Strengths:
    - No explicit models for transition but rather solved directly
  - Weaknesses:
    - Near-wall sub-grid scale models are immature for transitional flow
    - Requires large amount of computational resources (not yet feasible for design)
    - Sensitivity to Smagorinsky constant

← Implicit Large-Eddy Simulation

- **Direct numerical simulation**
  - Strengths:
    - Transitional flow solved directly
  - Weaknesses:
    - Takes enormous amount of computational resources
    - Strong grid dependence

γ, R_θ Algebraic Correlation Approaches(1)

- **RANS with algebraic turbulence model using Abu-Ghannam-Shaw** (bypass, J. Mech. Eng. Sci., Vol. 22 (5))**, Roberts** (separation, J. of Eng. for Power, Vol. 97) **with Dhawan-Narasimha** (JFM, Vol 3, 1958) **intermittency**
  - Dorney et al. (AIAA1996-2567, AIAA1998-3575, AIAA1999-742, AIAA2000-742, AIAA2000-737, AIAA JPP Vol 16 (1))

Bypass

$$R_{e\theta} = 163 + \exp\left[F(\lambda_\theta) - \frac{F(\lambda_\theta)}{6.91} TI\right]$$

Separation

$$R_{e_s} = 25{,}000 \log_{10}\left(\coth\left(TFx10\right)\right)$$

- **RANS with 2-equation turbulence model using Abu-Ghannam-Shaw, Mayley et al.** (ASME JT, Vol. 113) **etc. or Suzen et al.** (AIAA J Vol 40 (2)) **with Dhawan-Narasimha, Suzen-Huang** (AIAA2001-446)**, or Steelant-Dick** (ASME JFE Vol 123) **intermittency**
  - Cutrone et al. (GT2005-68330)
  - Jiang and Simon (GT2004-54223)

Bypass

$$R_{e\theta} = 400(TI)^{-5/8}$$

$$R_{e\theta} = 163 + \exp\left[F(\lambda_\theta) - \frac{F(\lambda_\theta)}{6.91} TI\right]$$

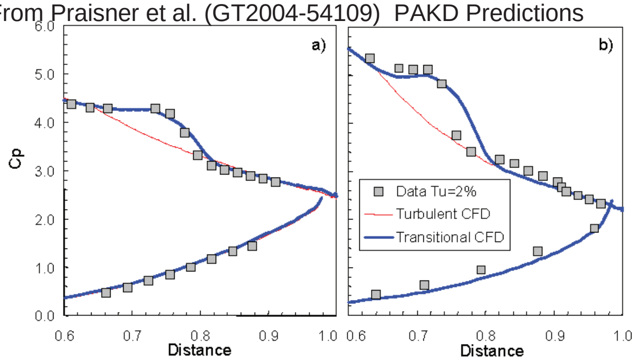
Separation

$$R_{e_s} = 25{,}000 \log_{10}\left(\coth\left(17.32 TI_e\right)\right) \quad R_{e_s} = 25{,}000 \log_{10}\left(\coth\left(TFx10\right)\right)$$

γ, R_θ Algebraic Correlation Approaches(2)

- **RANS with two-equation turbulence model using Praisner-Clark (bypass/separation) correlations**
  - Praisner, Clark et al. (GT2004-54108,9)
  - Davis, Clark, et al. (AIAA2008-4407)

From Praisner et al. (GT2004-54109) PAKD Predictions



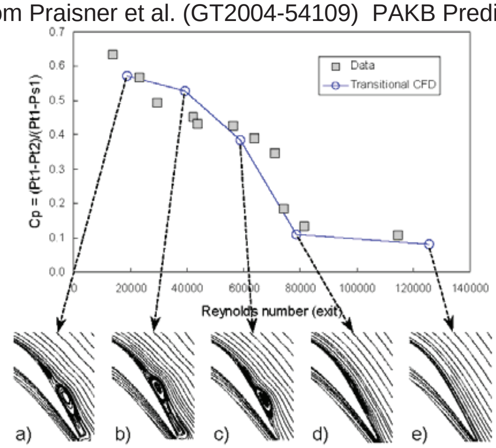
Bypass

$$Re_\theta = A\left(Tu\,\theta\,\frac{C_\mu \omega_{edge}}{u'_{edge}}\right)^B$$

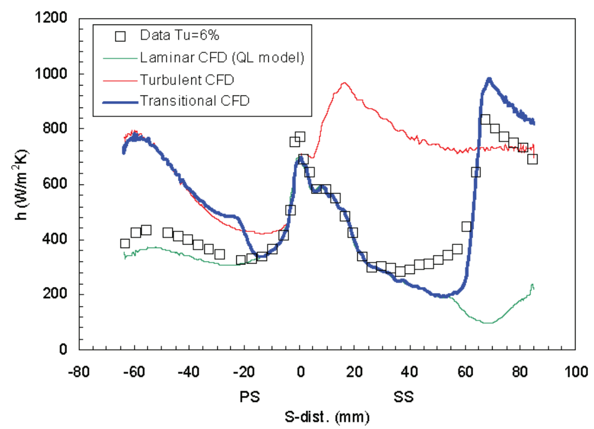
Separation

$$\frac{L_{transition}}{S_{separation}} = C\,Re^D_{\theta-separation}$$

From Praisner et al. (GT2004-54109) PAKB Predictions



From Praisner et al. (GT2004-54109) VKI Vane Predictions

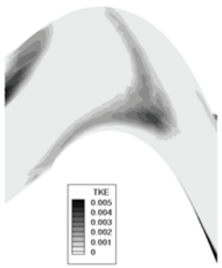


Intermittency Transport Equation Approaches

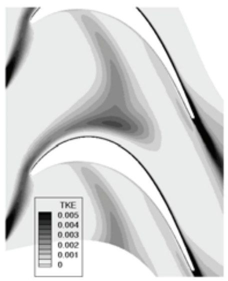
- **Intermittency equations are solved with transition criteria based on local freestream turbulence**
  - Lodefier and Dick (GT2005-68714, GT2006-90044)

$$\frac{\partial(\rho\zeta)}{\partial t}+\frac{\partial(\rho U_i\zeta)}{\partial x_i}=-E_\zeta+\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_\zeta}{\sigma_\zeta}\right)\frac{\partial\zeta}{\partial x_i}\right]$$

TKE Experiment



TKE Prediction



Free-stream Factor

$$E_\zeta = C_3\mu_\zeta\frac{U}{U_\infty^2}\frac{\partial U}{\partial n}\frac{\partial\zeta}{\partial n}$$

Near-wall intermittency

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho U_i\gamma)}{\partial x_i}=P_\gamma+\frac{\partial}{\partial x_i}\left[(\mu+\frac{\mu_t}{\sigma_\gamma})\frac{\partial\gamma}{\partial x_i}\right]$$

$$P_\gamma = 2\beta(1-\tau)\sqrt{-\ln(1-\gamma)}\rho\,[U_\infty F_s+(Uf_\tau-U_\infty)(2-F_s)$$

- **Intermittency equations are solved with transition criteria based on transition onset and length correlations**
  - Suzen, Huang, et al.

(ASME JFE Vol 122, ASME JT Vol 129, NASA CR 1999-209313, AIAA 2000-0287, AIAA2010-4325)

$$\frac{\partial\rho\gamma}{\partial t}+\frac{\partial\rho u_j\gamma}{\partial x_j}=$$

$$(1-\gamma)\left[\begin{array}{l}(1-F)2C_0\rho\sqrt{u_k u_k}\,f(s)f'(s)\\ +F\left(\frac{C_1\gamma}{k}\tau_{ij}\frac{\partial u_i}{\partial x_j}-C_2\gamma\rho\frac{k^{3/2}}{\varepsilon}\frac{u_i}{(u_k u_k)^{1/2}}\frac{\partial u_i}{\partial x_j}\frac{\partial\gamma}{\partial x_j}\right)\end{array}\right]$$

$$+C_3\rho\frac{k^2}{\varepsilon}\frac{\partial\gamma}{\partial x_j}\frac{\partial\gamma}{\partial x_j}$$

$$+\frac{\partial}{\partial x_j}\left(((1-\gamma)\gamma\sigma_{\gamma l}\mu+(1-\gamma)\sigma_{\gamma t}\mu_t)\frac{\partial\gamma}{\partial x_j}\right)$$

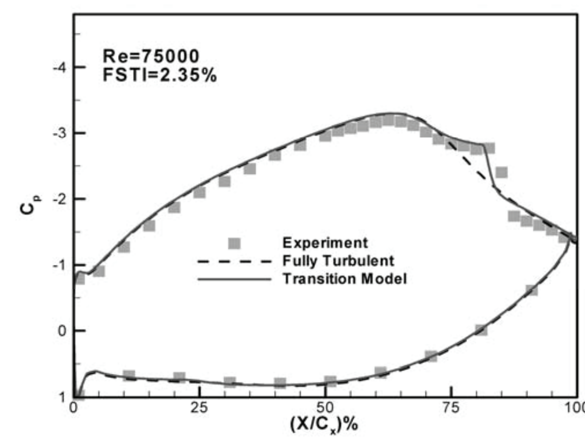
Intermittency Applied to Turbulent Viscosity $\mu^* = \gamma\,\mu_t$

γ–$R_{\theta t}$ Transport Equation Approach

- **2-Equation model for transition**
  - Langtry, Mentor et al. (AIAA J Vol 47 (12) 2009, GT2004-53452, GT2004-53454)
  - Content and Houdeville (AIAA 2010-4445)
  - Piotrowski et al. (GT2008-50796)

From Langtry and Menter (AIAA J Vol 47 (12), 2009)

PAKB Prediction



$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_{\gamma 1} - E_{\gamma 1} + P_{\gamma 2} - E_{\gamma 2} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_f}\right)\frac{\partial \gamma}{\partial x_j}\right]$$

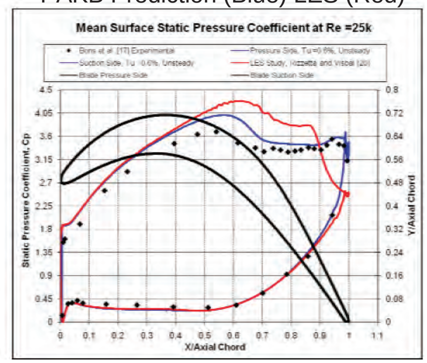
$$\frac{\partial(\rho \tilde{\mathrm{Re}}_{\theta t})}{\partial t} + \frac{\partial(\rho U_j \tilde{\mathrm{Re}}_{\theta t})}{\partial x_j} = P_{\theta t} + \frac{\partial}{\partial x_j}\left[\sigma_{\theta t}(\mu + \mu_t)\frac{\partial \tilde{\mathrm{Re}}_{\theta t}}{\partial x_j}\right]$$

- **Vorticity Reynolds number, that is directly related to momentum thickness Reynolds number, is used to trigger transition based on correlations for $Re_{\theta c}$ and $L_{transition}$**
  - Intermittency is applied to TKE Production and Destruction terms

k_L-k_T-ω Transport Model

From Sanders et al. (GT2008-50283)

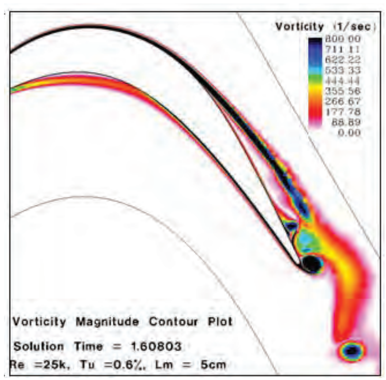
PAKB Prediction (Blue) LES (Red)



- **Walters-Leylek model** (ASME JT Vol 126, 2004)
  - Mayle and Schulz (ASME JT Vol 119, 1997)
  - Sanders et al. (GT2008-50283, AIAA2009-1467)
- **k_L contributes to large-scale and k_T contributes to small-scale turbulence production.**
- **Two kinetic energies can trade-off on each other. Transition occurs when k_T exceeds a particular threshold.**

From Sanders et al. (GT2008-50283)

PAKB LES Prediction



$$\frac{Dk_T}{Dt} = P_{k_T} + R + R_{NAT} - \omega k_T - D_T + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\alpha_T}{\sigma_k}\right)\frac{\partial k_T}{\partial x_j}\right]$$

$$\frac{Dk_L}{Dt} = P_{k_L} - R - R_{NAT} - D_L + \frac{\partial}{\partial x_j}\left[\nu \frac{\partial k_T}{\partial x_j}\right]$$

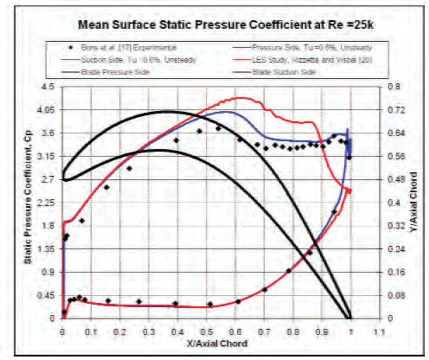
$$\frac{D\omega}{Dt} = P_\omega + C_{\omega R}\frac{\omega}{k_T}(R + R_{NAT}) - C_{\omega 2}\omega^2 - C_{\omega 3} f_\omega \alpha_T \left(\frac{\lambda_{eff}}{\lambda_T}\right)^{4/3}\frac{\sqrt{k_T}}{d^3} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\alpha_T}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]$$

Large-Eddy Simulation

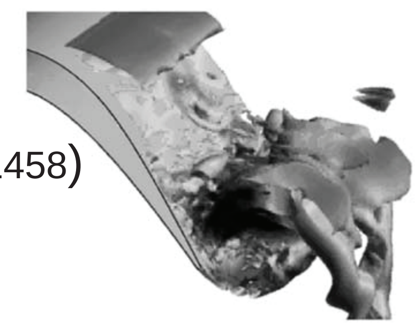
- **Transition is determined directly with dense computational grids. No additional transport or correlations required for transition. High-order numerical techniques often used.**
  - Michelassi et al (AIAA J Vol. 41 (11), 2003)
  - Rizzetta and Visbal (AIAA2003-3587, AIAA J, Vol 43 (9), 2005, AIAA J Vol 45 (10) 2007)
  - Gross and Fasel (AIAA2009-4275,AIAA2010-4736, AIAA J Vol 48 (6))
  - Sanders et al. (GT2008-50283)
  - Roberts and Yaras (GT2005-68666)
  - Biswas et al (AIAA2006-2881, GT2008-51458)
  - Poondru et al. (AIAA2006-2882)
  - Hah (AIAA2009-1061)
  - Galbraith and Visbal (AIAA2008-225)
  - Lan et al. (GT2009-59833)

From Sanders et al. (GT2008-50283)

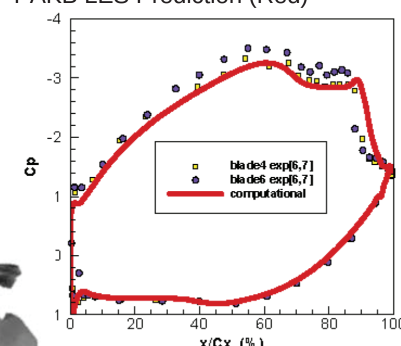
PAKB Prediction (Blue) LES (Red)

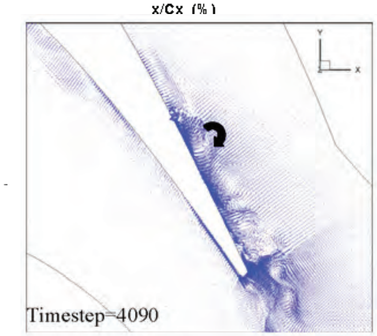


From Rizzetta and Visbal (AIAA J Vol 43 (9) 2005)



From Lan et al. (GT2009-59833)
PAKB LES Prediction (Red)

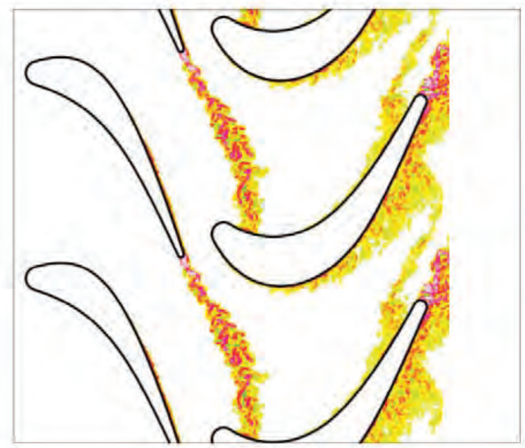




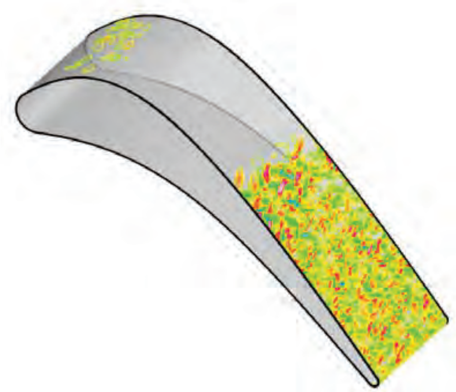
Direct Numerical Simulation

- **All turbulence scales are resolved with very dense computational grids. High-order accurate numerical techniques used. Not feasible for routine simulations due to very large computational resource requirement.**
  - Rai (AIAA2006-4460, AIAA2009-3685, AIAA2009-584)
  - Rai (AIAA2010-6533) (compressor)
  - Zakai (GT2006-90885) (compressor)

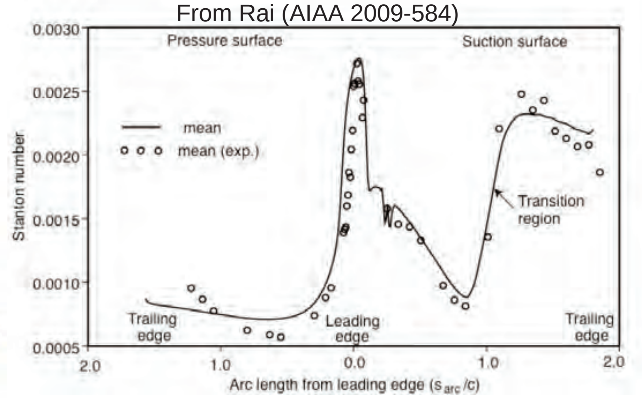
From Rai (AIAA 2009-3685)



From Rai (AIAA 2009-584)



From Rai (AIAA 2009-584)



Future Directions(1)

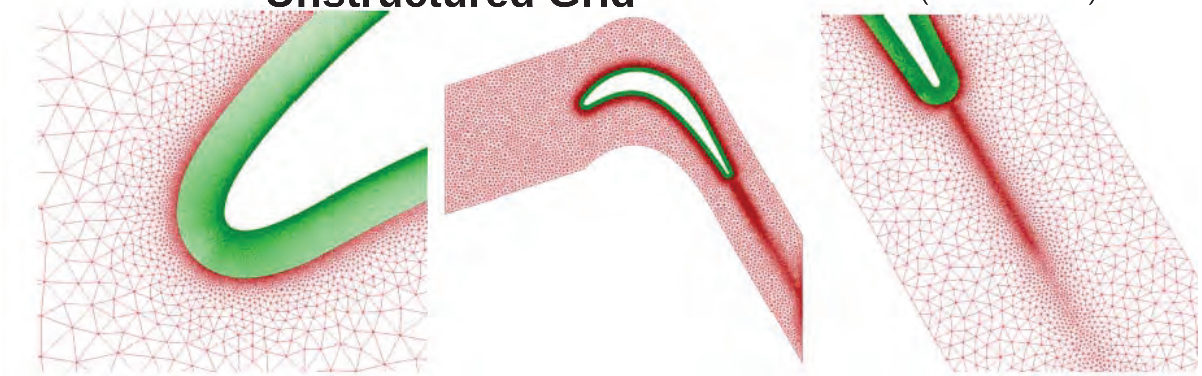
- **Langtry-Menter et al. and Pasquale et al. suggested requirements for future transitional-flow prediction capability** (AIAA2009-3812, AIAA J Vol 47 (12), 2009, GT2004-53452) **:**
  - "Allow the calibrated prediction of the onset and length of transition
  - Allow the inclusion of different transition mechanisms
  - Be formulated locally (no search or line-integration operations)
  - Avoid multiple solutions (same solution for initially laminar or turbulent boundary layer)
  - Not affect the underlying turbulence model in the fully turbulent regime
  - Allow a robust integration down to the wall with similar convergence as the underlying turbulence model
  - Be formulated independent from the coordinate system
  - Applicable to three-dimensional boundary layers"
  - Avoid reliance on techniques that utilize momentum thickness directly or boundary layer edge quantities that are difficult to obtain in unstructured, overlaid, and multi-block grid parallel techniques
  - Universal approach for all types of turbomachinery, wings, etc.

Parallel Computing on Different Grid Types

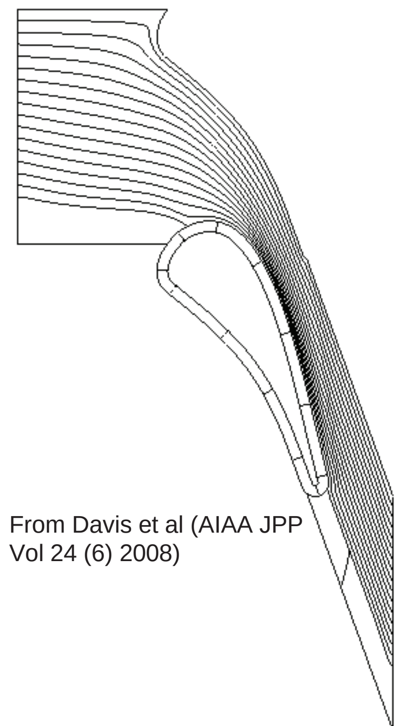
- **Unstructured, overlaid, and multi-block structured all have similar challenges in terms of parallel computing and transition modeling**

Unstructured Grid

From Sanders et al (GT2008-50283)



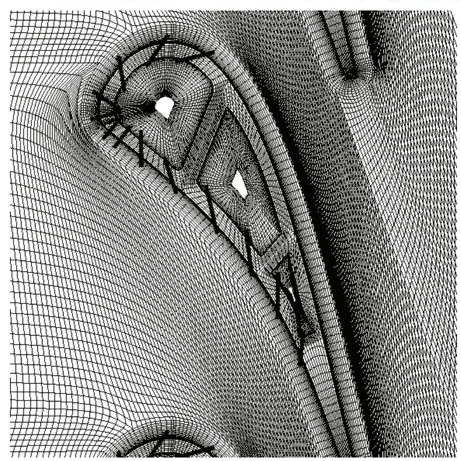
Multi-Block Structured Grid Blocks



From Davis et al (AIAA JPP Vol 24 (6) 2008)

Overlaid Grid

From Davis et al (AIAA2010-1461)



Future Directions(2)

- **These previously mentioned criteria and issues should direct us to a transport equation approach using**
  - γ–$R_{\theta t}$, γ, k_L-k_T-ω, or LES
- **All of these approaches have challenges to make them accurate, robust, and very well validated**
- **Few of these approaches have been demonstrated for turbomachinery flows near endwalls**
  - But we know that secondary-flows are another prediction weakness
- **Not all of the intermittency and transport transition models have been demonstrated for unsteady flows**
  - But we know that unsteady flow effects are important
- **This leads us to a discussion on the second bottleneck**
    - Fast, accurate, time-averaged, unsteady simulations needed

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Fast, accurate, time-averaged, unsteady simulations needed

Moving from Steady to Unsteady, TA CFD

- **In the past, "steady" flow simulations have been used exclusively for design and for nearly everything else except for forced-response/fatigue analysis**
  - Steady-flow results have provided accuracy generally to within 3-5% of actual performance
  - This accuracy is not good enough for modern "optimized" designs
- **We should now move past "steady" and pursue time-averaged, unsteady as the norm**
  - This is a large step to take and makes LPT design/analysis even more challenging
  - However, it enables us to consider unsteady, transitional transport simulation capability

URANS vs DES vs LES

- **Time-averaged, URANS requires around an order-in-magnitude more compute time compared to “steady” simulations**
  - Time-term is added
  - Time-resolution requires proper global time-step which adds at least an order-in-magnitude in compute time
  - Time-averaging requires additional compute time
- **Detached-eddy Simulation requires around ~3 times the grid density in the wall-normal and cross-flow directions compared to URANS to resolve outer-layer turbulence**
  - Very little additional steps are performed in the numerical algorithm
  - However, the additional grid density leads to nearly an order-in-magnitude increase in computational time compared to URANS
  - Also requires algebraic correlation or transport model for transition prediction since length-scales responsible for transition are not resolved

URANS vs DES vs LES

- **Large-eddy simulation requires ~5 times the grid density in the wall-normal and cross-flow directions compared to URANS for wall-layer flows**
  - Significant additional steps are performed in the numerical algorithm to created grid-filtered turbulent stresses
  - Proper time-resolution requires small enough time-steps to resolve higher frequencies due to turbulence transport
  - Additional grid density is absolutely required to compute turbulent stresses accurately and possibly model transition for LPT simulations
- **DNS would take ~10 times the grid density in the wall-normal and cross-flow directions compared to URANS making it infeasible**

How do we make that leap?

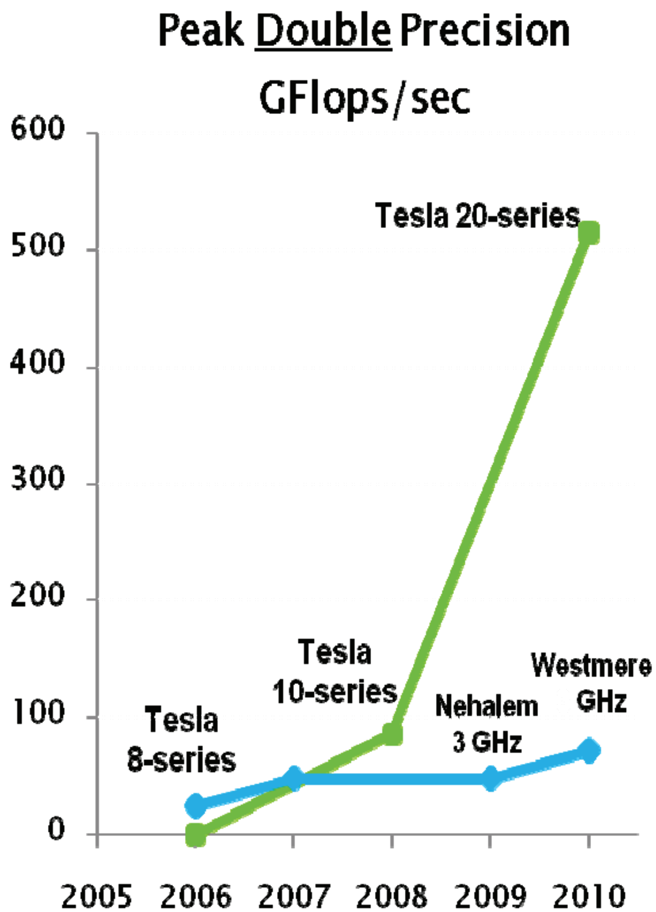
- **So….time-averaged DES and LES will require somewhere around**
  - 90-250 times the current "steady" computational time
  - 20-50 times the computer memory of current "steady" computations
- **High-order accurate numerical techniques can help to reduce computational grid requirements and solution time**
  - Move to compact, high-order control-volume techniques retro-fitted to existing codes
    - This is another separate seminar to cover these topics
- **How do we get there with today's technology?**
  - We could use more CPU/cores at a linear increase in cost
  - OR we could move to a different computing paradigm recognizing that many parts of our CFD codes lend themselves very well to massively-parallel computing

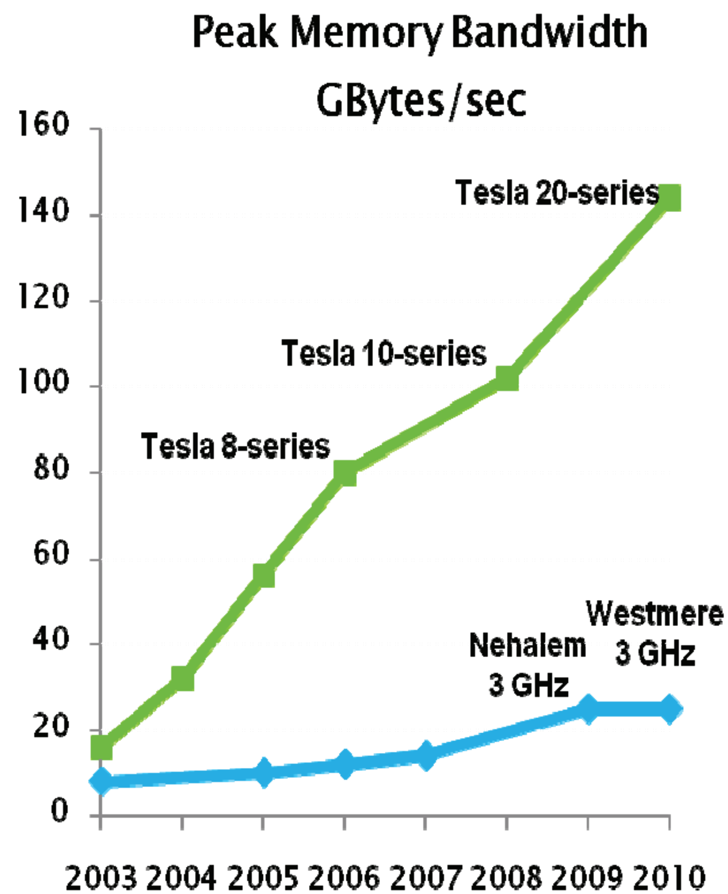
Let's Use GPUs with CPUs!

- **Graphical processing units (GPUs) have proven success for gaming applications**
- **We have recently shown GPUs to also be useful for scientific simulations**
- **GPU Costs:**
  - ~$500 for 128 floating-point units (GeForce) and ~$1500 for 448 floating-point units (Tesla-Fermi)
  - <u>Example</u>: Our GPU cluster in ECE
    - 8 nodes of single quad-cores (32 cores)
    - 1 GeForce GPU per core → 32 GPUs
    - 12 Teraflops of peak performance, ~$25,000-$30,000
  - Low space and power requirements

- **Cost Effective Means of Achieving our Goals!**

GPU vs CPU Performance Trends



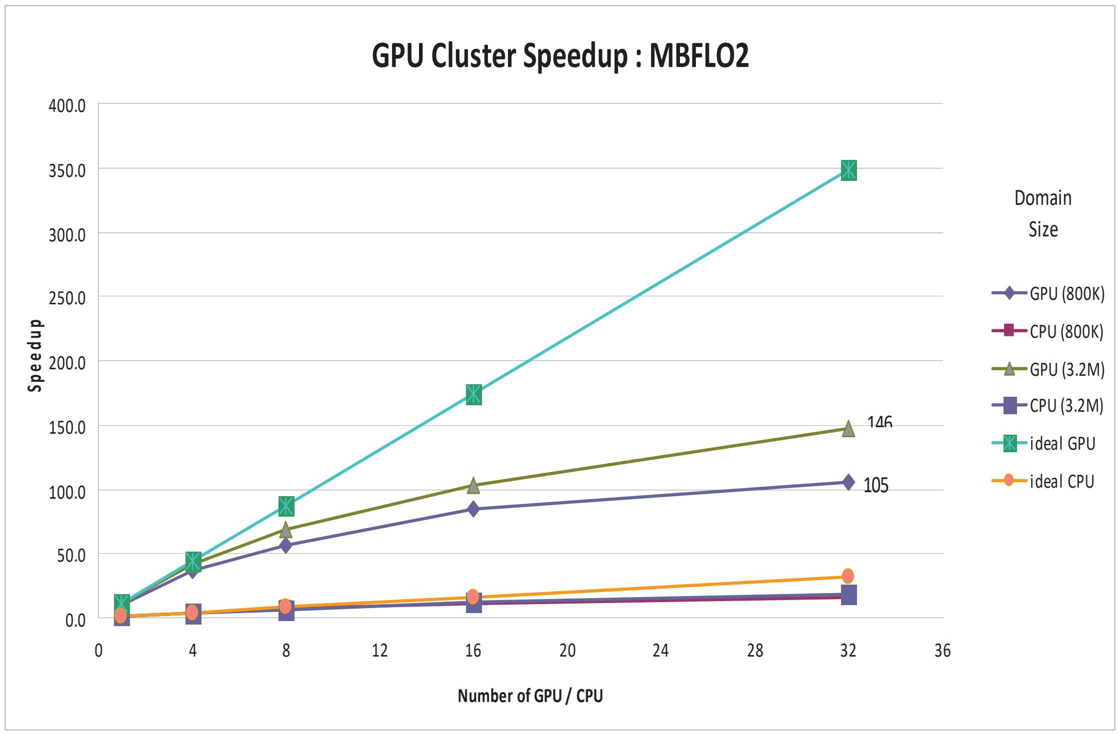


Figures courtesy Nvidia
(http://developer.download.nvidia.com/compute/cuda/2_0/docs/NVIDIA_CUDA_Programming_Guide_2.0.pdf)

Single-Precision Results (Older Technology)

- **Argonne National Laboratories 32 CPU/GPU cluster GeForce GPU Cards (Single Precision)**
  - Phillips et al. (AIAA2009-565) multi-block structured Euler with speed-up of 5 over equivalent number of CPUs
  - Corrigan et al. (AIAA2009-4001) unstructured-Grid RANS with speed-up of 32 over CPU

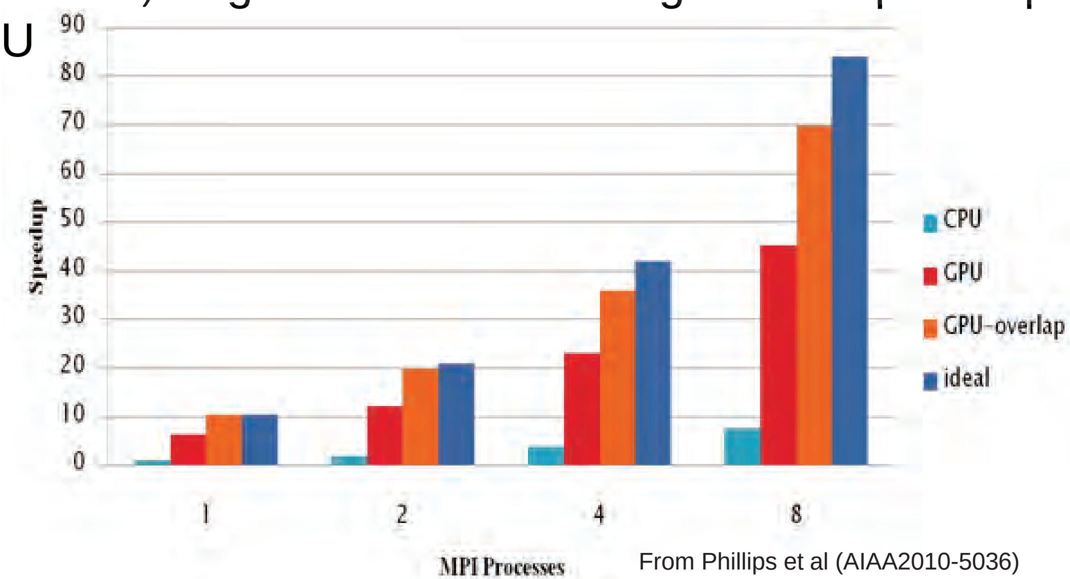
From Phillips et al (AIAA2009-565)



Double-Precision Results (Latest Technology)

- **NVIDIA CPU/GPU cluster Tesla (Fermi) GPU Cards (Double Precision)**
  - Phillips et al. (AIAA2010-5036) multi-block structured RANS with speed-up of 10.5 over equivalent number of CPUs
  - Shinn et al. (AIAA2010-5029) DNS with speed-ups of ~18.7 over CPU
  - Corrigan et al. (AIAA2009-4001) unstructured-grid RANS with speed-up of 7.4 over CPU
  - Jacobsen et al. (AIAA2010-522) single-block structured grid with speed-up of ~68 over single CPU

GPUs clearly show advances in speed that we need to make step to time-averaged DES…and perhaps more!



From Phillips et al (AIAA2010-5036)

Validation of Prediction Capability is Critical

- **The validation of CFD prediction tools is essential to ensure accuracy and robustness**
- **Many experiments have been conducted to investigate and measure low-Reynolds number flows in low-pressure turbines for understanding**
  - Design strategy (front vs aft-loading)
  - Separation control
- **This data is valuable for the validation of the next-generation of fast, accurate, transitional CFD solvers for not only LPT flows, but for ALL gas-turbine flows**

LPT Design Strategy Experiments(1)

- **Much experimental research of LPT flow has focused on design strategy (front- vs aft-loaded) as loading is increased:**
  - Designed with unknown code(s)
    - Designed in 1987 (see Hoheisel et al. ASME JT Vol 109, No.4)
    - Efforts include:
      - Hodson et al. (GT2003-38303,4 at Whittle Lab for T106)
      - DePalma (AIAA Vol. 40, No. 4 used k-ω with algebraic stress)
  - Design with unknown code(s)
    - T164 MTU design (see Hourmouziadis, AGARD lecture Series 167, 1985)
    - Efforts include:
      - Martinstetter et al. (AIAA2008-82) to investigate freestream turbulence and passing wakes
  - Design tool with "MISES" inviscid/viscous (Euler/boundary-layer) interaction procedure
    - e^N or Abu-Ghannam and Shaw transition prediction
    - Efforts include:
      - Sondergaard et al. (GT2002-30602, AIAA2008-4156 at AFRL for PAKB design with different pitch)
      - Prakash et al. (GT2008-50052 at GE for HL/NL series)

LPT Design Strategy Experiments(2)

- **Much experimental research of LPT flow has focused on design strategy (front- vs aft-loaded) as loading is increased:**
  - Design tool with 2D transitional, Navier-Stokes (P&W In-House)
    - Praisner-Clark transition model (algebraic) coupled with k-ω turbulence model
    - Effort by:
      - Popovic et al. (GT2006-91271 at Carlton/P&W for PAKB and optimized designs at increased pitch)
      - Praisner et al. (GT2008-50898 at P&W/Carlton/AFRL)
  - Design tool with Clark (AFRL) 2D transitional, Navier-Stokes (Dorney-Wildcat) design system
    - Praisner-Clark transition model (algebraic) coupled with BL-algebraic turbulence model
    - Efforts by:
      - Bons et al. (GT2005-68962, GT2006-90754) to investigate L1M, L1A, and PAKB
      - Volino et al. (GT2008-51445 and GT2009-59983) to investigate L1A without and with control
      - Pluim et al. (GT2009-59276) and Nessler, et al. (AIAA2009-302) to investigate L1A with wake passing

Further R&D Needed

- WE HAVE A LOT MORE WORK TO DO !!
- **We need academia to continue to**
  - Determine the best transition transport methodology
  - Develop high-order integration methods that can be retro-fitted into existing procedures
  - Continue to provide valuable experimental data for validation
  - Push super-computing technology to increase speed and reduce cost even further
- **We need industry to**
  - Work with academia and government to incorporate new technologies into design systems and provide feedback
  - Help provide valuable experimental data for validation
  - Provide realistic configurations for validation
- **We need government to**
  - Provide programs and funding to move forward with new technologies
  - Help perform experimental and numerical research to push technology
  - Be actively involved with academia and industry to bring people together for collaborations
  - Drive the development and maturation of new technologies

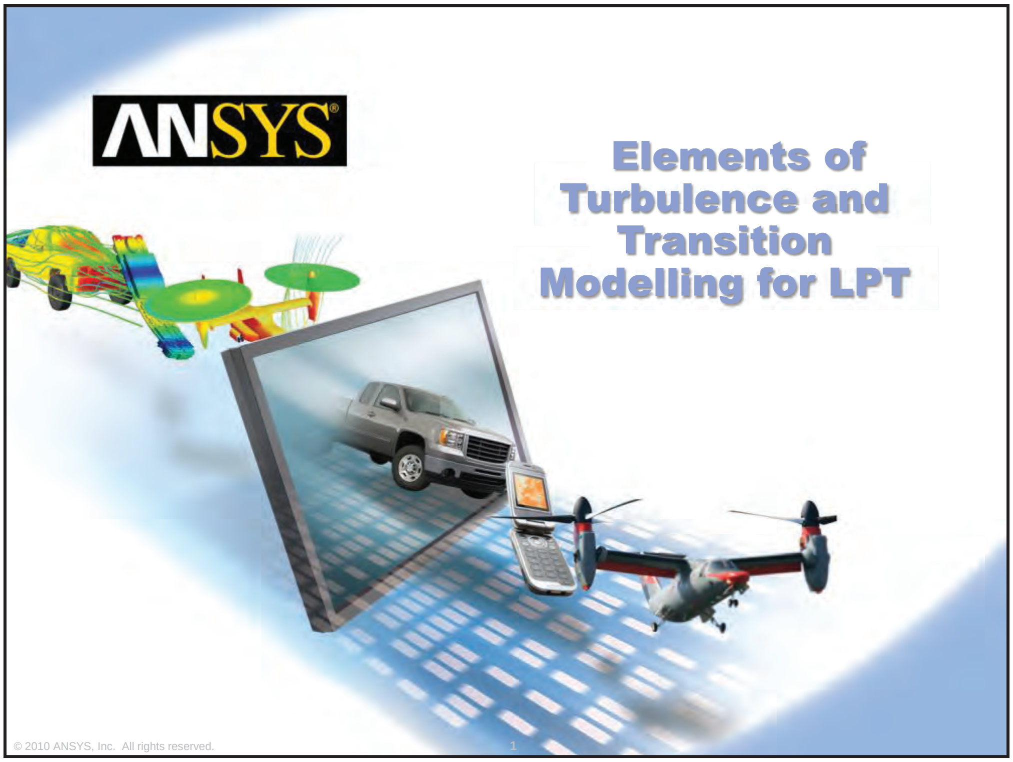
Summary

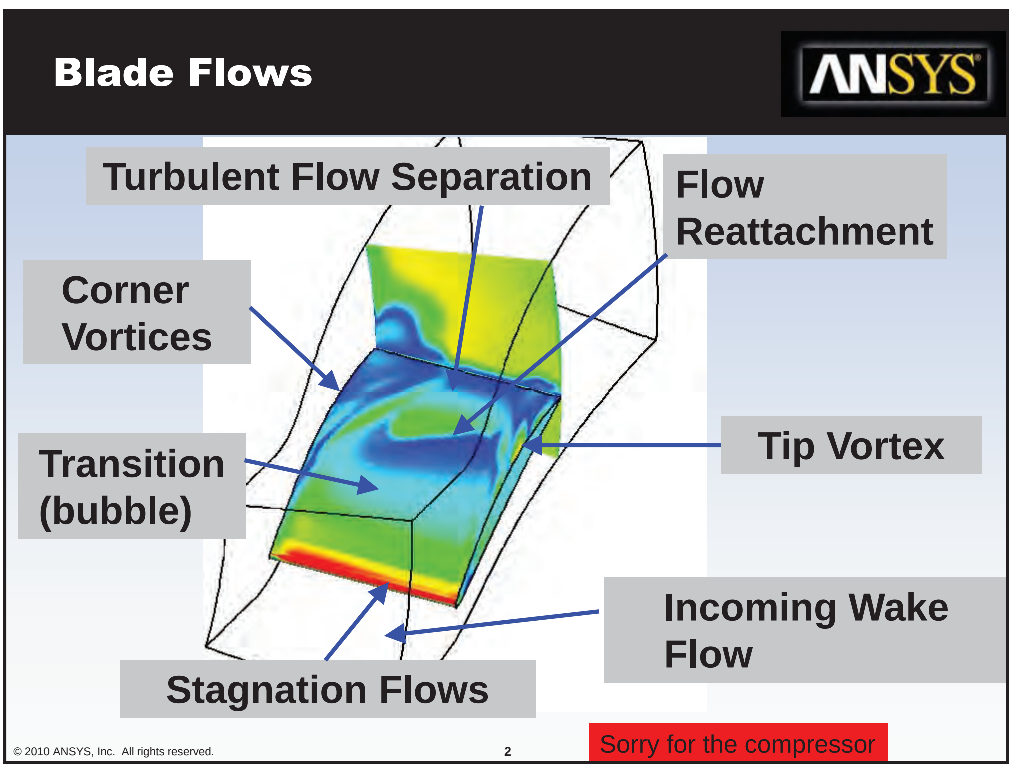
- **Summary of bottlenecks for CFD flow prediction in low-pressure turbines provided**
  - Transition prediction,
  - Speed of simulations, and
  - Experimental data for validation discussed
- **Provided references where you can find more information on these subjects**
- **Suggested some directions that, as a CFD developer, I feel we should be taking to move us to the next level in prediction accuracy and speed**

THANK YOU !

Elements of Turbulence and Transition Modelling for LPT

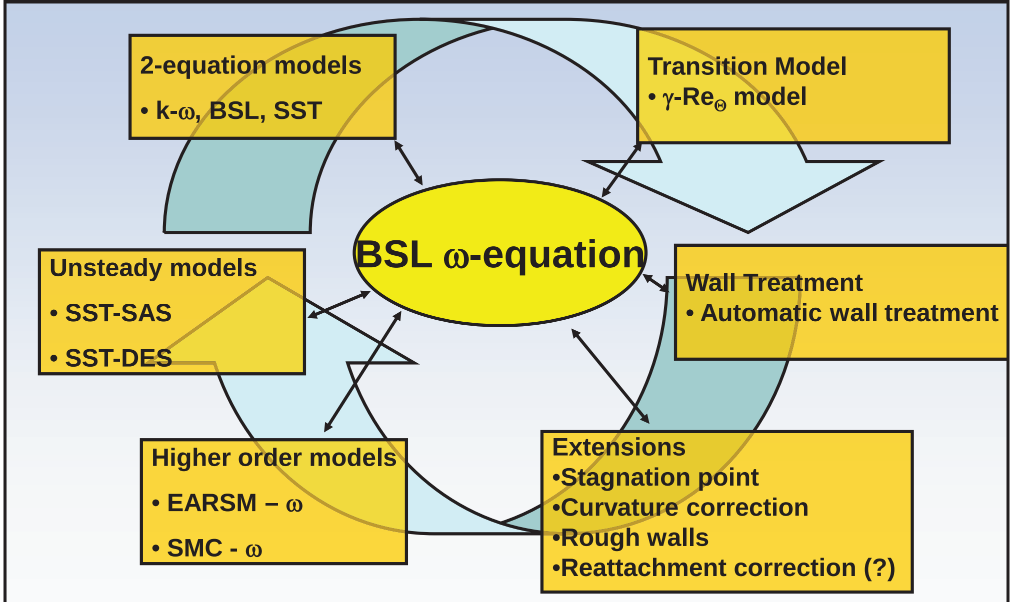
Florian Menter, ANSYS, Inc.





Modelling Strategy Requires Basic Model Framework

ANSYS



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k-ω Model (Wilcox)

ANSYS

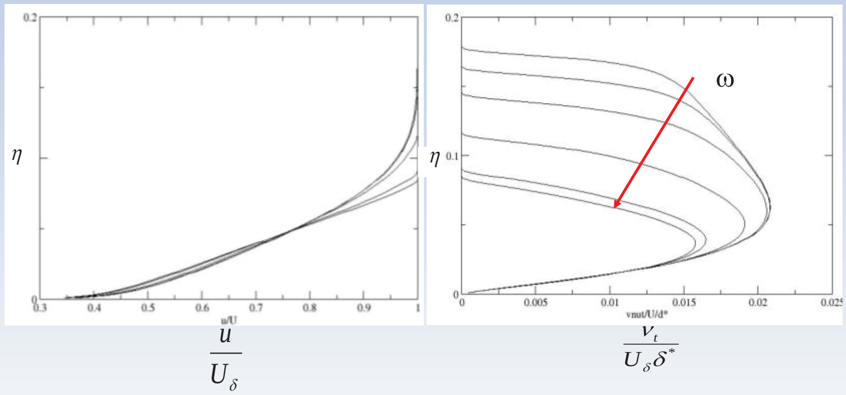
$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho \bar{U}_j k)}{\partial x_j}=P_k-\beta^*\rho k\omega+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\sigma_\kappa})\frac{\partial k}{\partial x_j}\right]$$

$$\frac{\partial(\rho \omega)}{\partial t}+\frac{\partial(\rho \bar{U}_j \omega)}{\partial x_j}=\alpha\frac{\omega}{k}P_k-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\sigma_\omega})\frac{\partial \omega}{\partial x_j}\right]$$

- **Advantages:**
  - –Simple formulation.
  - –Numerically robust.
  - –Grid resolution near wall $y^+ < 1\text{-}2$.
  - –Improved adverse pressure gradient behaviour.
- **Disadvantages:**
  - –Non-trivial boundary conditions.
  - –Free stream dependency problem
    - blending possible (SST-Model).

 4

„Freestream Sensitivity“ k-ω

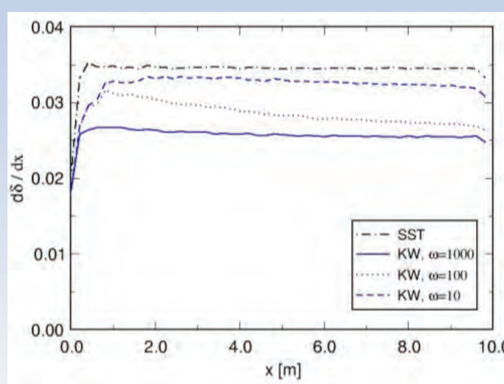


- With pressure gradient; c_f changes by 16%
- Sensitive to ω at edge of boundary layer!
- Confusion on sensitivity to inlet values

 5

„Freestream Sensitivity“ k-ω 2006

- Wilcox 2006 model has adopted some of the elements of the SST model
  - Cross-Diffusion
  - SST limiter
- However, Wilcox uses much lower constants
- Effect only limited
  - Less separation
  - Remaining freestream sensitivity



Mixing layer

- Change is spreading rate by ~ 30%
- Change in Eddy-Viscosity by ~50%

 6

BSL Model: Blending of k- ω and k- ε Model

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho \bar{U}_j k)}{\partial x_j}=P_k-\beta^*\rho k\omega+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\tilde{\sigma}_\kappa})\frac{\partial k}{\partial x_j}\right]$$

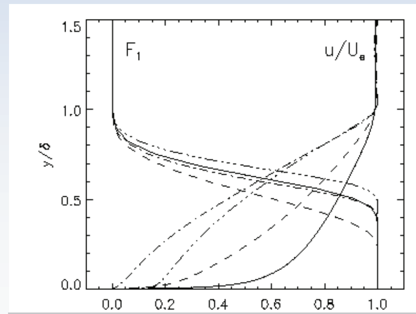
$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho \bar{U}_j\omega)}{\partial x_j}=\tilde{\alpha}\frac{\omega}{k}P_k-\tilde{\beta}\rho\omega^2+(1-F_1)\rho\frac{2}{\sigma_\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\tilde{\sigma}_\omega})\frac{\partial \omega}{\partial x_j}\right]$$

Term from k-ε model

Combination of k-ε and k-ω advantages

Near the wall k-ω

Away from the wall k-ε



Blending Function F_1

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Shear Stress Transport (SST) Model

Bradshaw relation: $-\overline{uv}=\nu_t\left|\frac{\partial U}{\partial y}\right|=a_1 k$

Standard model: $-\overline{uv}=a_1\sqrt{\frac{P_k}{\varepsilon}}k$

SST model: $\nu_t=\frac{a_1 k}{\max(S\times F_2, a_1\omega)}\rightarrow -\overline{uv}=a_1 k$

- Standard models (k-ε and k-ω, …) overpredict shear stress in adverse pressure gradient flows – no or delayed separation
- SST model enforces Bradshw relation – accurate separation prediction -> simplest Explicit Algebraic Reynolds Stress Model (EARSM).

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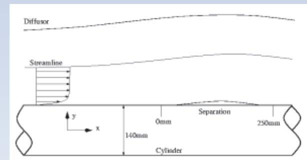
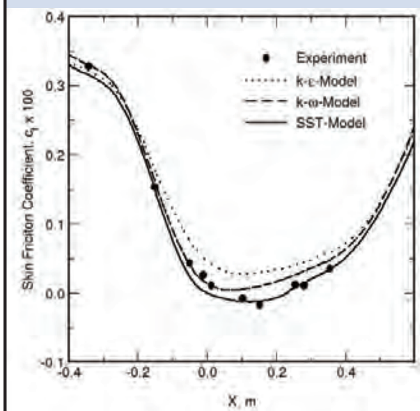
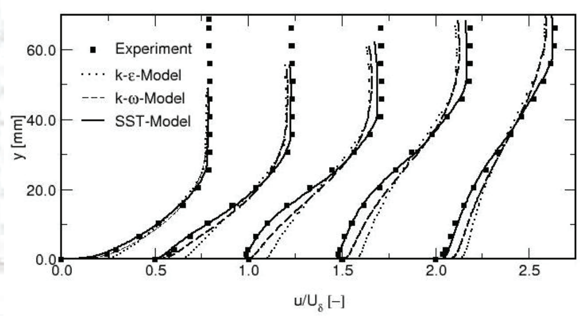
Diffuser Flow CS0 (NASA Testcase)

SST model gives accurate separation prediction, compared to k-ε and k-ω models

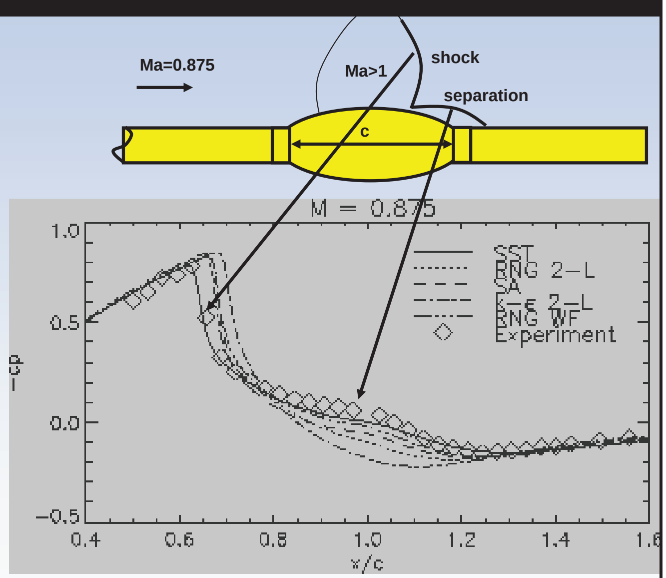






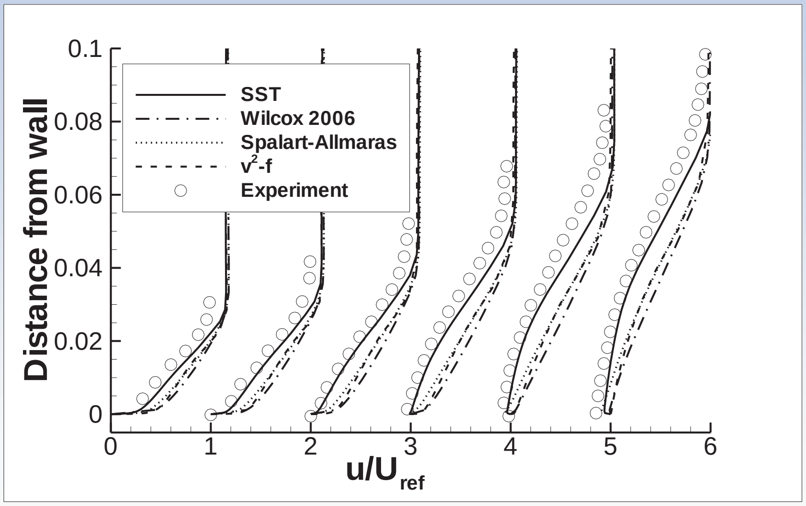
NASA Transonic Bump Flow

- Transonic bump flow
- Shock causes separation
- Separation prediction influences shock location
- SST model gives proper shock location



Batchello and Johnson bump

NACA 4412 Airfoil, a=14, Re=1.5x10^6



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Corner Separation

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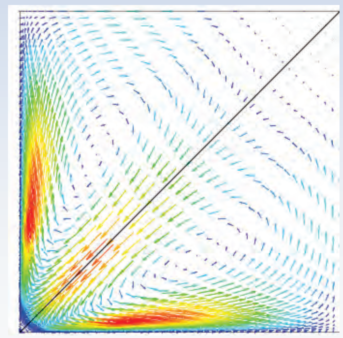
Corner Flows

- Early separation of linear Eddy Viscosity Models in corners observed
- Can be caused by lack of anisotropy in the stress formulation(differences in normal stresses near wall)
- Anisotropy is cause of secondary flows into the corner
- Reynolds Stress Model (RSM) could account for this – but is often not robust enough for complex flows
- Explicit Algebraic RSM (EARSM) offer an attractive alternative with reduced numerical effort and increased robustness

¼ of cross section of square duct. Secondary flow into corner



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EARSM – Stress Strain Relation – Wallin-Johansson

$$\tau_{ij} = \overline{u'_i u'_j} = k\left(a_{ij} + \frac{2}{3}\delta_{ij}\right)$$

$$a_{ij} = \boxed{\beta_1 T_{1,ij}} + \beta_2 T_{2,ij} + \beta_3 T_{3,ij} + \beta_4 T_{4,ij} + \beta_6 T_{6,ij}$$

Linear part of Stress-Strain relation

$$T_{1,ij} = S_{ij};\ T_{2,ij} = S_{ik}S_{kj} - \frac{1}{3}II_S\delta_{ij};\ T_{3,ij} = \Omega_{ik}\Omega_{kj} - \frac{1}{3}II_\Omega\delta_{ij};\ T_{4,ij} = S_{ik}\Omega_{kj} - \Omega_{ik}S_{kj}$$

$$T_{6,ij} = S_{ik}\Omega_{kl}\Omega_{lj} + \Omega_{ik}\Omega_{kl}S_{lj} - \frac{2}{3}IV\delta_{ij} - II_\Omega S_{ij};$$

$$\beta_1 = -\frac{N}{Q},\quad \beta_2 = 0,\quad \beta_3 = -\frac{2IV}{NQ_1},\quad \beta_4 = -\frac{1}{Q},\quad \beta_6 = -\frac{N}{Q_1},$$

$$N = C_1' + \frac{9}{4}\frac{P_k}{\varepsilon}$$ Non-linearity due to P_k

$$A_1 = 1.2;\quad C_1' = \frac{9}{4}(C_1 - 1),\quad C_1 = 1.8$$

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BSL-EARSM Formulation

ANSYS

1. Keep eddy viscosity in diffusion terms of *k*- and ω–equations

$$\begin{cases} \dfrac{Dk}{Dt} = \tilde{P}_k - \beta^* k\omega + \nabla\cdot\left(\left(\nu + \sigma_k \nu_t\right)\nabla k\right) \\ \dfrac{D\omega}{Dt} = \dfrac{\gamma\omega}{k}\tilde{P}_k - \beta\omega^2 + \dfrac{\sigma_d}{\omega}(\nabla k)\cdot(\nabla\omega) + \nabla\cdot\left(\left(\nu + \sigma_\omega \nu_t\right)\nabla\omega\right) \end{cases}$$

$$\nu_t = k/\omega$$

2. Change

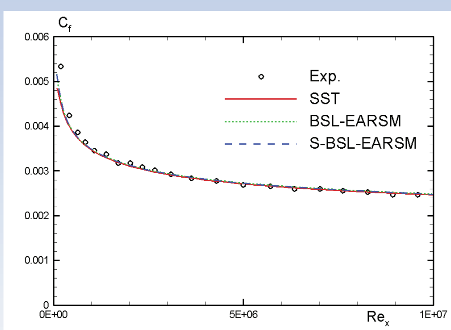
$$A_1 = 1.2 \quad \rightarrow \quad A_1 = 1.245$$

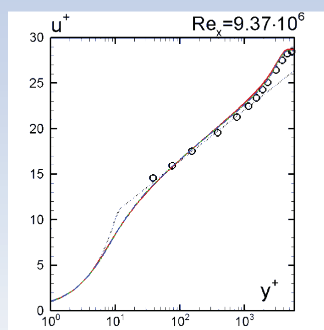
3. Keep production limiter:

$$\tilde{P}_k = \min\left(-\tau_{ij}\frac{\partial U_i}{\partial x_j}, 10\cdot\rho\beta^* k\omega\right)$$

Flat Plate

ANSYS





- Calibrated for log layer
- Results very close to SST model
- Combination of (S-) WJ-EARSM and BSL (A_1=1.245)

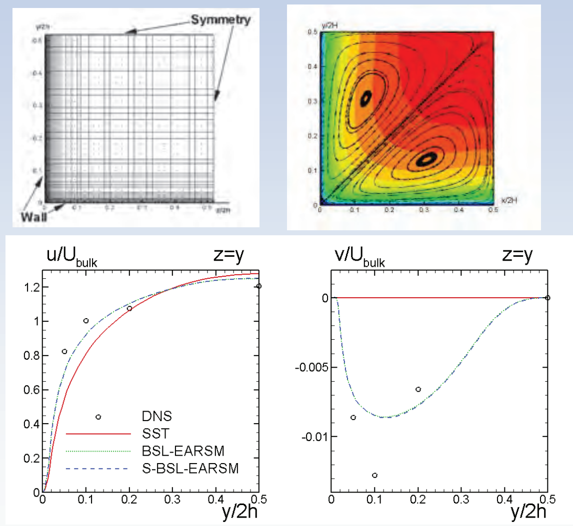
Fully Developed Square Duct Flow

Secondary Flow requires anisotropies

The results in secondary velocity driving fluid into the corner

Higher velocity of axial flow near corner

Less prone to separation?



DNS of Huser and Biringen, (1993)

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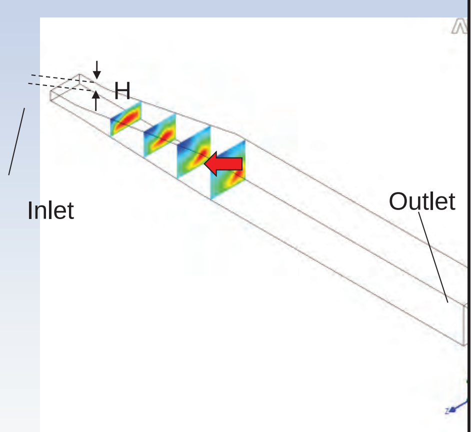
Numerical set-up

- Computational domain dimensions:
  - -3H < X < 45H
  - 0 < Y < 4H
  - 0 < Z < 4H
- Mesh
  - 145 x 91 x 121 nodes
  - 1,596,595 nodes totally
  - $\langle Y^+ \rangle = 0.22$
- Boundary conditions
  - Developed flow at inlet
  - Zero gauge pressure at outlet



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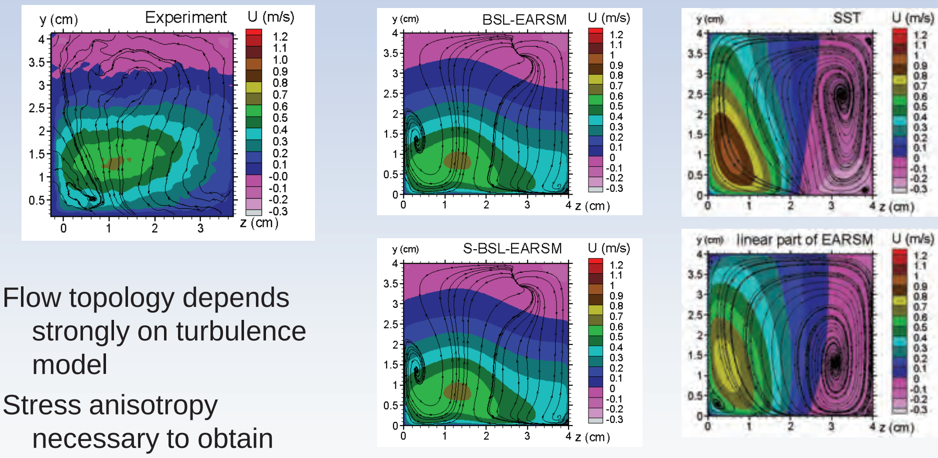
Stanford Diffuser – Flow Topology

X/H=16

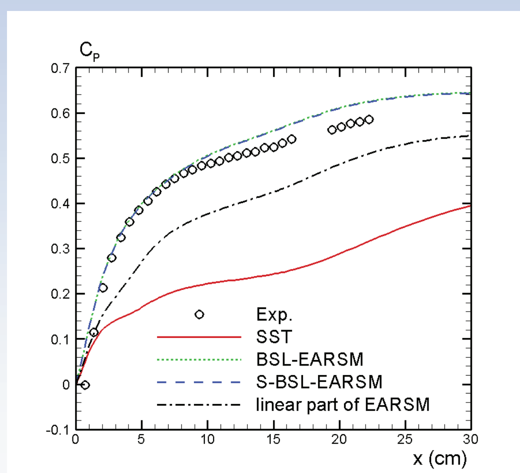


Flow topology depends strongly on turbulence model

Stress anisotropy necessary to obtain correct behaviour

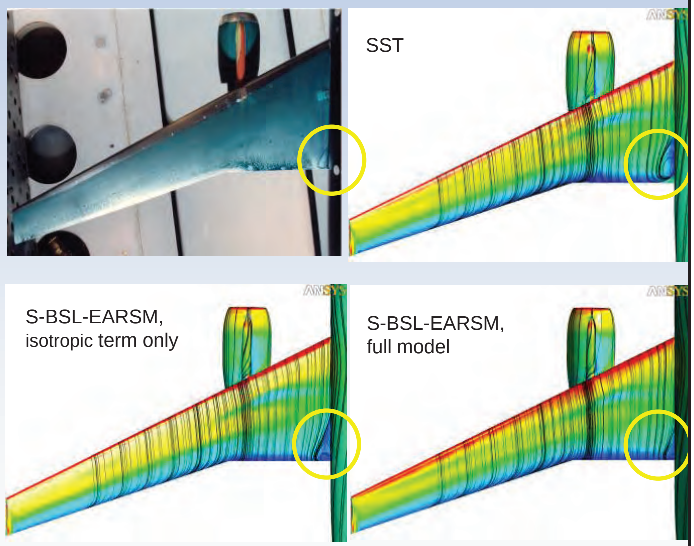
Pressure Distribution

- **BSL-EARSM and S-BSL-EARSM give the same results**
- **"Linear" EARSM (only β_1 coefficient active) and SST give reduced pressure rise due to topology difference**
- **True benefit of EARSM**



Wing-Body Separation

- Corner separation overpredicted by SST and “linear “ BSL-EARSM (only β_1 coefficient active)
- Non-linear EARSM stress-strain relation gives reduced separation
- Consistent with expectations



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Flow Reattachment

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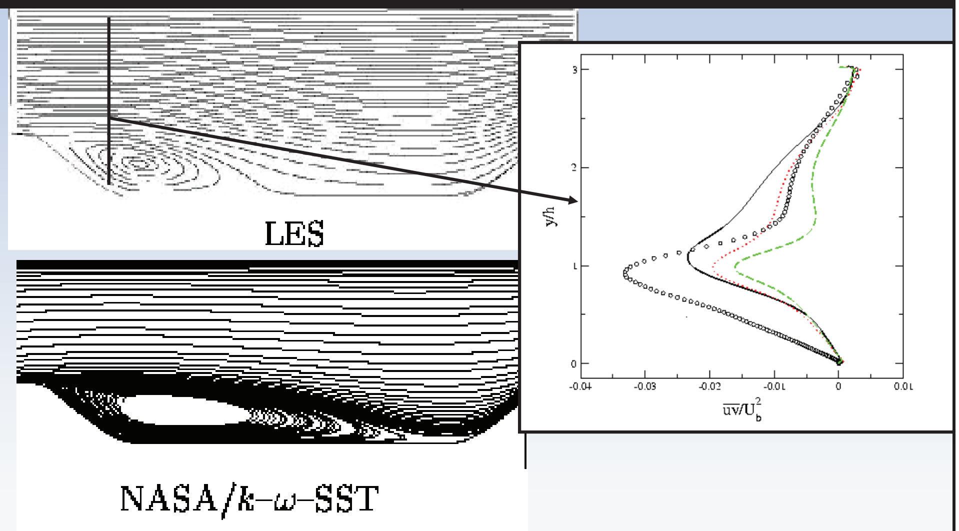
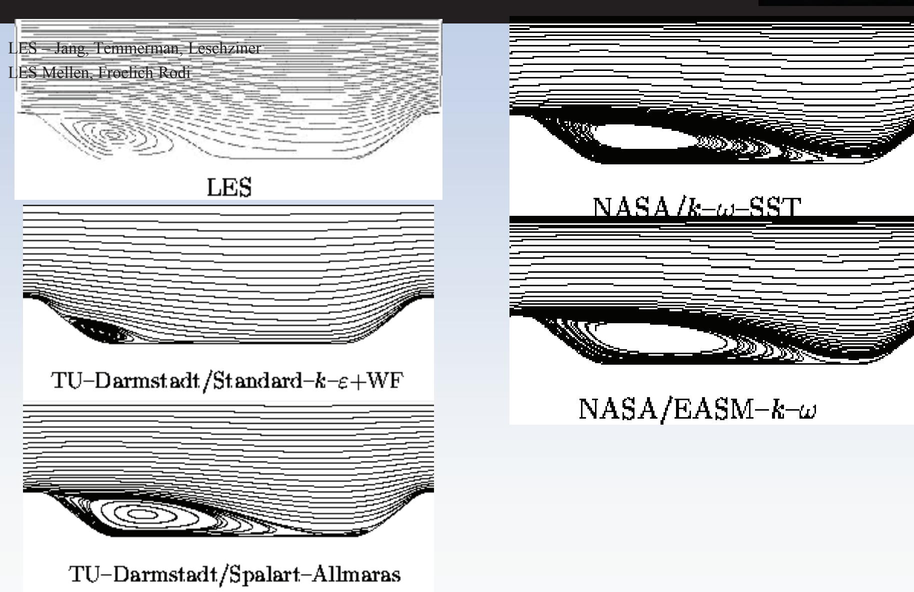
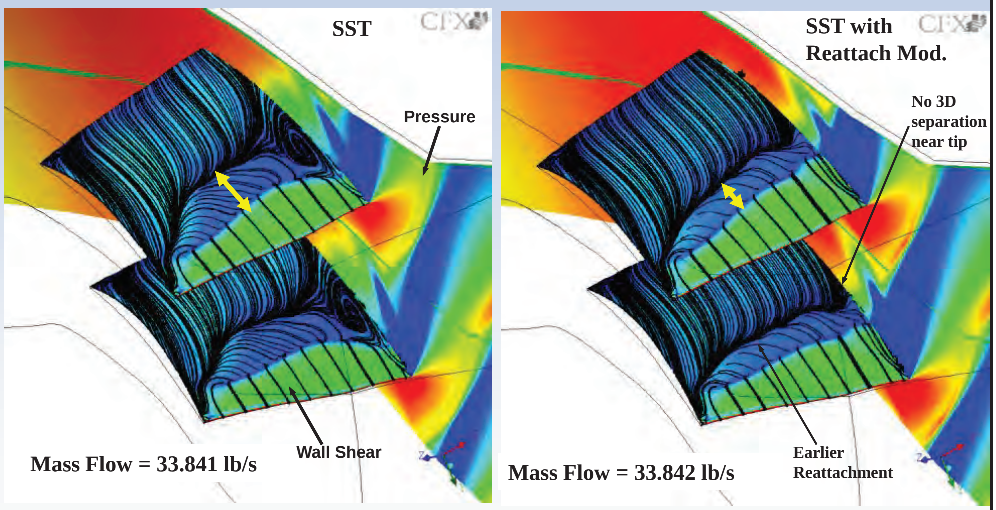
2D Periodic Hill Flow



2D Periodic Hill Flow



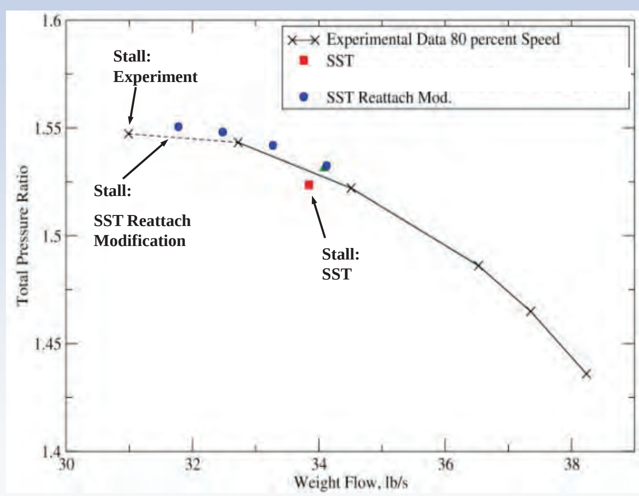
Part II: Effect of Reattach modification on Rotor 35



Much reduced separation zone

Rotor 35 Pressure Rise with SST + Reattachment Modification

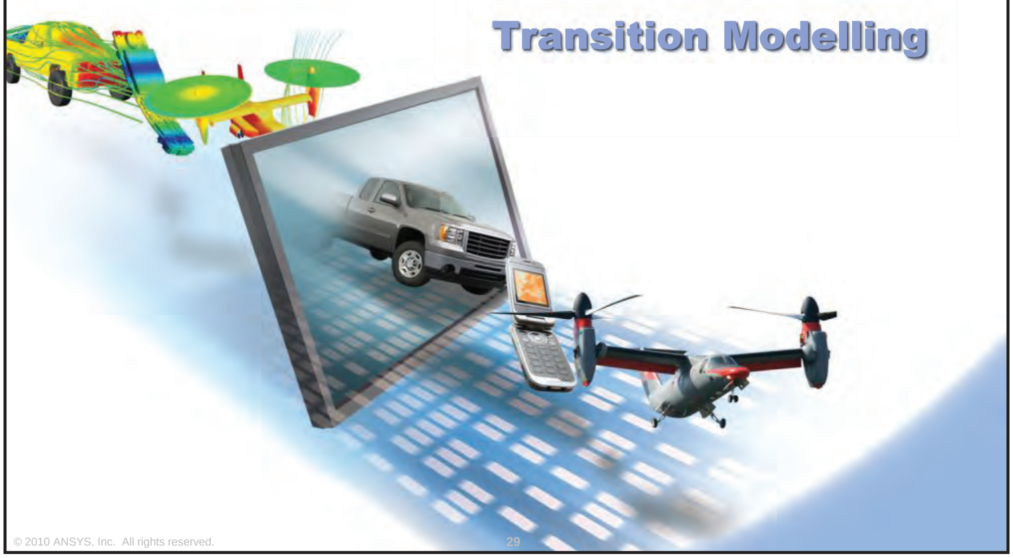
- SST with reattachment modification predict improved stall characteristics for compressor flows
- Unique modification not available in any other CFD code



Flow Reattachment and Recovery

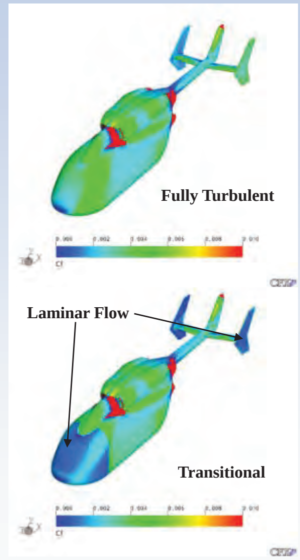
- Flow reattachment after large separation zones and flow recovery downstream of separation are two different problems.
- Number 1 problem in RANS modelling of boundary layer flows.
- Reattachment is more important as RANS models predict overly large separation zones – which can also result in early stall.
- Currently no model (and it seems little ideas).
- Might not be relevant for low-Re flows, where separation is laminar and reattachment is turbulent. The physics of the shear layer is then different.

Transition Modelling



Transition Model Requirements

- **Compatible with modern CFD code:**
  - Unknown application
  - Complex geometries
  - Unknown grid topology
  - Unstructured meshes (no search directions)
  - Parallel codes – domain decomposition
- **Requirements:**
  - Absolutely no search algorithms
  - Absolutely no integration along lines
  - Local formulation
  - Different transition mechanisms
  - Robust
  - No excessive grid resolution



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RANS-Based Transition Models

- Numerous transport equation based models are now becoming available
- From the outside they are based on different modelling concepts:
  - physics modelling – laminar kinetic energy
  - local correlation based transition models (LCTM) Menter and Langtry)
- While the argumentation is different, the mechanism are fairly similar (triggering based on exp. observations).
- Practically – it does not matter much. The most carelfuly calibrated model is the best model.

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Transition Model Formulation

- 4 Transport Equations
  - SST equations (k and ω)
  - Intermittency (γ) Equation
    - Fraction of turbulent vs laminar flow
    - Transition onset controlled by relation between vorticity Reynolds number and $Re_{\theta t}$
  - Transition Onset Reynolds number Equation
    - Used to pass information about freestream conditions into b.l. e.g. impinging wakes
- New Empirical Correlation
  - Similar to Abu-Ghannam and Shaw, improvements for Natural transition
- Modification for Separation Induced Transition
  - Forces rapid transition once laminar sep. occurs
  - Locally Intermittency can be larger than one

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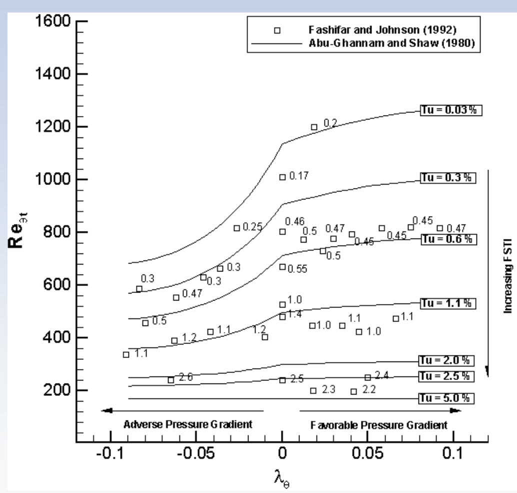
Transition Onset Correlations

Transition onset is affected by:

- Free-stream turbulence turbulence intensity (FSTI)
- Pressure gradients (λ_θ)
- Separation
- Reynolds number (Re_θ)
- Mach number
- Freestream length scale
- Surface conditions:
  - Roughness
  - Temperature
  - Curvature
- The history of the above parameters



$$Re_{\theta t} = f(Tu, \lambda_\Theta)$$

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Non-local formulations

ANSYS

Transition onset:

- Compute Re_Θ for all laminar bl-profiles and compare with $Re_{\Theta t}$

Length of transition

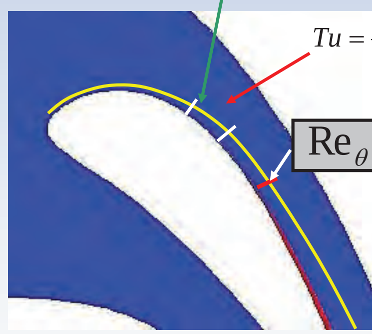
- Trigger turbulence model with ramp-function

Correlation

- Evaluated at edge of the boundary layer

$$\theta = \int_0^\delta \frac{u}{U}\left(1-\frac{u}{U}\right)dy \rightarrow \mathrm{Re}_\theta = \frac{\rho U \theta}{\mu}$$

$$Tu = \frac{\sqrt{2k/3}}{U}$$



$$\mathrm{Re}_\theta \geq \mathrm{Re}_{\theta t}$$

$$\mathrm{Re}_{\theta t} = f(Tu, \lambda_\Theta)$$

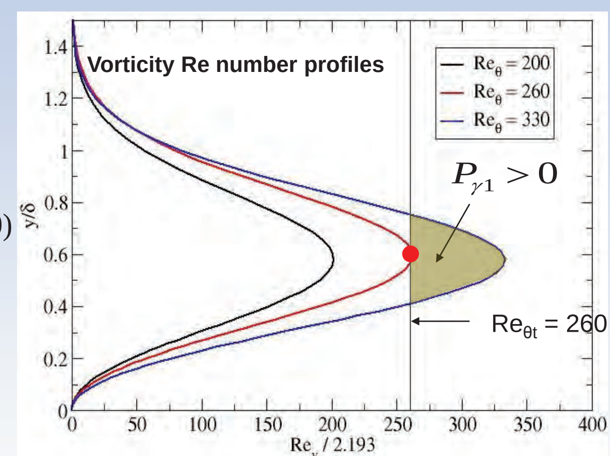
Production of Intermittency

ANSYS

$$\mathrm{Re}_v = \frac{\rho y^2}{\mu}\left|\frac{\partial u}{\partial y}\right|$$

$$F_{onset} \sim \max\left(\frac{\mathrm{Re}_v}{2.193\,\mathrm{Re}_{\theta t}} - 1, 0\right)$$

$$\mathrm{Re}_{\theta t} = f(Tu, \lambda_\theta)$$



Transport Equation for Intermittency γ

ANSYS

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho U_j\gamma)}{\partial x_j}=P_\gamma-E_\gamma+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_f}\right)\frac{\partial\gamma}{\partial x_j}\right]$$

Transition Sources

$$P_{\gamma 1}=F_{length}\rho S(1-\gamma)\left[\gamma F_{onset}\right]^{0.5}$$

F_{onset} transition onset when:

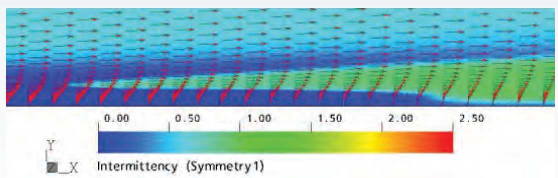
$$\mathrm{Re}_\theta \geq \mathrm{Re}_{\theta t}$$

Destruction / Relaminarization sources

$$E_\gamma=c_{a2}\rho\gamma(1-c_{e2}\gamma)\Omega F_{turb}$$

F_{length} length of transition

F_{turb} laminar criteria ($\mu_t/\mu < 4.0$)



Transport Equation for $\mathrm{Re}_{\theta t}$

ANSYS

$$\frac{\partial(\rho\widetilde{\mathrm{Re}}_{\theta t})}{\partial t}+\frac{\partial(\rho U_j\widetilde{\mathrm{Re}}_{\theta t})}{\partial x_j}=P_{\theta t}+\frac{\partial}{\partial x_j}\left[\sigma_{\theta t}(\mu+\mu_t)\frac{\partial\widetilde{\mathrm{Re}}_{\theta t}}{\partial x_j}\right]$$

$$P_{\theta t}=c_{\theta t}\frac{\rho}{t}\left(\mathrm{Re}_{\theta t}-\widetilde{\mathrm{Re}}_{\theta t}\right)\left(1.0-F_{\theta t}\right) \qquad t=\frac{500\mu}{\rho U^2}$$

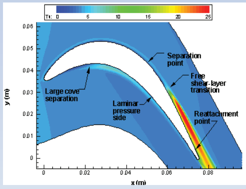
blending function = 1 in laminar b.l.
0 in freestream

$c_{\theta t}=0.1$

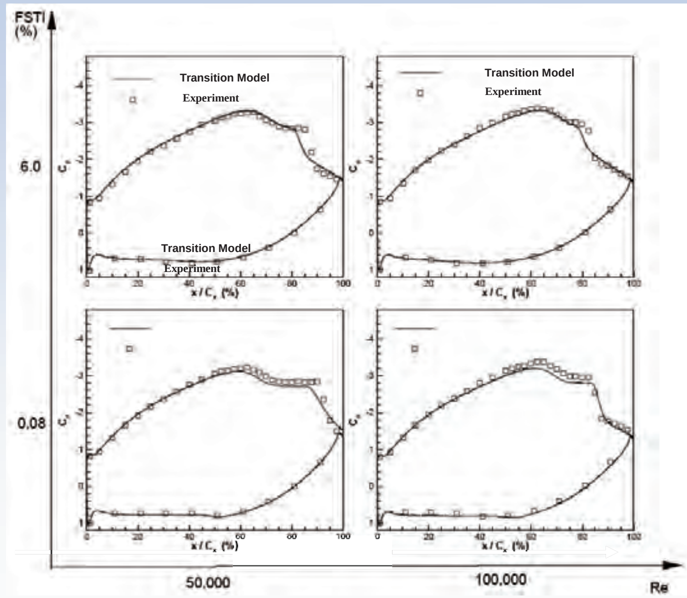
$\sigma_{\theta t}=10.0$ **controls lag between value in freestream and boundary layer i.e. flow history effects**

Separation Induced Transition On an LP-Turbine

ANSYS

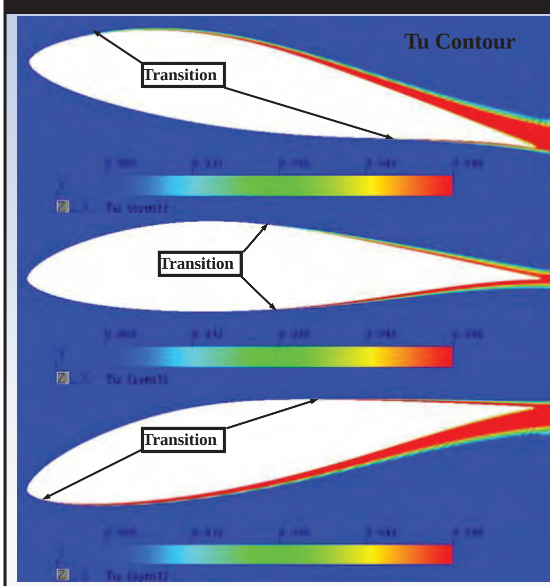


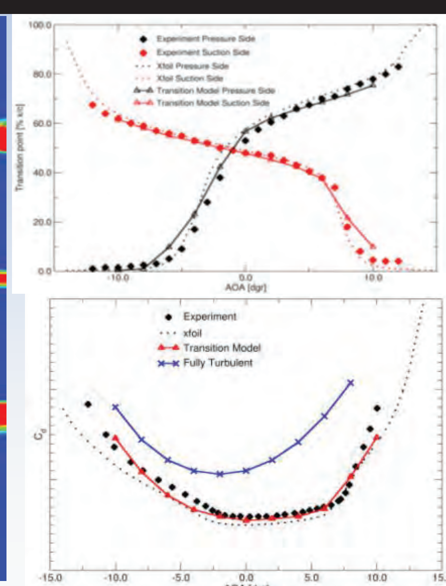
- Pratt and Whitney Pak-B LP turbine blade
- Re_x= 50 000, 75 000 and 100 000
- FSTI = 0.08, 2.25, 6.0 percent



Wind Turbine Airfoil

ANSYS



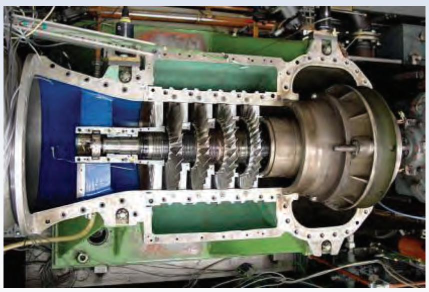


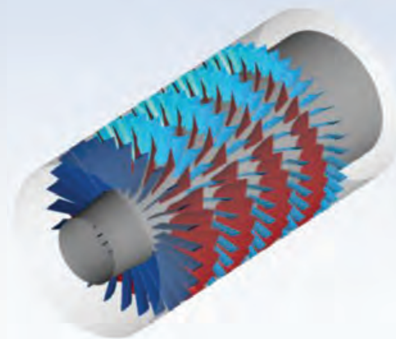
Test Case Description

4 stage high-speed axial compressor

Institute of Turbomachinery and Fluid Dynamics

– http://www.tfd.uni-hannover.de





Courtesy of TFD Hannover

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Grid Information

	Grid 1	Grid 2	Grid 3
Number of nodes	958,642	2,706,109	7,877,939
Minimum grid angle	48.8°	48.2°	51.5°
Max. edge length ratio	1,345	1,518	3,257
Averaged y+	8.2	4.6	1.5

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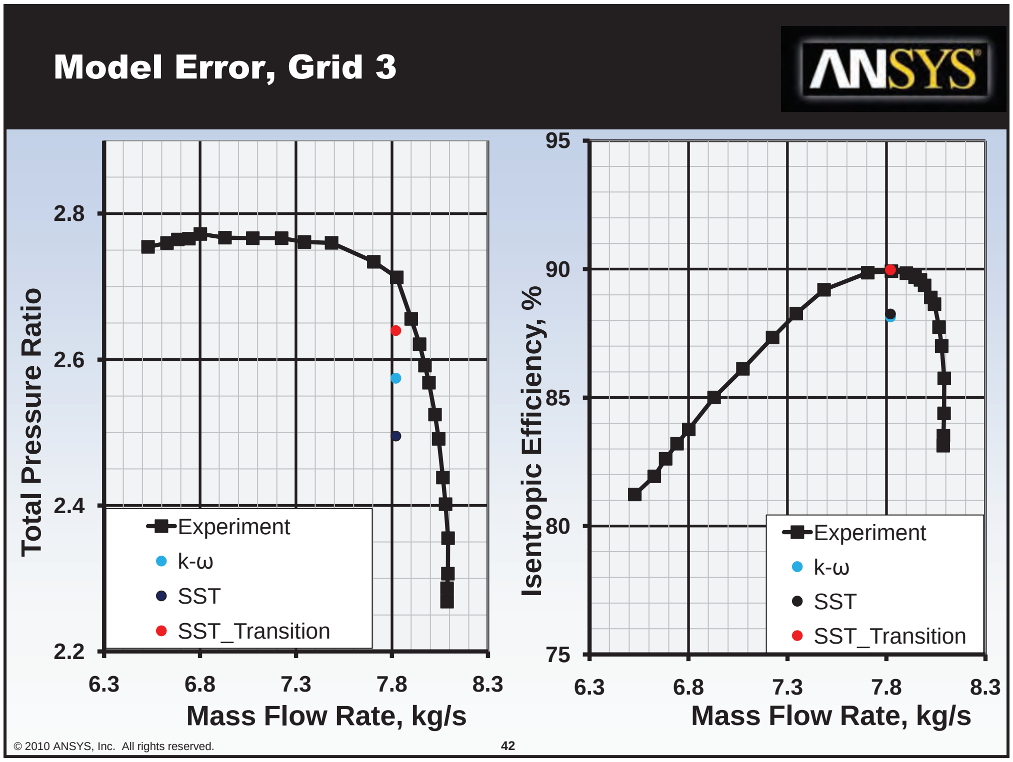
Model Error, Grid 3
ANSYS
Total Pressure Ratio
2.8
2.6
2.4
2.2
6.3
6.8
7.3
7.8
8.3
Mass Flow Rate, kg/s
Experiment
k-ω
SST
SST_Transition
Isentropic Efficiency, %
95
90
85
80
75
6.3
6.8
7.3
7.8
8.3
Mass Flow Rate, kg/s
Experiment
k-ω
SST
SST_Transition
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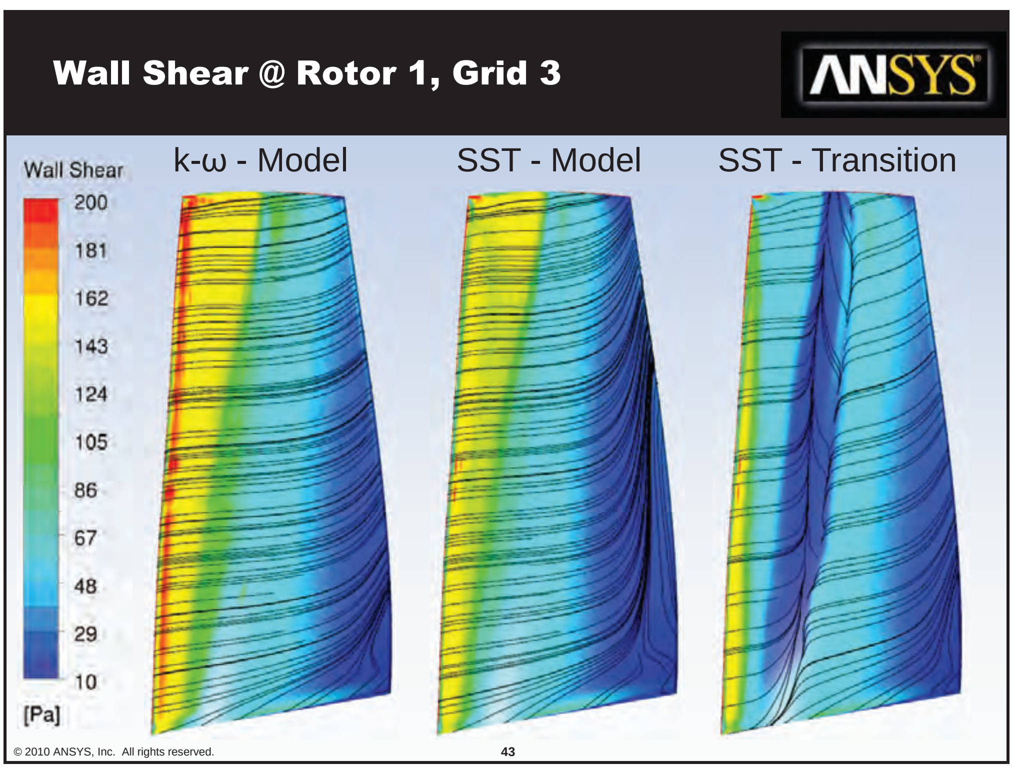
Wall Shear @ Rotor 1, Grid 3
ANSYS
Wall Shear
200
181
162
143
124
105
86
67
48
29
10
[Pa]
k-ω - Model
SST - Model
SST - Transition
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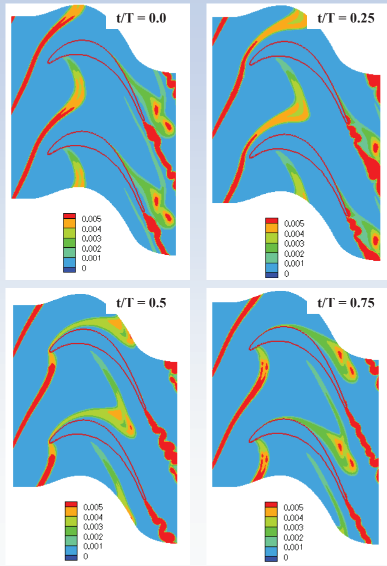
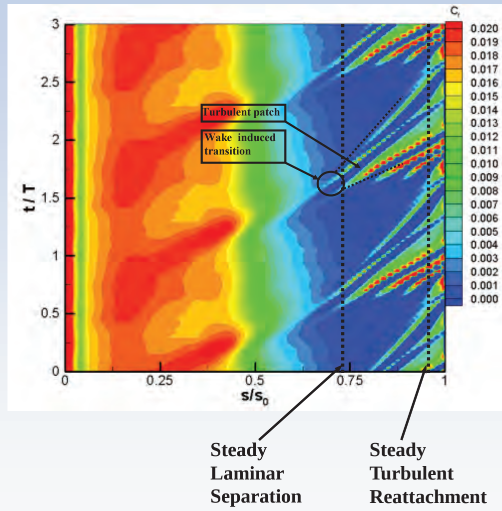
Unsteady Wake Induced Transition





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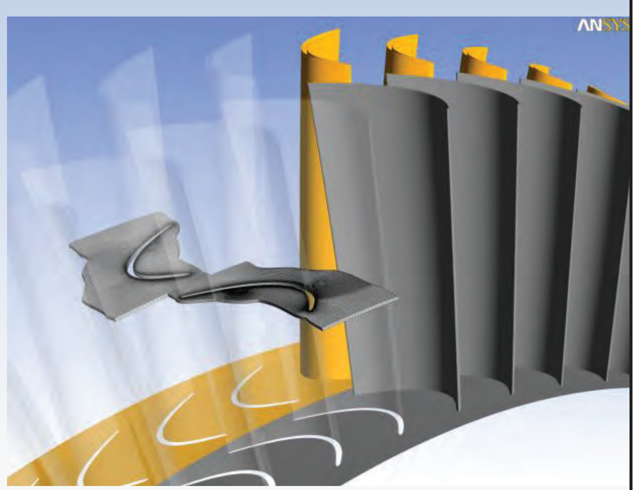
Unsteady LPT

- New Prototype Advanced Unsteady Blade Row feature in CFX
- Based on Time-inclination method
- Allows single blade – unequal pitch simulations in unsteady mode
- Blade designed by PCA and ANSYS



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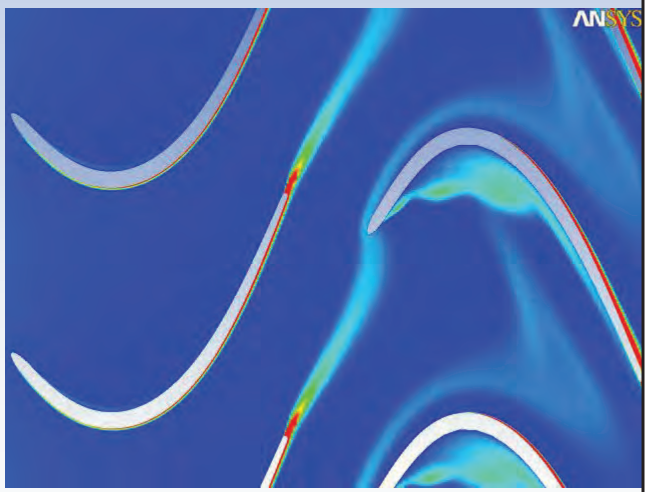
Unsteady LPT

- Blade-Wake Interaction
- Wake is strongly turned and distorted – can Eddy-viscosity models compute this?
- Wake hits blade and changes transition location. Transition model captures principle effect.



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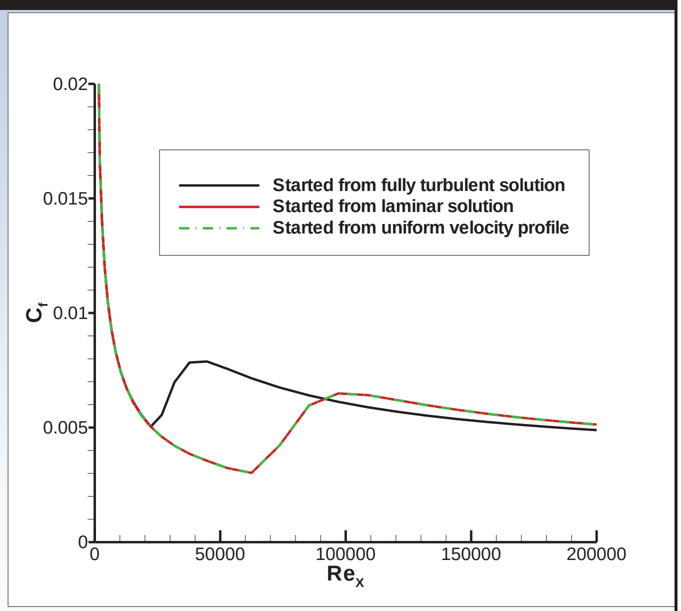
Skin friction coefficient

- Low-Re number turbulence models for transition prediction?
- Unreliable as calibrated for viscous sublayer
- Hysteresis effects
- Picture Wilcox low-Re
- Not recommended



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Transition Modelling LPT

- Transition has an essential effect, especially for highly loaded blades and low Re numbers
- Laminar-turbulent bubbles have to be re-visited and modelled more carefully
- Rough wall transition is an issue to consider closely
- Only limited experience with unsteady rotor-stator interaction
- Models can be further simplified

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Motivation for Scale Resolving Simulations (SRS)

In numerous cases RANS models do not provide the required accuracy for the simulation at hand:

- Flows with large separation zones
- Tip vortex flows
- Cavity flows rotating stall and impact on downstream rows
- Wakes?

However – only a small number of today's CFD simulations use SRS (1-2%)

Eddy Viscosity Models - SRS

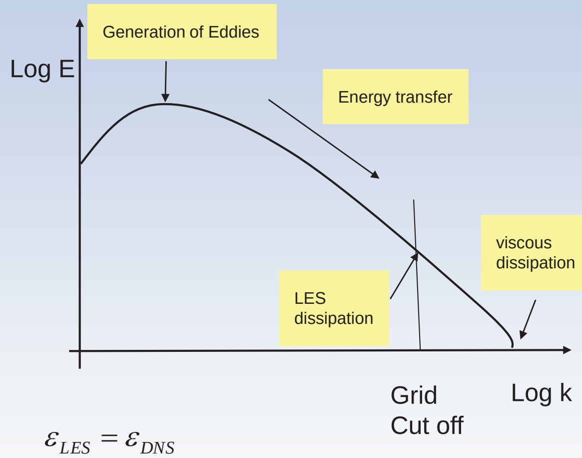
- Averaged Navier-Stokes (RANS/LES) Equations with Eddy Viscosity:

$$\frac{\partial(\overline{U}_i)}{\partial t}+\frac{\partial(\overline{U}_j\overline{U}_i)}{\partial x_j}=-\frac{1}{\rho}\frac{\partial\overline{P}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\nu+\nu_t\right)\left(\frac{\partial\overline{U}_i}{\partial x_j}+\frac{\partial\overline{U}_j}{\partial x_i}\right)\right]$$

- **Formally (U)RANS and LES equations are derived differently:**
  - **(U)RANS – Reynolds averaging**
  - **LES – Filtering of equations in space**
- **Practically the equations are modeled the same way – using EVM**
- **The practical difference between (U)RANS and LES is the size of the eddy viscosity**
- **Only for this reason are “hybrid” models (DES etc.) possible.**

Effect of LES Model

- **Role of LES model:**
  - **Eddies cannot be resolved down to the molecular dissipation limit**
  - **Dissipation of turbulent kinetic energy at grid-resolution limit requires eddy viscosity**
  - **Arguably the only function that LES models perform**
  - **This means that all relevant scales have to be resolved properly**



$$\varepsilon_{LES} = \varepsilon_{DNS}$$

$$\varepsilon_{DNS} = \nu \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \qquad \varepsilon_{LES} = \nu_t^{LES} \frac{\partial \hat{u}_i}{\partial x_j} \frac{\partial \hat{u}_i}{\partial x_j} \qquad \frac{\nu_{LES}}{\nu} = \frac{\partial u_i / \partial x_j \cdot \partial u_i / \partial x_j}{\partial \hat{u}_i / \partial x_j \cdot \partial \hat{u}_i / \partial x_j} >> 1$$

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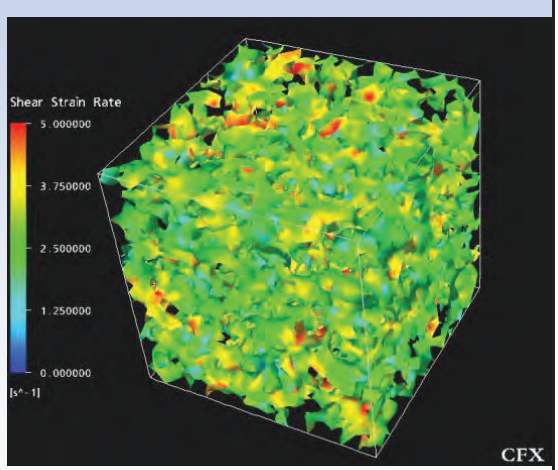
Decaying Isotropic Turbulence (DIT)

- Standard LES testcase
- Artificial turbulence is generated as initial condition (see picture)
- Turbulence is then allowed to decay – integrating the Navier-Stokes equations (LES form)
- Compare turbulent spectrum at different times against experiment of Compte-Bellot



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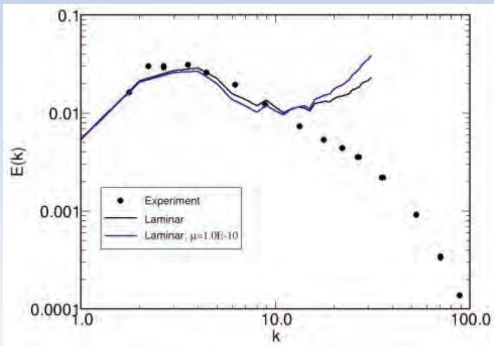
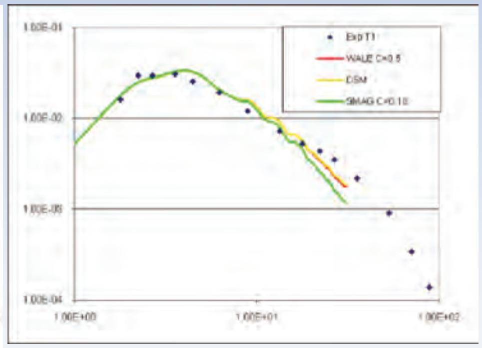
DIT Spectrum t=0.87

ANSYS

No LES Model | With LES Model





Without LES model energy is accumulated at small scales (large wave number *k*)

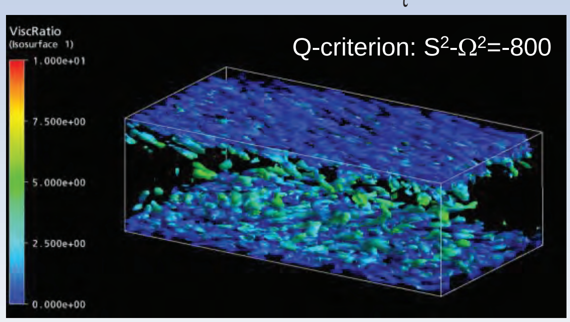
With LES models, energy is dissipated at grid resolution limit

Large Eddy Simulation

ANSYS

- Near wall structures re small
- Scale with Re number ~Re^2
- Can only be resolved for low Re flows and small domains

Periodic Channel flow: Re_τ=395



Turbine Blade	No Nodes	No Time Steps	Effort
RANS	~10^6	10^2-10^3	1
LES	~10^9	10^4-10^5 (x5?)	10^{5-6}

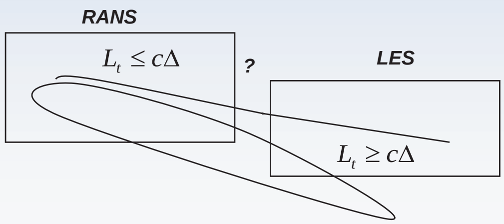
Hybrid Models: DES

Hybrid Model:

- RANS equations in boundary layer
- LES „ detached “ regions

Switch of model

- Based on ratio of turbulent length-scale to grid size
- Different numerical treatment in RANS and LES regions



- **Overcomes threshold limit of LES**
- **Strong grid sensitivity in RANS region**
- **Open question concerning transition region between RANS and LES**

DES for SST - Strelets

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho \bar{U}_j k)}{\partial x_j} = P_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\tilde{\sigma}_\kappa}) \frac{\partial k}{\partial x_j} \right]$$

$$\rho\varepsilon = \beta^* \rho k \omega = \rho \frac{k^{3/2}}{L_t} \rightarrow \rho \frac{k^{3/2}}{\min\left(L_t, C_{DES}\Delta\right)}$$

$$\Delta = \max(\Delta x, \Delta y, \Delta z) \qquad L_t = \frac{\sqrt{k}}{\beta^* \omega}$$

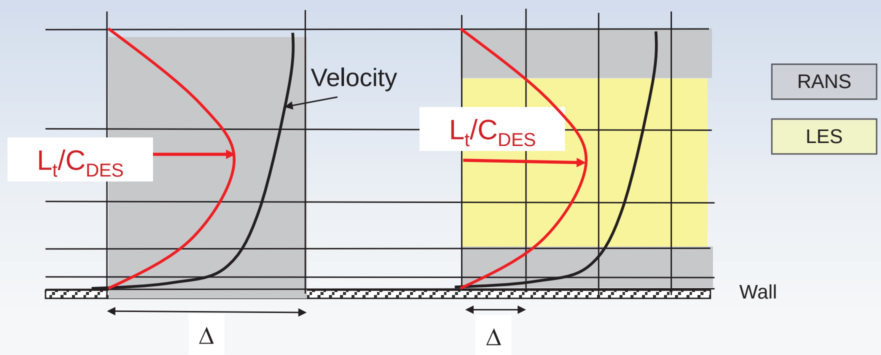
- **In LES limit:**

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho \bar{U}_j k)}{\partial x_j} = P_k - \frac{k^{3/2}}{C_{DES}\Delta} + \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\tilde{\sigma}_\kappa}) \frac{\partial k}{\partial x_j} \right]$$

Problems with DES

Fine grids in boundary layer destroy RANS mode

$$\tilde{L}_t = \min(L_t ; C_{DES}\Delta)$$



Grid-Induced Separation (GIS)

(D)DES for SST

- **Destruction term original SST model :**

$$E = -\beta^{*} \rho k \omega$$

- **Destruction term DES-SST model:**

$$E = -\beta^{*} k\omega \cdot F_{DES} \qquad L_t = \frac{\sqrt{k}}{\beta^{*}\omega} \qquad \Delta = \max(\Delta x, \Delta y, \Delta z)$$

- **Shielded DES function proposed by CFX**

$$F_{DES-SST} = \max\left(\frac{L_t}{C_{DES}\Delta} \cdot (1 - F_{SST}), 1\right); \quad F_{SST} = 0, F_1 \; or \; F_2$$

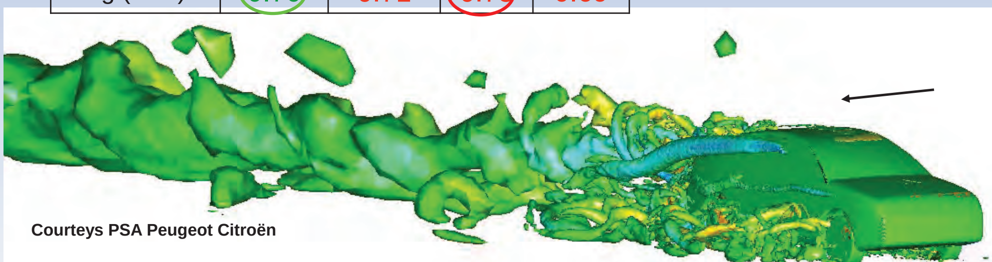
- **Delayed DES now adopted by Spalart and Strelets using own shielding function - DDES**

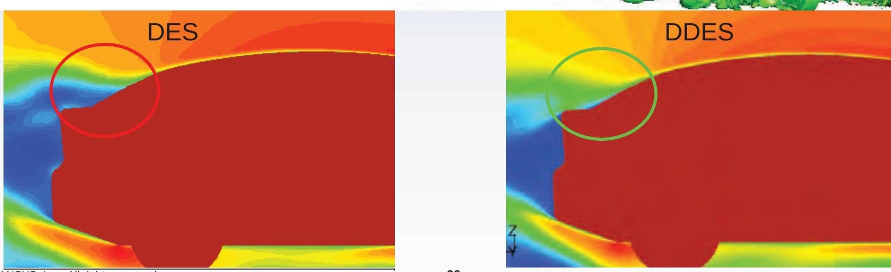
DES/DDES of Separated Flow around a realistic Car model exposed to Crosswind

Model	Exp.	DDES	DES	LES
Drag (SCx)	0.70	0.71	0.75	0.69

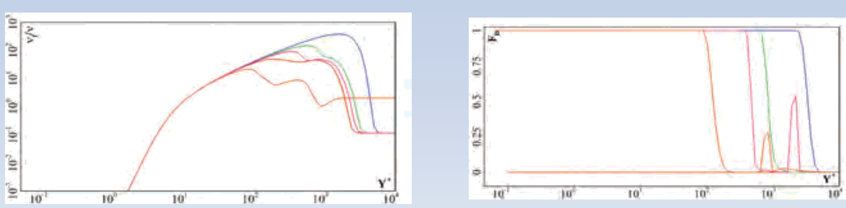
U=40 m/s Yaw angle 20°

$Re_H \sim 10^6$

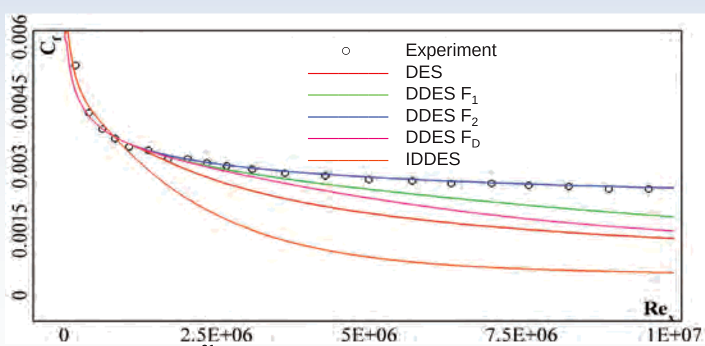




Flat Plate with Different DES Models with h_{max}=0.1·δ



Model	$h_{max}/\delta_{\vert cf-cf\_rans\vert /cf\_rans<0.01}$
DES	0.5
DDES F1	0.35
DDES F2	0.0
DDES FD	0.35
IDDES	0.7



DES for Internal Flows

- Hard to control the grid to avoid negative impact on RANS regions (boundary layers)
- Shielding required, but conservative shielding suppresses LES functionality
- DES and DDES variants are not well suited for internal flows.

Scale Adaptive Simulation (SAS)

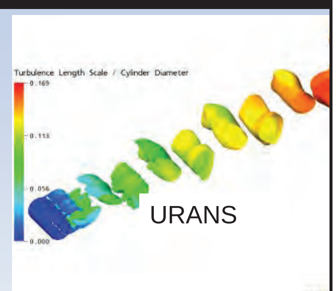
Many flows should be computed unsteady
- Accuracy improvements
- Additional information (acoustics, unsteady forces, ..)

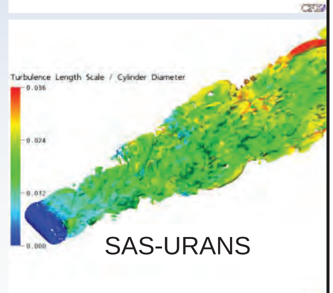
Why is URANS behaving as it is?

Is that a result of the Reynolds averaging or of the specific for of the derived equations?

Can URANS models be constructed which avoid “single mode unsteadiness?

What is a suitable model for hybrid RANS/LES coupling?





Source Terms Equilibrium

ANSYS

Only one Scale in Sources (S~1/T)

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho U_j k)}{\partial x_j}=\mu_t\left(S^2-c_\mu\omega^2\right)+\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)$$

$$\frac{\partial(\rho \omega)}{\partial t}+\frac{\partial(\rho U_j \omega)}{\partial x_j}=\rho\left(c_{\omega 1}S^2-c_{\omega 2}\omega^2\right)+\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\omega}\frac{\partial \omega}{\partial x_j}\right)$$

Input S → Turbulence Model → Output k / Output ω

One input scale – two output scales?
Source terms do not contain information on two independent scales

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Determination of *L* in *k*-ω Model

ANSYS

- Diffusion term carries information on shear-layer thickness δ
- Finite thickness layer required
- No scale-resolution inside layer – independent of level of S in shear layer

$$\frac{\partial(k)}{\partial t}+\frac{\partial(U_k k)}{\partial x_k}=\frac{k}{\omega}(S^2-c_\mu\omega^2)+\frac{\partial}{\partial y}\left[\frac{k}{\omega}\frac{\partial k}{\partial y}\right]$$

$$0=\frac{k}{\omega}(S^2-c_\mu\omega^2)+c\frac{1}{\delta}\left[\frac{k}{\omega}\frac{k}{\delta}\right]$$

$\omega \sim S$ **from ω-equation**

$$0=cS^2+\tilde{c}\frac{k}{\delta^2} \qquad k\sim S^2\delta^2$$

$$L\sim\frac{\sqrt{k}}{\omega}\sim\frac{\sqrt{S^2\delta^2}}{S}\sim\delta$$

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Two-Point Velocity Correlations

Measurement of velocity fluctuations with two probes at two different locations

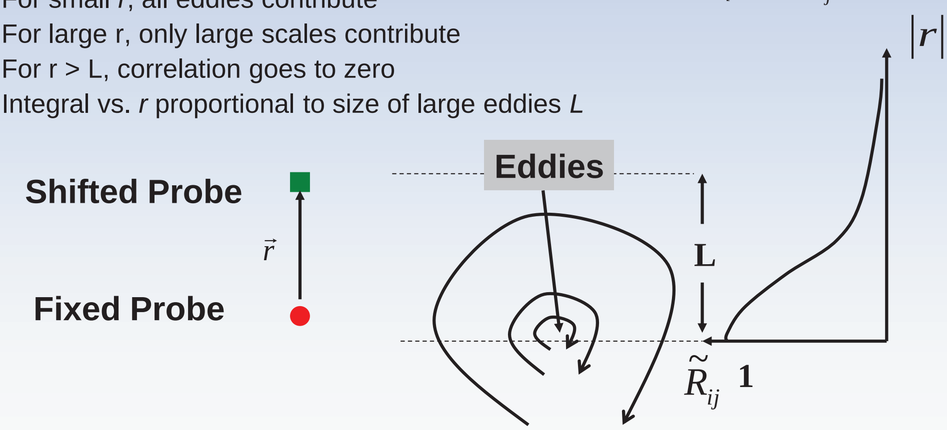
For small r, all eddies contribute

For large r, only large scales contribute

For r > L, correlation goes to zero

Integral vs. r proportional to size of large eddies L

$$\tilde{R}_{ij} = \frac{\overline{u_i'(\vec{x},t)u_j'(\vec{x}+\vec{r},t)}}{\overline{u_i'(\vec{x},t)u_j'(\vec{x},t)}}$$



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New 2-Equation Model (KSKL)

$$\frac{\partial(k)}{\partial t} + \frac{\partial(U_j k)}{\partial x_j} = P_k - c_\mu^{3/4}\frac{k^{3/2}}{L} + \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)$$

$$\frac{\partial \Phi}{\partial t} + \frac{\partial(U_j \Phi)}{\partial x_j} = \frac{\Phi}{k}\left(\zeta_1 P_k - \zeta_2 \frac{1}{\kappa^2} L^2 \nu_t (U'')^2\right) - \zeta_3 \cdot k + \frac{\partial}{\partial y}\left[\frac{\nu_t}{\sigma_\Phi}\frac{\partial \Phi}{\partial y}\right]$$

- With:

$$\Phi = \sqrt{k}L \qquad \nu_t = c_\mu^{1/4}\Phi \qquad |U'| = \sqrt{\frac{\partial U_i}{\partial x_j}\frac{\partial U_i}{\partial x_j}}; \quad |U''| = \sqrt{\frac{\partial^2 U_i}{\partial x_j \partial x_j}\frac{\partial^2 U_i}{\partial x_k \partial x_k}}; \quad L_{\nu K} = \kappa\left|\frac{U'}{U''}\right|$$

v. Karman length-scale as natural length-scale:

$$L_t \sim \kappa\left|\frac{\partial U/\partial y}{\partial^2 U/\partial y^2}\right| = L_{\nu K}$$

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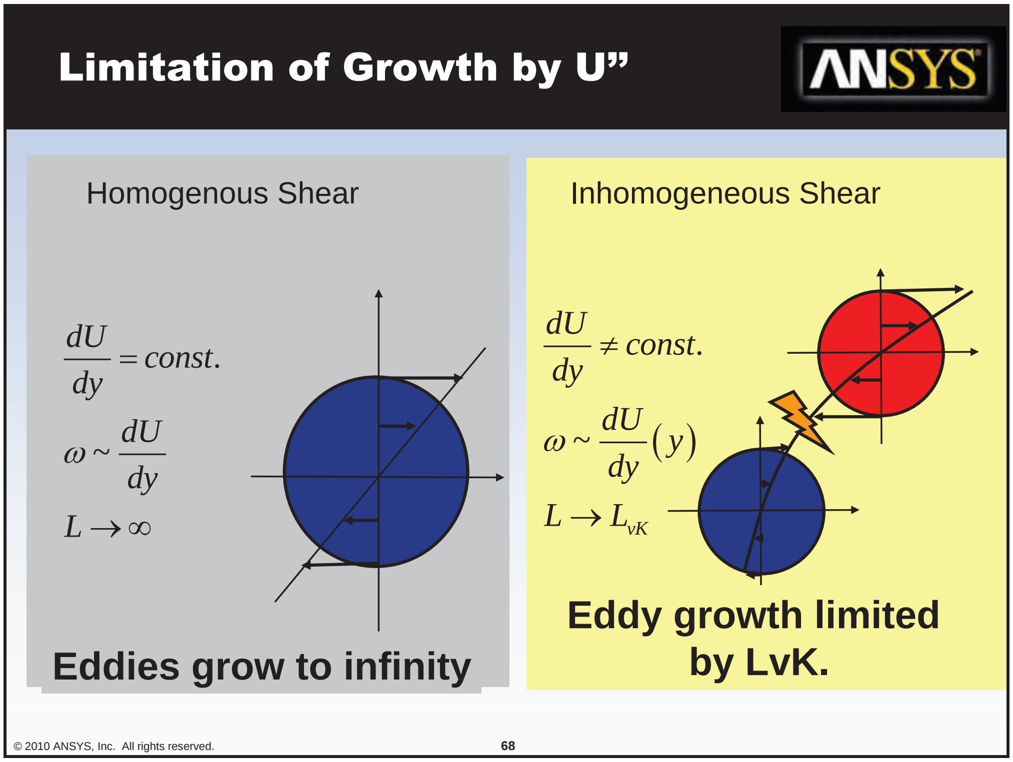
Limitation of Growth by U”
ANSYS
Homogenous Shear
$\frac{dU}{dy} = const.$
$\omega \sim \frac{dU}{dy}$
$L \to \infty$
Eddies grow to infinity
Inhomogeneous Shear
$\frac{dU}{dy} \neq const.$
$\omega \sim \frac{dU}{dy}(y)$
$L \to L_{vK}$
Eddy growth limited by LvK.
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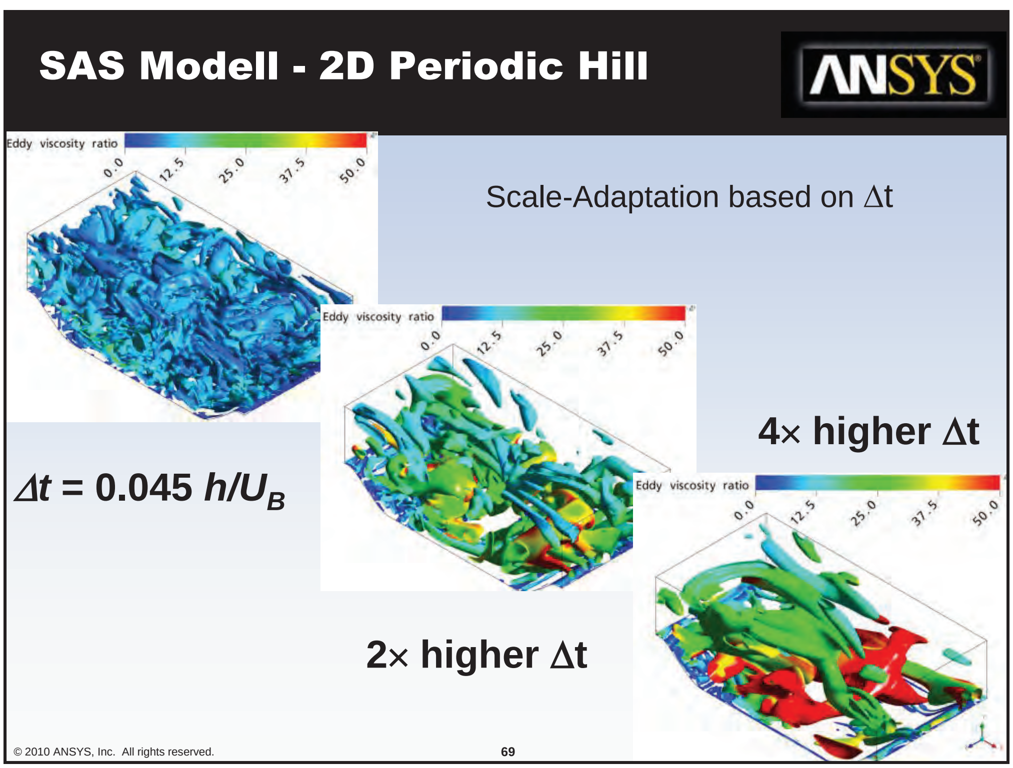
SAS Modell - 2D Periodic Hill
ANSYS
Scale-Adaptation based on Δt
Eddy viscosity ratio
0.0
12.5
25.0
37.5
50.0
$\Delta t = 0.045\ h/U_B$
2× higher Δt
4× higher Δt
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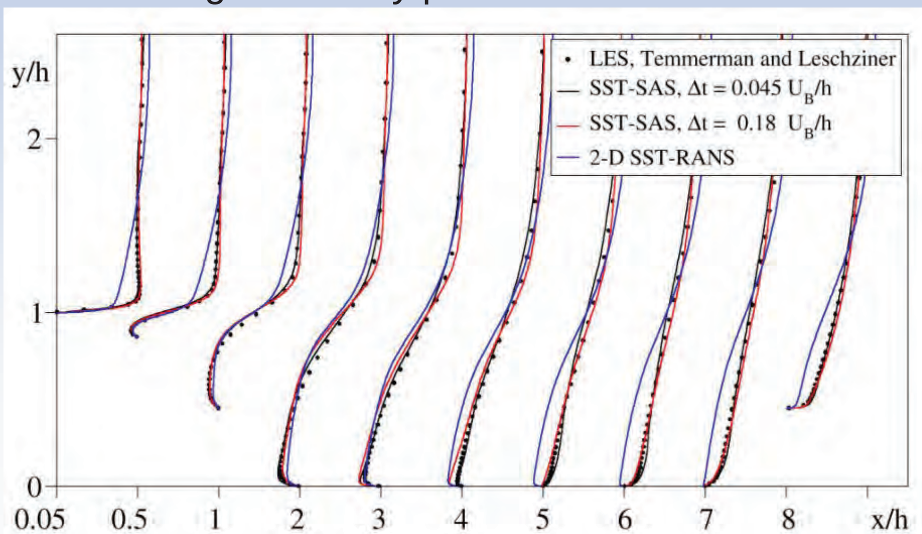
SAS Modell - 2D Periodic Hill

Time averaged velocity profiles U



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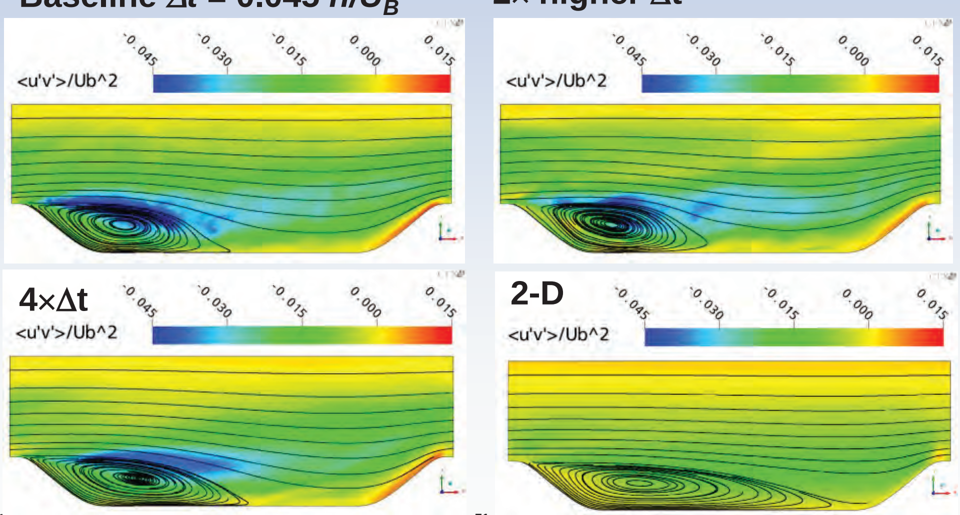
2D Periodic Hill

- Stromlinien und Reynoldsspannung $u'v'$

Baseline Δt = 0.045 h/U_B **2× higher Δt**



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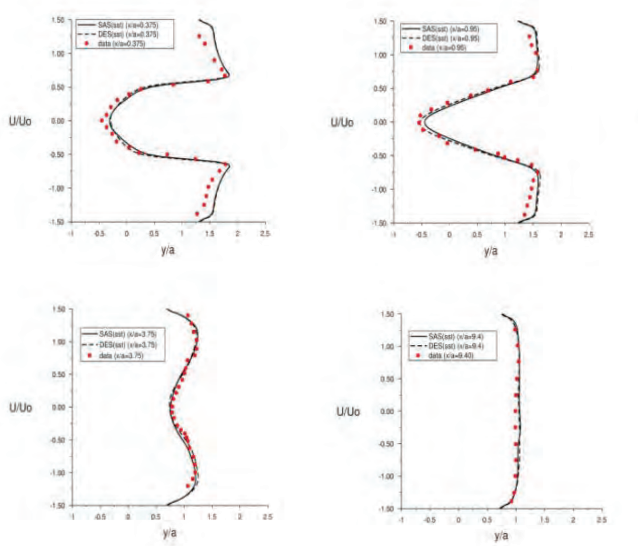
Fluent-SAS Model (Davor Cokljat)
Volvo Bluff Body : Cold Case

SAS-SST

DES-SST

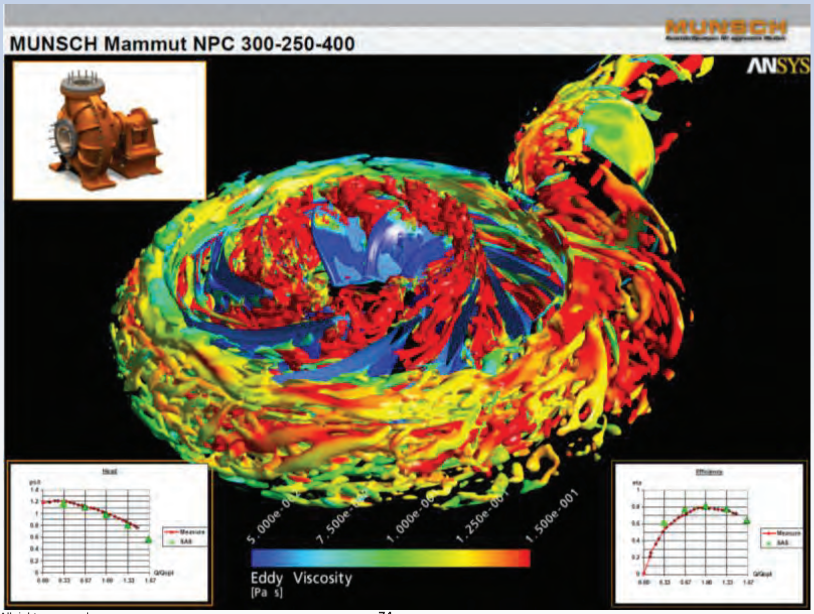
Q = 1e6

Fluent-SAS Model (Davor Cokljat)
Volvo Bluff Body : Cold Case



Time-averaged U-velocity

Munsch Pump – SAS Example



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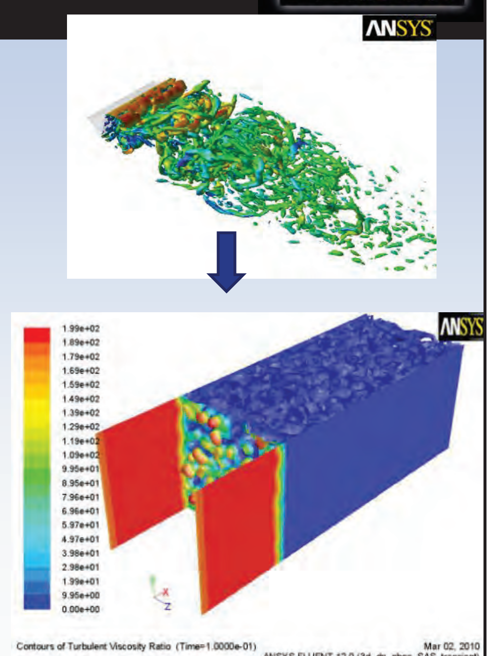
Zonal RANS-LES Models

- In many flows an area where LES is required is embedded in a larger RANS region
- In such cases, a zonal method is advantageous
- RANS and LES regions are separately defined and use different models
- Synthetic turbulence is generated at the interface to convert RANS to LES turbulence



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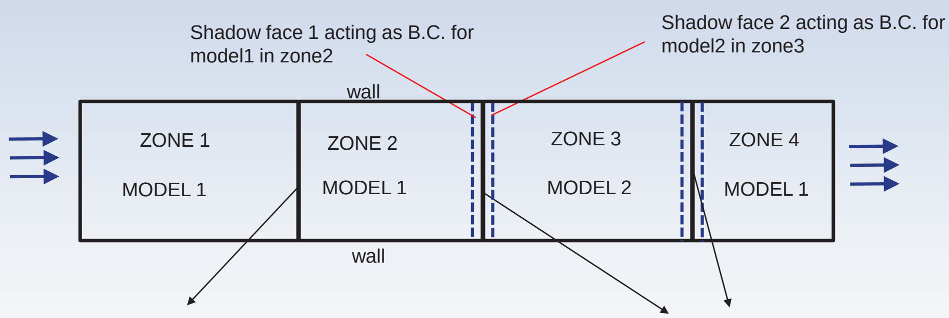
Coupled Zonal Modelling

In ELES e.g. model2 can be LES turbulence model embedded in a RANS or SAS model (model1), or vice versa



There is NO need for model interaction at this interface since models are the same in Zones 1 and 2

There is STRONG need for model interaction at this interface since models are different in Zone 2 → 3 and Zone 3 → 4

Inflow Boundary and Condition *Vortex Method*

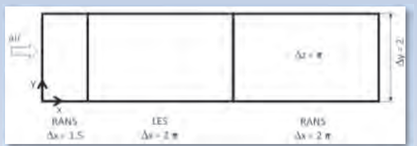
In essence, vorticity-transport is modeled by distributing and tracking many point-vortices on a plane (Sergent, Bertoglio)

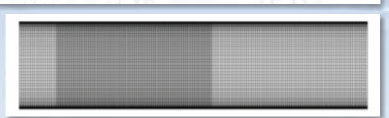
$$\omega(\mathbf{x},t)=\sum_{k=1}^{N}\Gamma_k(t)\,\eta(|\mathbf{x}-\mathbf{x}_k|,t)$$

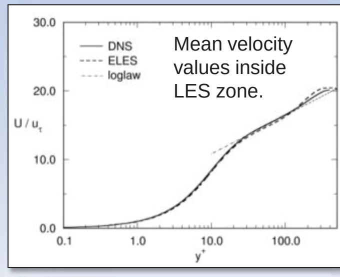
Velocity field computed using the Biot-Savart's law

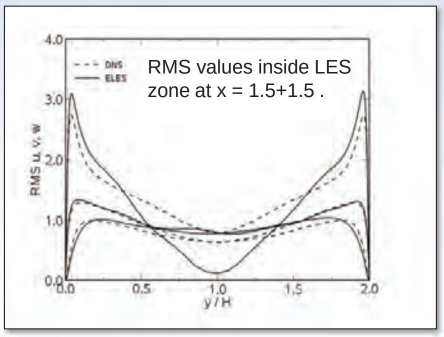
$$\mathbf{u}(\mathbf{x},t)=-\frac{1}{2\pi}\iint\frac{(\mathbf{x}-\mathbf{x}')\times\omega(\mathbf{x}')\mathbf{e}_z}{|\mathbf{x}-\mathbf{x}'|^2}\,d\mathbf{x}'$$

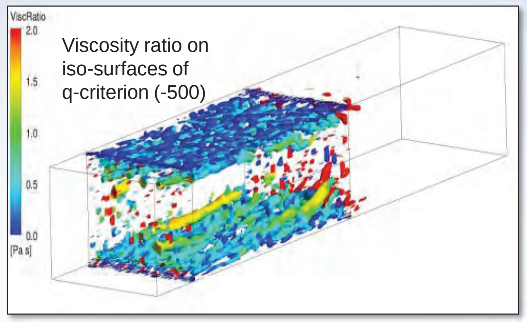
Example: Fully developed channel flow, Re=395











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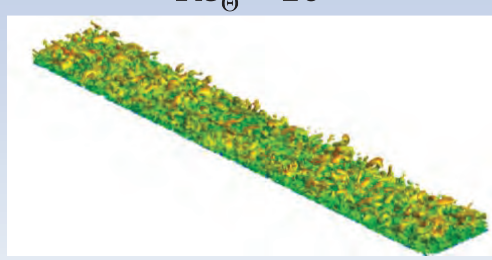
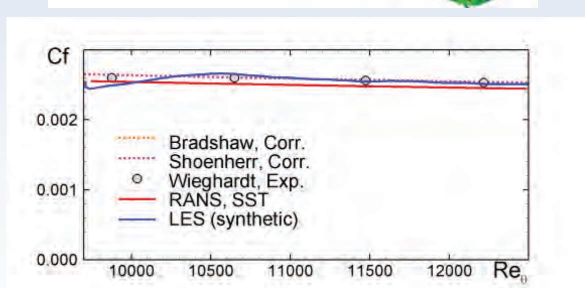
Wall-Modelled LES

- Inner Part of Boundary Layer is covered by RANS, outer part by LES
- Avoids Re number scaling of LES
- Boundary layers require (10x20x30) cells per Boundary Layer volume (δxδxδ)
- Developed in cooperation with NTS (Prof. Strelets group)

$\mathrm{Re}_\Theta \approx 10^4$





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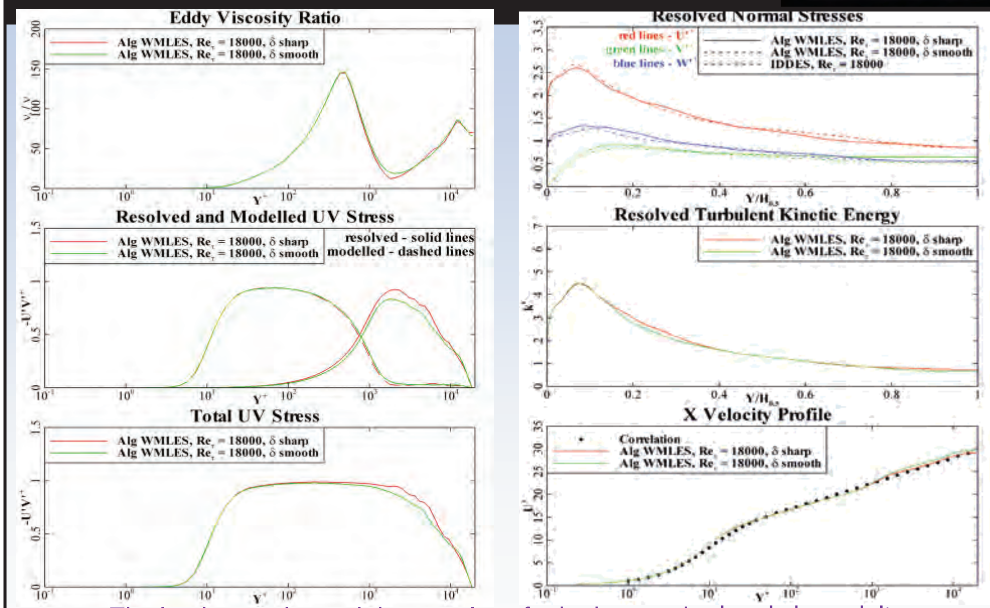
Results with smoothed Δ for Re_τ=18000

$\Delta := \min\left(C_w \cdot \max(d_w; h_{max}); h_{max}\right)$ $\Delta := \min\left(C_w \cdot (d_w^{a} \cdot h_{max}^{1-a}); h_{max}\right)$

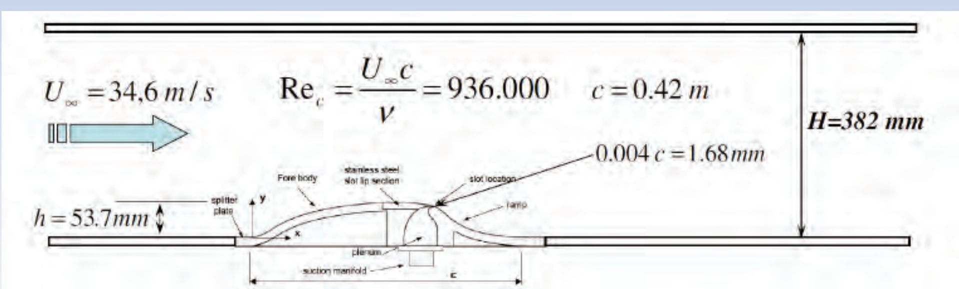


The log-layer mismatch is very close for both smoothed and sharp delta

The resolved UV stresses are more smooth with smooth delta

Flow over a wall mounted, 2D hump (ATAAC)

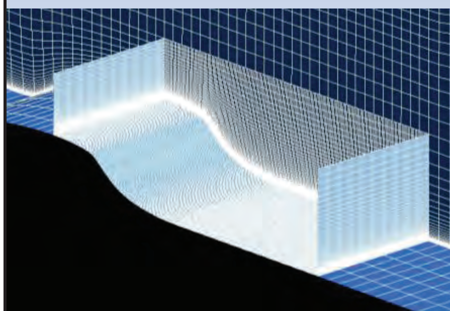
Flow configuration:



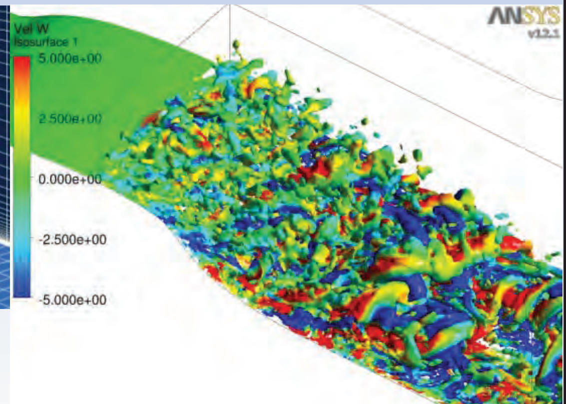
Simulation: baseline (no control)

Flow over a wall mounted, 2D hump

Q criterion:



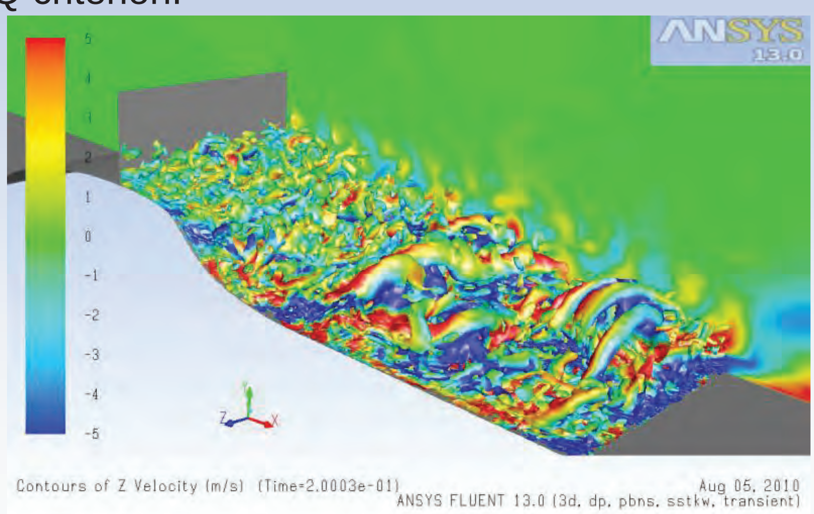
Embedded LES Grid



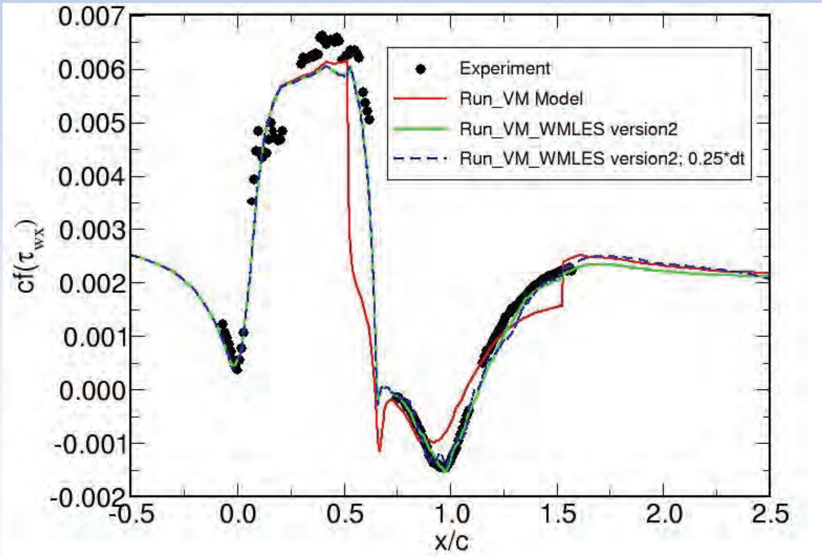
VM_WMLES_CD

Flow over a wall mounted, 2D hump (ATAAC) (3)

Q criterion:



Flow over a wall mounted, 2D hump (ATAAC) (5)



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Turbulence Modelling LPT

- Turbulence Modelling has made significant advancements in recent years
  - EARSM
  - Laminar-turbulent transition modelling
  - SAS/DES, hybrid, Zonal modelling
  - Zonal models with Interfaces
- We need to improve and optimize the individual components
- We need to integrate them to work together
- We need to validate and calibrate for a wide range of experiments

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Session 8
Invited Overviews

NASA/CP—2020-220327

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The Antecedent Hidden Benefit From the Calmed Region

Paul Gostelow

University *of* Leicester

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Hypothesis

... that we were getting an efficiency benefit from the calmed region all along, without recognizing it. It was masked by a reduced level of turbulence.

This is why it was previously possible to achieve outstanding efficiency levels. These became the expectation.

When the loading was successfully increased due in part to exploitation of the calmed region, there was no commensurate efficiency improvement.

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The Starting Point

... in the flow physics was the discovery by Schubauer and Klebanoff of the calmed region behind a turbulent spot. After the spot or turbulent patch the flow becomes calm, but the stable turbulent velocity profile persists – the best of both worlds. The velocity profile gradually relaxes back to the less stable profile, ending the calming effect.

Wakes passing over a flat plate or a blade created an even stronger calmed region. This encouraged a move to wider blade spacing and higher lift.

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There Were No Guarantees

... on efficiency but it was hoped that existing high efficiencies could be maintained or even exceeded.

Use of the calmed region was to prove successful in facilitating higher loadings, and hence reduced blade count, but did not result in improved efficiency. Why is this?

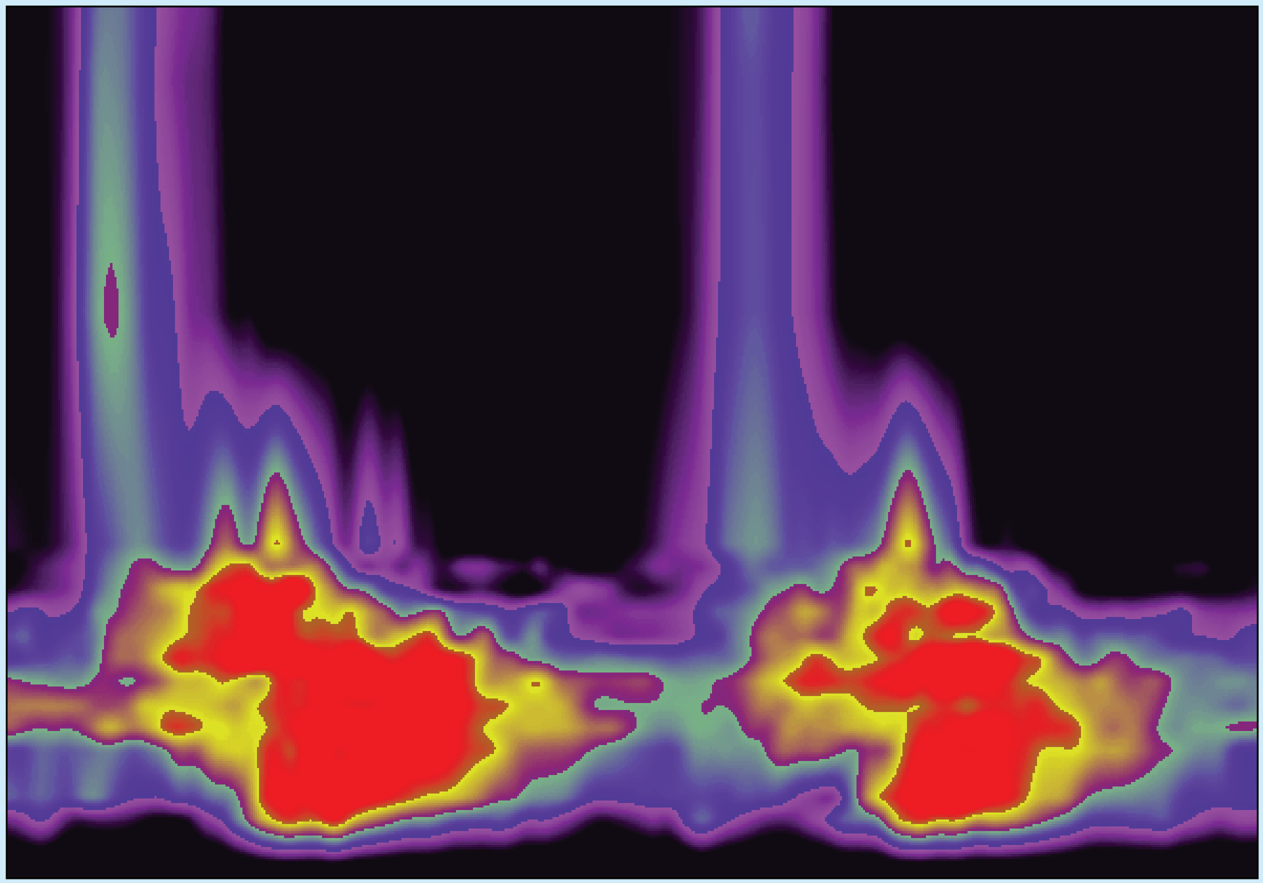
To find out we will need to trace what was done on triggered spots and wake interactions.

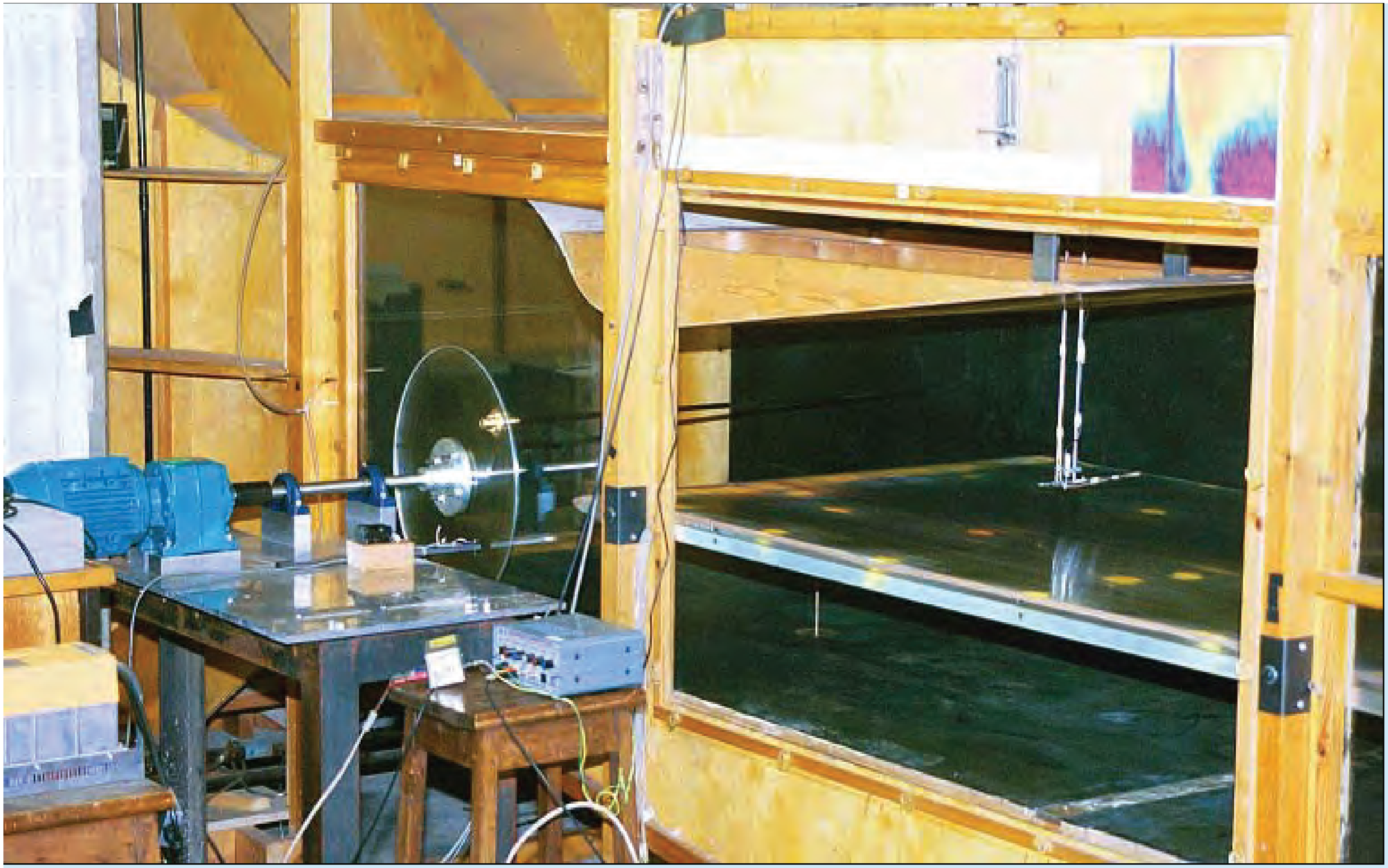
Early machines

Turbulent patches on University of Tasmania compressor blade

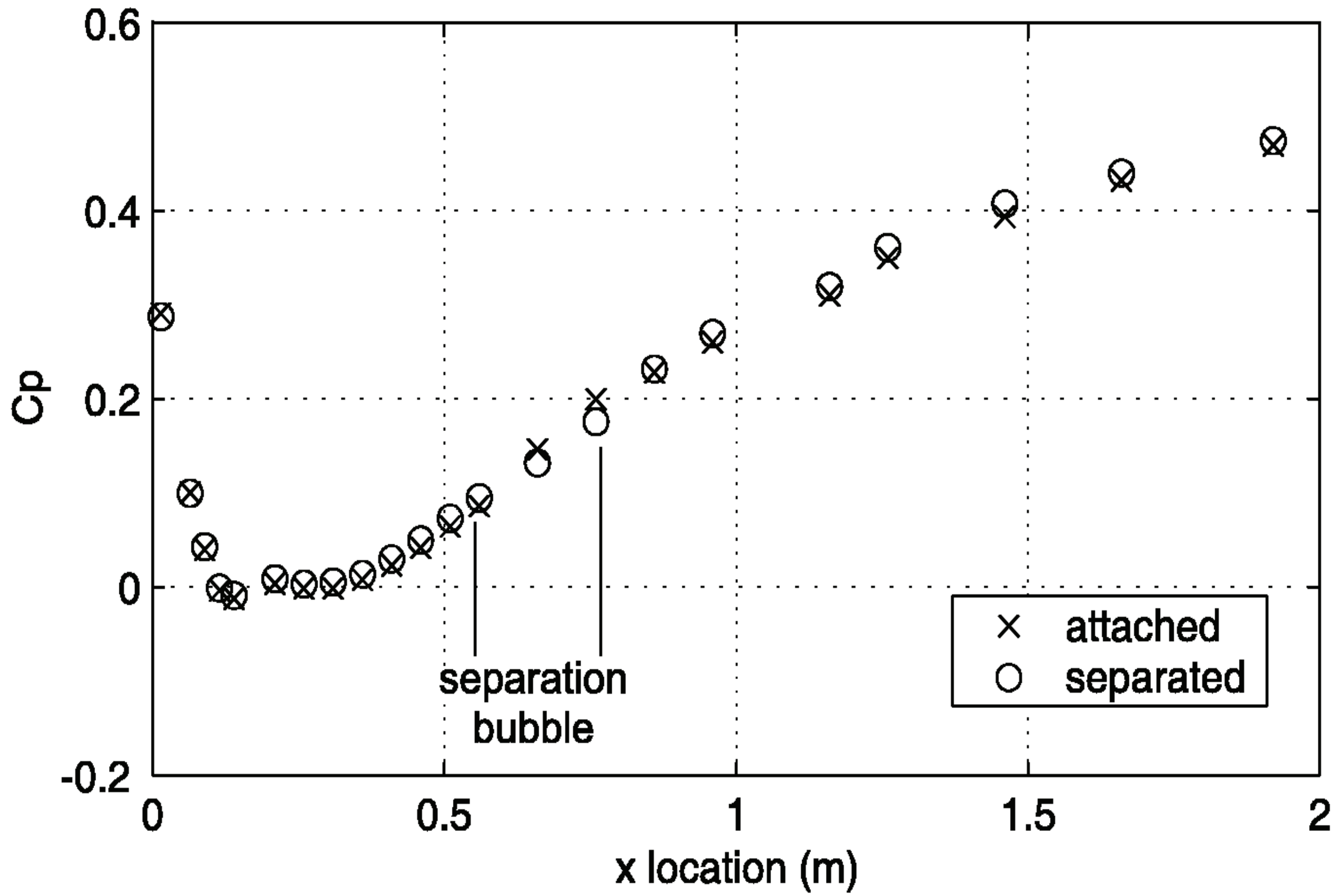
Early machines had wakes following each other closely.

The calmed region is there but we can't see it.





Working section - *showing wake generator, fairing, hot wire and flat plate*



***Pressure* distribution** *- for separated and attached boundary layers*

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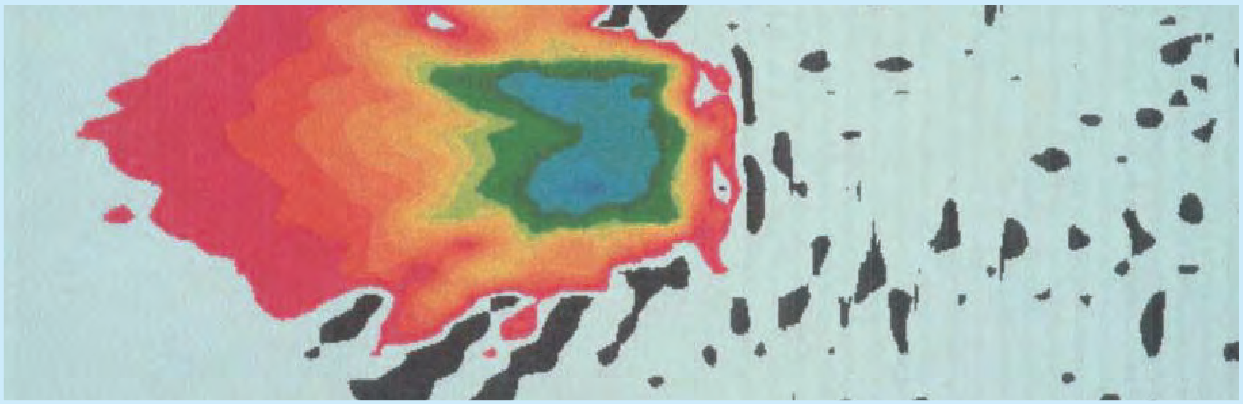
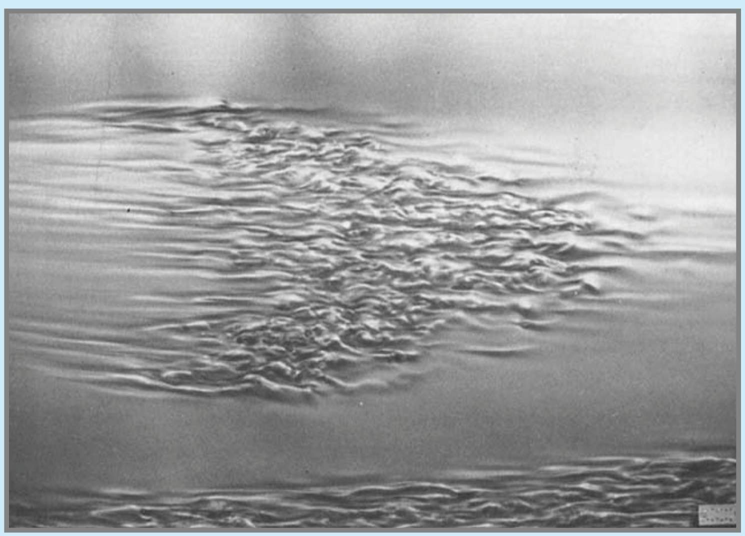
Triggered turbulent spots



Spot under adverse pressure gradient

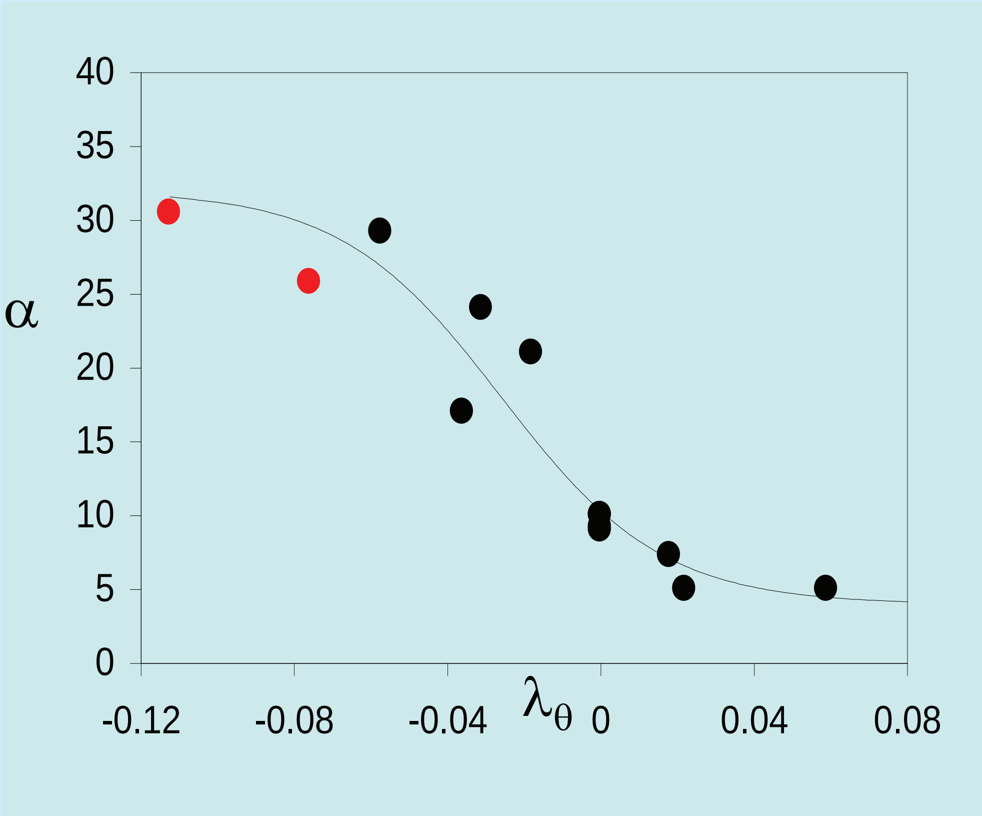


Classical Emmons spot

Solomon, Walker, Gostelow method predicted transition length under varying pressure gradients, based on spot formation rates and spot-spreading angles. Can this approach be extended to separated flow transition and bubble closure?

Extension of Solomon, Walker and Gostelow correlation to separated flows

$$\alpha = 4.0 + (22.14/(0.79 + 2.72\exp(47.63\lambda_\theta)))$$



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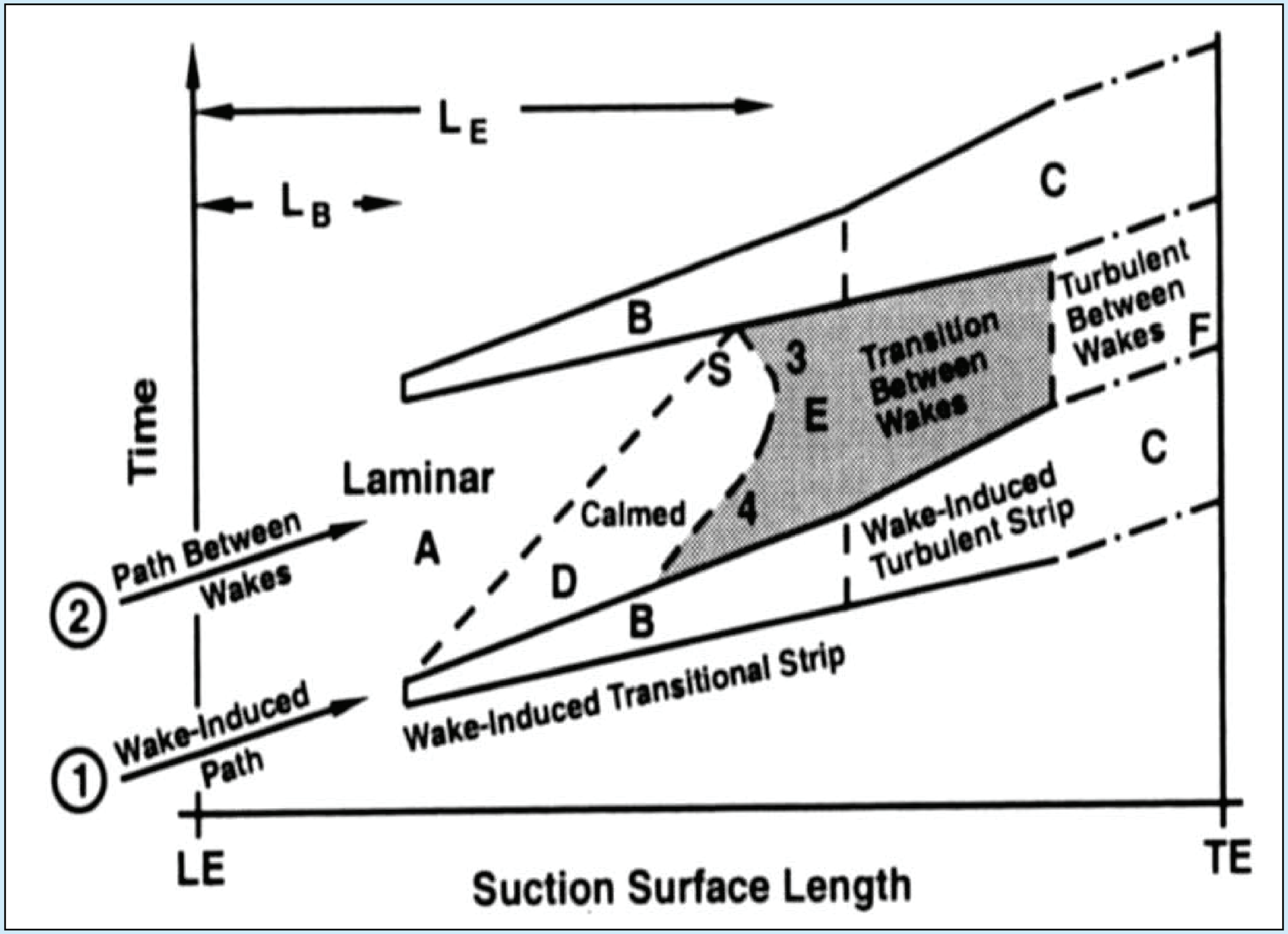
Schematic of suction surface flow



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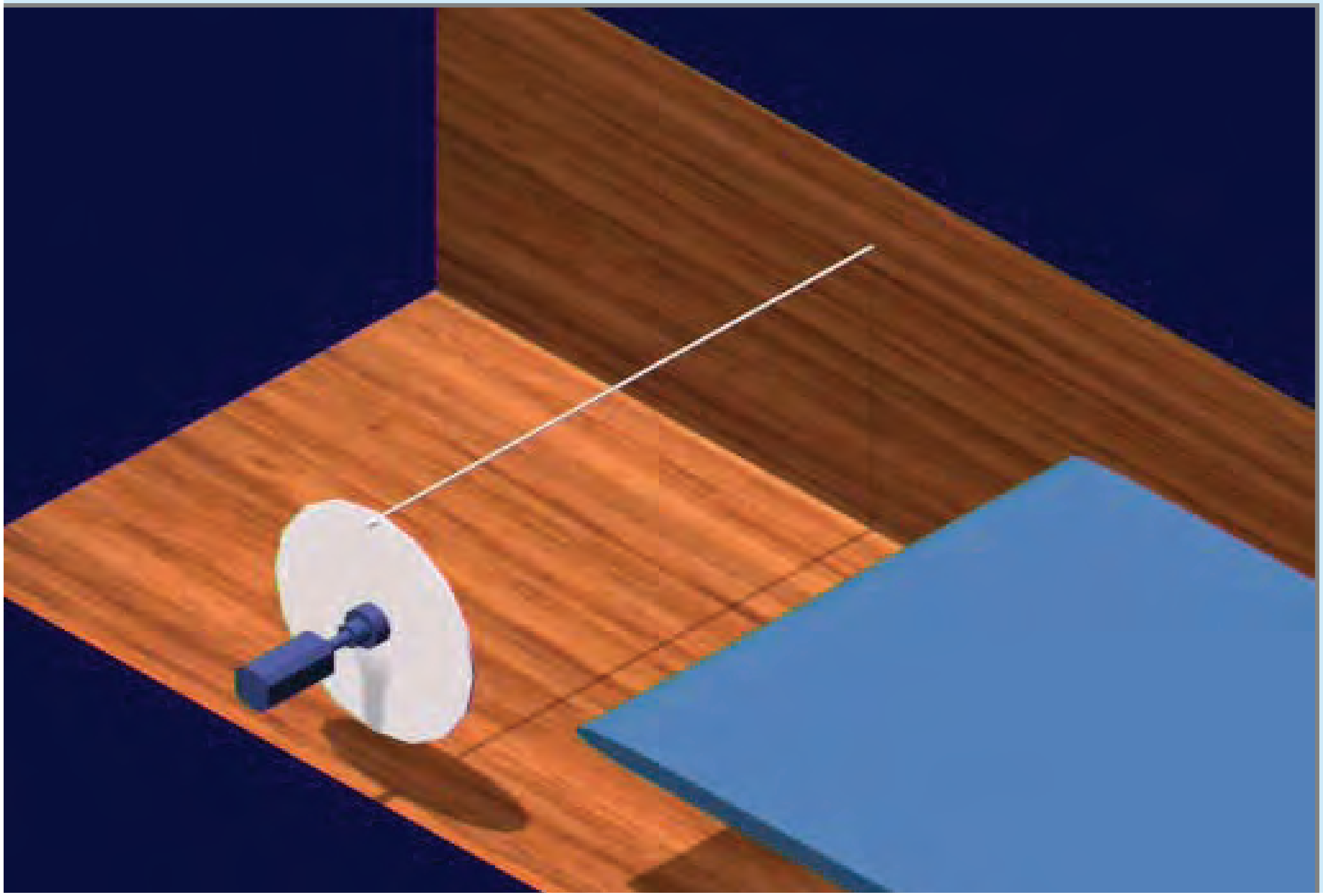
Schematic of wake generator



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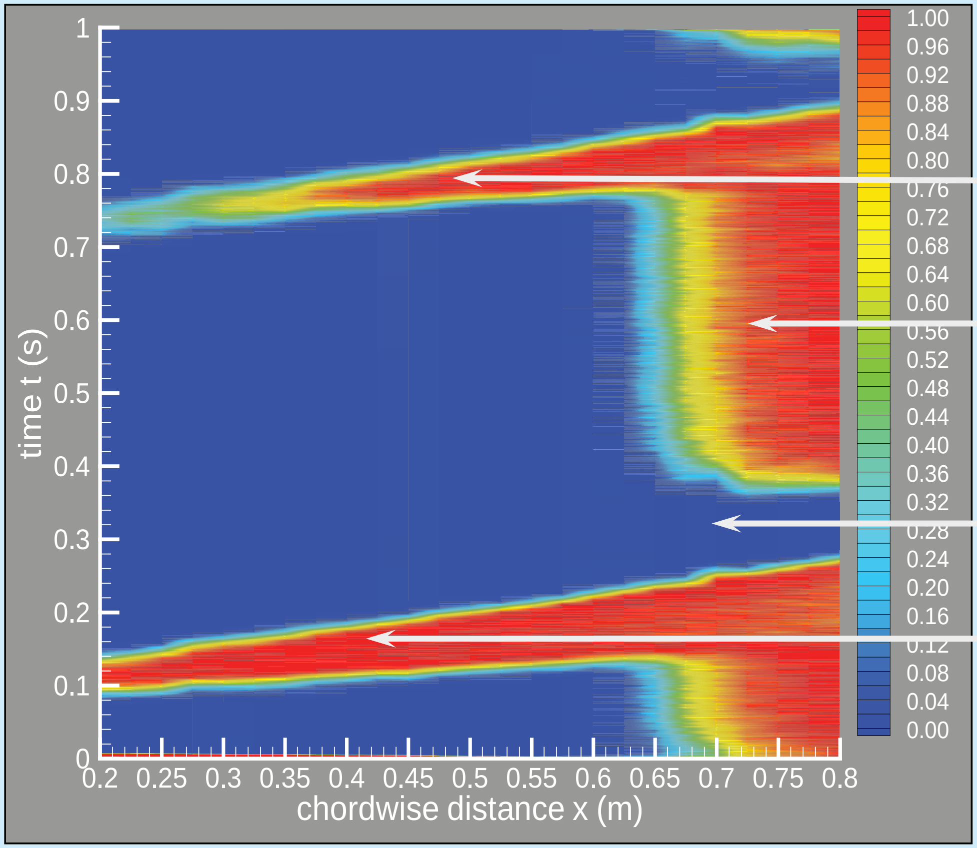
Single rod. Three kinds of transition



Intermittency contours from hot wire

Far wake is weaker, giving triggered natural transition.

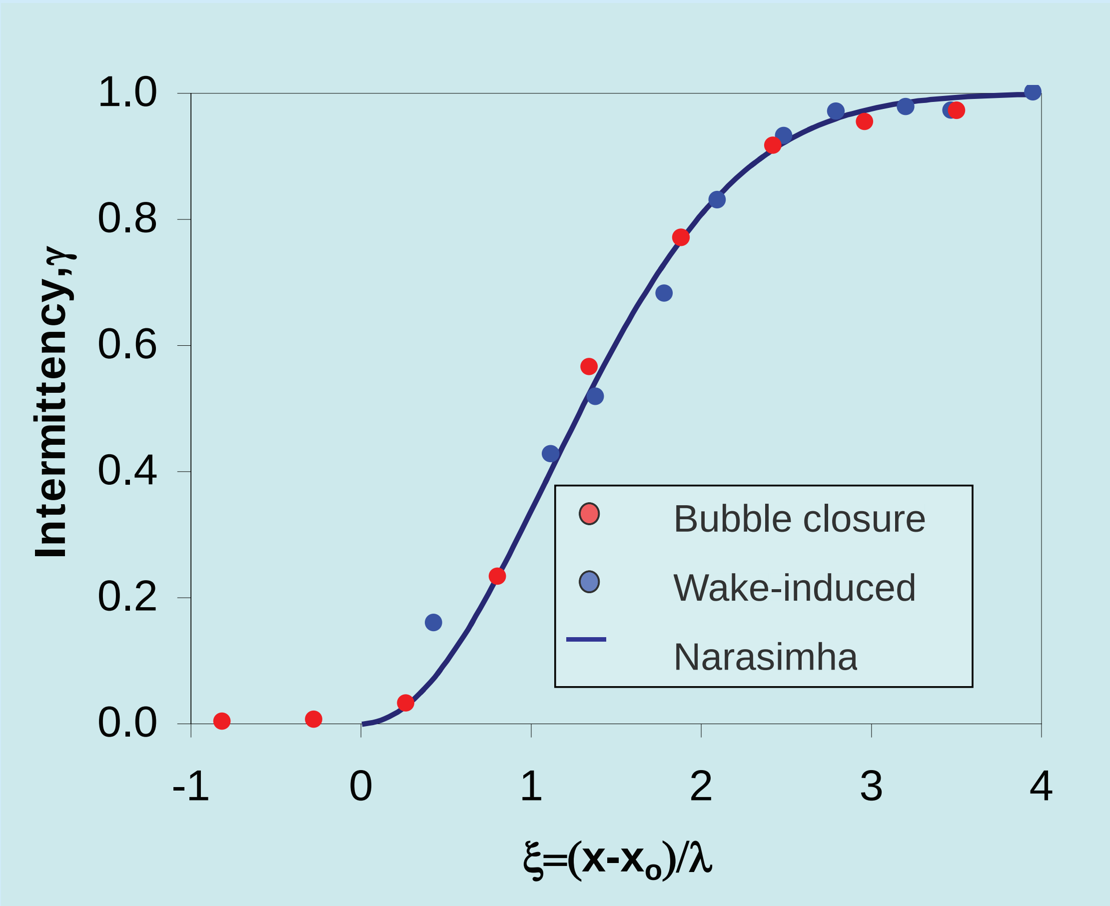
Later natural transition, closing the bubble.

Calmed region.

Near wake is stronger. By-pass transition?

Measured intermittency distribution

- agreed well with Narasimha distribution



Enabled extension of our transition prediction method to separated flows.

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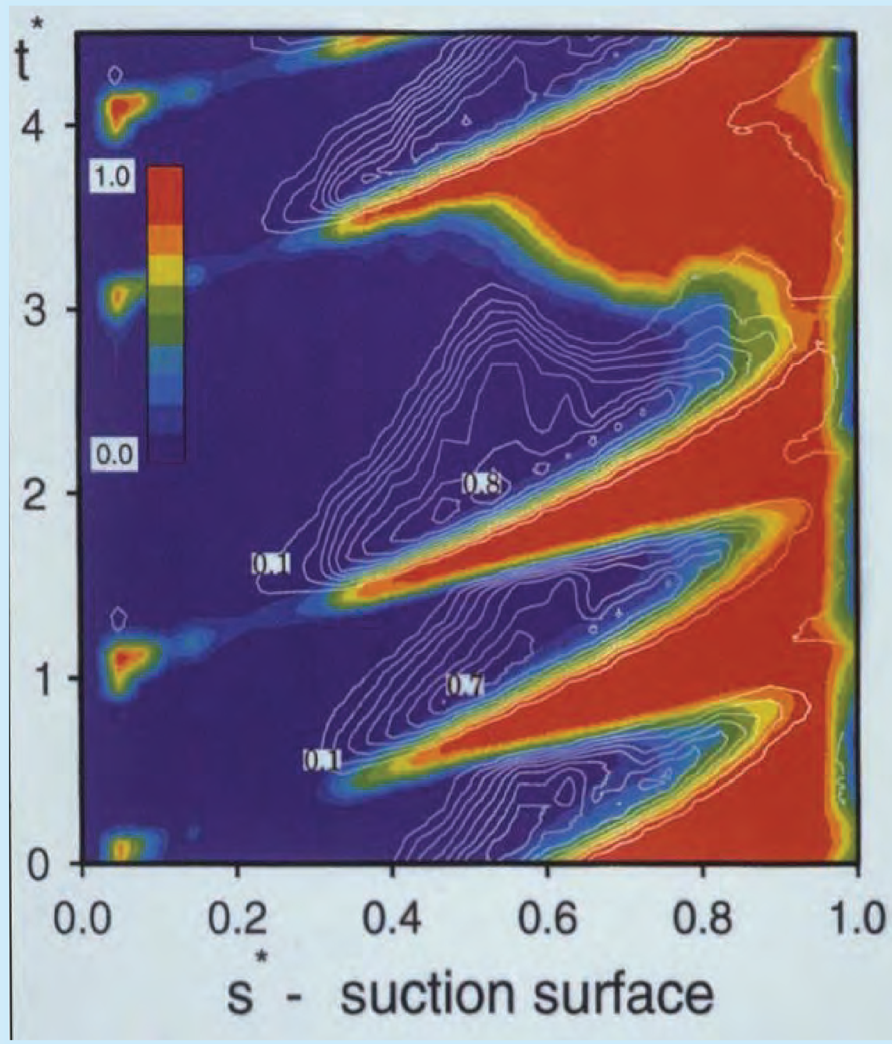
Intermittency of turbulence: x~t diagram

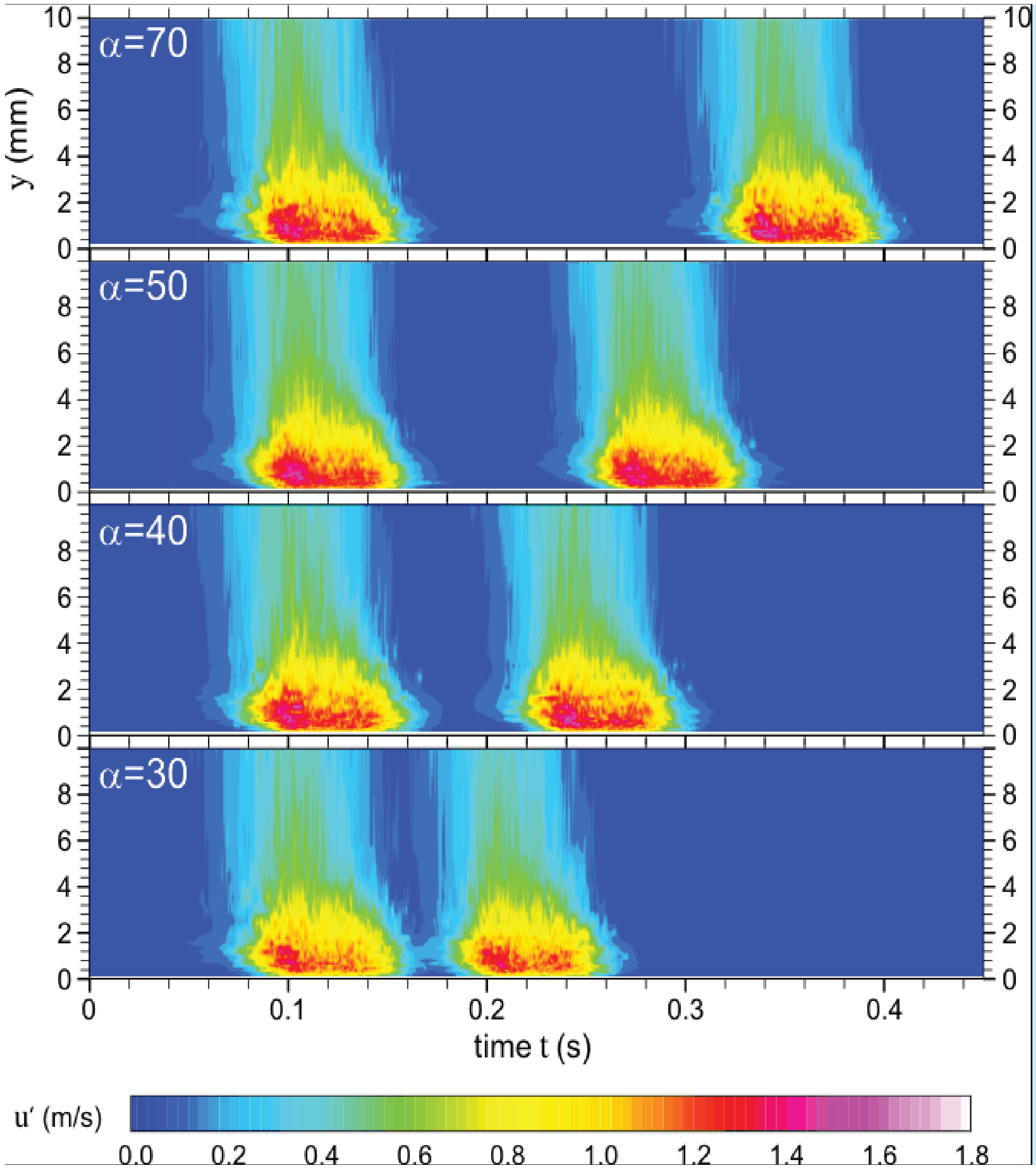
An important breakthrough was this plot, by Walker and Solomon, of turbulence level through compressor blades. They removed one upstream blade and it showed that the calmed region was delaying transition significantly.



Gutmark and Blackwelder

- performed an interesting experiment. The time interval between triggered turbulent spots was systematically varied. Close proximity saw celerity and disturbance level of following spot diminished. Does a wake-induced turbulent patch exhibit similar behavior?

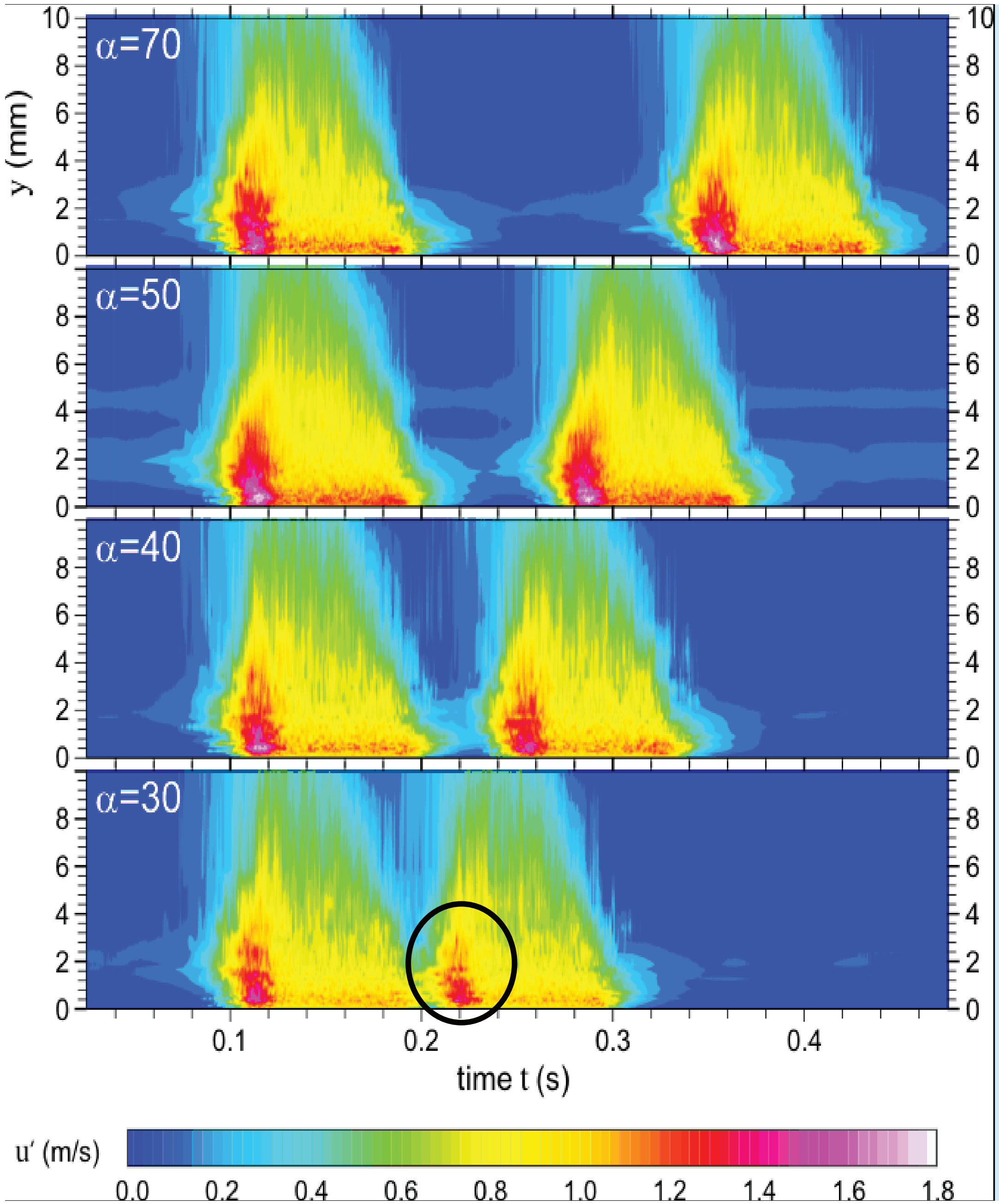
So we presented wakes in pairs at different spacing intervals; it was proposed to investigate wake interaction effects in more detail. Wake spacing was systematically varied; for close wake spacings the calmed region acted to suppress the turbulence in the following turbulent patch.



Effect of increasing wake proximity at x = 0.20 m

At this early upstream location, the surrounding boundary layer is laminar.

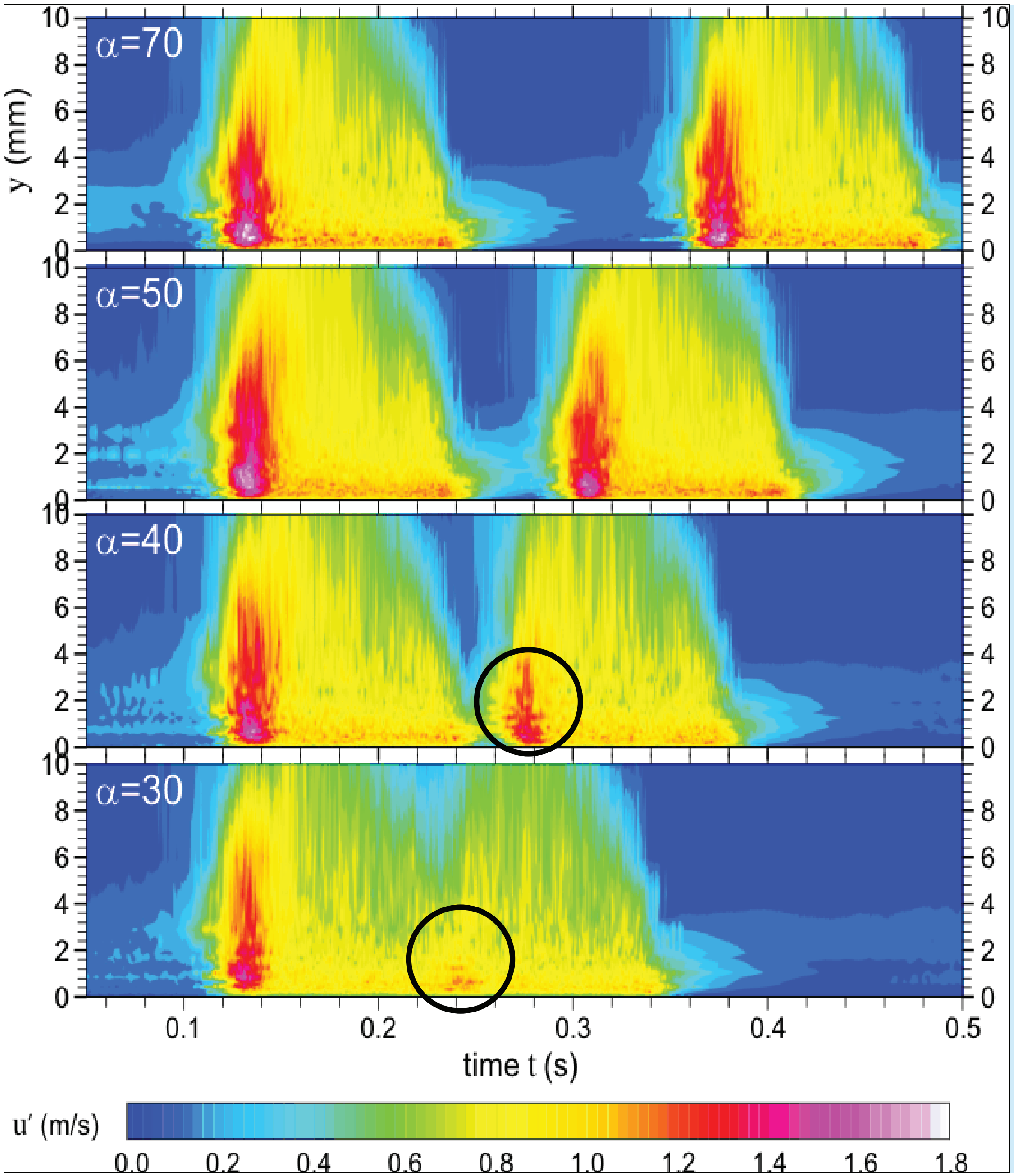
Here, the turbulent strips are newly developed and small in size. Thus, the second of each pair has not grown sufficiently to encroach upon the first turbulent strip.



Effect of increasing wake proximity at x = 0.40 m

Contours of rms velocity. The turbulent strips have grown in size. For the closest spacing case, α=30, the second strip has just made contact with the first strip, displaying a slight reduction in rms.

The surrounding boundary layer is now highly inflexional, yet still laminar.

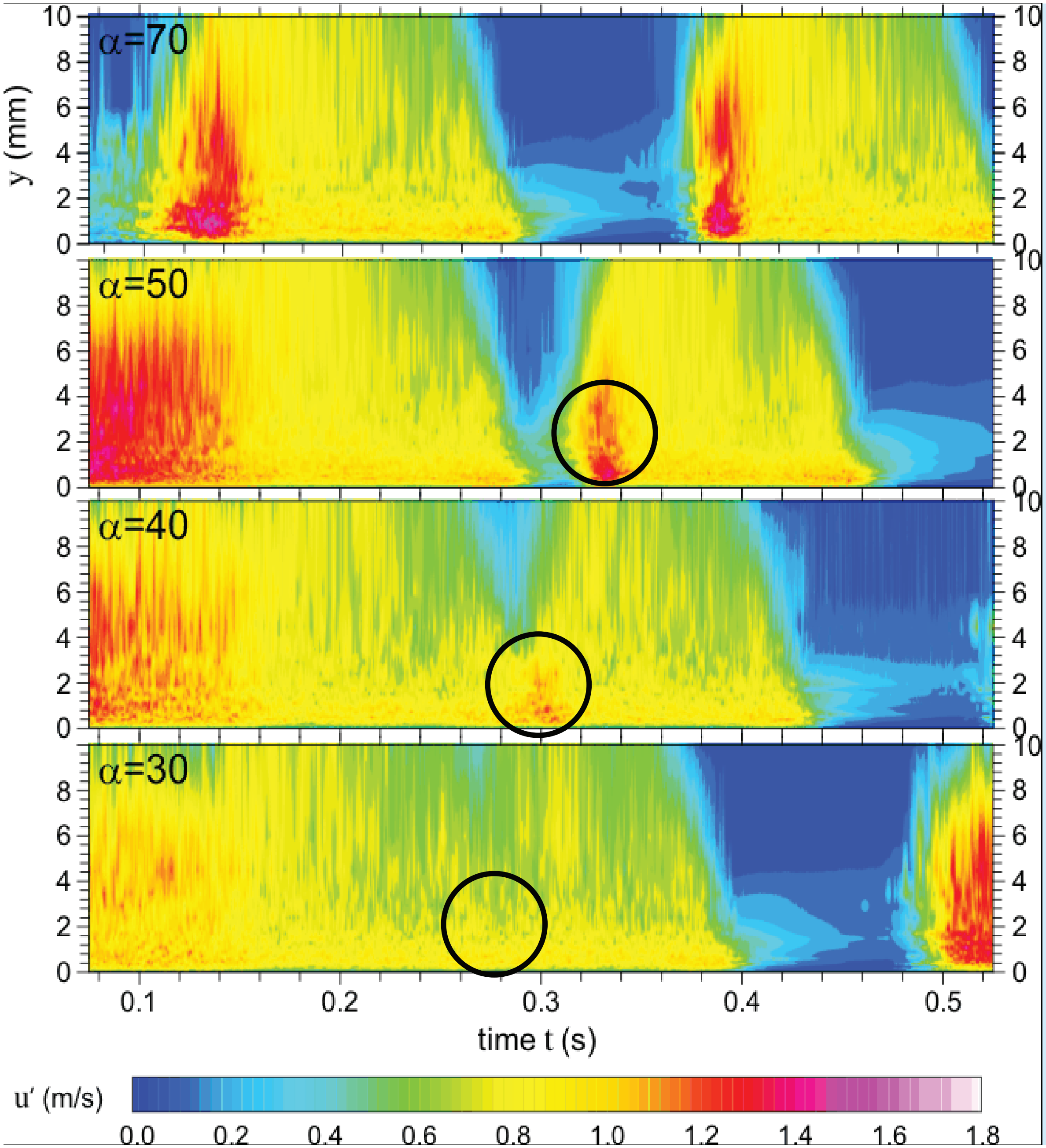


Effect of increasing wake proximity at x = 0.60 m.

The boundary layer is now separated in those areas surrounding the turbulent strips.

The strips are now significant in size, with the α=40 case demonstrating contact.

The closest case, α=30, shows an almost complete reduction of rms in the second strip.

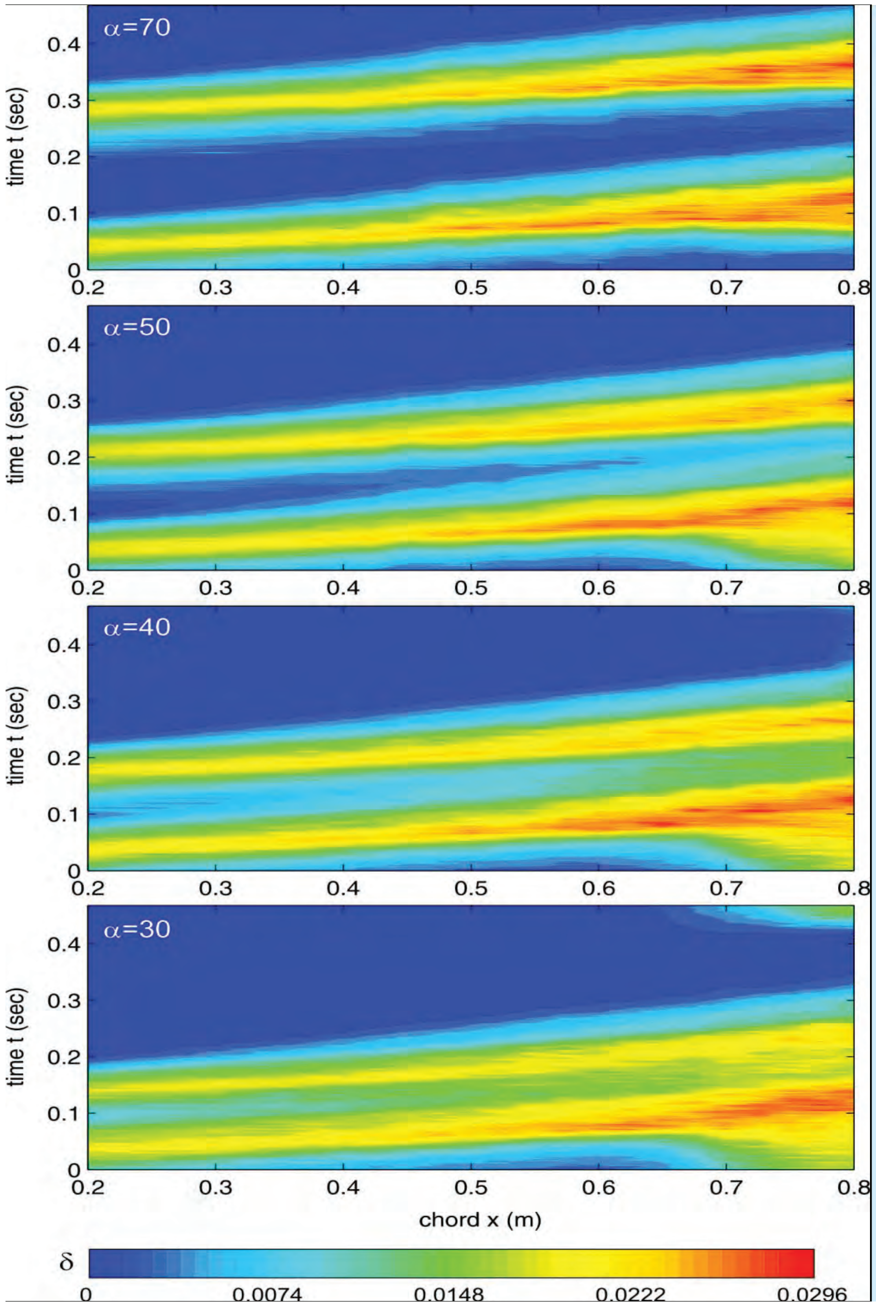


Effect of increasing wake proximity at x = 0.80 m.

The boundary layer is now reattached and fully turbulent.

The second strip of the closest case has propagated into the trailing region of the first strip, merging the two.

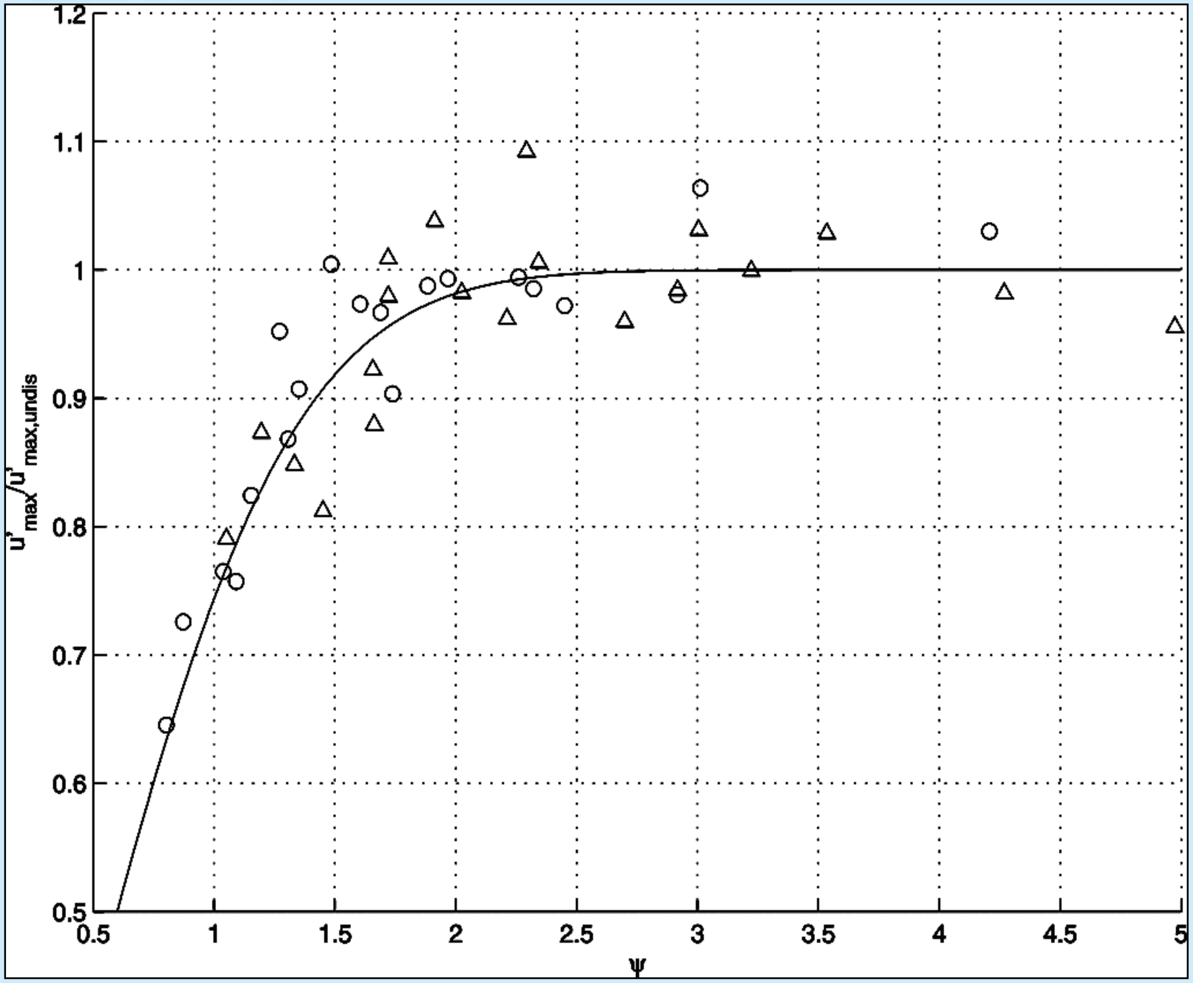
The cases of α=40 and 50 demonstrate the same behavior as the early α=30 locations.



Effect of increasing wake proximity in x - t plane

Contours of rms turbulence integrated over height of boundary layer.

Variation of peak RMS with wake proximity parameter at x = 0.80 m



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To investigate whether this phenomenon was a recurring one, or whether the flow then reverted back to its unperturbed state, the experiments were repeated with four rods instead of two.

The experiments encompassed a wide range of variables, including direction and speed of rod rotation.

It was found that the subsequent wakes were also suppressed by the calming effect. This repeating situation may also be anticipated in a turbomachine.

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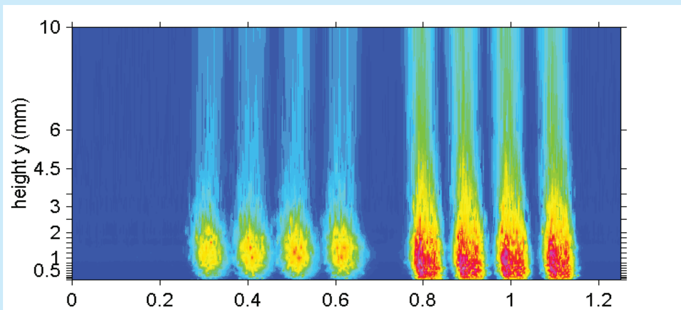
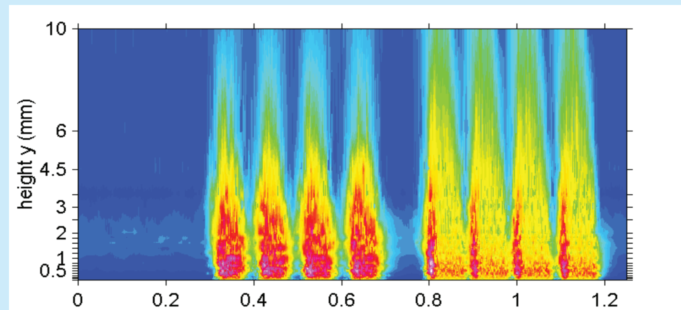
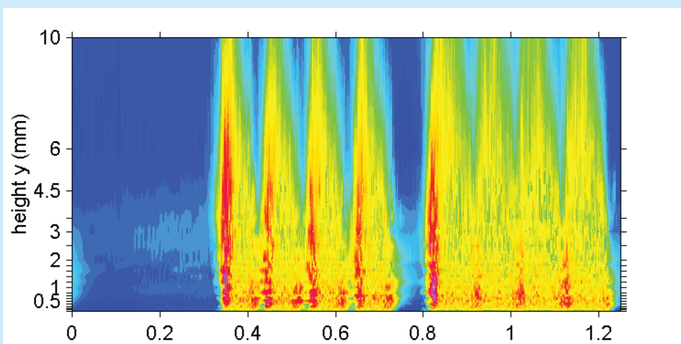


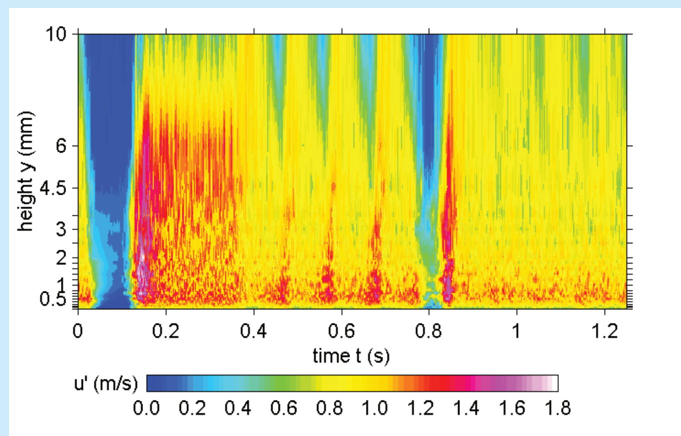
x=0.2



x=0.4

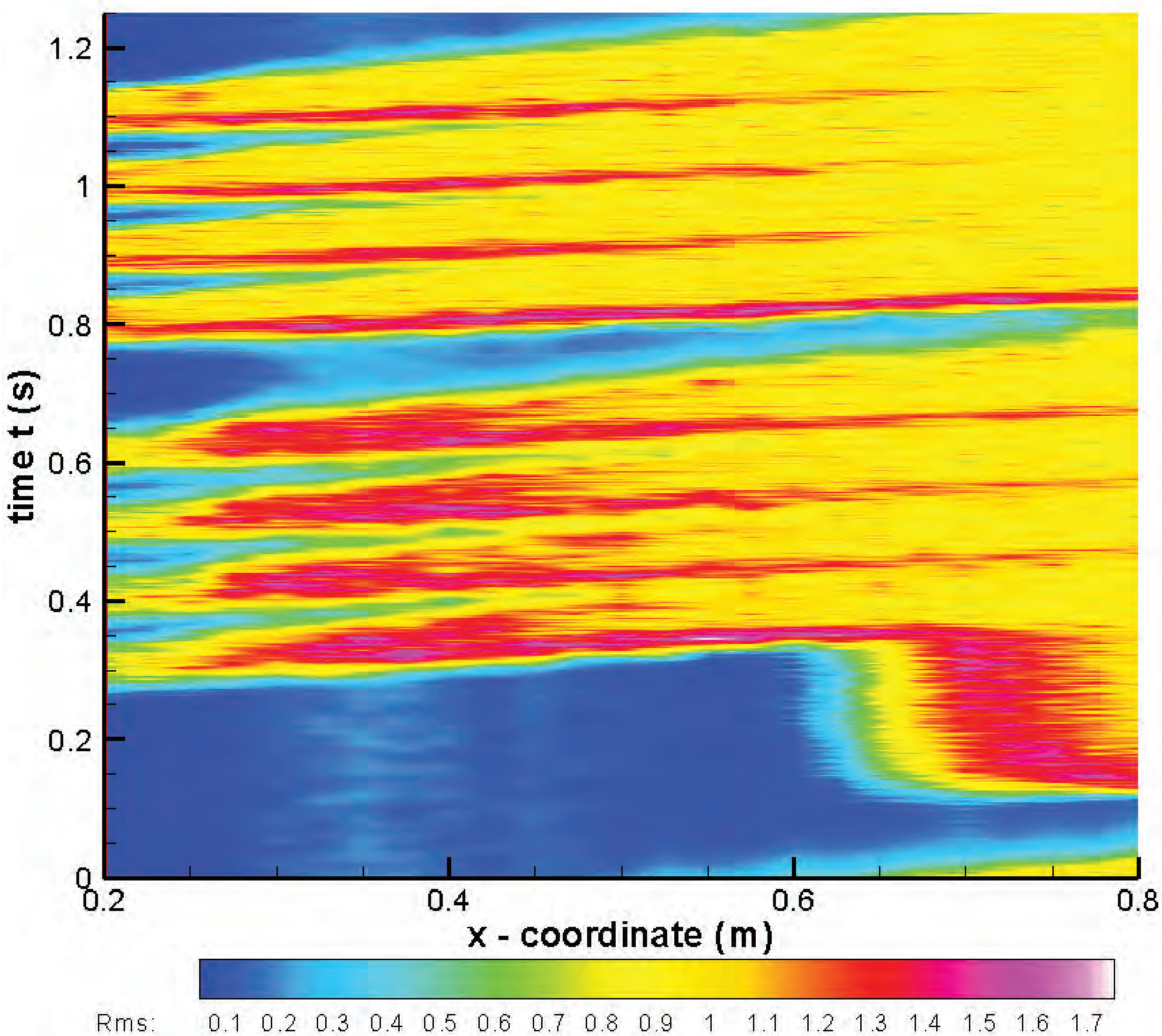


x=0.6



x=0.8

Four pairs of wakes at 30^{o} spacing



Top four wakes are "near wakes" giving by-pass transition.

Lower four are the weaker "far wakes" giving a natural transition.

Before this is the undisturbed natural transition and before this is a calmed region.

x~t diagram for RMS u' at y = 2 mm, 30°spacing

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Conclusions
Main Observations

- *Similar behavior between strong APG tests on triggered spots, wake-disturbed flat plate boundary layers, and on blading.*
- *Universal intermittency distribution valid for closure of laminar separation bubbles and for transition under wakes.*
- *Calmed region follows each wake-induced turbulent strip.*
- *Calmed region acts to suppress disturbances even within the turbulent region of a wake-induced patch.*
- *Turbulence reduced due to calmed region interaction.*
- *When spacing increased there was no efficiency improvement because calmed region had been acting all along.*
- *Continued to suppress turbulence for multiple wakes.*

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CONCLUSIONS

- *The approach was to start with a relatively simple arrangement and build up to a complex one.*
- *Similarities observed in the responses of adverse pressure gradient flows with triggered turbulent spots, in wake-disturbed boundary layers, and with multiple propagating wakes.*
- *Throughout the investigations the influence of the calmed region was very strong.*
- *The calmed region was first noticed in investigations of single triggered turbulent spots. It was found present in all cases investigated and particularly strong after a wake-induced turbulent strip.*

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- *The wake spacing was systematically varied; for close wake spacings the calmed region suppressed turbulence in the following turbulent patch.*
- *Although difficult to detect, the calmed region acts to suppress disturbances, even within the turbulent region of a wake-induced patch. It is therefore acting but undetected in many practical situations.*
- *There therefore exists some inherent degree of stabilisation and reduced disturbance level due to the calming effect.*
- *The practical benefits of the calmed region have been demonstrated and are flying in low pressure turbines; similar benefits might exist for compressor blading.*

NASA/CP—2020-220327

Intermittency Based Transition Model Validation

Y. Bora Suzen
North Dakota State University, Fargo, ND
Department of Mechanical Engineering
Bora.Suzen@ndsu.edu

George P.G. Huang
Wright State University, Dayton, OH
Department of Mechanical & Materials Engineering
George.Huang@wright.edu

NASA-Industry LPT/PT Efficiency Improvements Workshop
August 10-11, 2010

Outline

- Low-Pressure Turbine (LPT) flow physics
- Test/validation experimental cases
- Intermittency based transition modeling
    - Intermittency transport model
- Model development/testing/validation using experiments
- Concluding remarks

LPT Flows

<u>Interplay of Physical Mechanisms</u>

- Laminar/turbulent flow separation
- Wake/boundary layer interactions
- Flow transition
  - By-pass transition
  - Separated-flow transition
  - Wake-induced periodic transition
  - Relaminarization

<u>Important Parameters</u>

- Re
- FTI & FSL
- Favorable and adverse P-gradients
- Mach number
- Curvature
- Wake turbulence
- Unsteadiness

$\Rightarrow$ *Modeling transitional flows under diverse conditions*

$\Rightarrow$ ***Intermittency concept + turbulence model***

$\Rightarrow$ *Detailed experimental LPT flow data for model development/testing/validation*

LPT Test/Validation Cases

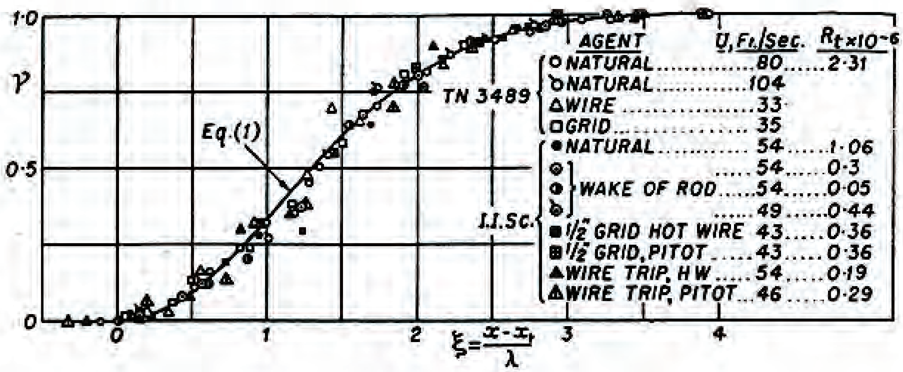
- **Flat Plate Experiments (Effects of Re, FSTI, dp/ds)**
  - ERCOFTAC Benchmarks, Coupland (1993)
  - Separated and Transitional Boundary Layer Experiments of Hultgren and Volino(2000)
- **Blade Passage and Cascade Experiments (Effects of Re, FSTI, dp/ds, Flow Separation)**
  - PAK-B Blade Passage Experiments of Volino (2002)
  - PAK-B Blade Passage Experiments of Simon (2000)
  - PAK-B Cascade Experiments of Corke et al. (2002)
  - PAK-B Cascade Experiments of Lake et al. (1999, 2000)
  - PSU Compressor Cascade Experiments of Zierke and Deutsch (1989)
  - Genoa Cascade Experiments of Ubaldi et al. (1996)
  - VKI Cascade Experiments of Arts et al. (1990)
- **Unsteady Wake/Blade Interaction Experiments (Effects of Unsteadiness)**
  - PAK-B Blade Passage Experiments of Kaszeta et al. (2001, 2003)
  - T106A Cascade Experiments of Stieger (2002)
  - SSME Cascade Experiments of Schobeiri and Pappu (1997)
  - PAK-B Cascade Experiments of Schobeiri and Ozturk (2003)
  - TD106D-EIZ Cascade Experiments of Stadtmuller and Fottner (2001)
- **3-D Experiments**
  - RGW compressor

Intermittency Factor, γ

Universal Streamwise Distribution:

- Correlation of Dhawan and Narasimha (1958):

$$\gamma = \begin{cases} 1 - \exp[-(x - x_t)^2 n\sigma/U] & (x \geq x_t) \\ 0 & (x < x_t) \end{cases}$$



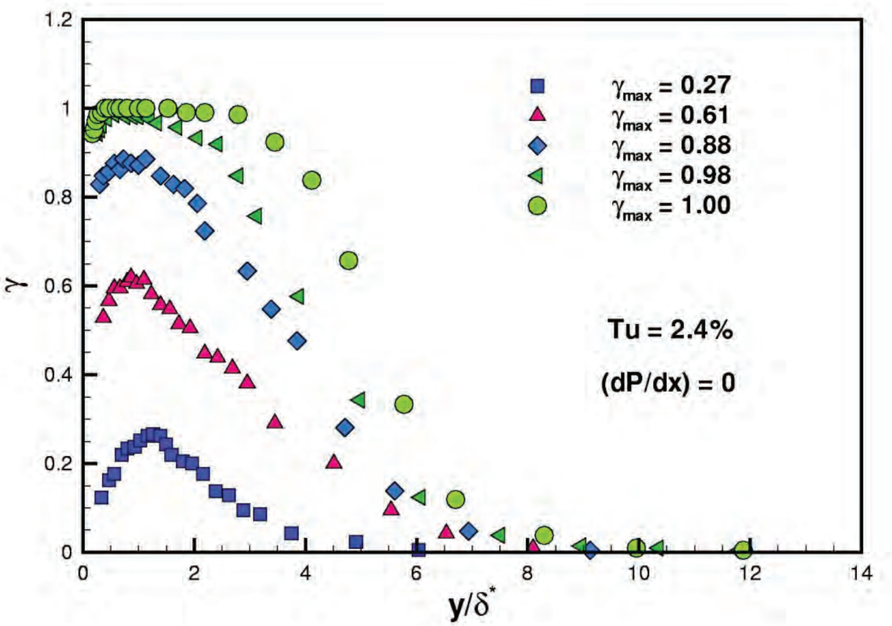
- Effects of pressure gradient and free stream turbulence

$$n\sigma/U = f(\lambda_\theta, \mathrm{Tu}, \alpha)$$

Gostelow, *et al.*, (1994), Solomon, *et al.*, (1995)

Intermittency Factor, γ

Variation in Cross-Stream Direction:



From Sohn and Reshotko (1991)

- Peaks between $y/\delta^* = 1$ and $y/\delta^* = 2$
- Decays to zero near $y/\delta^* = 8$

Transport Model for Intermittency

Desired Characteristics:

- ***Streamwise γ distribution of Dhawan and Narasimha***
  - Transport γ model of Steelant and Dick (1996)
    - No cross-stream variation of γ
- ***Realistic γ profile in cross-stream direction***
  - k–ε–γ turbulence model of Cho and Chung (1992)
    - For free shear flows, not for transition

Blending of:

- Steelant and Dick Model
- Cho and Chung Model

$$P_\gamma = (1- F)\, P_{SD} + F\, P_{CC}$$

Transport Model for Intermittency

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho U_j\gamma)}{\partial x_j}=(1-\gamma)\left[(1-F)T_0+F(T_1-T_2)\right]+T_3+D_\gamma$$

Produces the desired characteristics:

- Streamwise γ distribution of Dhawan and Narasimha
- Realistic γ profile in cross-stream direction

Implementation:

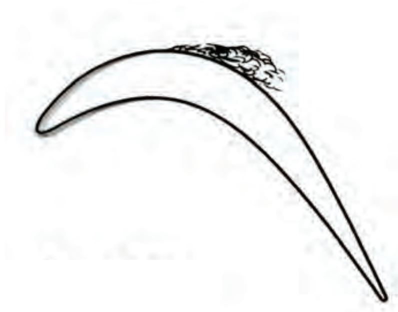
- In the mean flow equations,

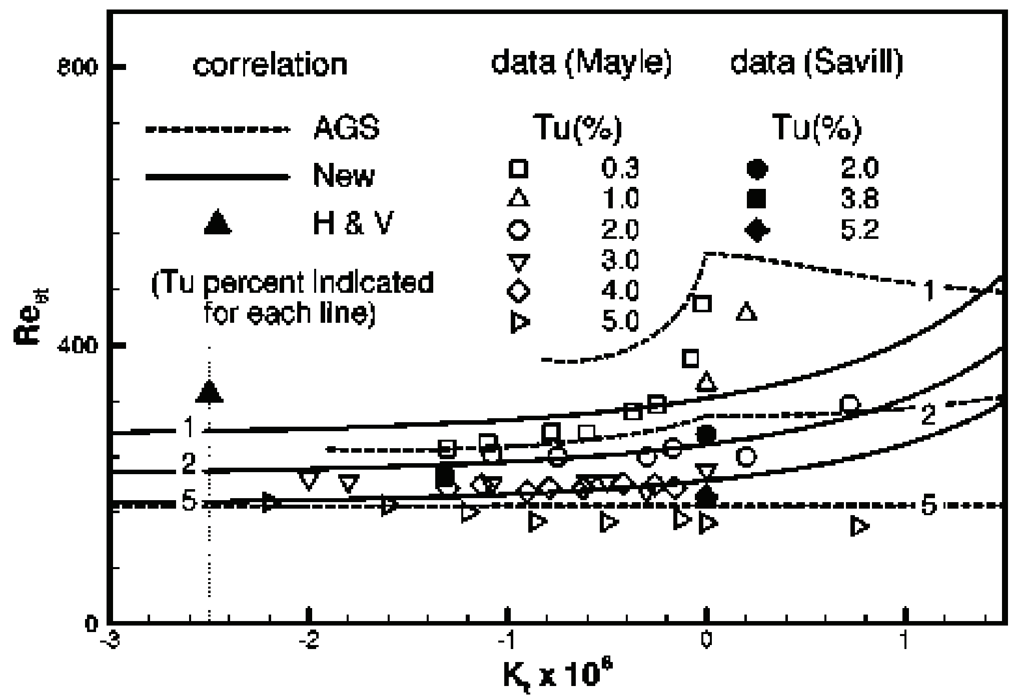
  $$\mu_t^* = \gamma\,\mu_t$$

  - μ_t – from SST model of Menter
- Onset point of transition from correlations
  - Attached flow transition
  - Separated flow transition

Attached-flow Transition

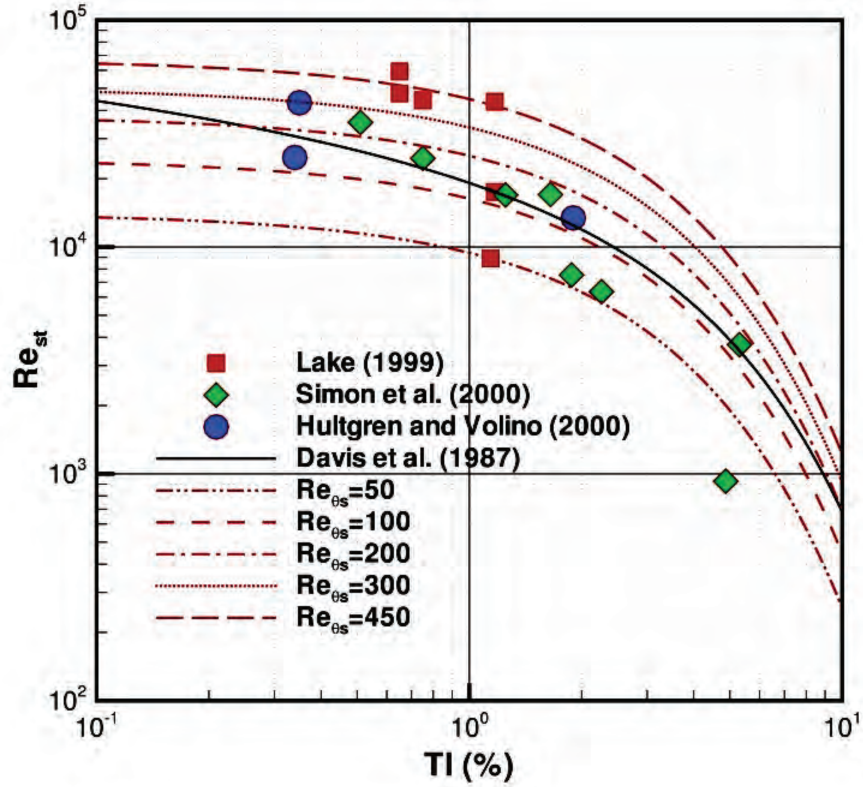
$$Re_{\theta_t} = (120 + 150Tu^{-2/3})coth[4(0.3 - K_t \times 10^5)]$$





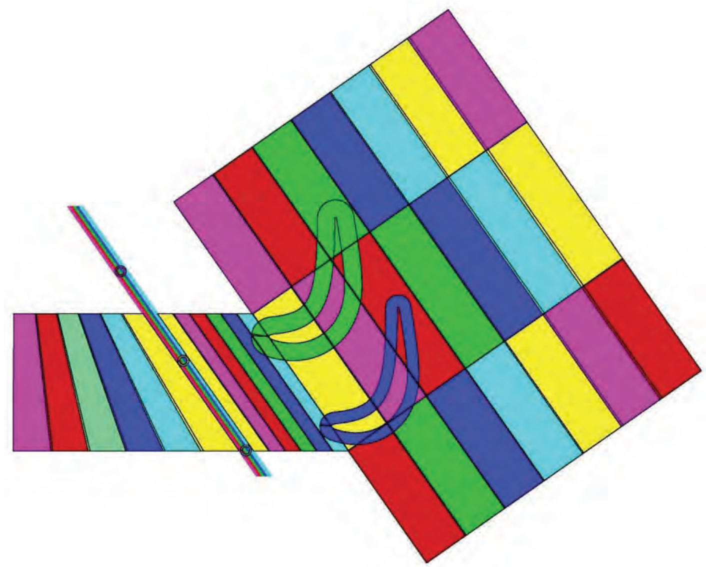
Separated-flow Transition

$$Re_{\mathrm{st}} = 874 Re_{\theta \mathrm{s}}^{0.71} \exp[-0.4 Tu]$$



Computational Tools

- Boundary layer code for initial development and testing
- Single zone Navier-Stokes code TURCOM & GHOST verification of results from boundary layer code and checking hysteresis effects
- Multi-block Navier-Stokes solver GHOST
    - 2nd order in both time and space
    - Advection terms $\rightarrow$ QUICK scheme
    - Viscous terms $\rightarrow$ central differencing
    - Capable of handling
        - Complex geometries
        - Moving and overset grids
    - MPI
    - Hsu et al. AIAA-2003-0766, Suzen & Huang AIAA-2003-1256.



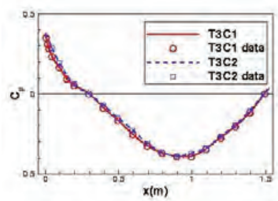
Test/Validation Cases

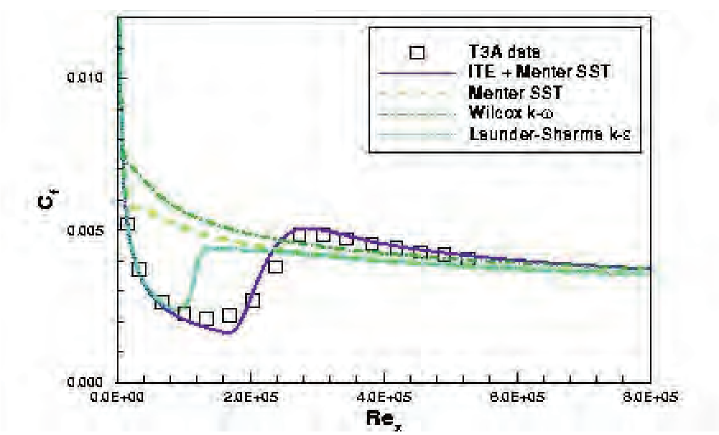
- **Flat Plate Experiments (Effects of Re, FSTI, dp/ds)**
  - ERCOFTAC Benchmarks, Coupland (1993)
  - Separated and Transitional Boundary Layer Experiments of Hultgren and Volino(2000)
- **Blade Passage and Cascade Experiments (Effects of Re, FSTI, dp/ds, Flow Separation)**
  - PAK-B Blade Passage Experiments of Volino (2002)
  - PAK-B Blade Passage Experiments of Simon (2000)
  - PAK-B Cascade Experiments of Corke et al. (2002)
  - PAK-B Cascade Experiments of Lake et al. (1999, 2000)
  - PSU Compressor Cascade Experiments of Zierke and Deutsch (1989)
  - Genoa Cascade Experiments of Ubaldi et al. (1996)
  - VKI Cascade Experiments of Arts et al. (1990)
- **Unsteady Wake/Blade Interaction Experiments (Effects of Unsteadiness)**
  - PAK-B Blade Passage Experiments of Kaszeta et al. (2001, 2003)
  - T106A Cascade Experiments of Stieger (2002)
  - SSME Cascade Experiments of Schobeiri and Pappu (1997)
  - PAK-B Cascade Experiments of Schobeiri and Ozturk (2003)
  - TD106D-EIZ Cascade Experiments of Stadtmuller and Fottner (2001)
- **3-D Experiments**
  - RGW compressor

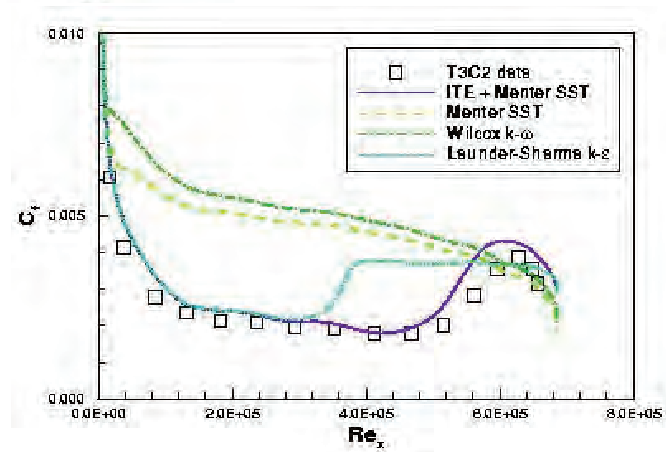
ERCOFTAC Benchmarks, Coupland (1993)

- **Effects of FSTI, Re, and dp/ds on transition.**
- Zero pressure gradient
    - T3A case, FSTI = 3.0%
    - T3B case, FSTI = 6.0%
- Favorable-to-adverse pressure gradient
    - T3C1 case, FSTI = 6.6%
    - T3C2 case, FSTI = 3.0%

Experimental data include:
- Boundary layer integral parameters
- Skin friction coefficients
- Mean velocity profiles
- Mean axial and normal velocity turbulent fluctuations



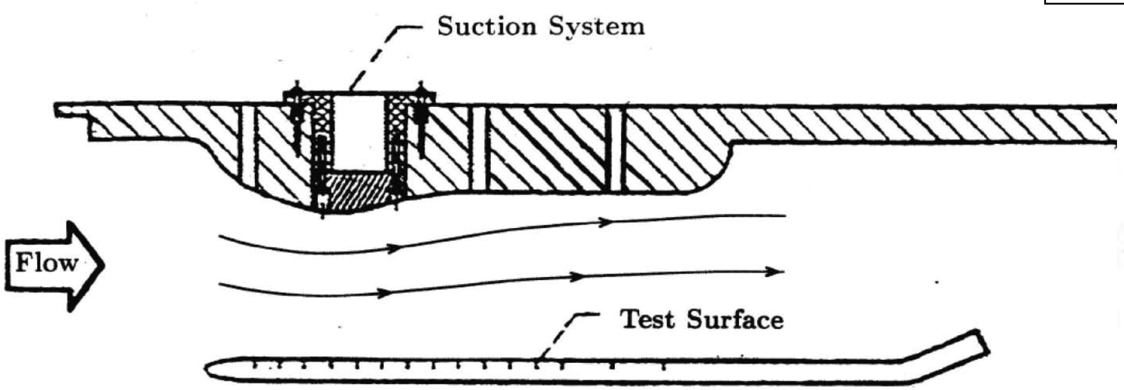


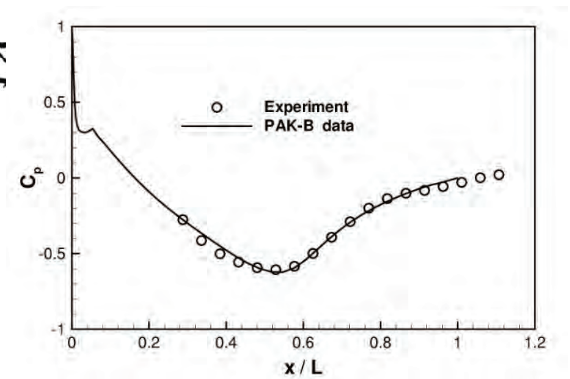


Experiments of Hultgren and Volino (2000)

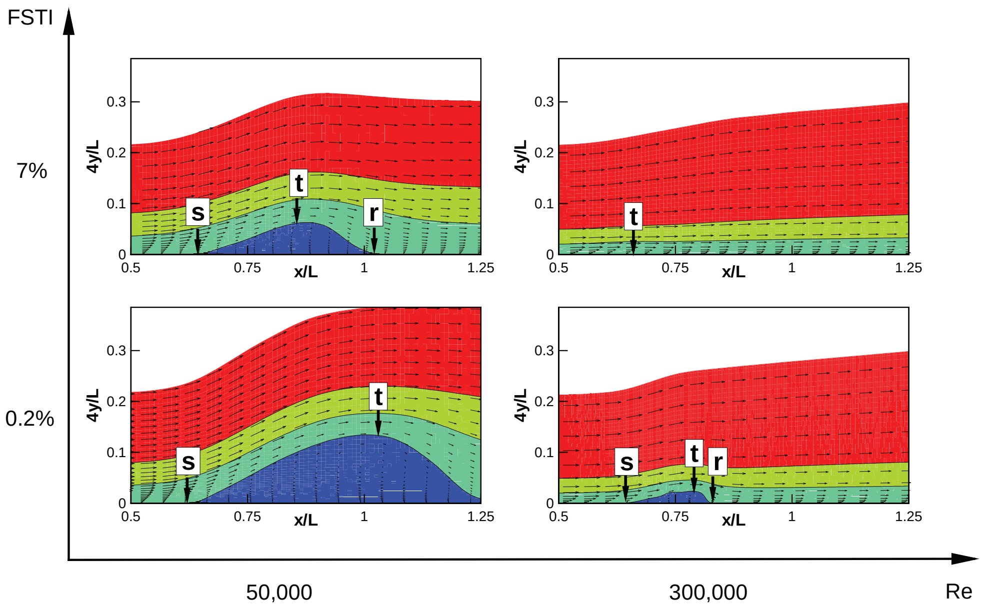
- **Effects of Re and FSTI on flow separation and transition under low-pressure turbine airfoil conditions**
- Re = 50,000 to 300,000
- FSTI = 0.2% and 7%
- PW PAK-B blade pressure distribution

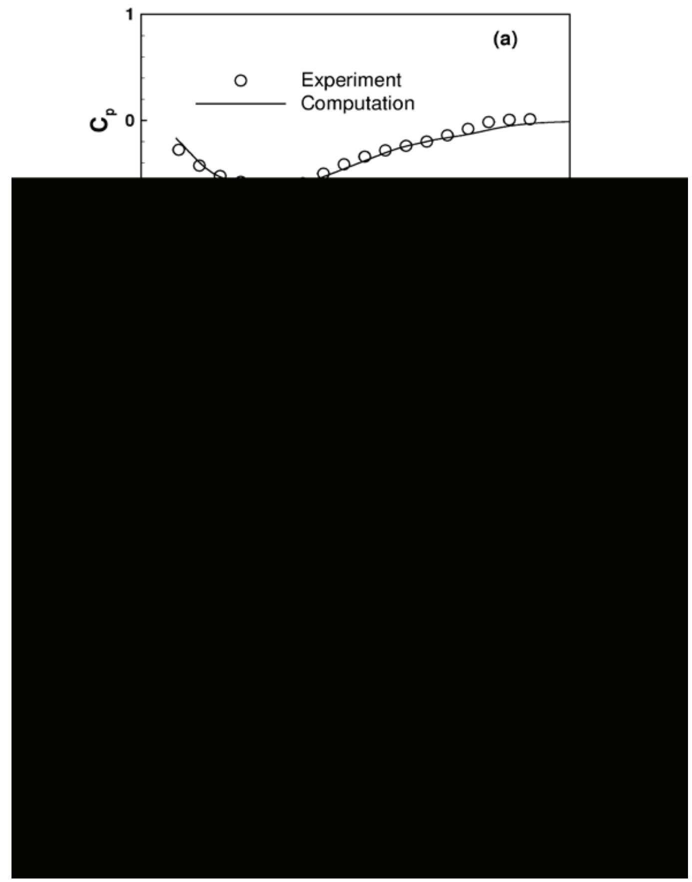
Experimental data include:
- Pressure coefficient and freestream velocity distributions
- Velocity, turbulent kinetic energy, intermittency profiles
- Boundary layer integral parameters





Experiments of Hultgren and Volino (2000)



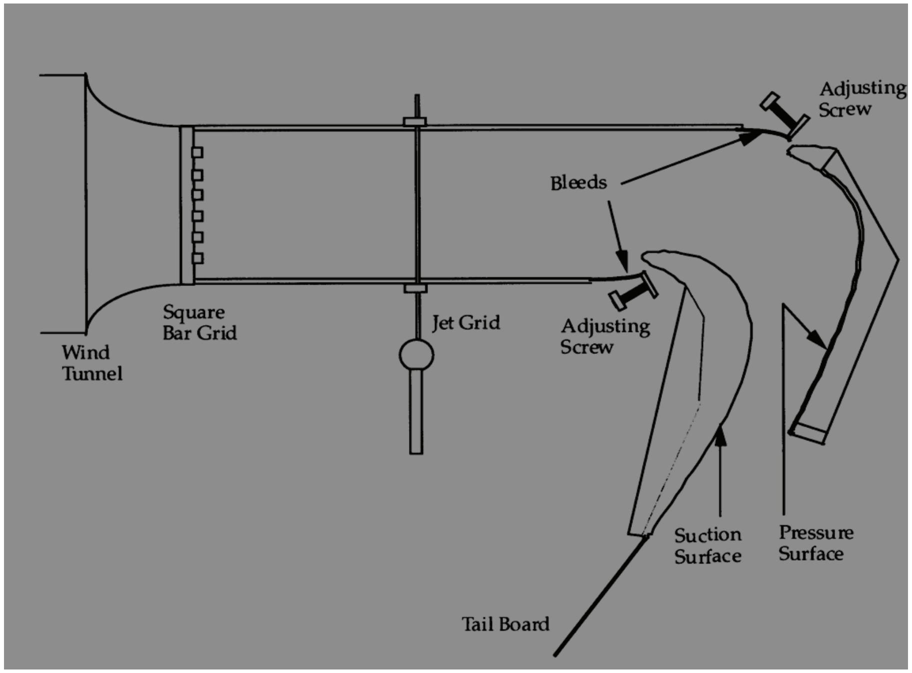


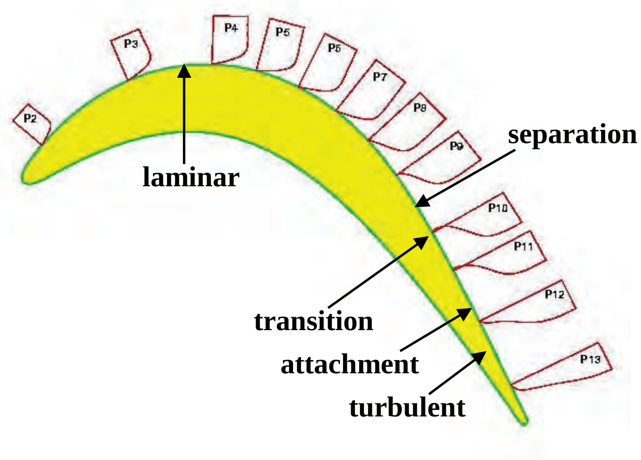
Re=50,000, FSTI=7%

Experiments of Simon et al. (2000)

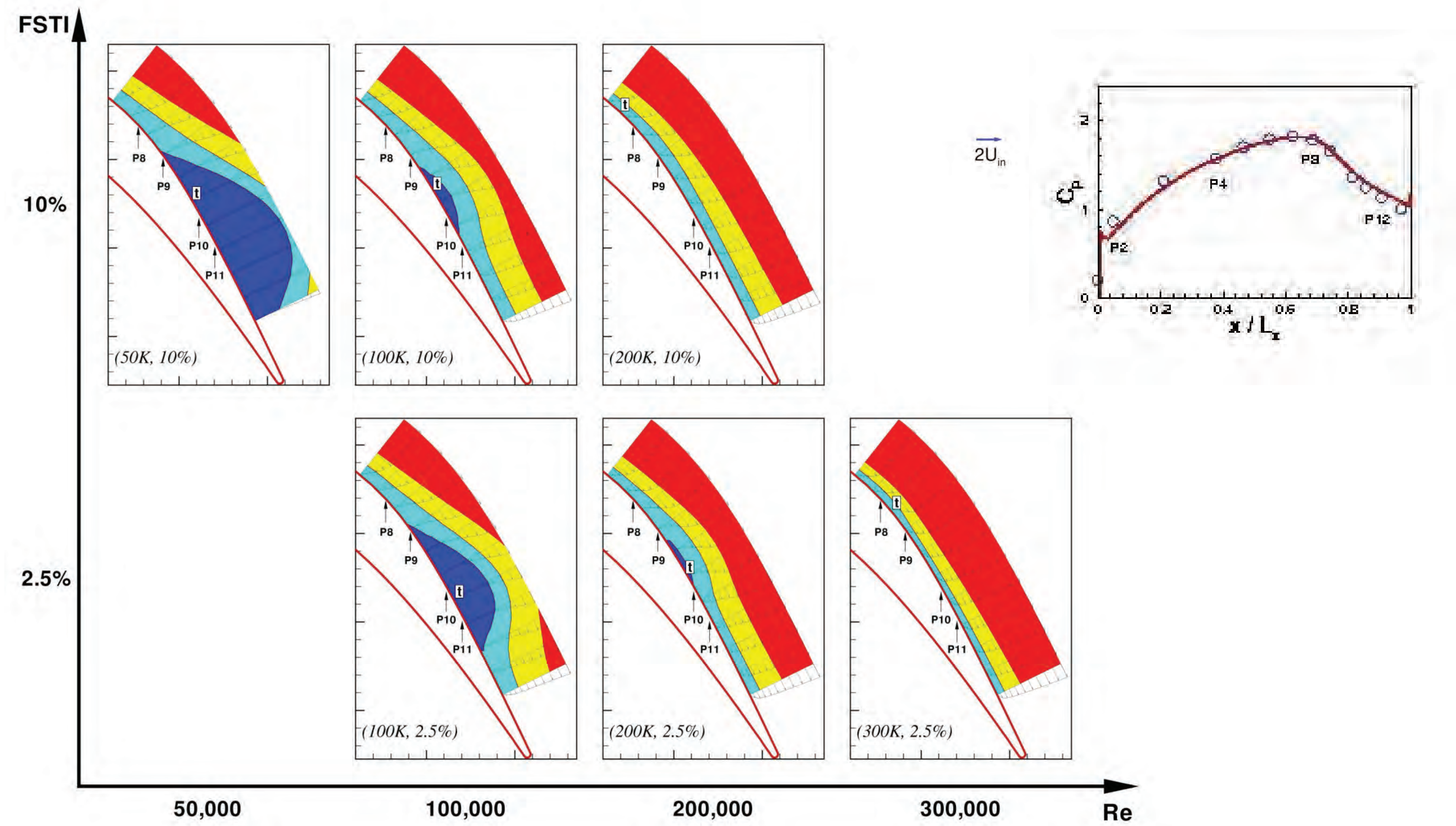
- **Effects of Re and FSTI on flow separation and transition**
- Re = 50,000 to 300,000
- FSTI = 0.5% to 10%
- PW PAK-B blade passage

Experimental data include:
- Pressure coefficients
- Velocity, turbulence intensity, velocity fluctuation, and intermittency profiles at 13 stations on the suction surface



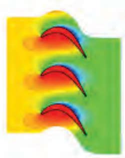
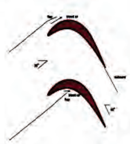


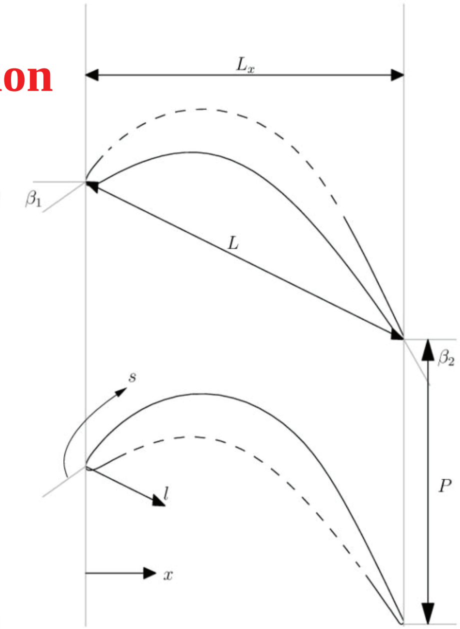
Experiments of Simon et al. (2000)



Low Pressure Turbine Cascade Experiments

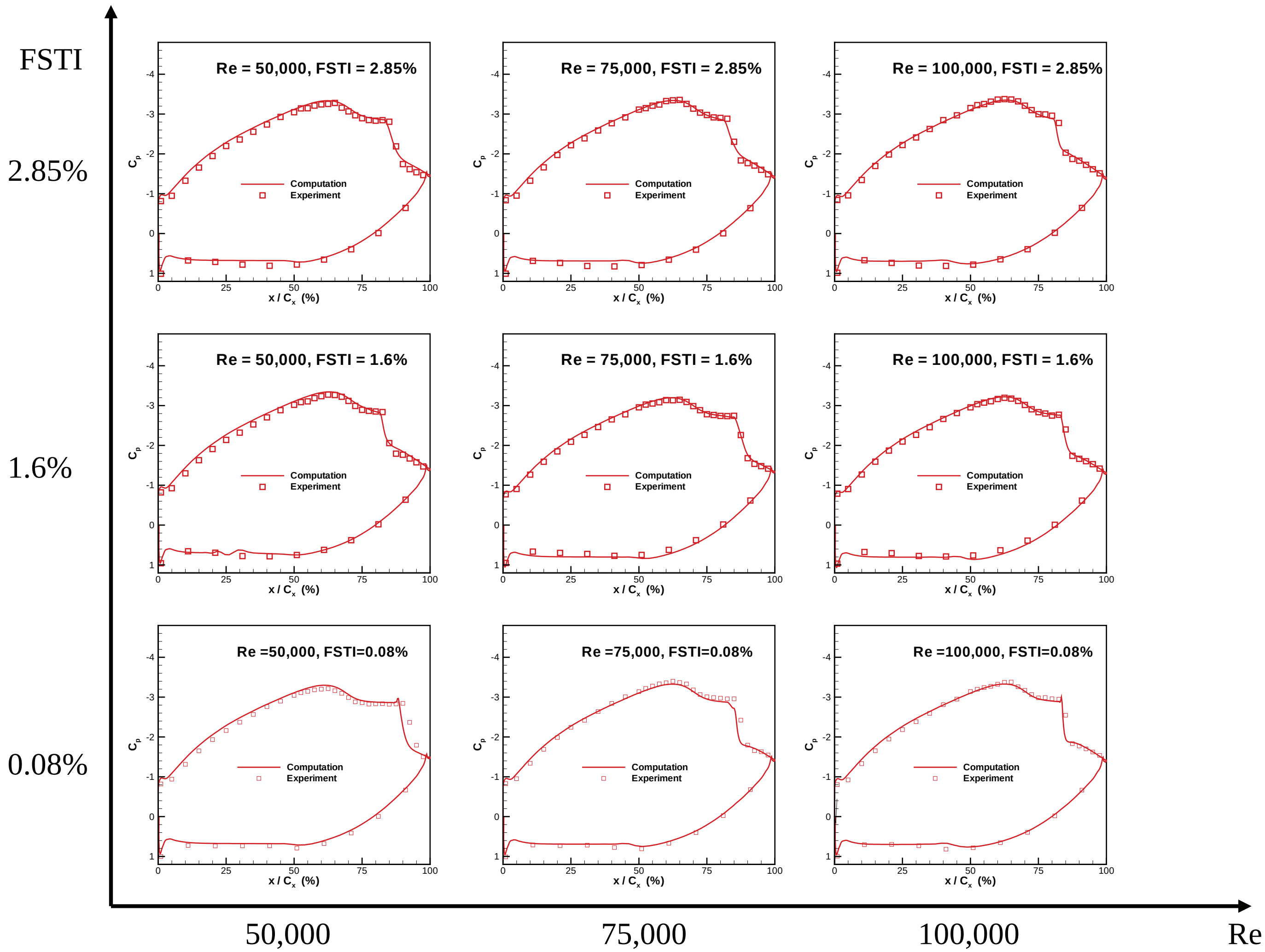
• **Effects of Re and FSTI on flow separation and transition**

Source	Test Section	Re ($U_{in}C_x/\nu$)	FSTI (%)	Data used for Comparison
Lake et.al (1999, 2000)	P&W PAK-B cascade	43,000	1 & 4	C_p
		86,000	1 & 4	C_p
		172,000	1 & 4	C_p
Corke et al. (2002)	P&W PAK-B cascade	10,000	0.08	C_p
		25,000	0.08	C_p
		50,000	0.08, 1.6, 2.85	C_p, velocity
		75,000	0.08, 1.6, 2.85	C_p, velocity
		100,000	0.08, 1.6, 2.85	C_p, velocity
Volino (2002)	P&W PAK-B passage	10,291	0.5	C_p, velocity
		20,581	0.5	C_p, velocity
		41,162	0.5	C_p, velocity
		82,324	0.5	C_p, velocity



Chord length, L
Axial chord length, L_x
Axial chord to chord ratio, $L_x/L=0.906$
Pitch to chord ratio, P/L = 0.8
Blade inlet angle, $\beta_1 =$ 35°
Blade outlet angle, $\beta_2 =$ -60°

Experiments of Corke *et al*. (2002)

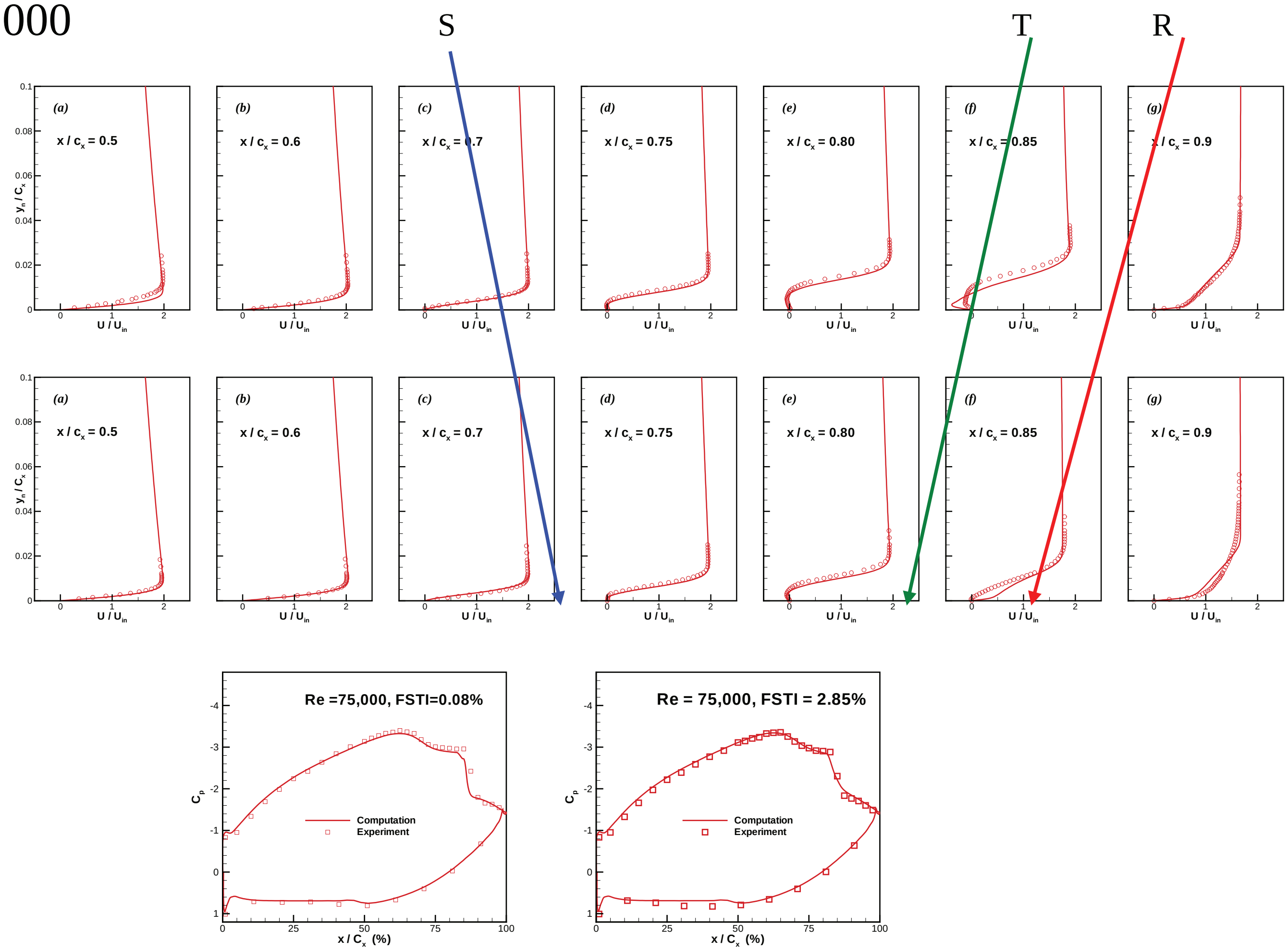


Experiments of Corke *et al*. (2002)

- Re = 75,000

FSTI = 0.08%

FSTI = 2.85%



NDSU

Low Pressure Turbine Flows

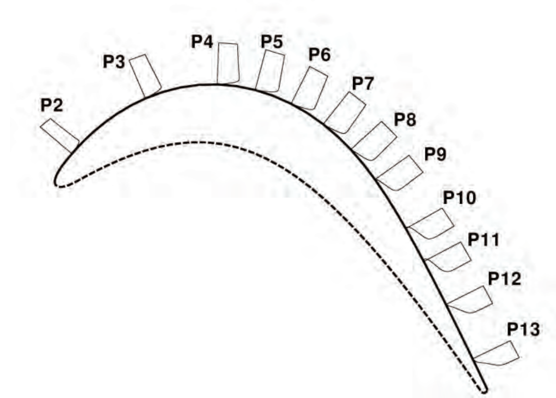
- Intermittency Transport Model is validated against several *steady* LPT benchmark experiments representing a wide range of operating conditions:
  - Flat plate experiments (Re, FSTI, dp/ds)
  - Blade passage and cascade experiments (Re, FSTI, dp/ds, Separation)
- Overall good agreements with the experimental data are obtained.
- Captured the dynamic interplay between separation, transition, reattachment under the effects of
  - Reynolds number variations
  - FSTI variations

Next $\Rightarrow$ Extension to Unsteady Wake/Blade Interactions (Unsteadiness)

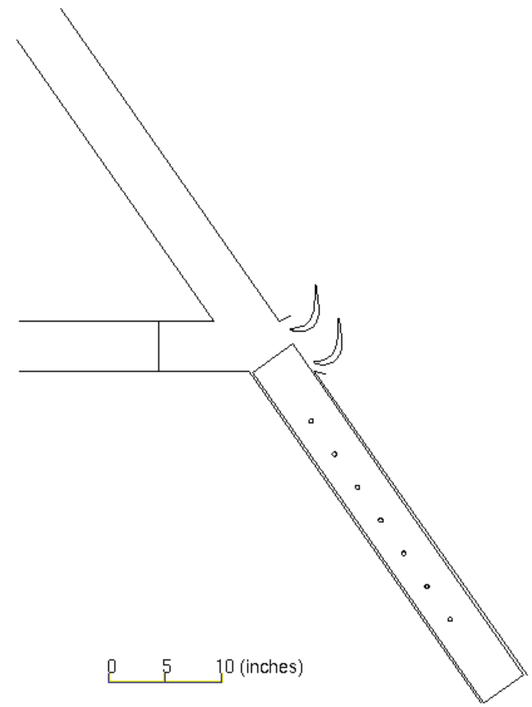
- PAK-B Blade Passage Experiments of Kaszeta et al. (2001,2003)
- T106A Cascade Experiments of Stieger (2002)

Experiments of Kaszeta et al. (2001, 2003)

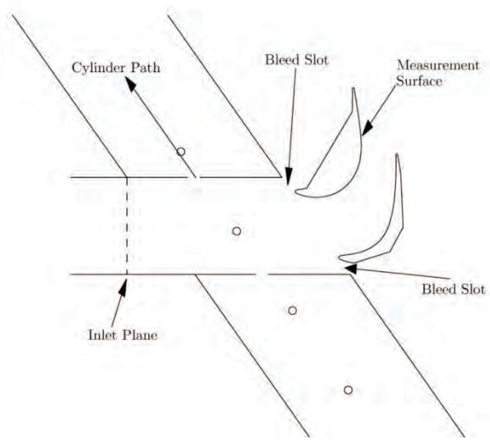
- **Effects of periodic wake passing on separation and transition**
- Re = 50,000 (Re_c = 23,000)
- FSTI = 2.5%
- PAK-B blade passage
- L_r/P = 1 and 2

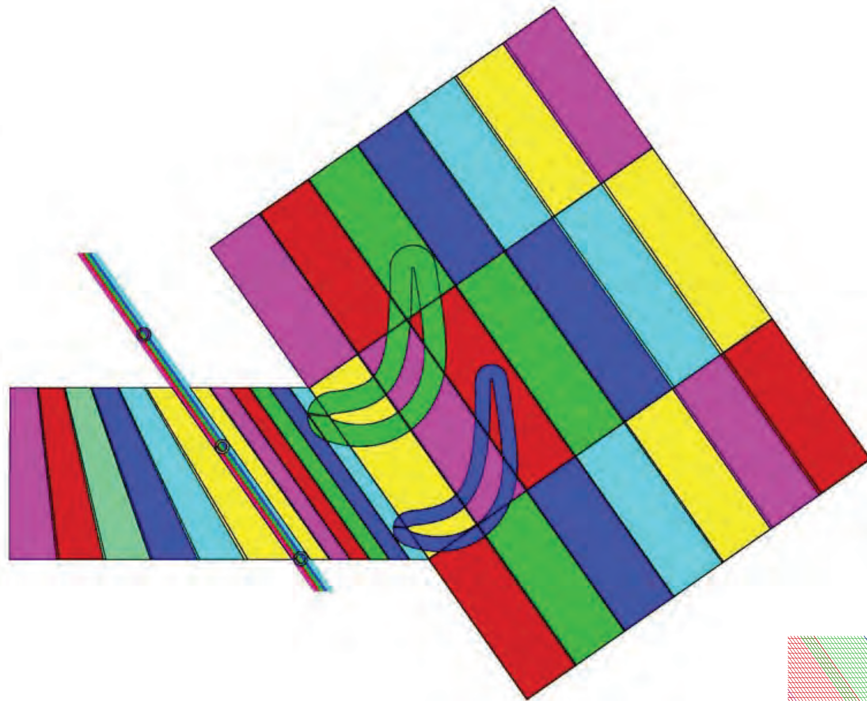


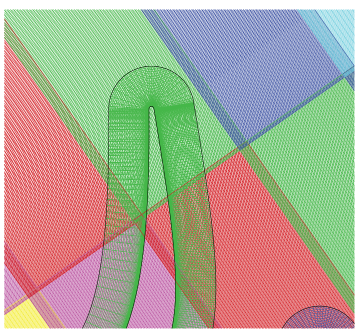
Experimental data includes:
Time resolved and phase averaged wall-normal profiles of velocity, turbulence intensity, and intermittency at twelve streamwise stations on the suction surface



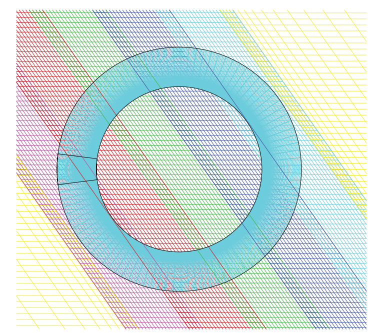
Experiments of Kaszeta et al. (2001, 2003)



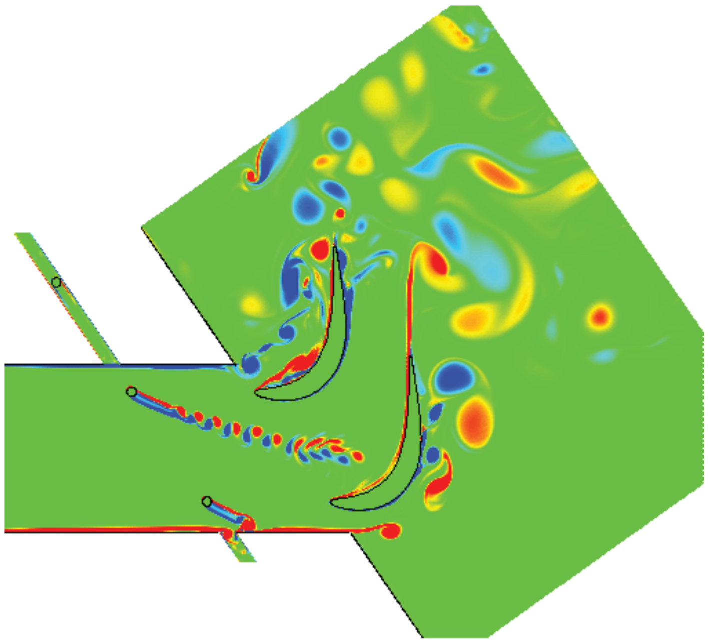




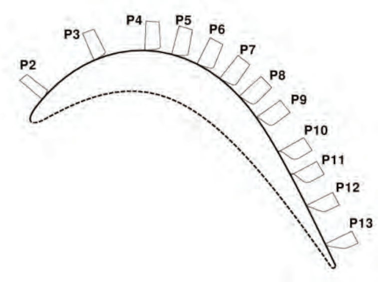
- 43 zones
- ~0.6 million points
- $y^+ < 0.5$ near walls

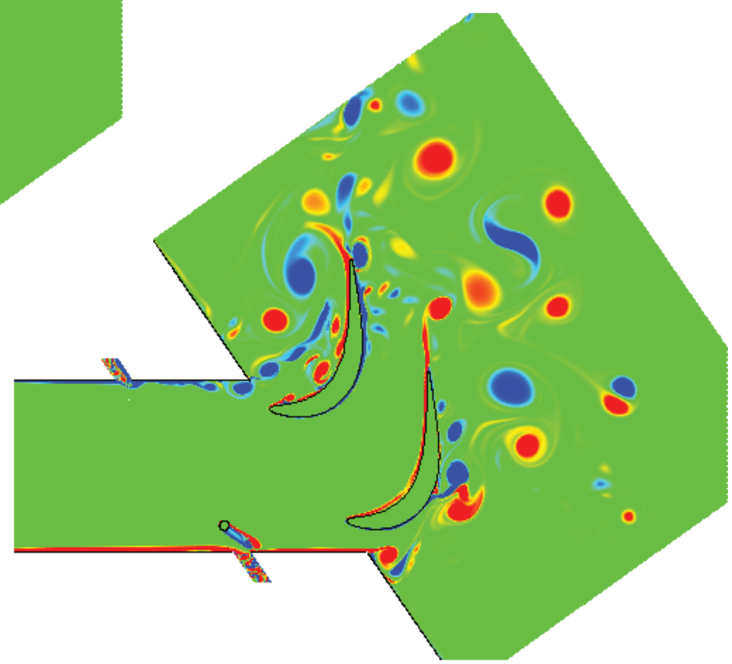


Experiments of Kaszeta et al. (2001,2003)



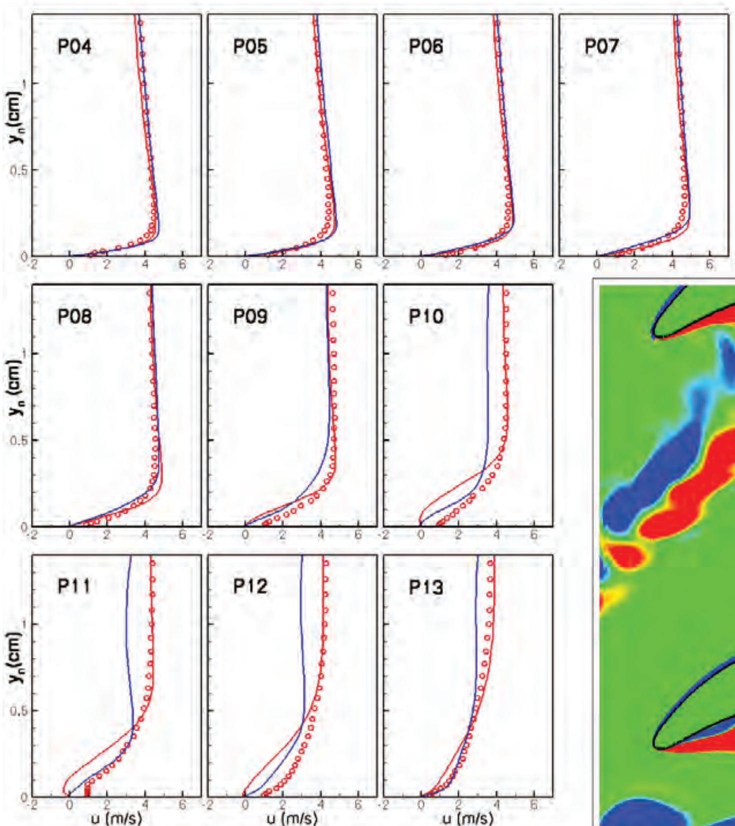
High wake
passing frequency

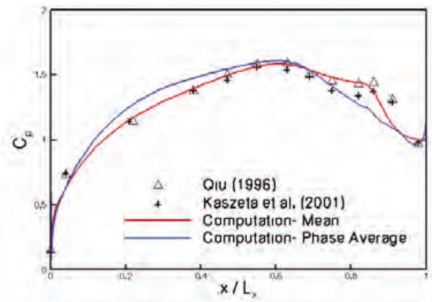


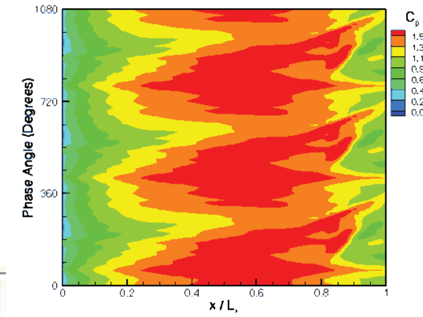


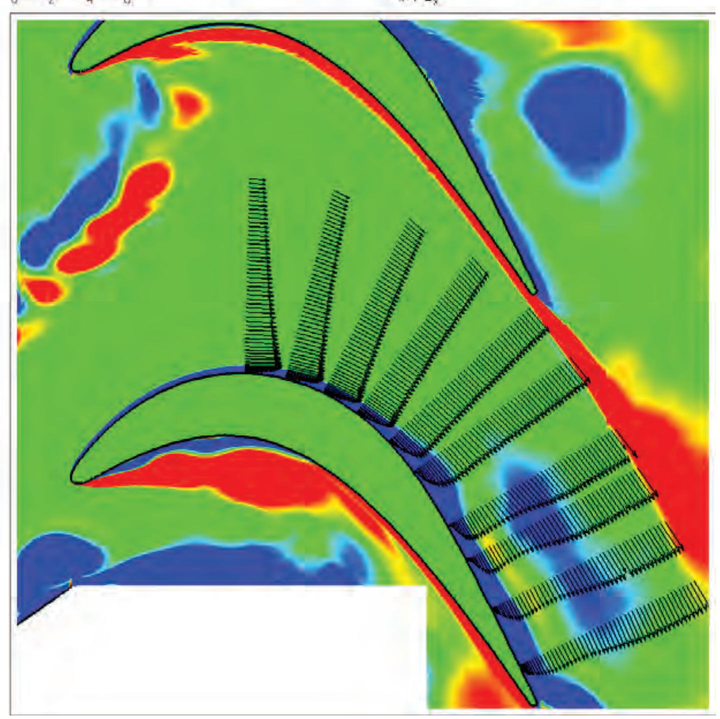
Reduced wake
passing frequency

Experiments of Kaszeta et al. – High Freq.



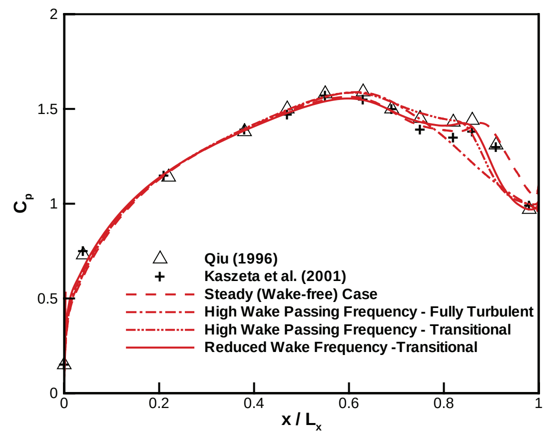


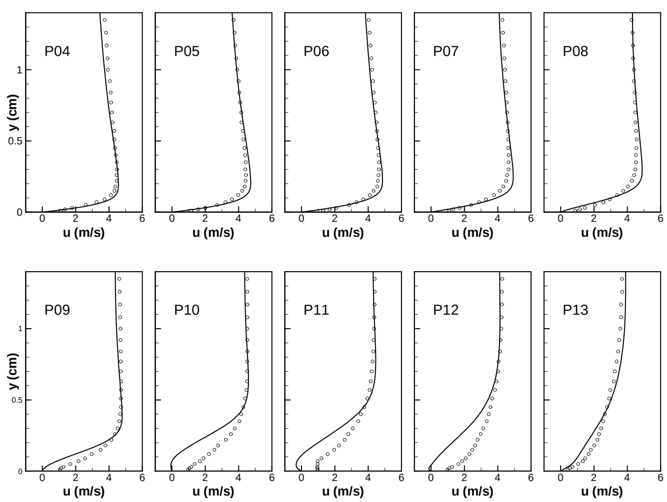




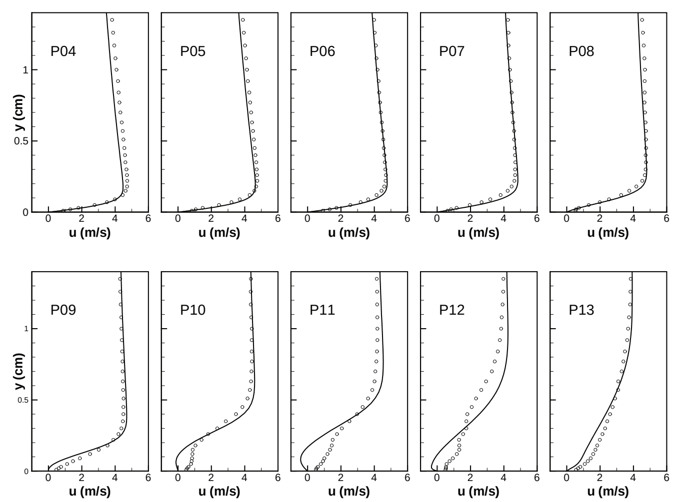
Experiments of Kaszeta et al. (2001, 2003)

- C_p distributions
- Mean velocity





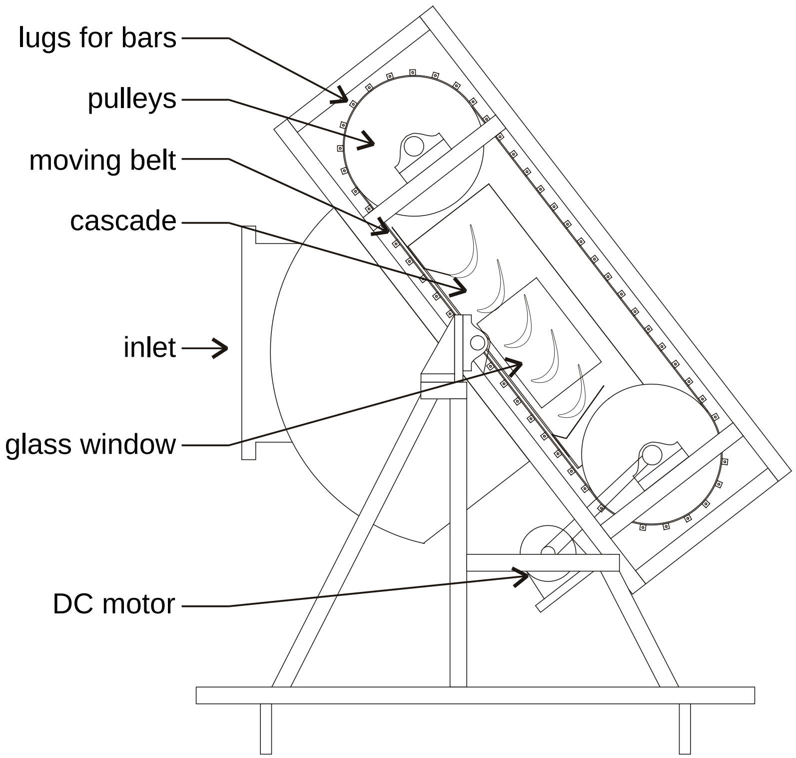
High Frequency

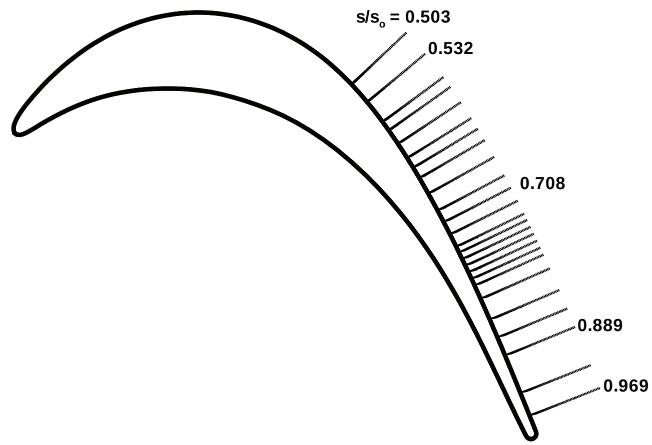


Low Frequency

Experiments of Stieger (2002)

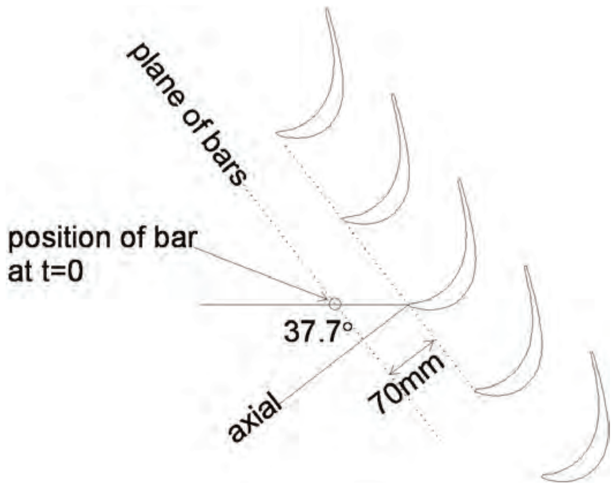
- **Effects of unsteady wake passing on boundary layer development**
- Re_c = 91,000
- FSTI = 0.1%
- T106 turbine blade cascade





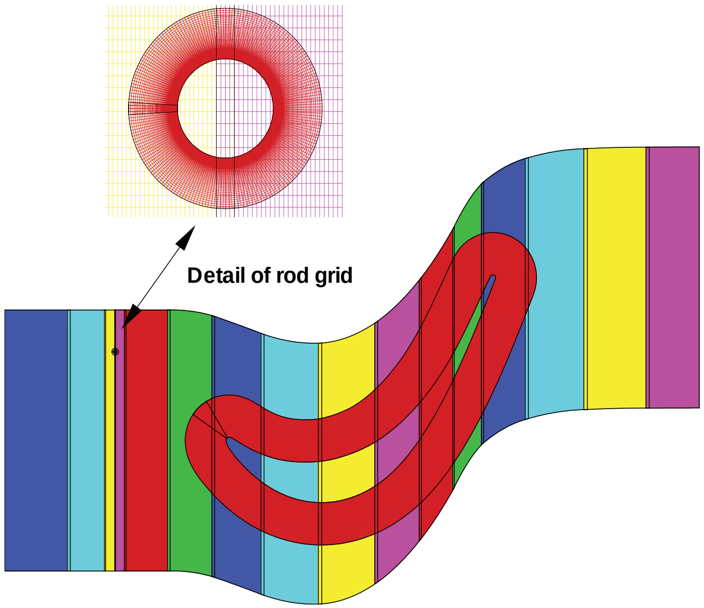
Experimental data include:
- Unsteady boundary layer velocity, turbulence intensity, pressure measurements along the suction surface at twenty five stations.

Experiments of Stieger (2002)



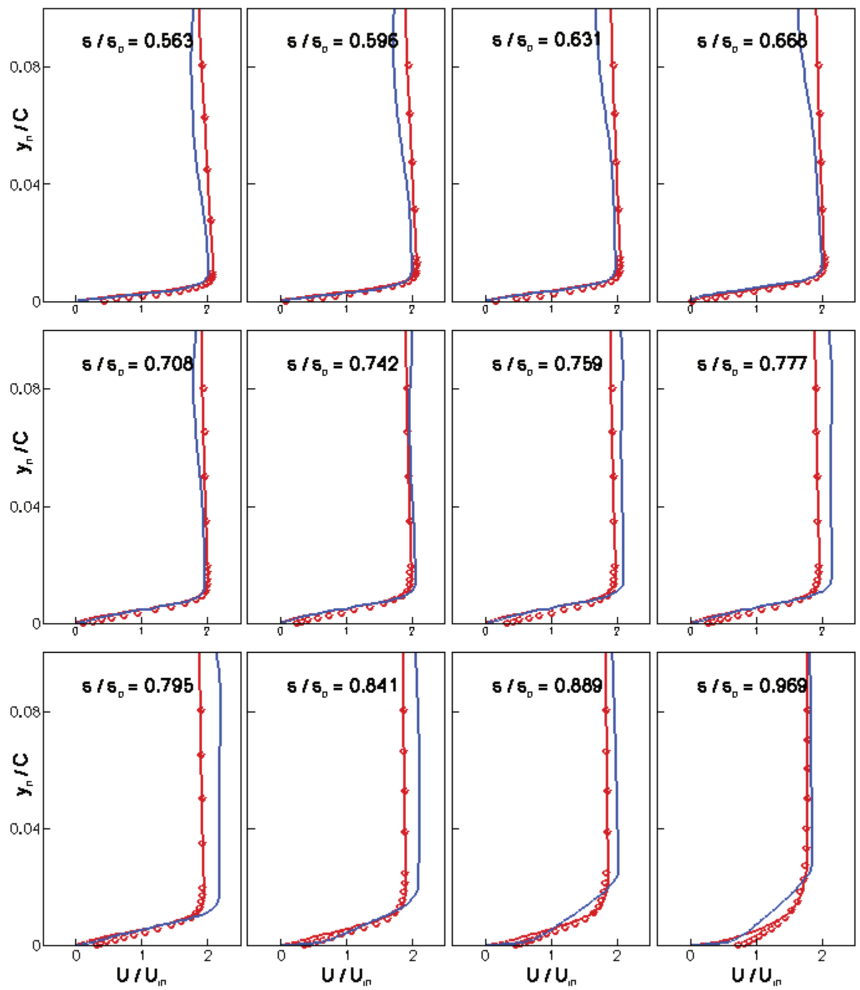
T106 Cascade Details

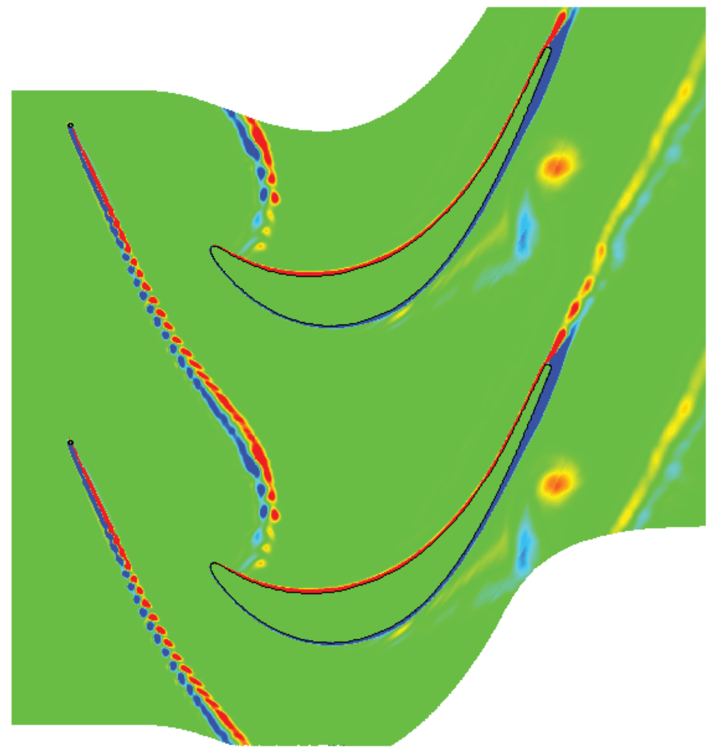
Chord	198mm
Blade stagger	59.3°
Cascade pitch	158mm
Inlet flow angle	37.7°
Design exit flow angle	63.2°
Bar diameter	2.05mm
Axial Distance: bars to LE	70mm
Flow Coefficient (U_{axial}/U_{bar})	0.83



- 18 zones
- ~0.8 million points
- $y^+ < 0.5$ near walls

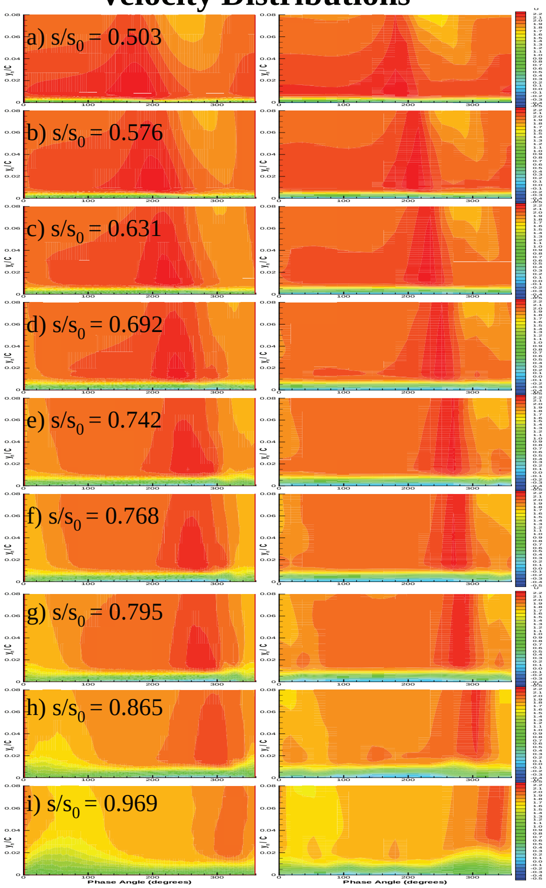
Experiments of Stieger (2002)



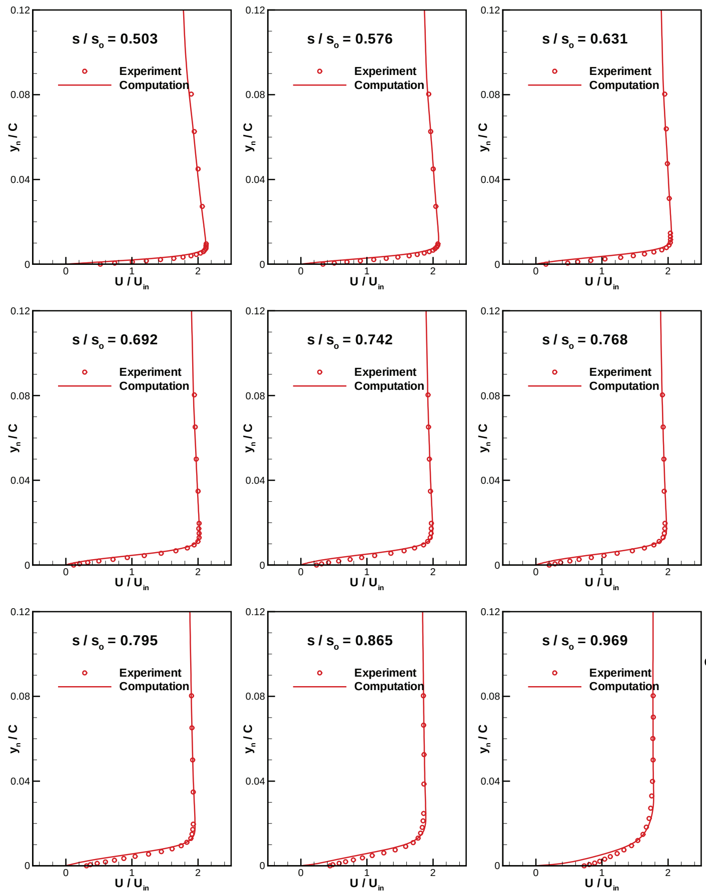


Experiments of Stieger (2002)

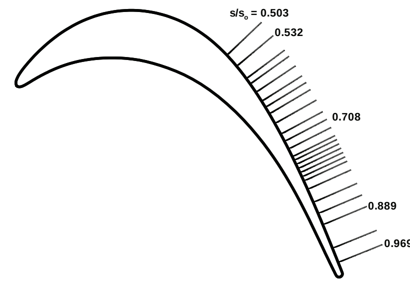
Phase-Averaged Velocity Distributions



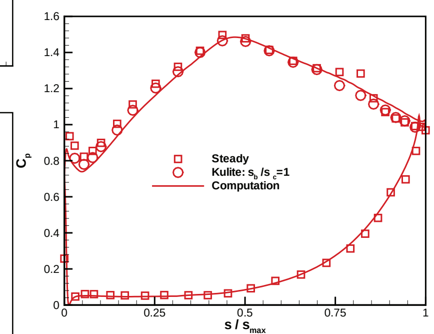
Phase angle **Experiment** | Phase angle **Computation**



Mean Velocity Distributions



Mean Pressure Coefficient Distribution



Concluding Remarks

➢ Predicting capabilities of the model are demonstrated by numerical simulations of a wide range of benchmark transitional LPT experiments:

- ➢ Flat plate experiments (Effects of Re, FSTI, dp/ds)
- ➢ Cascade experiments (Effects of Re, FSTI, dp/ds, Flow Separation)
- ➢ Unsteady wake/blade interaction experiments (Effects of Unsteadiness)

➢ Simulations captured the dynamic interplay between separation, transition and reattachment under diverse flow conditions. Overall good agreements with the experimental data are obtained.

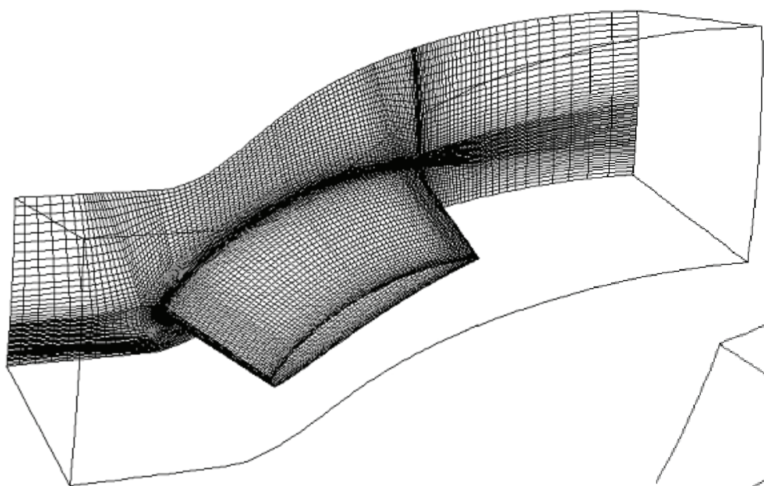
➢ Results indicate that the *intermittency transport modeling approach* provides an accurate and practical computational tool for transitional flow simulations.

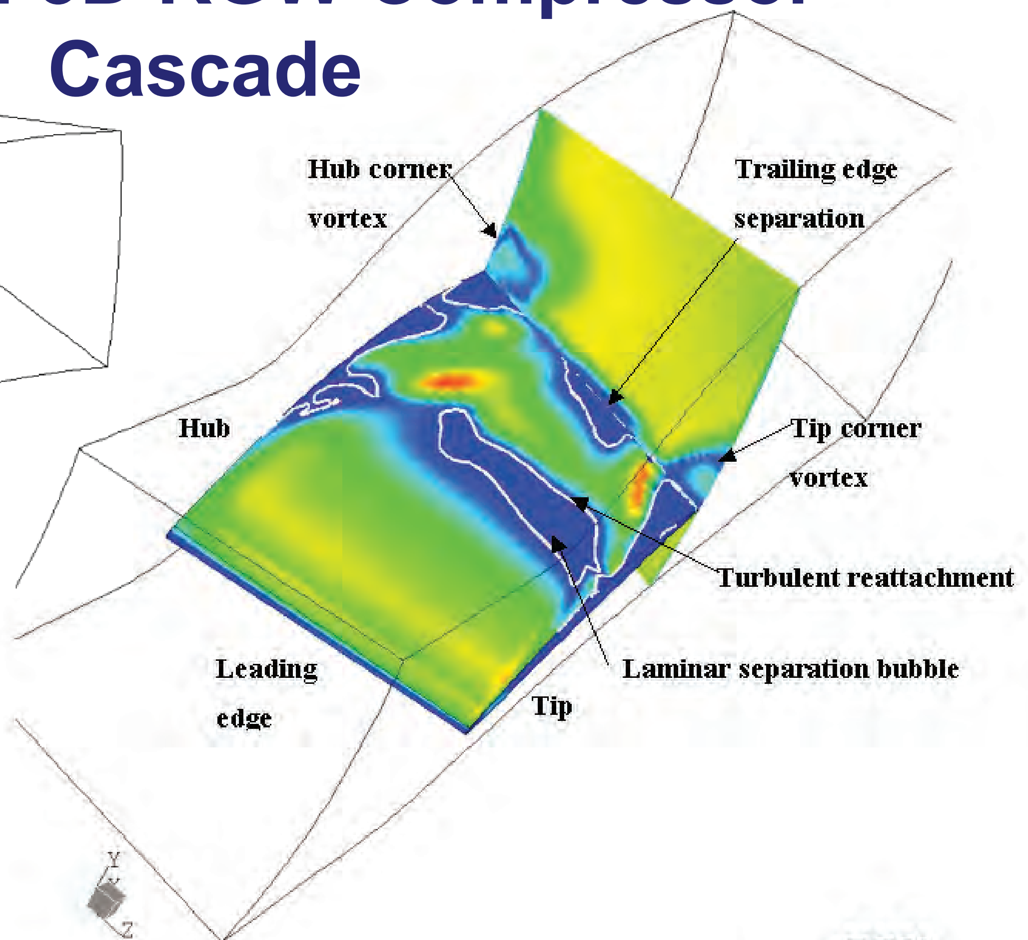
However,

- Dependence on non-local integral parameter, θ
- In order to extend to 3-D and unstructured grids local formulation needed

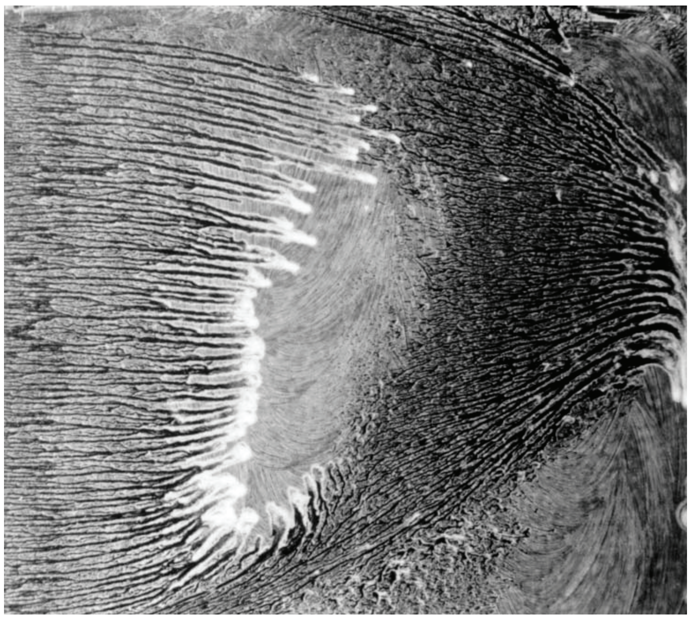
  ⇒ *New model based on local formulations in collaboration with CFX and GE developed using the same testing /validation steps.*

Test Cases: 3D RGW Compressor Cascade

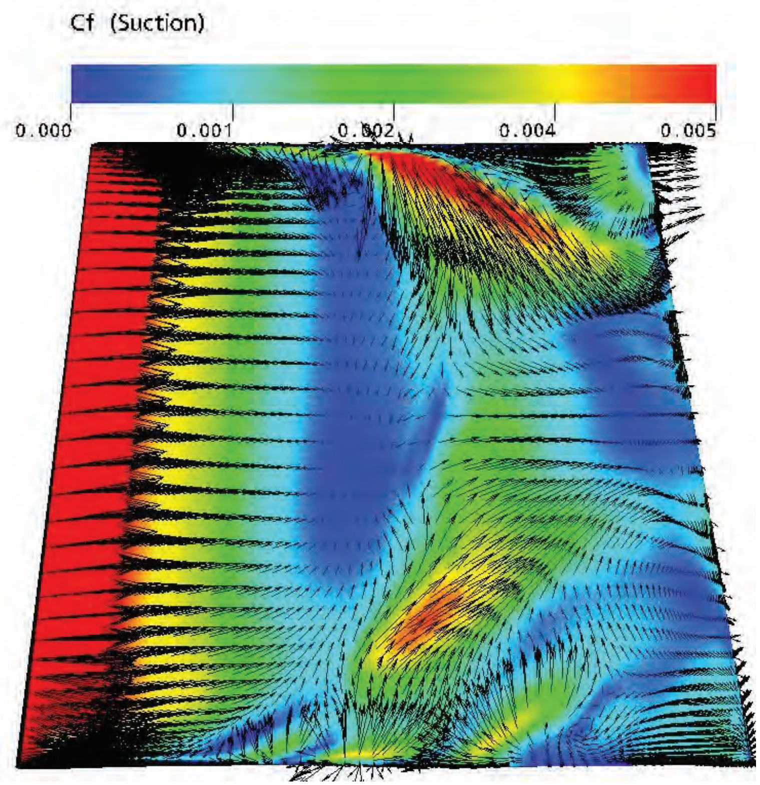




RGW Compressor
FSTI = 1.25 %
Re_x = 430 000
$Re_{\theta c}$ = 400



Experimental Oil Flow



Predicted Surface Velocity and Contour of Skin Friction (Cf)

NASA/CP—2020-220327

CFDL Computational Fluid Dynamics Laboratory

Direct Numerical Simulations of Separation and Separation Control

NASA-Industry Low-pressure & Power Turbine Efficiency Improvement Workshop
August 10-11, 2010, Cleveland, OH

Wolfgang Balzer, Andreas Gross and Hermann F. Fasel

Department of Aerospace and Mechanical Engineering
The University of Arizona, Tucson, Arizona 85721

Supported by AFOSR (Dr. Thomas Beutner, Dr. John D. Schmisseur, Lt. Col. Rhett Jefferies, Dr. Douglas R. Smith)

Computer time provided by DoD HPCMO Challenge project C2R, C4A:

The University of Arizona

W. Balzer, A. Gross and H.F. Fasel

Direct Numerical Simulation

Year	Citation
Before 1970	0
1970-79	12
1980-89	116
1990-97	536

Ronald D. Joslin, "Discussion of DNS: Past, Present, and Future", 1997

2010: CiteSeer.com: 912

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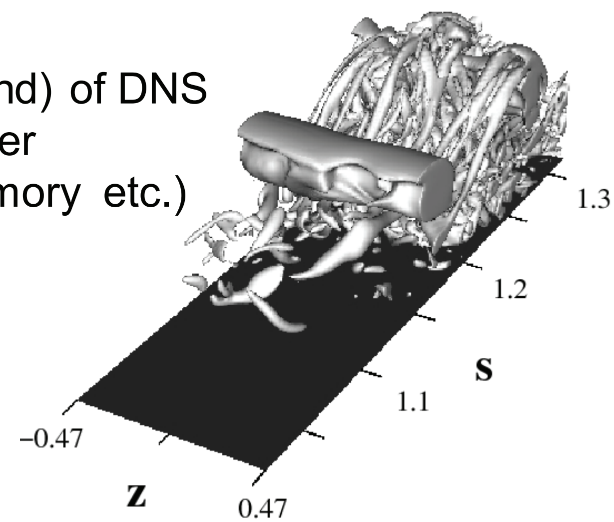
DNS …

- ⇨ "numerical experiments" without the use of turbulence modeling
- ⇨ extremely high-resolved simulations to examine the transition process and fully developed turbulence at the smallest scales
- ⇨ useful for the assessment and calibration of turbulence models
- ⇨ ideally suited for transition research due to low disturbance levels
- ⇨ require large grid sizes and small time steps
- ⇨ Quality (resolution) and productivity (turn-around) of DNS research largely depends on available computer resources (fast proc. speed, interconnect, memory etc.)

DNS for LPT research:

"Whenever we looked at DNS results (Durbin, Rodi) we learned something"

J.Paul Gostelow



Instantaneous flow structures in a separation bubble under LPT flow conditions

W. Balzer, A. Gross and H.F. Fasel

Simulations are carried out on High-Performance Supercomputing systems designed for scientific computing from the ground up

1 Petaflop = ***1,000,000,000,000,000*** floating point operations per second
(pocket calculator operates at about 10 Flops)

Peak Performance	**1.38 Petaflops**
System Memory	300 Terabytes
Disk Space	10.7 Petabytes
Disk Bandwidth	240+ Gigabytes/second
Processor Cores	150,000

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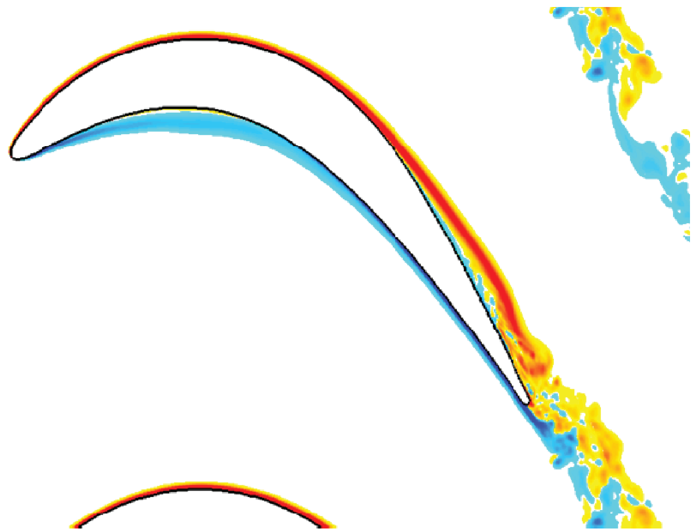
DNS of LPT flows

AFOSR funded, 2002-2008



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Two in-house developed Research Codes:

(1) "Coarse" resolution DNS of entire LPT geometry

- ⇨ Multi-domain finite volume code for ***compressible N-S equations***
- ⇨ more versatile but less efficient code
- ⇨ $9^{th}/4^{th}$-order accurate in convective/viscous terms
- ⇨ 2^{nd}-order accurate implicit time-integration (Adams-Moulton)

(2) Fully resolved DNS of curved plate model geometry (same pressure gradient and curvature as LPT blade)

- ⇨ ***incompressible*** N-S equations in vorticity-velocity formulation
- ⇨ highly efficient but less versatile code
- ⇨ 4^{th}-order accurate in space and time
- ⇨ spectral treatment of the spanwise direction

Both codes are MPI parallelized and successfully ran on various modern supercomputers (SGI, IBM, Cray, HP)

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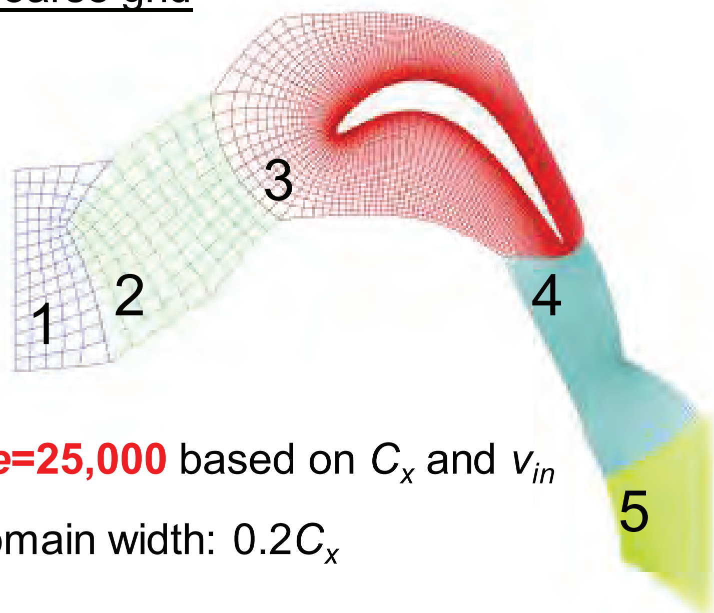
(1) "Coarse" resolution DNS of entire LPT geometry

coarse grid



Re=25,000 based on C_x and v_{in}

domain width: $0.2C_x$

3 grid resolutions:

block	coarse	medium	fine
1	5×15×16	10×30 ×32	20×60 ×64
2	10×10×16	20×20 ×32	40×40 ×64
3	250×50×16	500×100 ×32	1000×150 ×64
4	130×50×16	260×100 ×32	520×200 ×64
5	52×55×16	105×110 ×32	210×220 ×64
total	352,560	2,824,000	**19,392,000**

⇨ Pratt and Whitney Pack B LPT blade

⇨ also did L1M simulations

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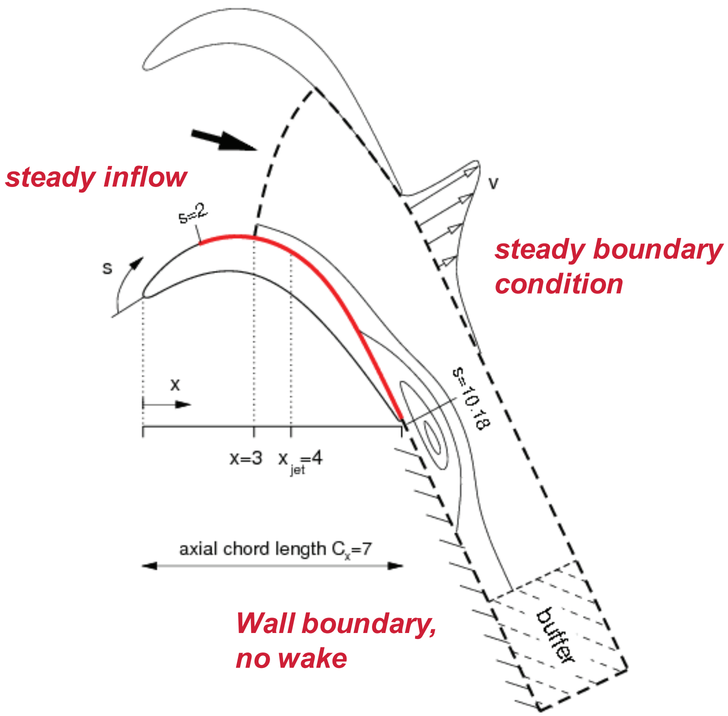
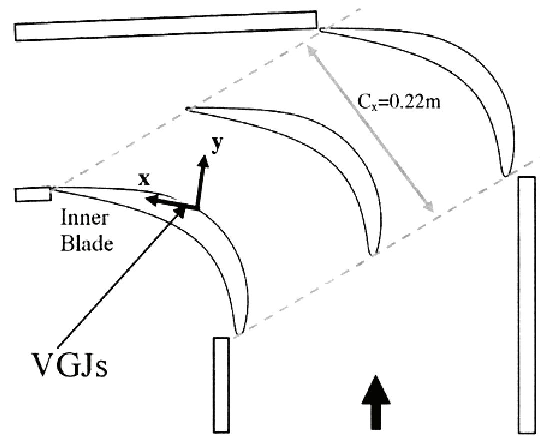
(2) Fully resolved DNS of curved plate model geometry





Experimental setup, J. Bons, Ohio State

Largest grid size: 1601 × 193 × 320 (~99 million)

Focus all available computational resources on region of interest

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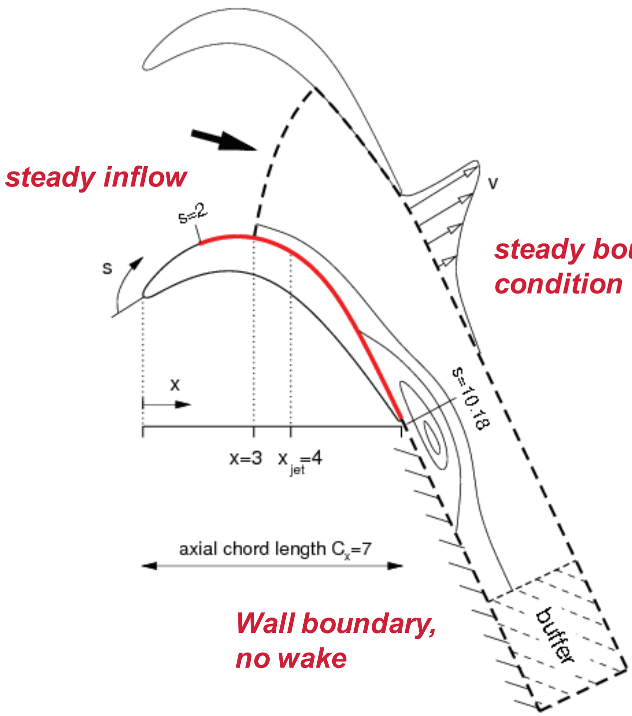
(2) Fully resolved DNS of curved plate model geometry



Curved wall simulations are **not** aimed at quantitatively *predicting* real LPT cascade

Rather study the fundamental physical mechanisms associated with separation and separation control.

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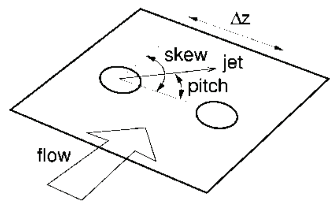
Flow Control

vortex generator jets and plasma actuator

vortex generator jets (VGJs)

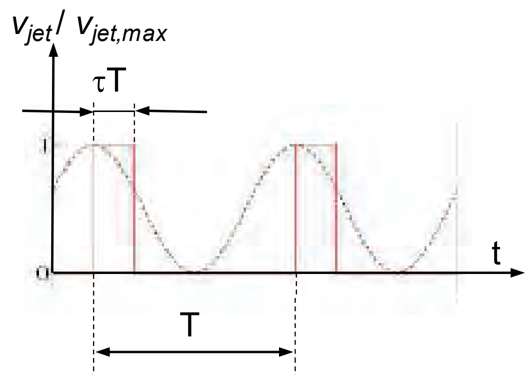


- steady & pulsed
- vertical & angled injection,
  (30° pitch, 90° skew)
- investigated effect of
  a) blowing ratio $B=v_{jet}/v_{in}$
  b) forcing frequency F^+
  c) duty cycle t
  d) hole spacing
  e) spanwise domain width

plasma actuator

experiment, Mack et al.

- modeled by volume force
- used for separation control on airfoil



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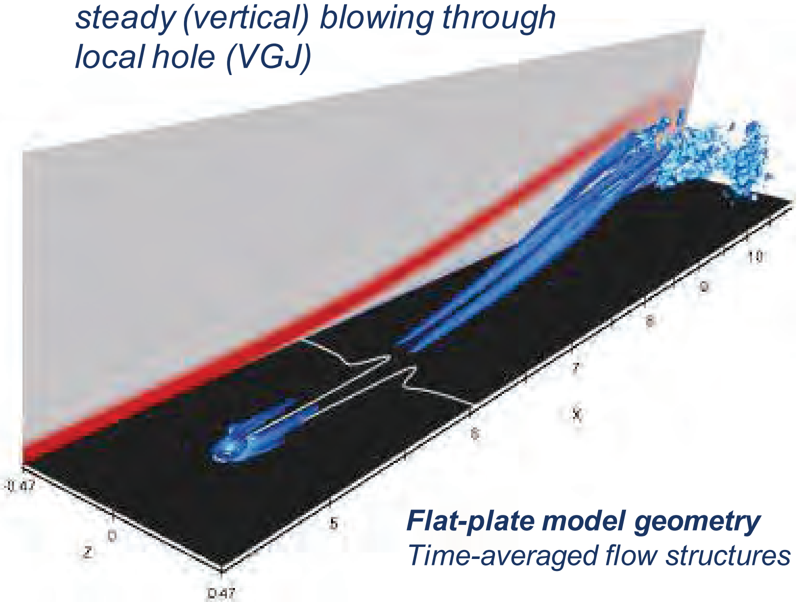
Steady actuation

⇨ Effective separation control: Entrainment of free stream fluid due to steady streamwise vortices *(confirmed findings of experiments)*

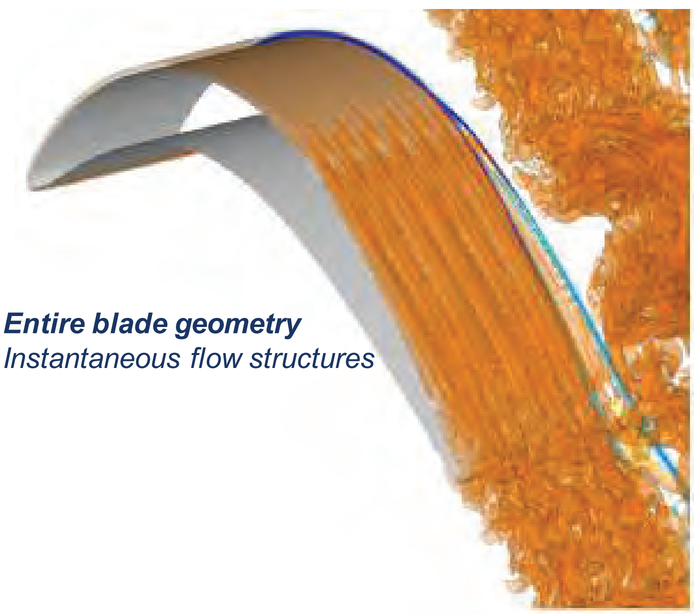
⇨ Steady actuation (passive or active) is less effective than unsteady actuation

streamwise vortices caused by steady (vertical) blowing through local hole (VGJ)



Flat-plate model geometry
Time-averaged flow structures

generation of counter-rotating streamwise vortices using steady volume forces



Entire blade geometry
Instantaneous flow structures

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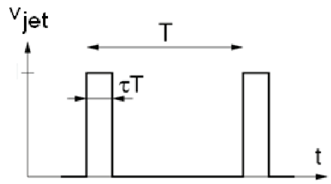
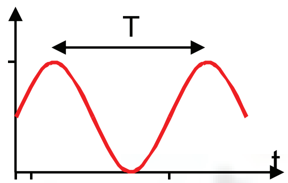
Unsteady actuation

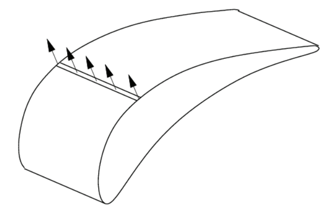
pulsed blowing through localized hole



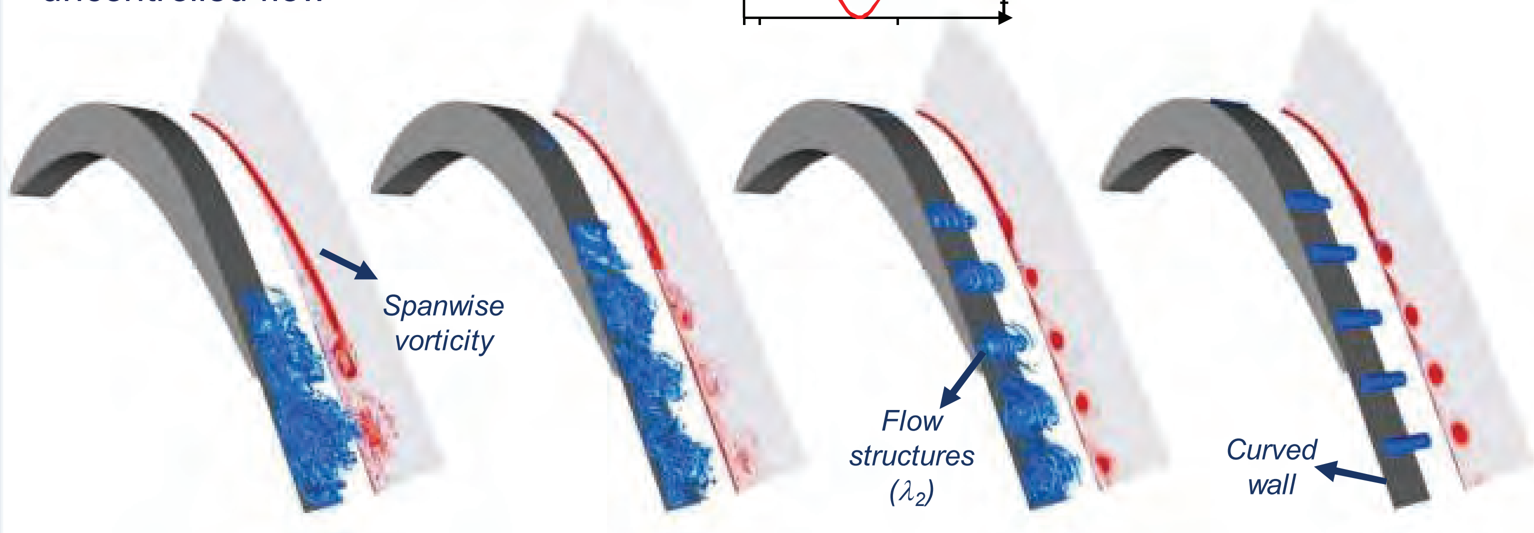
harmonic blowing through closely spaced holes



harmonic blowing through 2D slot



uncontrolled flow



Flow structures become increasingly more 2D

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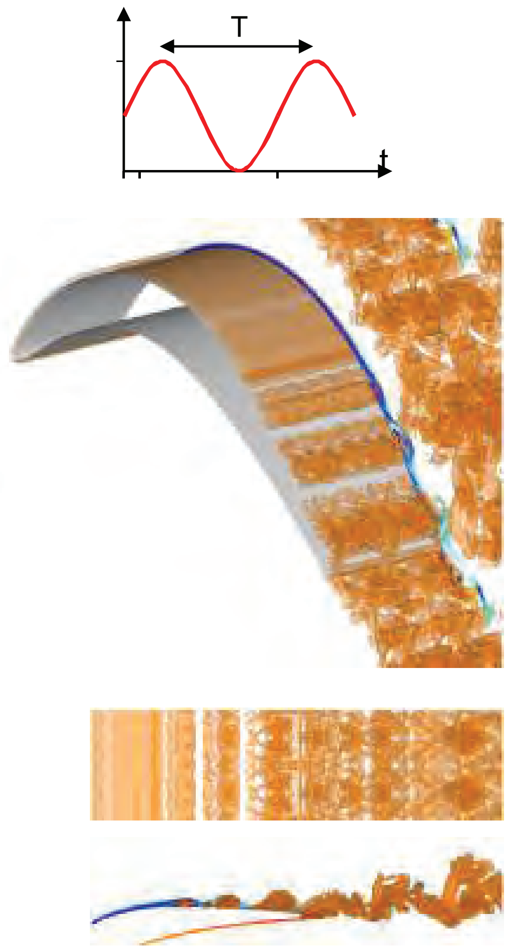
pulsed blowing through localized hole

harmonic blowing through closely spaced holes



harmonic blowing through 2D slot

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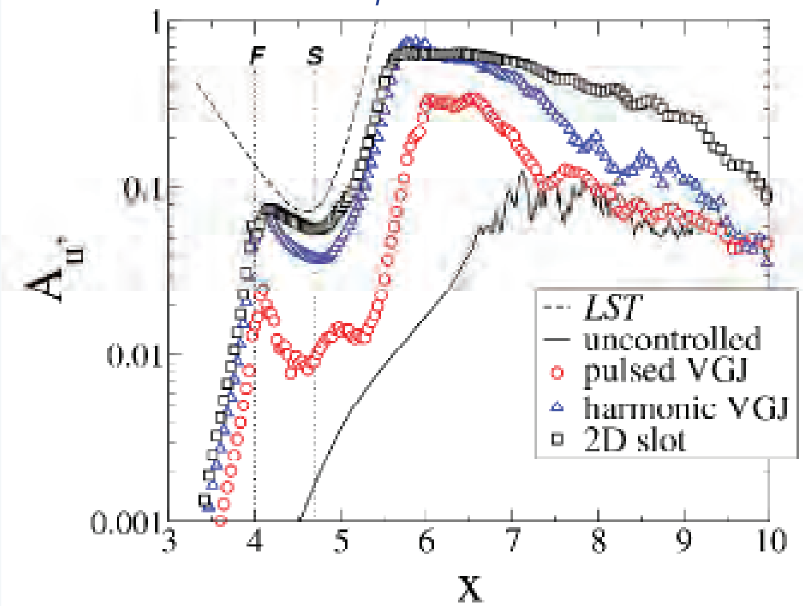
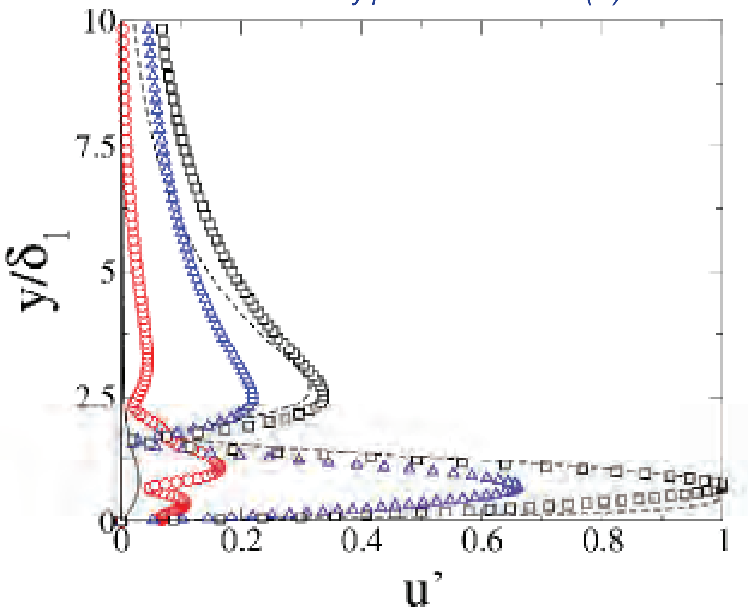
Unsteady actuation

Fourier amplitudes of u' at f=64Hz



*u' velocity profiles at x=4.7 (**S**)*



⇨ Separated boundary layer profile is inflectional and unstable to 2D disturbance

⇨ Effective separation control due **exploiting linear hydrodynamic instability mechanism**

⇨ causing earlier transitioning of the flow *(as seen in experiments)*

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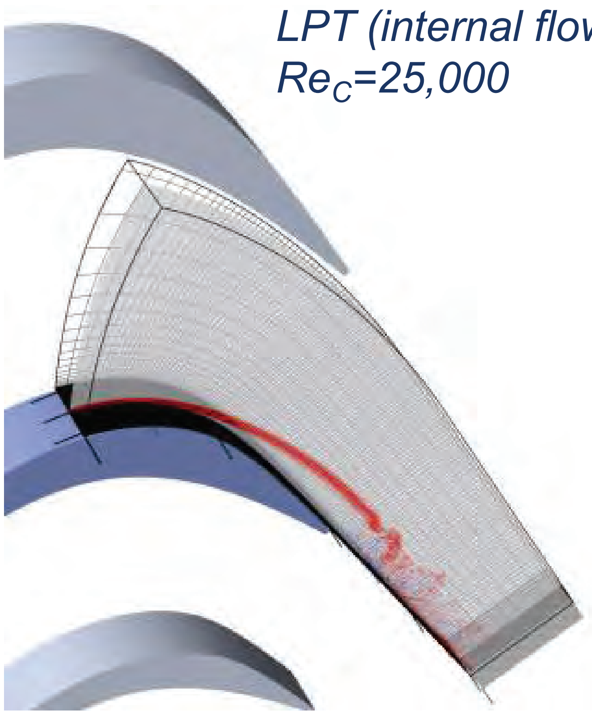
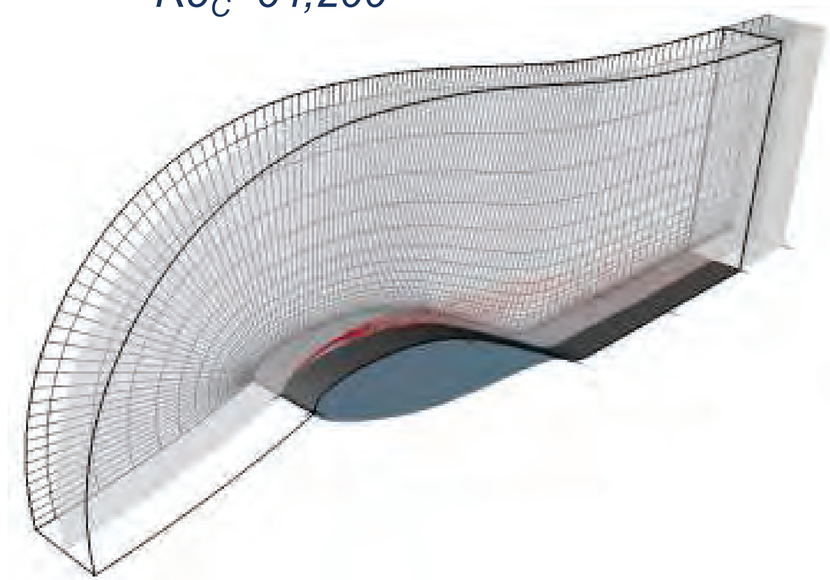
Summary and Conclusions

⇨ DNS at Arizona has been successfully applied to investigate separation and separation control for low-Reynolds number flow applications





The effect of Free-stream Turbulence

Mayle, R. E., 1991

"In general, one may say that the turbulence level for all the through-flow components in a gas turbine engine, except the fan, is high."

"For transition at high free-stream turbulence levels, the first and possibly second stages of the natural transition process are completely bypassed …"

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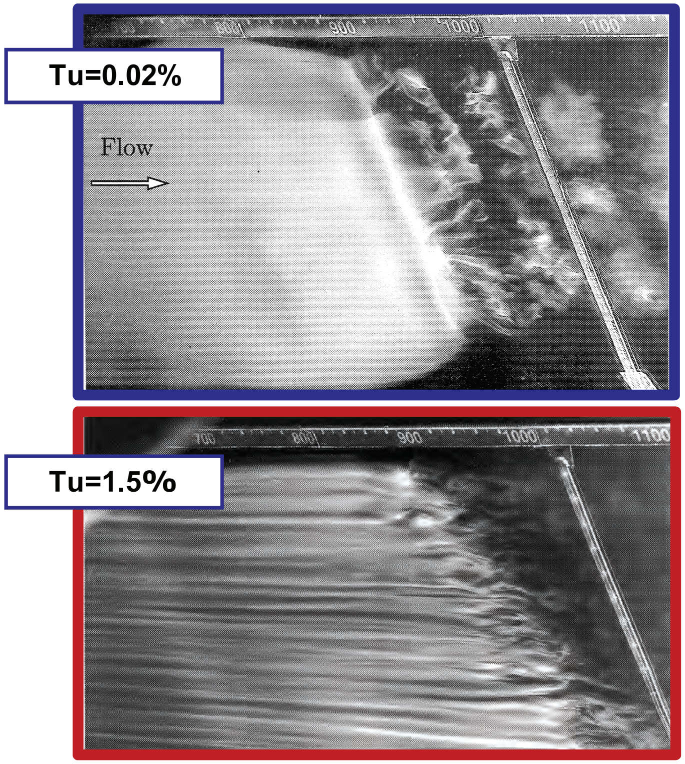
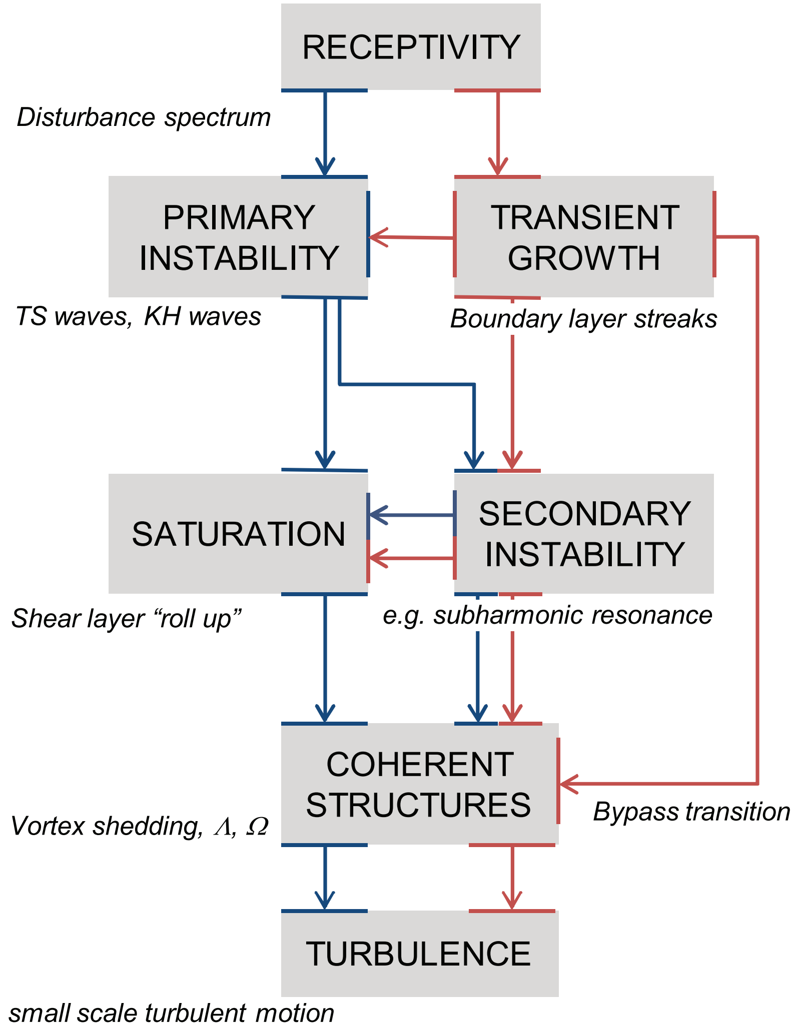
Transition Process

Smoke visualization of a laminar separation bubble



Häggmark, C., "Investigations of disturbances developing in a laminar separation bubble flow," PhD thesis, Trita-MEK Stockholm, ISSN 0348-467X, 2000



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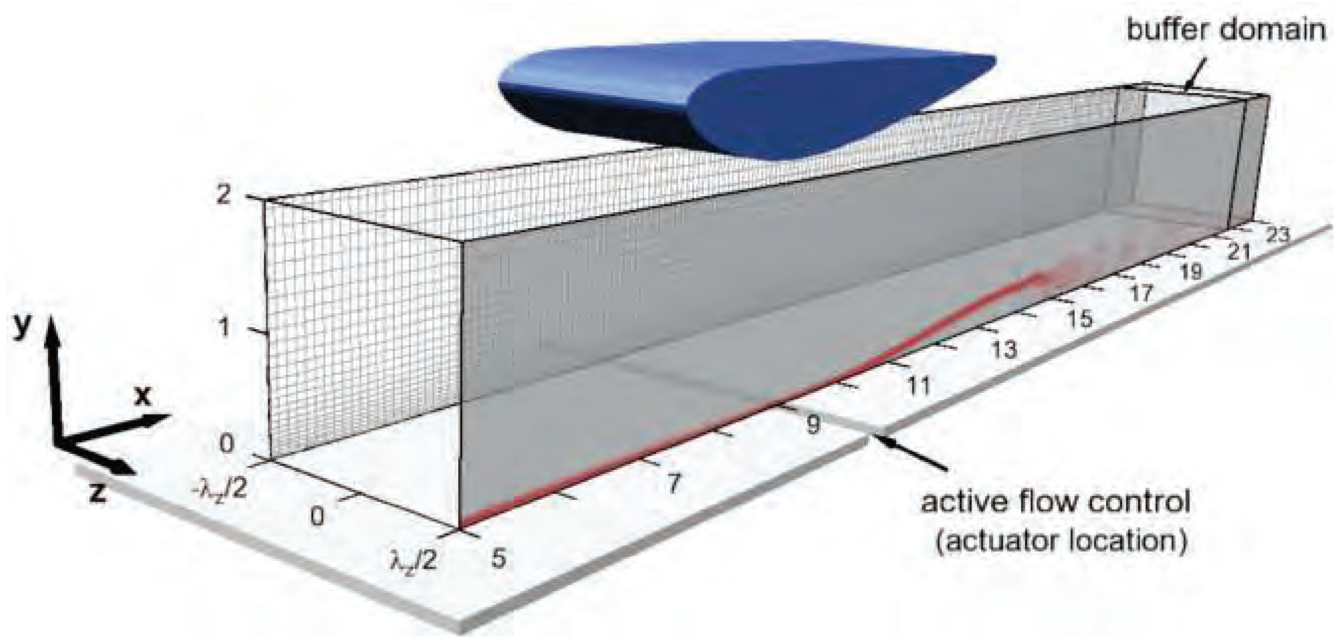
Integration Domain

- Setup motivated by wind-tunnel experiments by M. Gaster (Tu≈0.05%).
- Separation bubble forms on flat plate
- In DNS, pressure gradient is imposed by choosing an appropriate v-velocity distribution at the free-stream boundary
- Optionally, active flow control upstream of separation through two-dimensional blowing and suction slot



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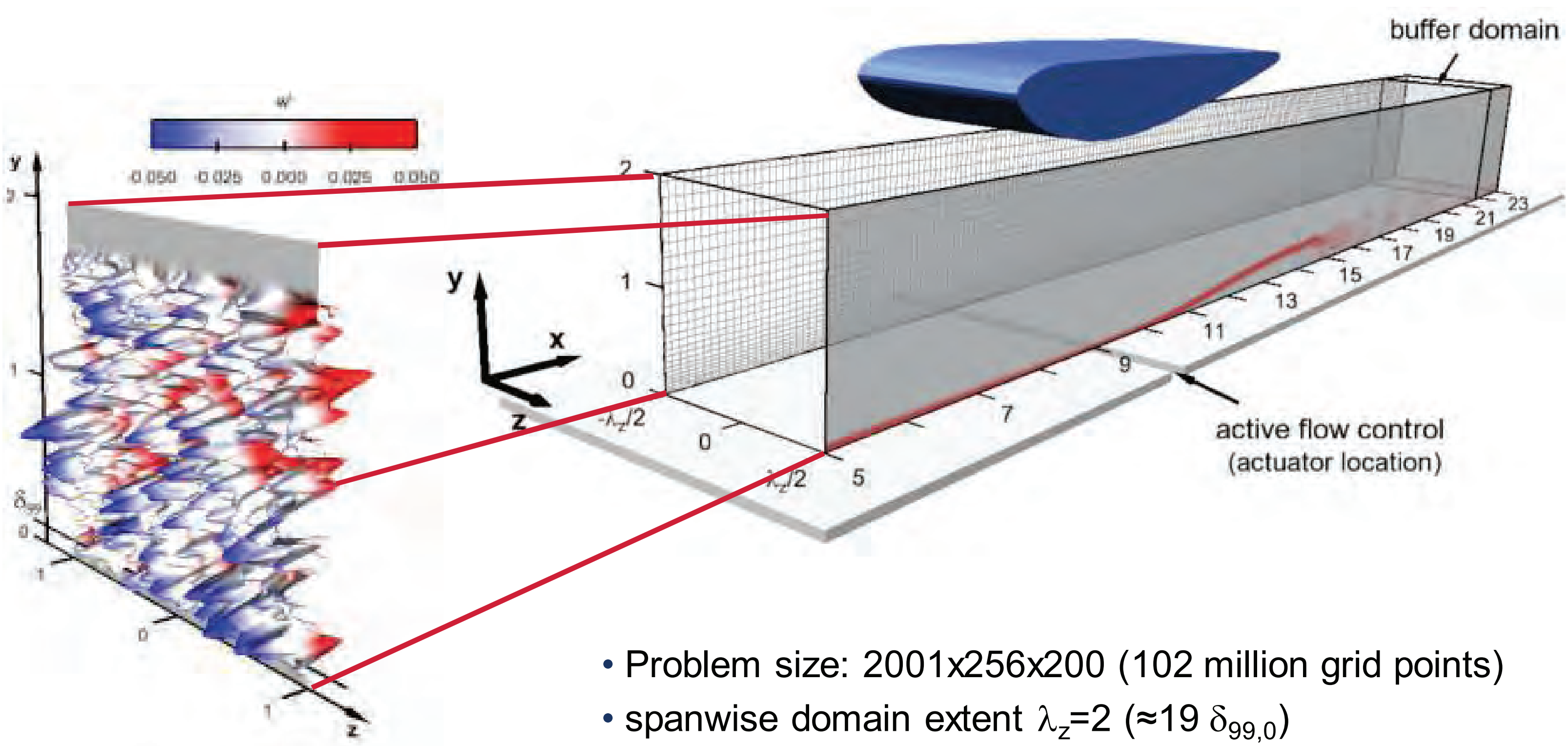
Integration Domain

- Realistic free-stream turbulent inflow with **Tu=0.05%, 0.5%, 2.5%**
- Turbulent integral length scale **$L_{11}=5\delta_1$**



- Problem size: 2001x256x200 (102 million grid points)
- spanwise domain extent λ_z=2 (≈19 $\delta_{99,0}$)
- **Re_c≈62,000, Re_x≈90,000**

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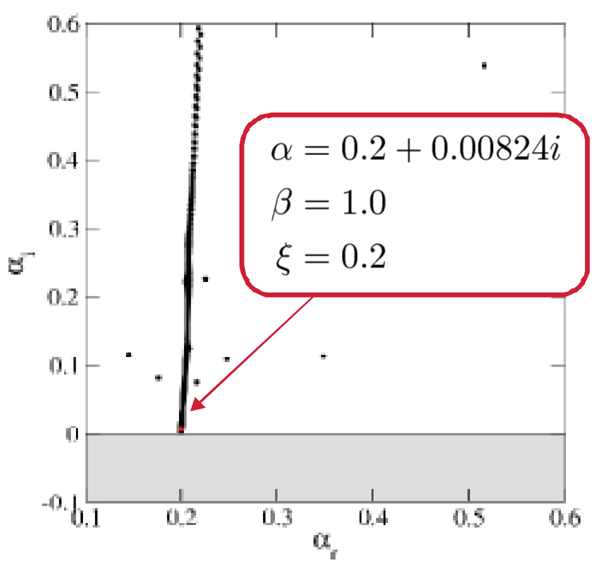
Generation of Inflow Disturbances

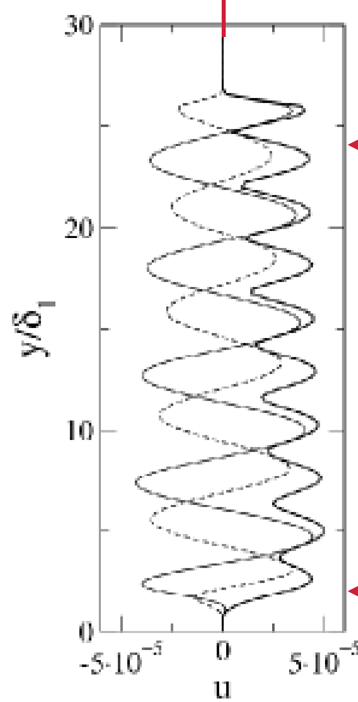
Jacobs, R. G.and Durbin, P.A., "Simulations of bypass transition," J. Fluid. Mech., Vol. 285, 2001, pp. 69-94

P.A. Durbin, G. Medic, and T. Zaki, "Bypass Transition via continuous modes and unsteady effects on film cooling," Minnowbrook 2003

$$\mathbf{V}(x_0, y, z, t) = \mathbf{V}_B(y) + \mathbf{v}'(x_0, y, z, t)$$

$$\mathbf{v}'(x_0, y, z, t) = \sum_{\omega} \sum_{k_z} \sum_{k_y} \hat{\mathbf{v}}(k_y, k_z, \omega) \Psi(\omega, k_y, k_z; y) e^{ik_z z} e^{-i\omega t}$$





oscillatory in the free stream

"continuous" modes are good candidates for generation of a set of inflow disturbances

natural decay into the boundary layer

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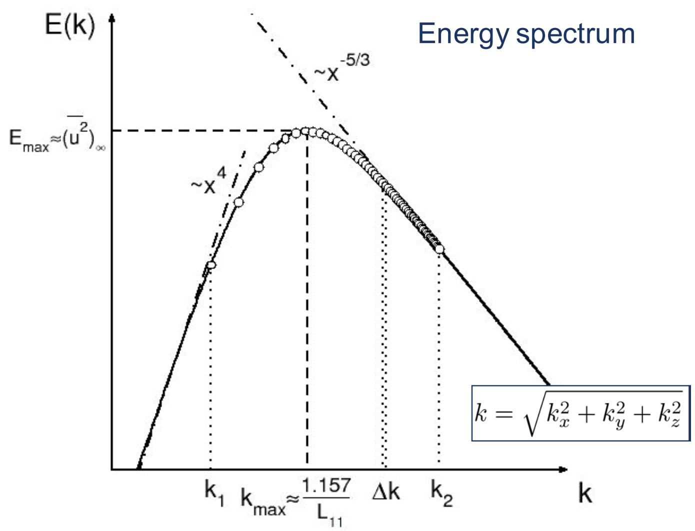
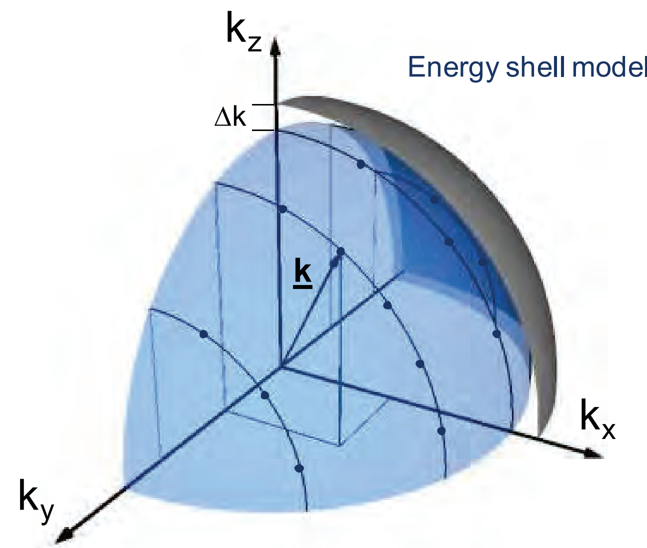
Generation of Inflow Disturbances

$$\mathbf{V}(x_0,y,z,t) = \mathbf{V}_B(y) + \mathbf{v}'(x_0,y,z,t)$$

$$\mathbf{v}'(x_0,y,z,t) = \sum_{\omega}\sum_{k_z}\sum_{k_y} \hat{\mathbf{v}}(k_y,k_z,\omega)\,\Psi(\omega,k_y,k_z;y)\,e^{ik_z z}e^{-i\omega t}$$





Method only requires the choice of free-stream turbulence intensity, **Tu**, and an turbulent integral length scale, $\mathbf{L_{11}}$

$$Tu = 100\,\frac{\sqrt{\frac{1}{3}\left((\overline{u^2})_\infty + (\overline{v^2})_\infty + (\overline{w^2})_\infty\right)}}{U_\infty}$$

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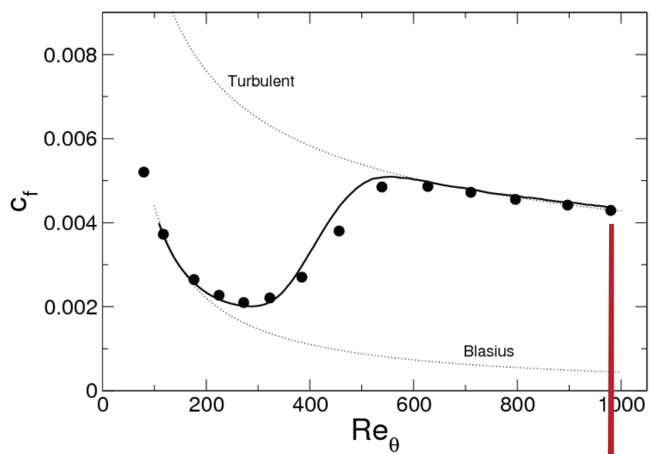
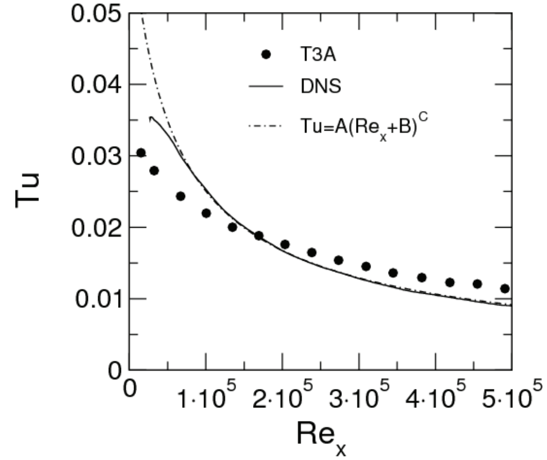
Validation case T3A

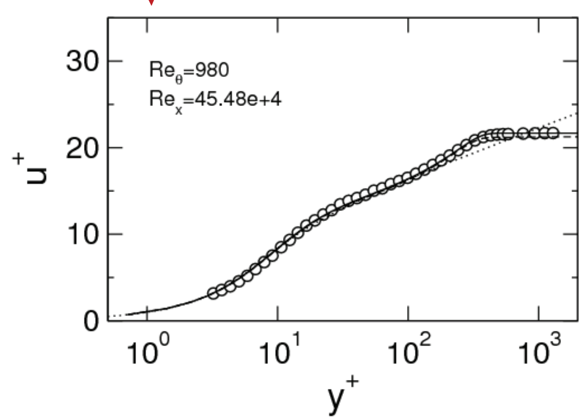
Skin-friction coefficient



FST decay in the free stream



Turbulent boundary-layer profiles



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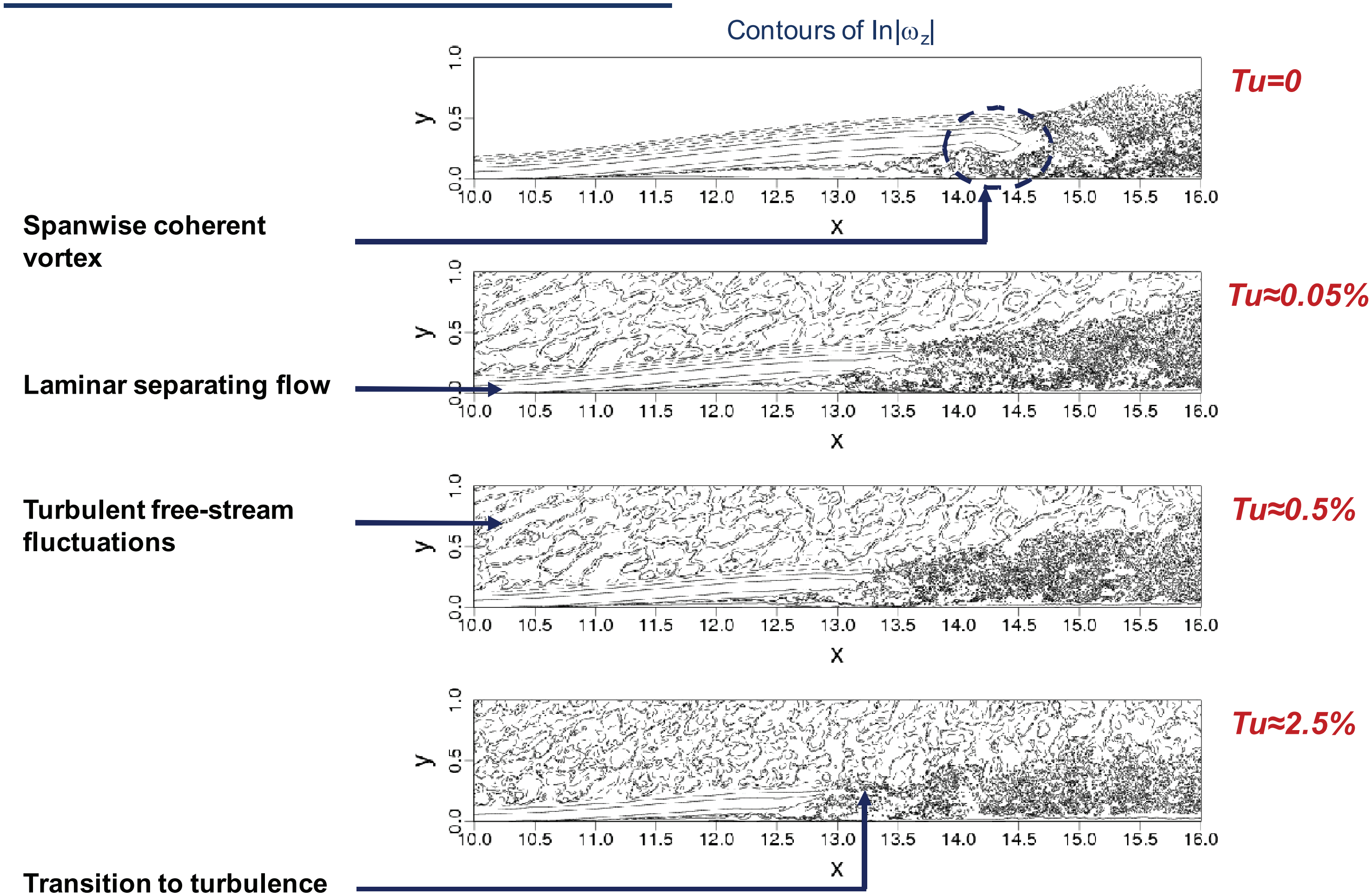
Effect of free-stream turbulence



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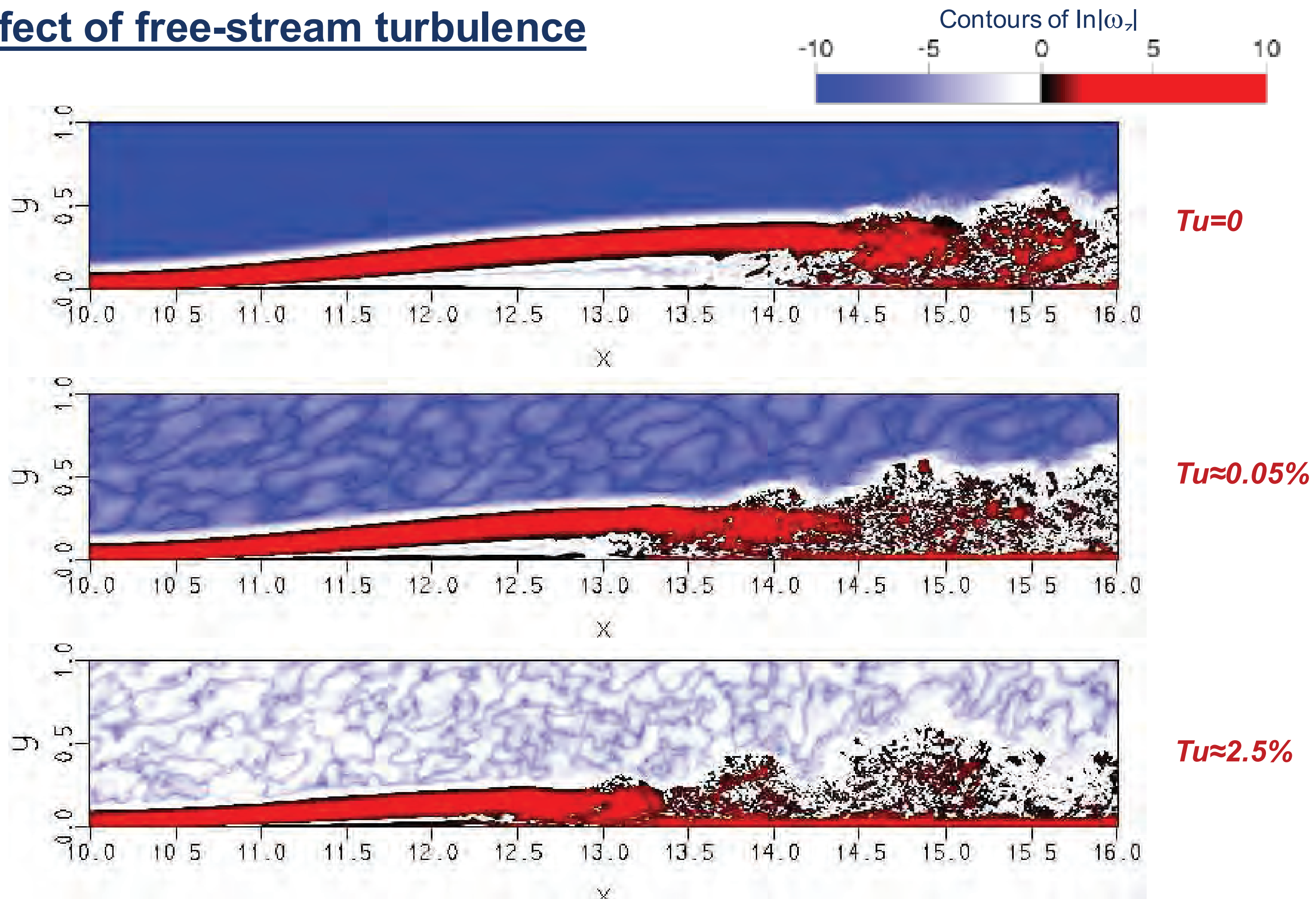
Effect of free-stream turbulence



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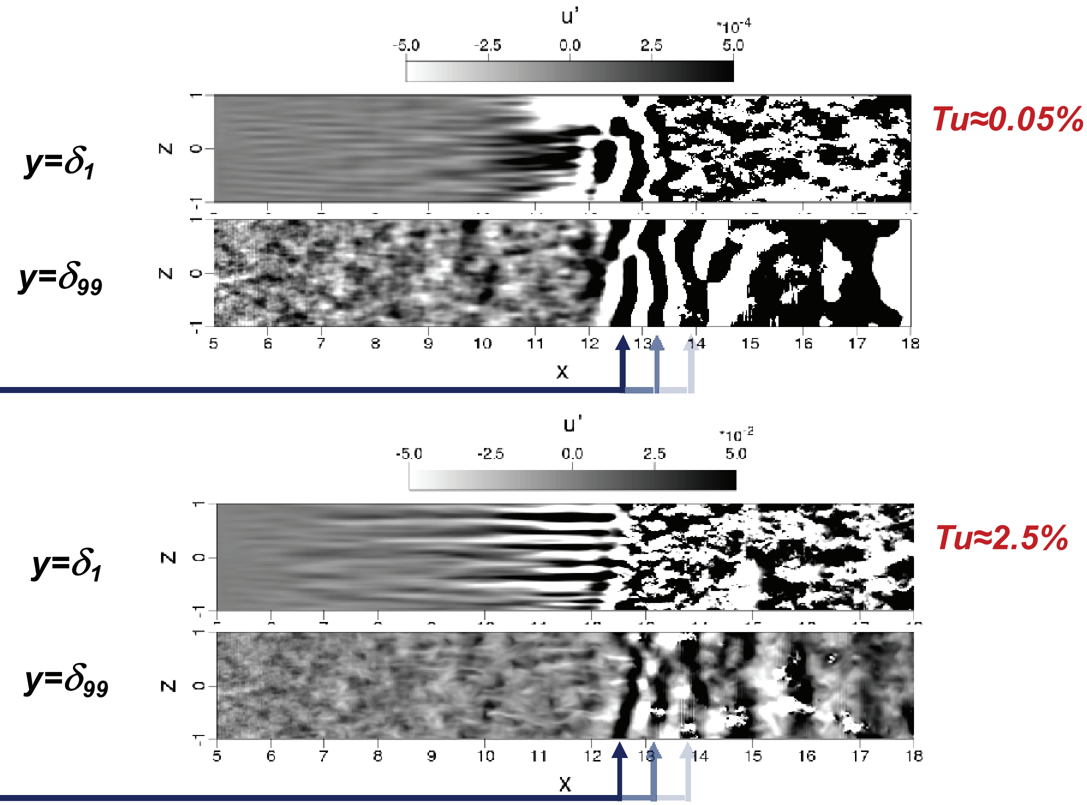
Effect of free-stream turbulence

- Outside the boundary layer: free-stream turbulent fluctuations
- Inside the boundary layer: streamwise elongated streaks

Contours of streamwise disturbance velocity u'

$u' = u - \bar{u}$

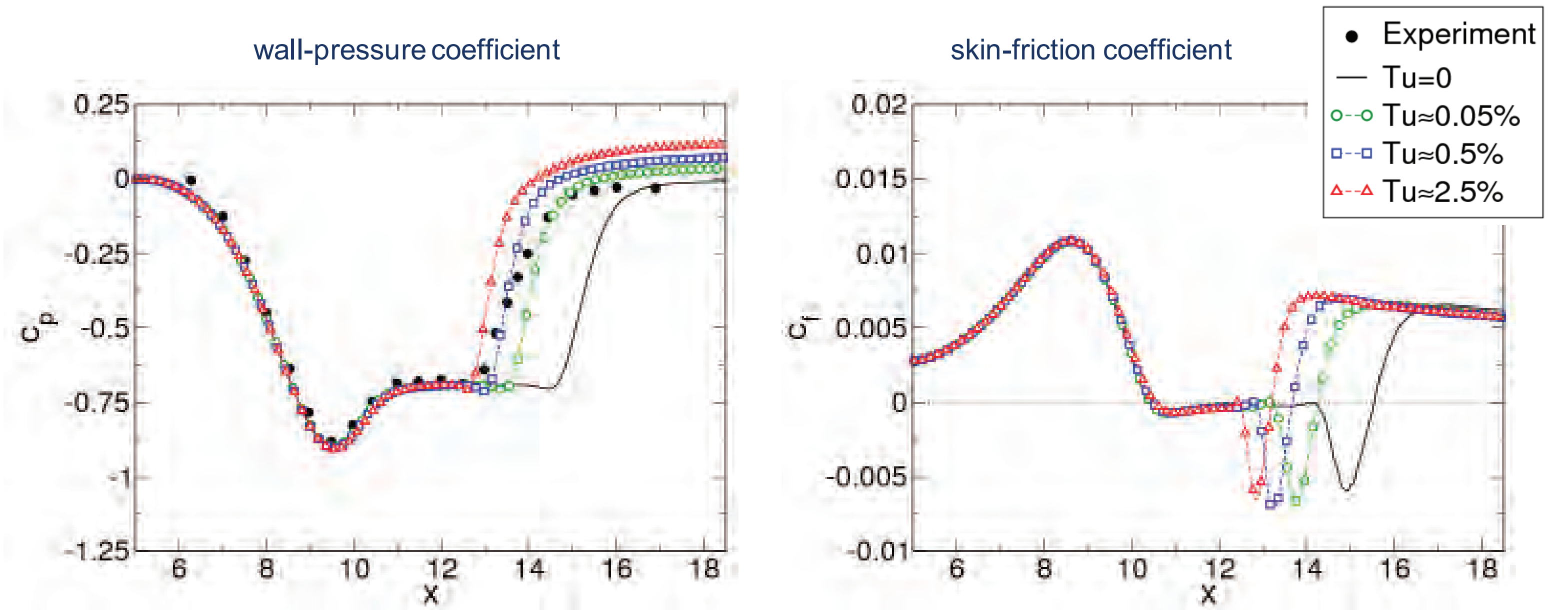


2-D vortex shedding

2-D coherent vortex shedding also for higher levels of FST

Time- and spanwise averaged Results

- Time- and spanwise averaged quantities of approach flow remain almost unchanged.
- Better comparison to experiment when simulating with realistic free-stream environment.
- Considered levels of FST not high enough to completely suppress separation.



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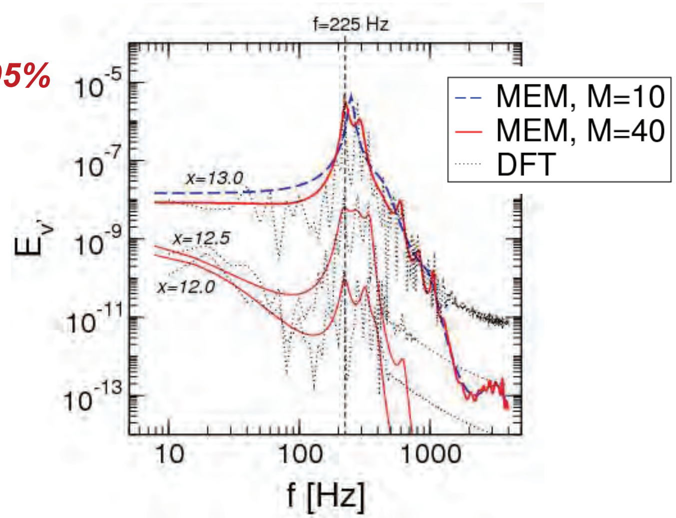
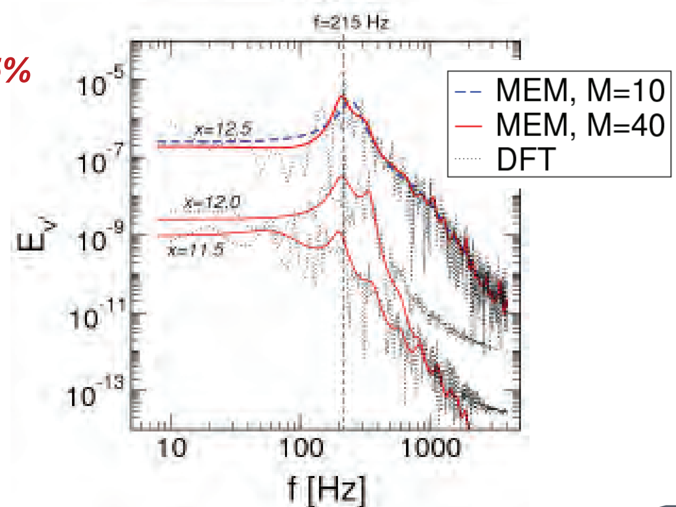
Spectral Analysis

- Discrete Fourier Transform
- Maximum Entropy Method of different order (M=10,40)
- dominant frequency in the order of 210Hz < f* < 260 Hz
- Strouhal number $St_\theta = \frac{f\theta_S}{U_S}$ based on local free-stream velocity and momentum thickness at separation: $St_\theta \approx 8 \cdot 10^{-3} - 8.8 \cdot 10^{-3}$

Tu≈0.05%



Tu≈2.5%



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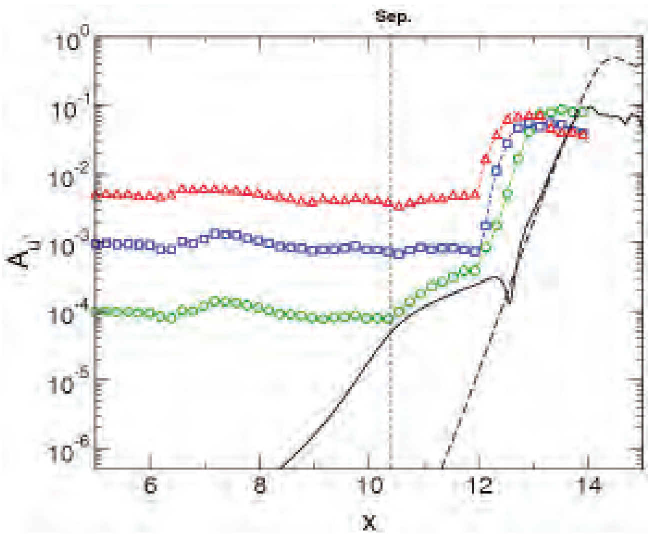
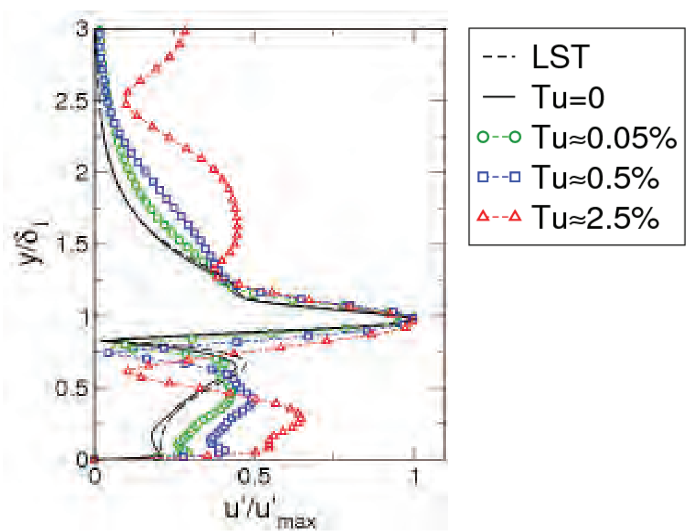
Linear Stability Theory

- exponential growth for 2-D disturbance waves with fundamental frequency (f*=240 Hz)
- good agreement between DNS and Linear Stability Theory (LST) serves as confirmation of linear mechanism (inviscid shear-layer instability) – ***not bypassed***
- increased disturbance level in the attached, laminar boundary layer for increased FST but no downstream growth

Downstream development of Fourier amplitude (max. over y)



Amplitude distribution of u'-velocity



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Summary and Conclusions

- ⇨ Successful implementation of numerical model for the generation of *realistic free-stream turbulence* (FST) into incompressible Navier-Stokes solver.
- ⇨ Increased levels of FST cause earlier transition and a reduction in separation length and height.
- ⇨ Inviscid shear-layer instability was confirmed. This stage of the transition process is not bypassed.
- ⇨ DNS have become more affordable (for us). Investigation of free-stream turbulence:
  - ≈ 200 wall-clock hours, ≈ 8 days
  - ≈ 28,500 CPU hours
  - \$15,000 – 30,000 (estimated at \$0.5 – \$1.0/CPU hour)

Levels and length scales not necessarily typical for LPT flow in the current flow

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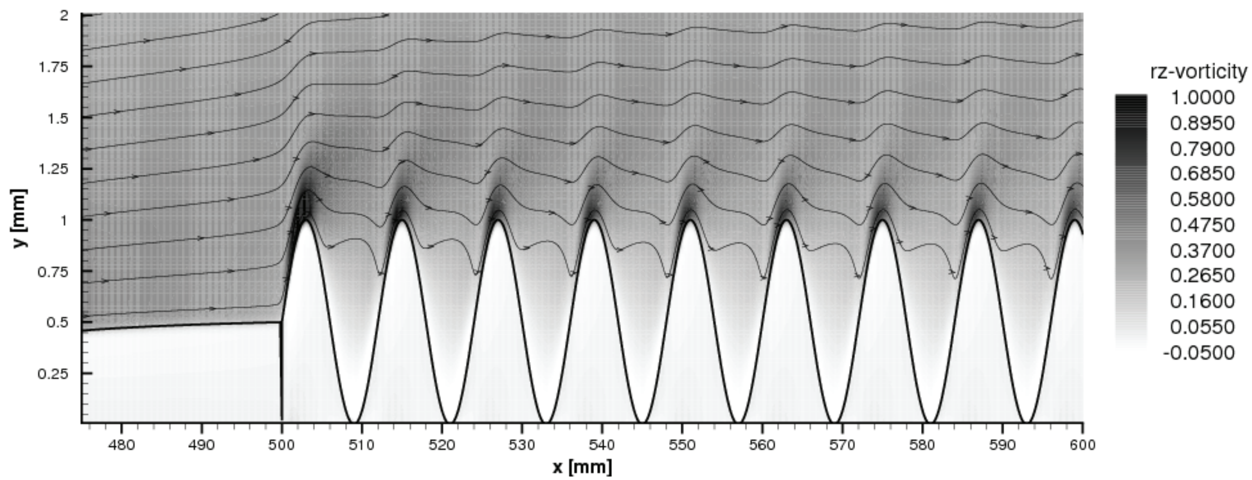
Summary and Conclusions

⇨ We currently also look into surface roughness



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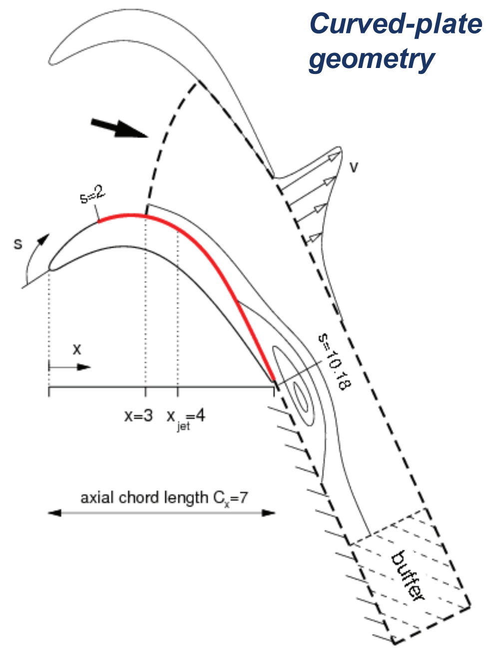
Additional Slides

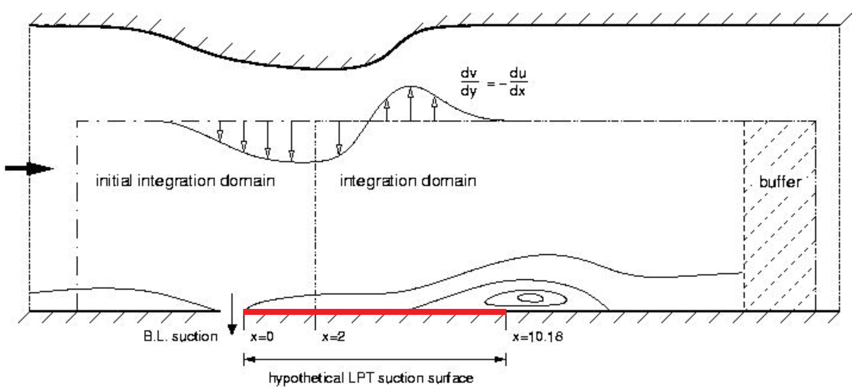
Om Sharma asked us to add slides from our presentation at
MINNOWBROOK V (20-23 AUGUST 2006)

In particular, we investigated the **effect of curvature** by considering a laminar separation bubble on a flat plate and a curved plate under similar flow conditions

Curved-plate model geometry



Flat-plate model geometry



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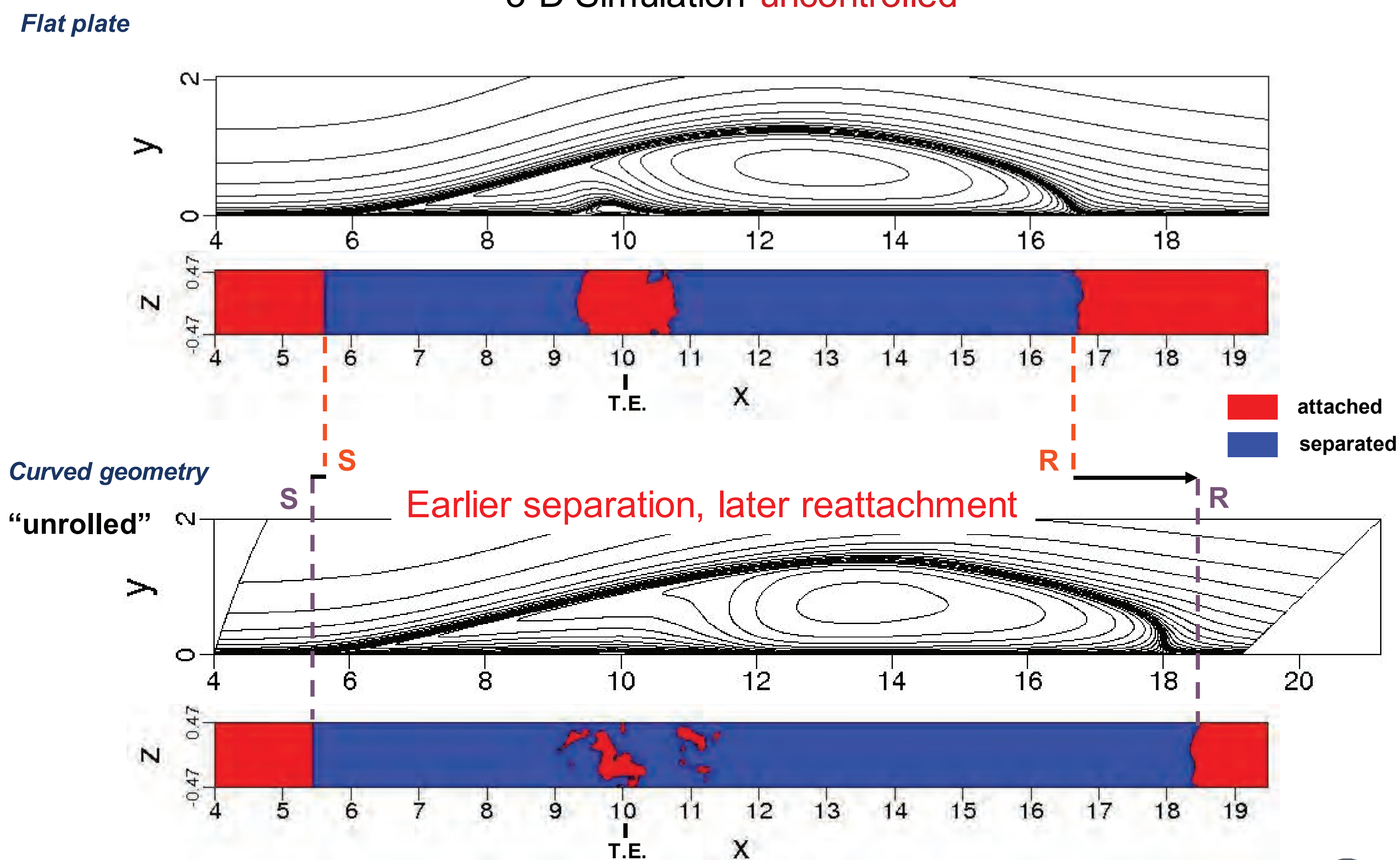
3-D Simulation uncontrolled



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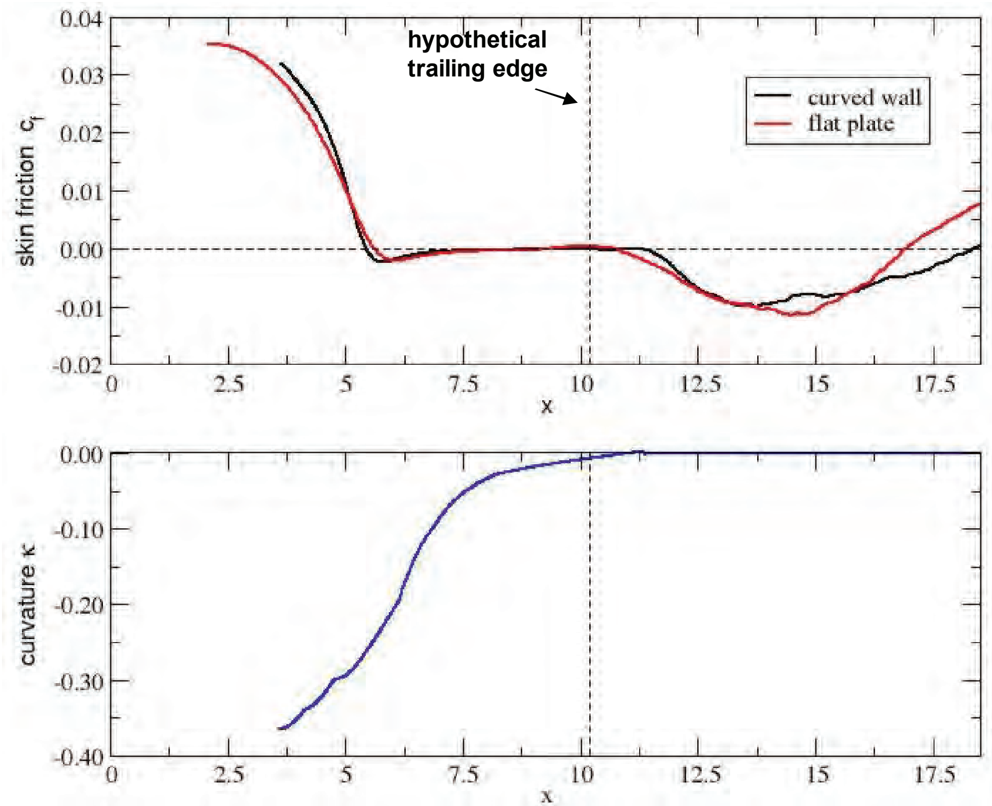
3-D Simulation uncontrolled

Reduction of

- skin friction
- distance to separation



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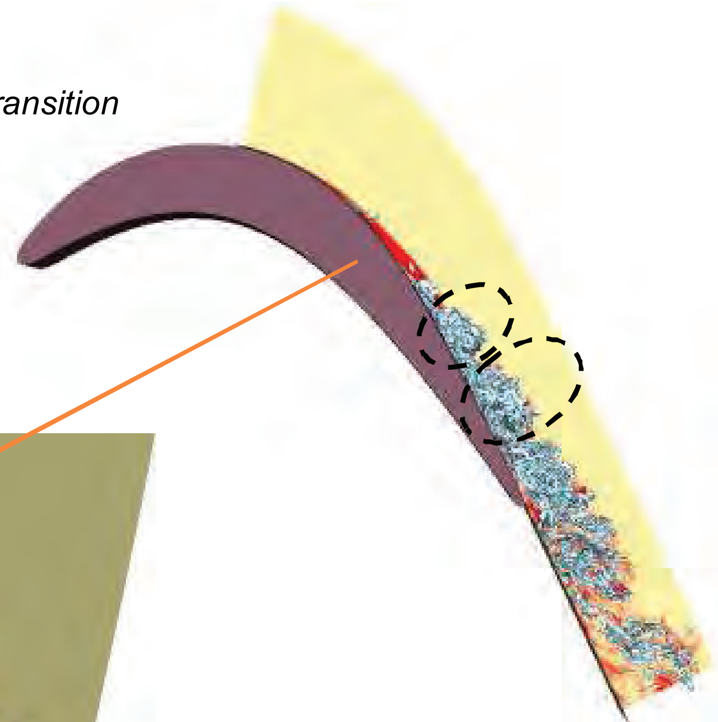
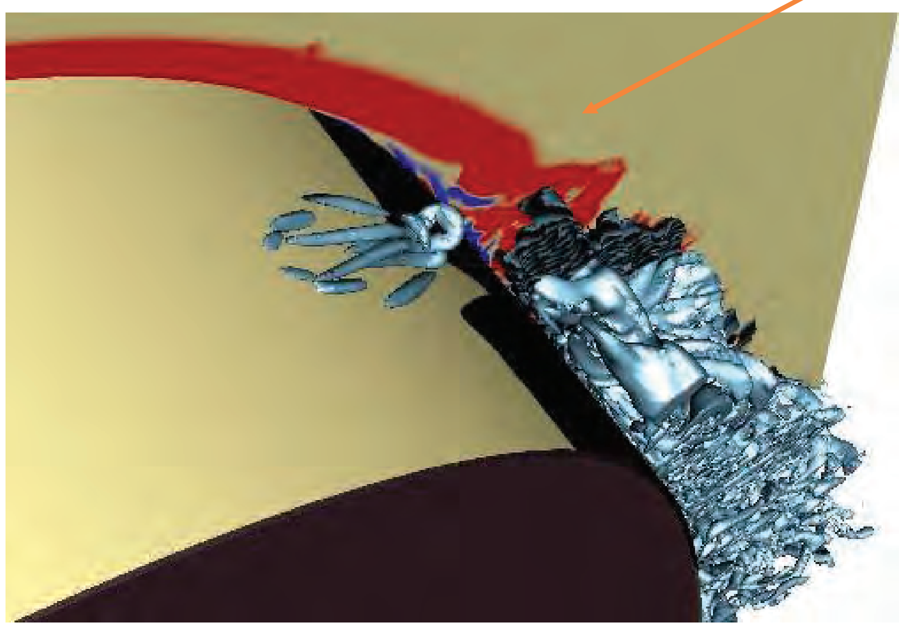
As seen for flat plate scenario

- *pulsed VGJs are highly effective in initiating by-pass transition and introduce large spanwise coherent structures*
- *structures closely resemble late stages of classical Klebanoff - type transition*
- *small-scale structures concentrated in areas with strong spanwise coherence*





hair-pin vortices stronger than for flat-plate
- Curvature increases receptivity!

W. Balzer, A. Gross and H.F. Fasel

Flat plate

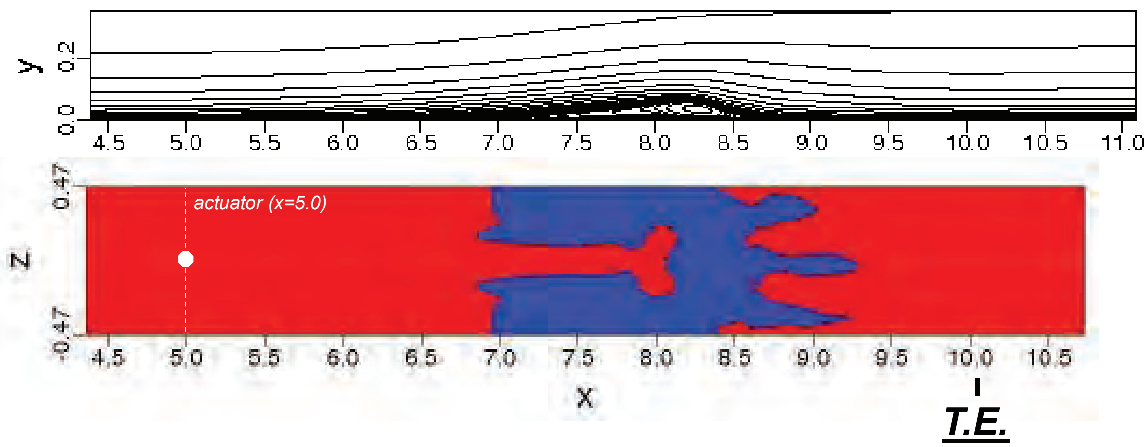
3-D Simulation controlled

Pulsed vertical VGJs, duty cycle τ=10%

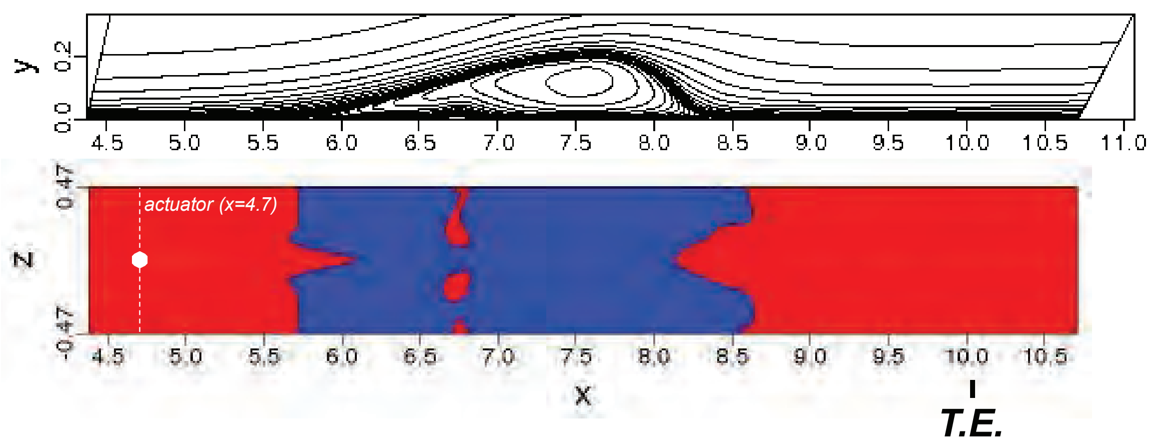
Streamlines
(time and spanwise average)

Wall-vorticity ω_z
(time average)

- attached
- separated



Curved geometry
"unrolled"



Preliminary Conclusion
Curvature: stronger separation
Tougher to control (although better receptivity of actuator).

To be continued …

CFDL Computational Fluid Dynamics Laboratory

Thank you …

Direct Numerical Simulations of Separation and Separation Control

NASA-Industry Low-pressure & Power Turbine Efficiency Improvement Workshop
August 10-11, 2010, Cleveland, OH

Wolfgang Balzer, Andreas Gross and Hermann F. Fasel

Department of Aerospace and Mechanical Engineering
The University of Arizona, Tucson, Arizona 85721

{wbalzer, faselh}@email.arizona.edu

… Questions

The University of Arizona

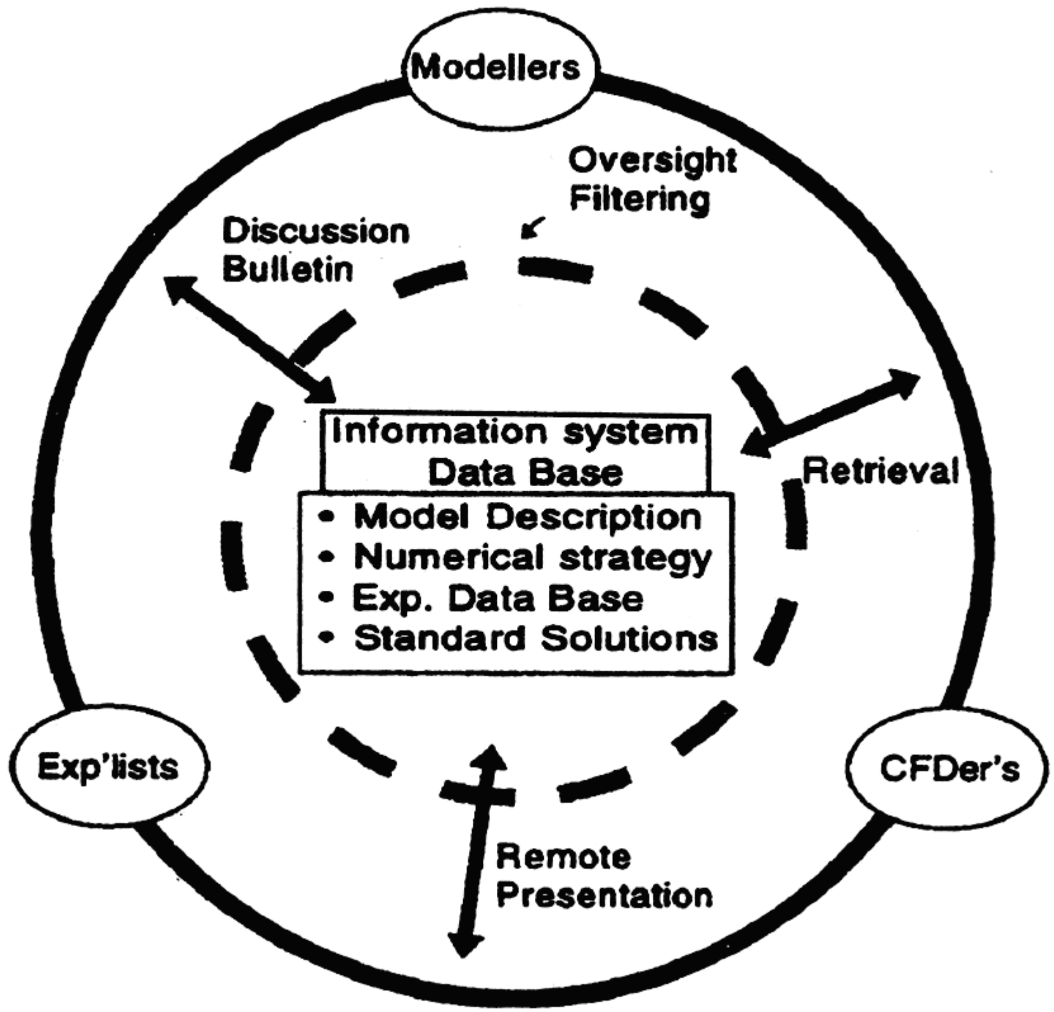
NASA/CP—2020-220327

Overview of Turbulence Model Benchmarking Discussion Group Activities and Survey Study

George P. Huang
Wright State University, Dayton, OH
Brian R. Smith
Lockheed Martin Aeronautics Company, Fort Worth, TX
Christopher L. Rumsey
NASA Langley Research Center, Hampton, VA

NASA-Industry LPT/PT Efficiency Improvements Workshop
OAI, Cleveland, OH,
August 10-11, 2010

Turbulence modeling workbench

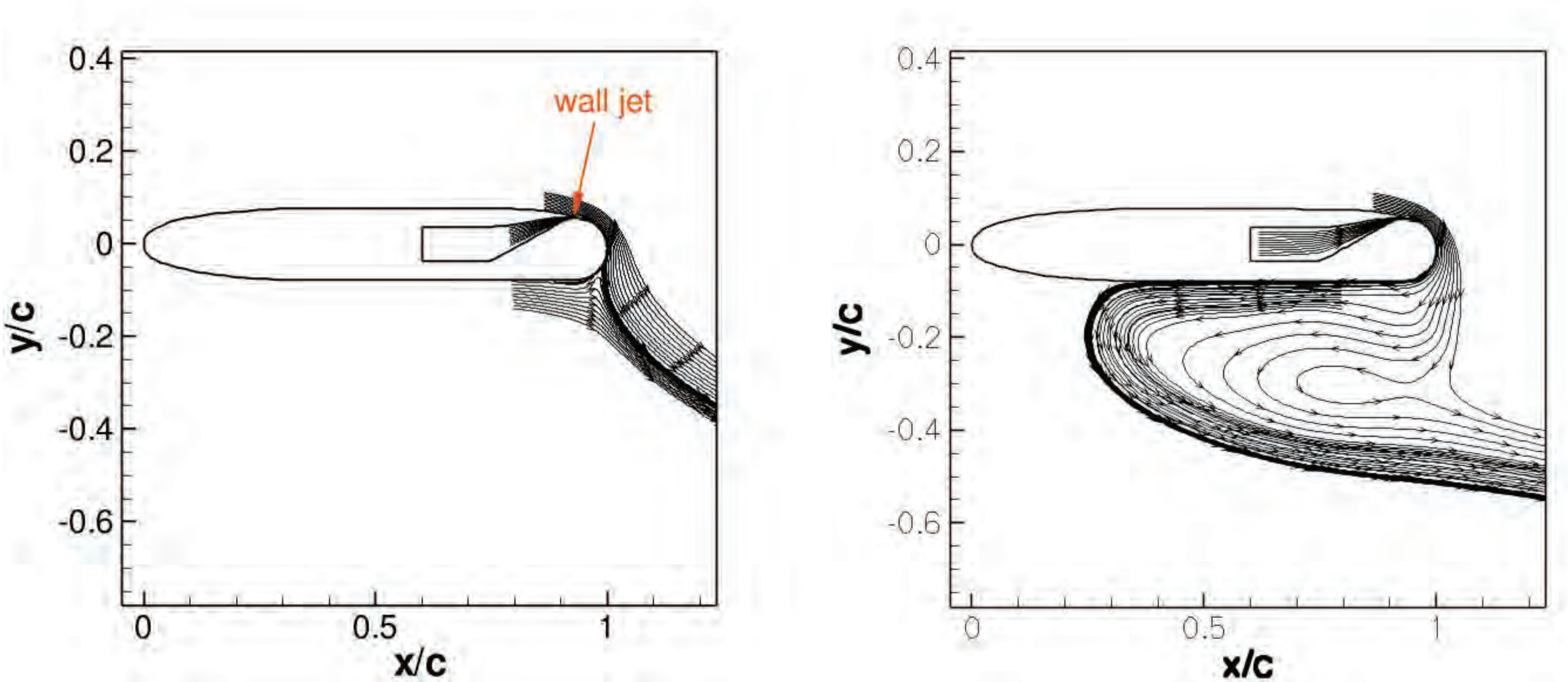


Introduction

- Need for improved turbulence modeling “usage” practices in the CFD community
  - inconsistencies in model formulation or implementation in different codes make it difficult to draw firm conclusions from multi-code and multi-turbulence model CFD studies
  - naming conventions and processes to insure model implementation consistency
- Also want to avoid difficulties & inconsistencies that can occur when attempting to implement models from papers/reports
- Verification vs. Validation
  - Verification: Are we solving the equations correctly?
  - Validation: Are we solving the correct equations?

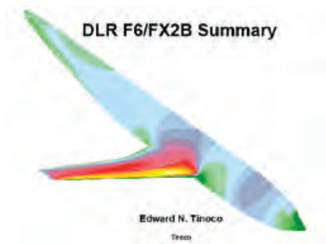
What we want to avoid

"Same" turbulence model - different results!

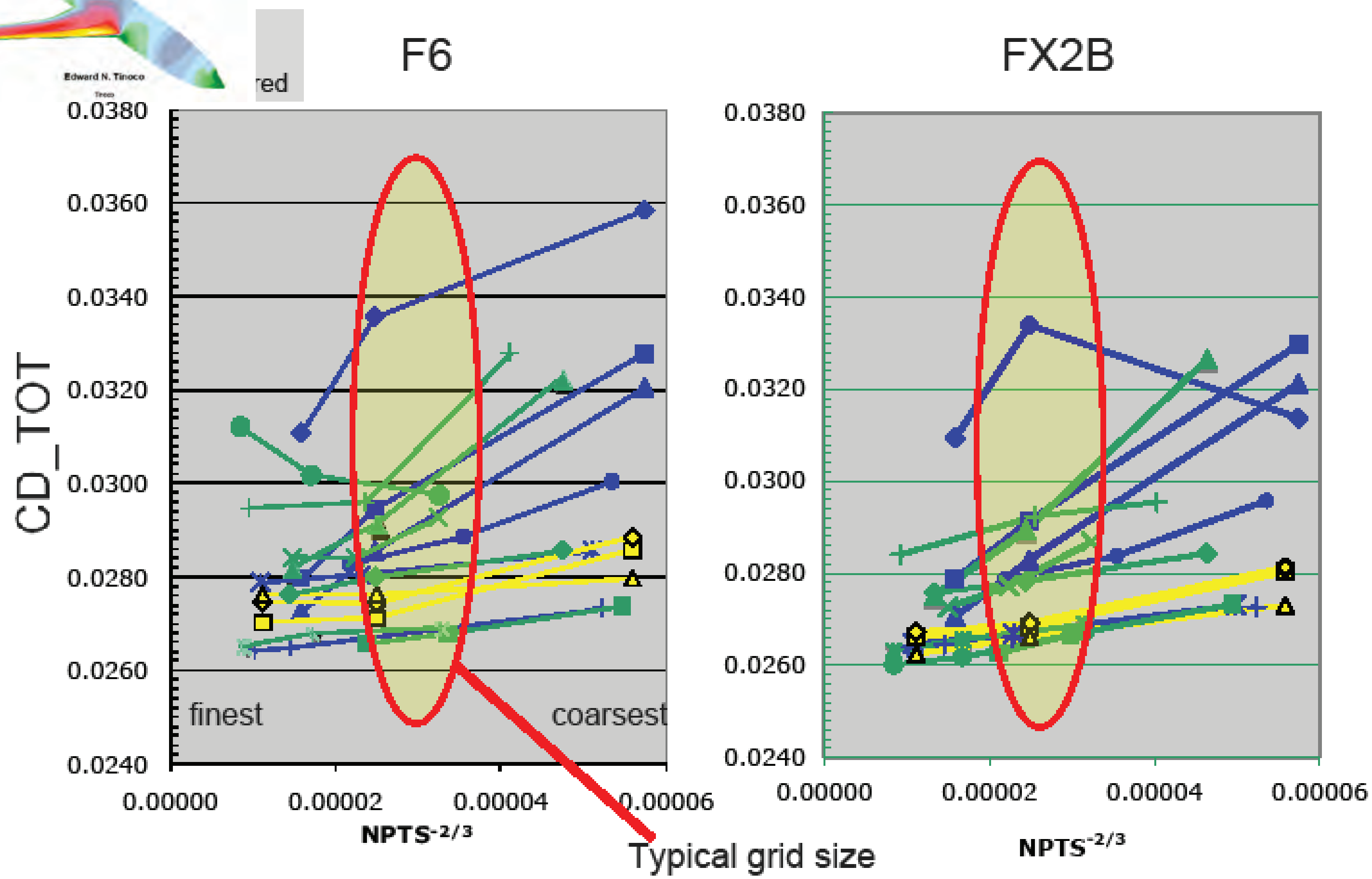


Sensitive cases can depend in part on model implementation differences (see, e.g.: 2004 NASA/ONR Circulation Control Workshop)

What we want to try to avoid



Example from Drag Prediction Workshop III

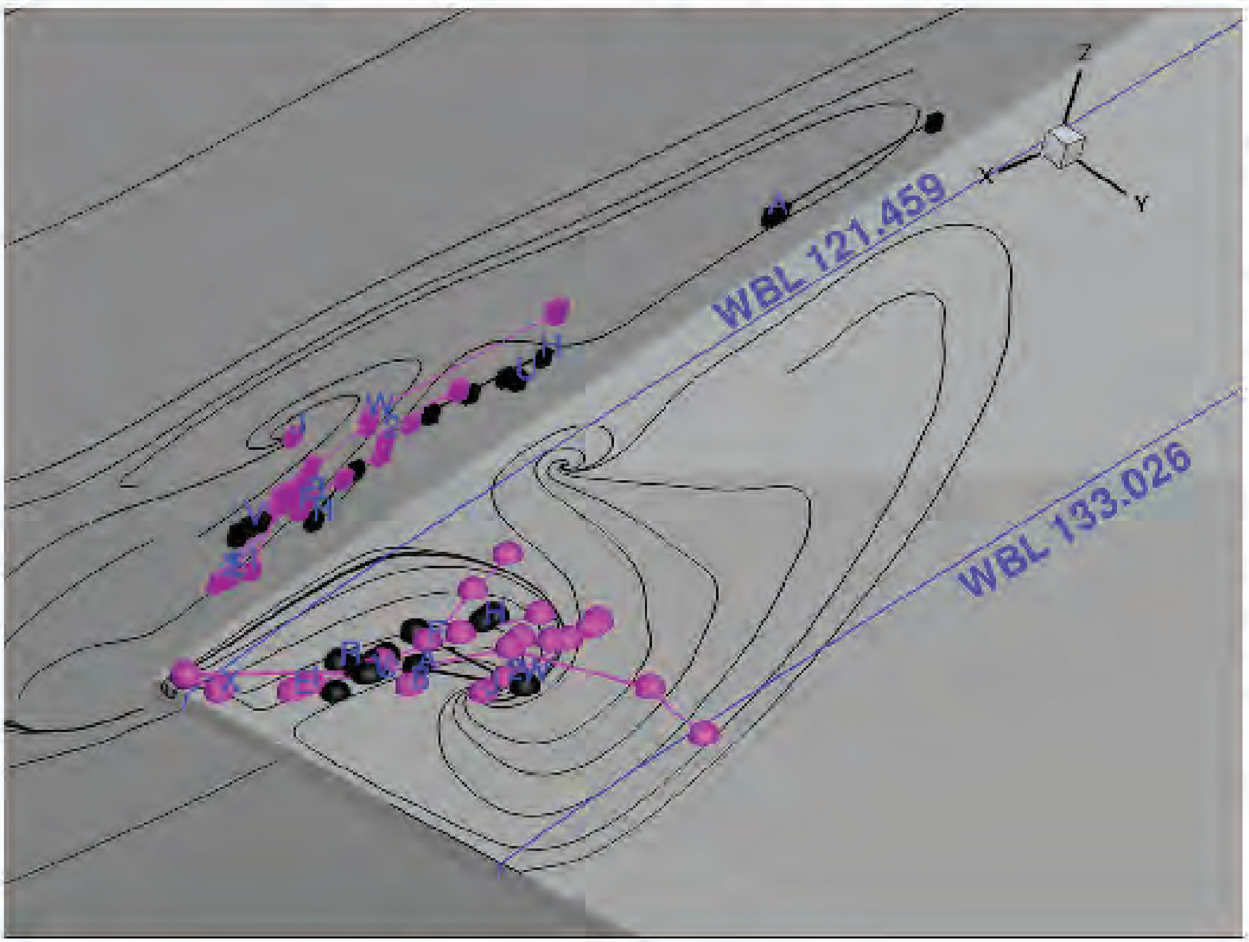


from Vassberg et al, AIAA Paper 2008-6918, August 2008

What we want to try to avoid

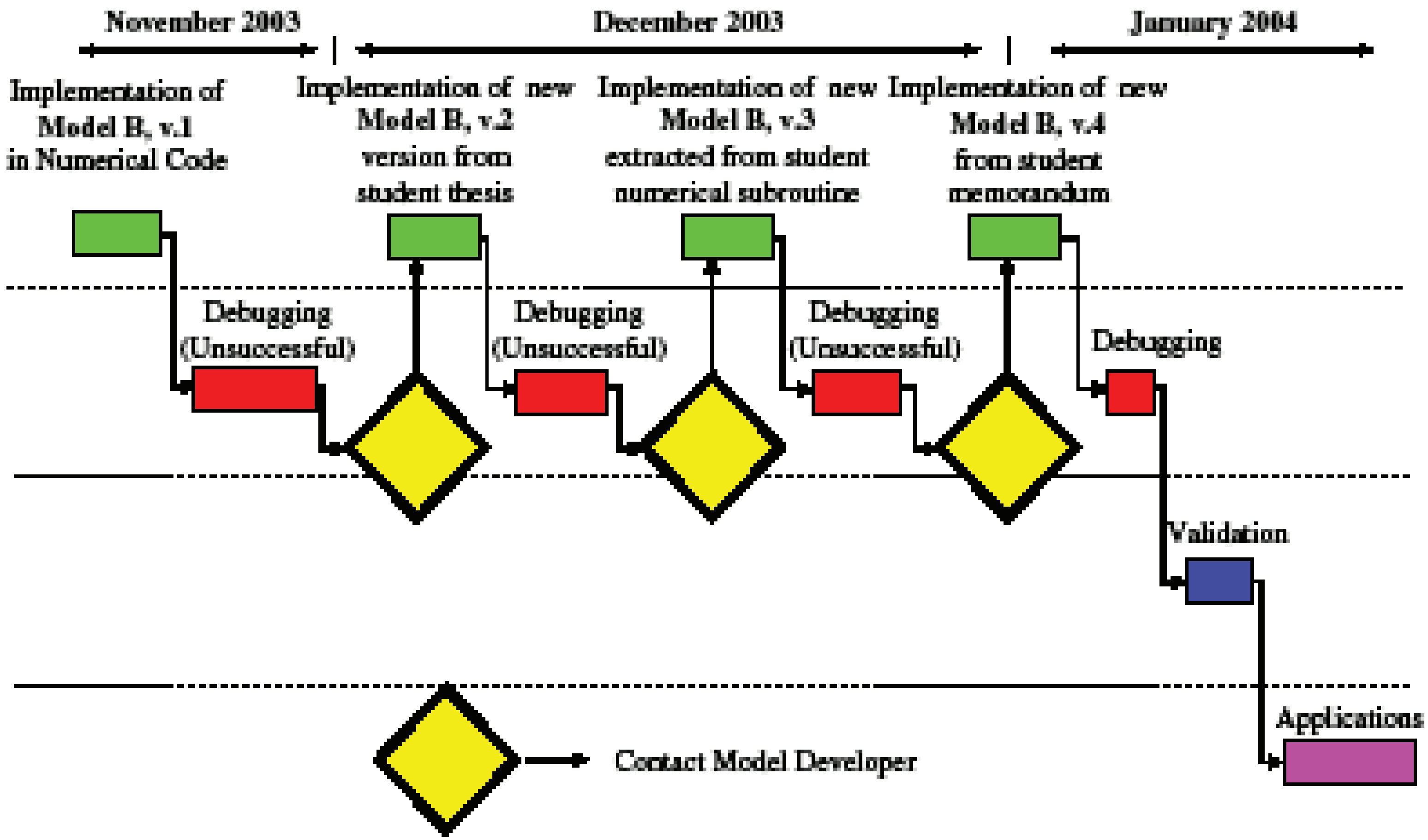
Example from Drag Prediction Workshop IV

Side of Body Separation Reported

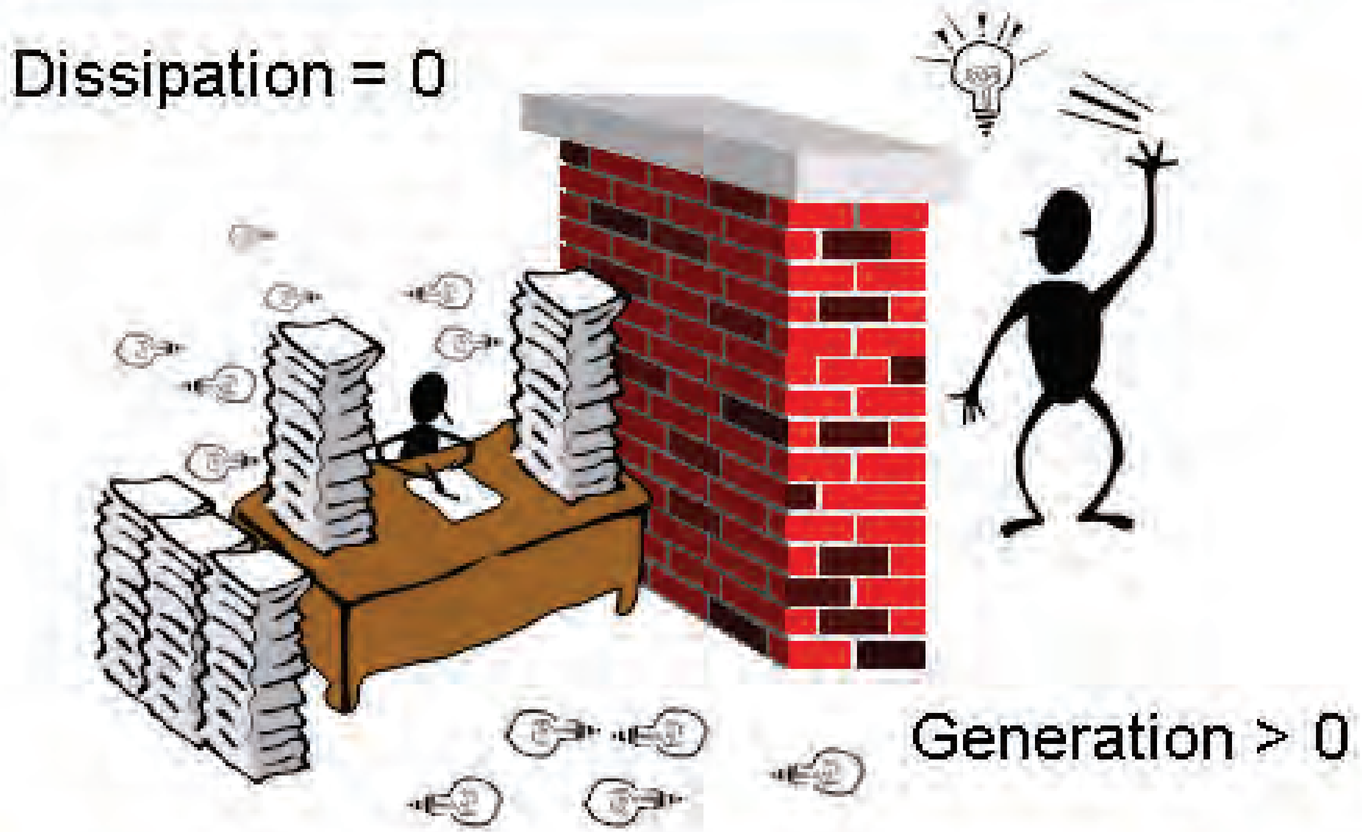


ID	Turb. Model
A	SST k-w
B	SA
E	SA
F	SA
H	SA
I	SA
J	SA
P	SA
R	SST k-w
U	SA
V	SST k-w
W	k-e
X	SA
2	SA
4	SA

What we want to try to avoid



What we want to try to avoid



Members of Turbulence Model Benchmarking Discussion Group

- We have a balanced group with Government, University and Industrial participation
- Members include model developers, CFD experts in model implementation, and researchers with experience in model evaluation
  - Brian Smith – Lockheed Martin Aeronautics Company
  - Christopher Rumsey – NASA Langley Research Center
  - George Huang – Wright State University
  - Nick Georgiadis – NASA Glenn Research Center
  - Hassan Hassan – North Carolina State University
  - Won-Wook Kim – Pratt & Whitney
  - Philippe Spalart – Boeing
  - Bora Suzen – North Dakota State University
  - Dennis Yoder – NASA Glenn Research Center
- Membership is open to any interested researcher

Group Objectives

- To develop a repository for turbulence model documentation
  - Have model authors clearly document model formulations
  - Have a rating system associated with models that describes the maturity of the model
- To include benchmark test cases in the repository
  - Help people implementing a model to make sure they have model implemented correctly
  - Allow CFD users to have a basis of comparison of relative predictions of different turbulence models for different turbulent flows.

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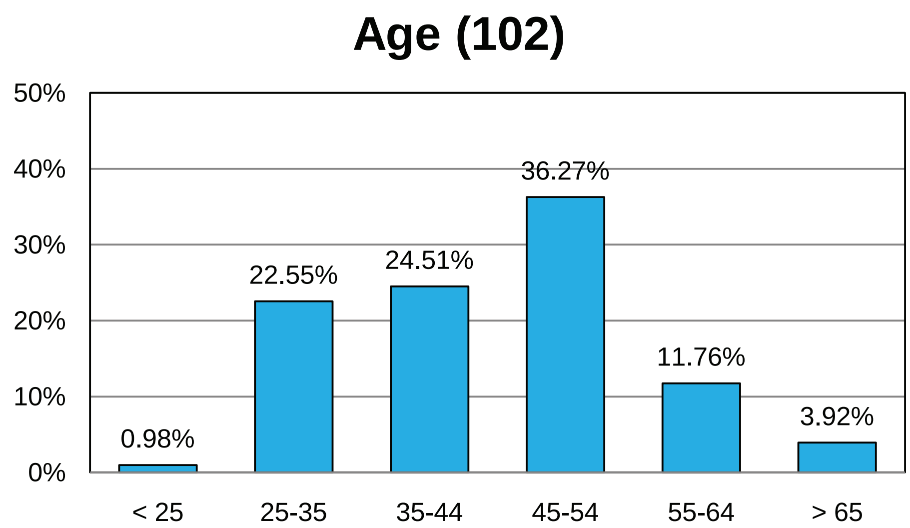
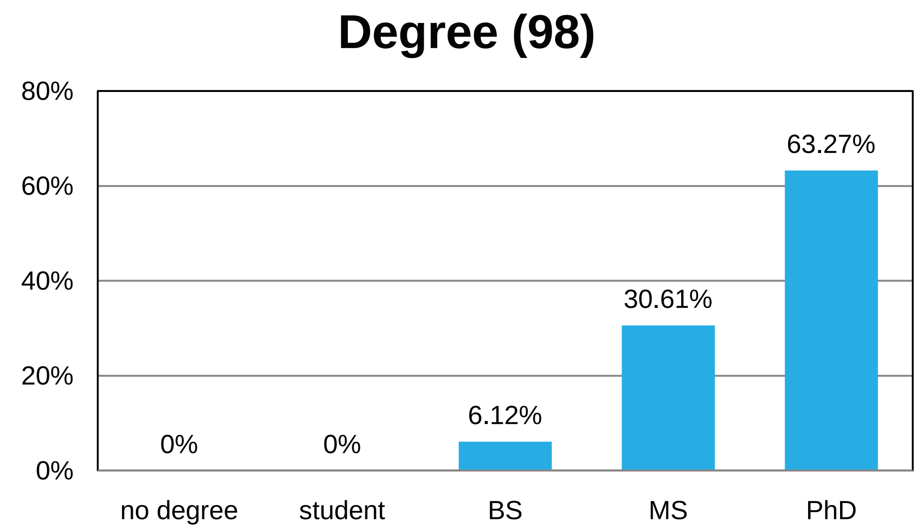
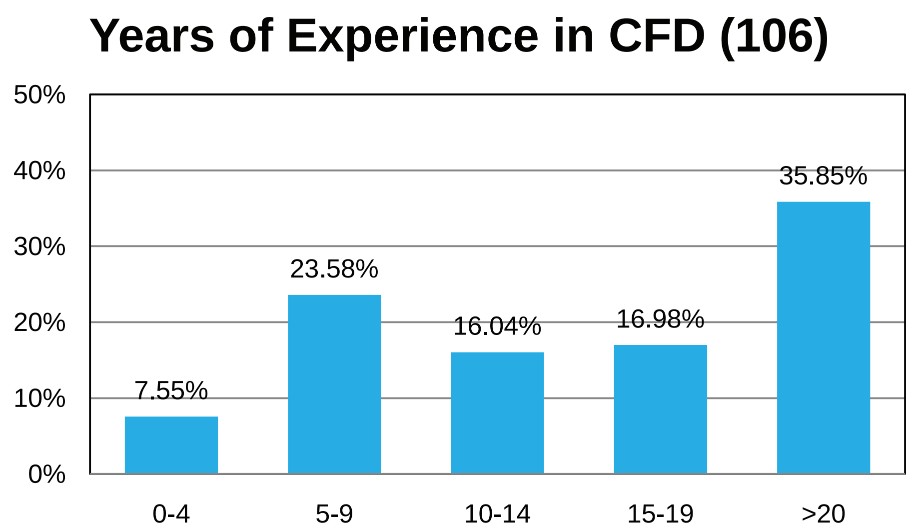
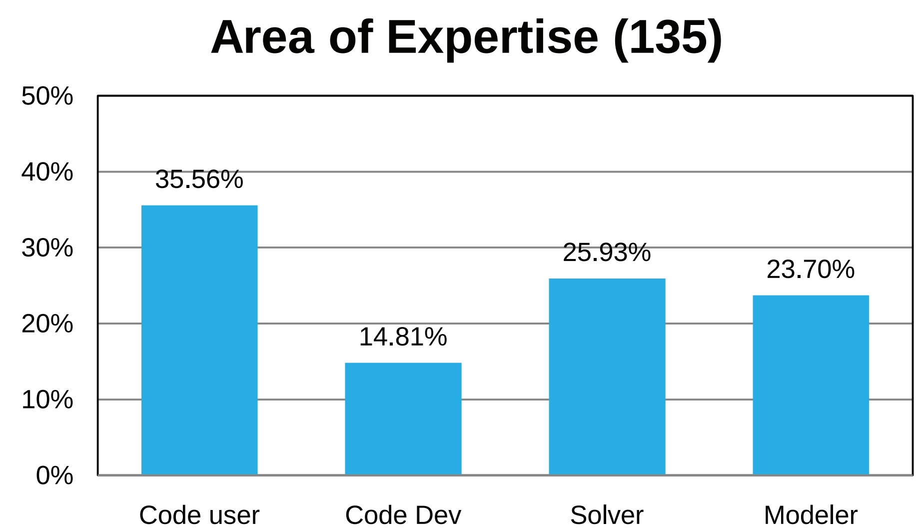
Survey Profiles



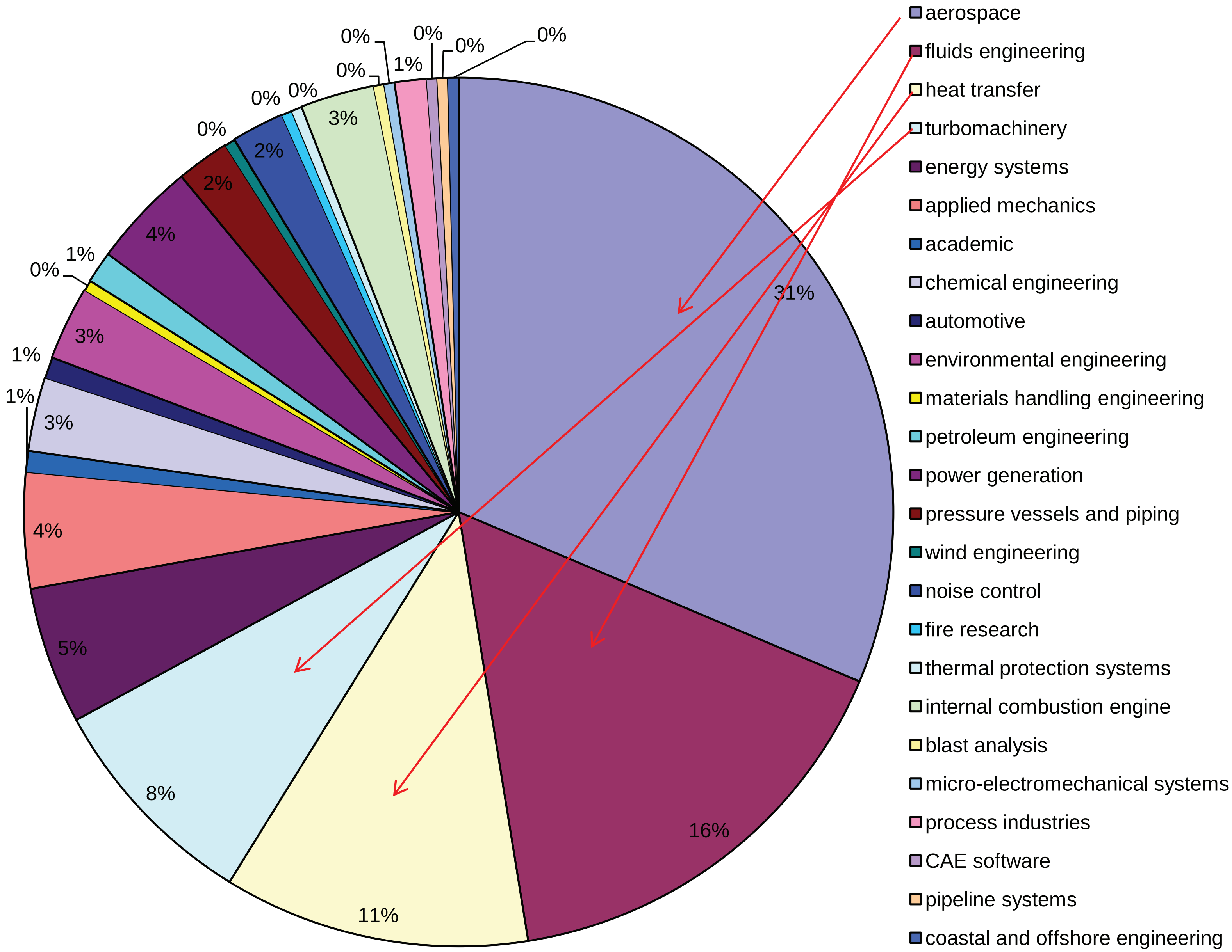






Profiles

- We have a total of 108 replies.
- Most are in aerospace-related Industry.
- Most of them have PhD degree and > 93% have at least a MS degree.
- Average age is around 45 years.
- 1/3 have more than 20 years experience in CFD while the age ranges are quite wide spread.
- Areas of expertise are also widely distributed among code users, code developers, solver developers and turbulence modelers.


31%
16%
11%
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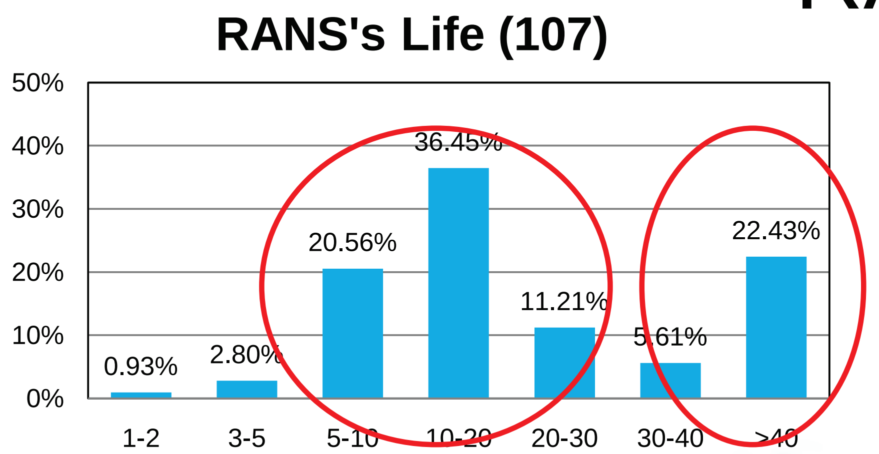
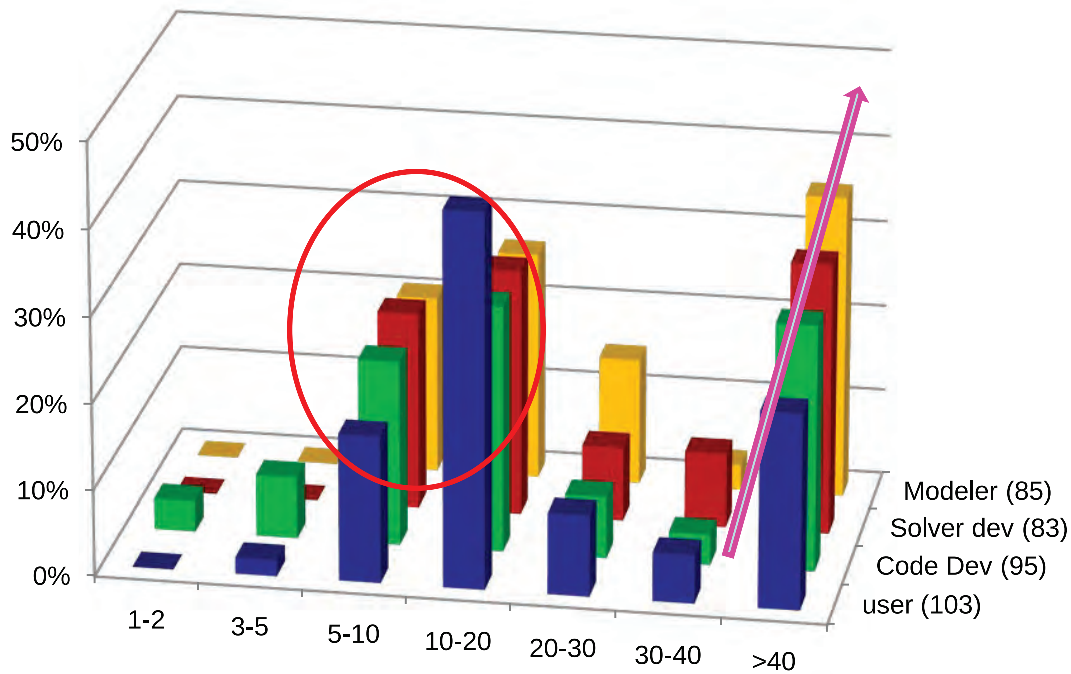
aerospace
fluids engineering
heat transfer
turbomachinery
energy systems
applied mechanics
academic
chemical engineering
automotive
environmental engineering
materials handling engineering
petroleum engineering
power generation
pressure vessels and piping
wind engineering
noise control
fire research
thermal protection systems
internal combustion engine
blast analysis
micro-electromechanical systems
process industries
CAE software
pipeline systems
coastal and offshore engineering

RANS


RANS's Life (107)
50%
40%
30%
20%
10%
0%
0.93%
2.80%
20.56%
36.45%
11.21%
5.61%
22.43%
1-2
3-5
5-10
10-20
20-30
30-40
>40


50%
40%
30%
20%
10%
0%
1-2
3-5
5-10
10-20
20-30
30-40
>40
Modeler (85)
Solver dev (83)
Code Dev (95)
user (103)

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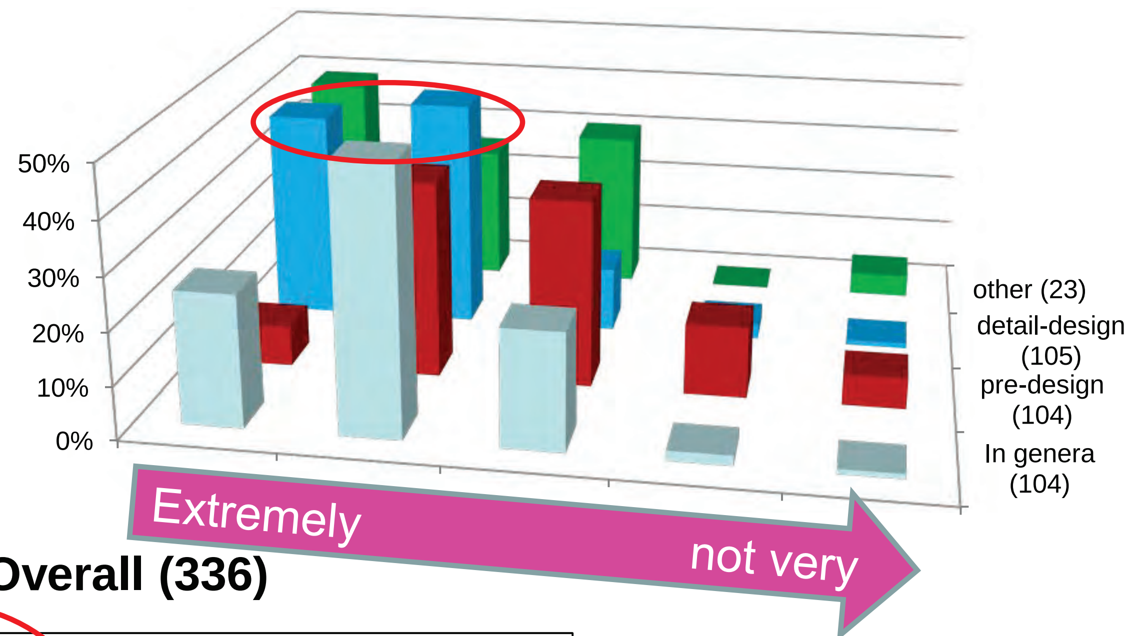
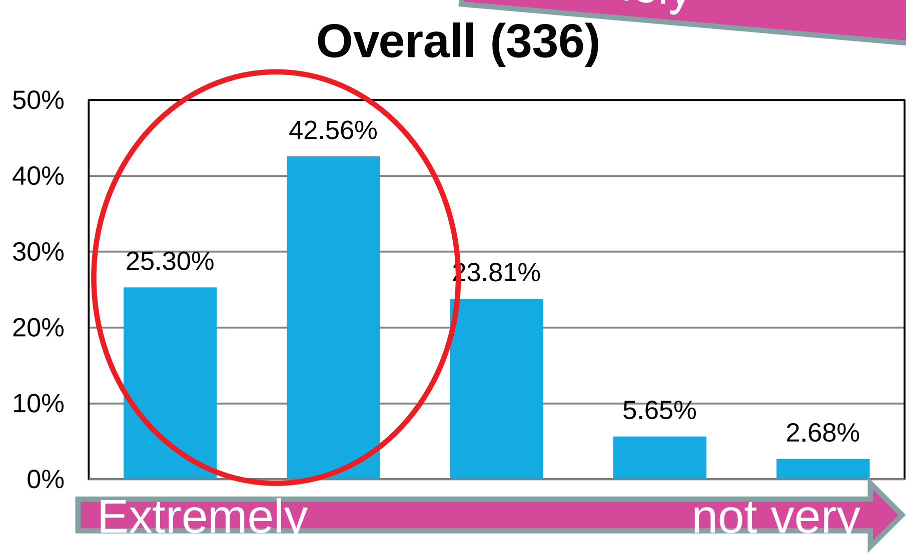
RANS's life

- 21% believe it will ends in 5-10 years.
- Majority (36%) believe 10-20 years.
- 22% believe it will not come during their life time.
- Modelers > Solver > Code Dev > User

How critical is the accuracy of RANS to the success of CFD designs?





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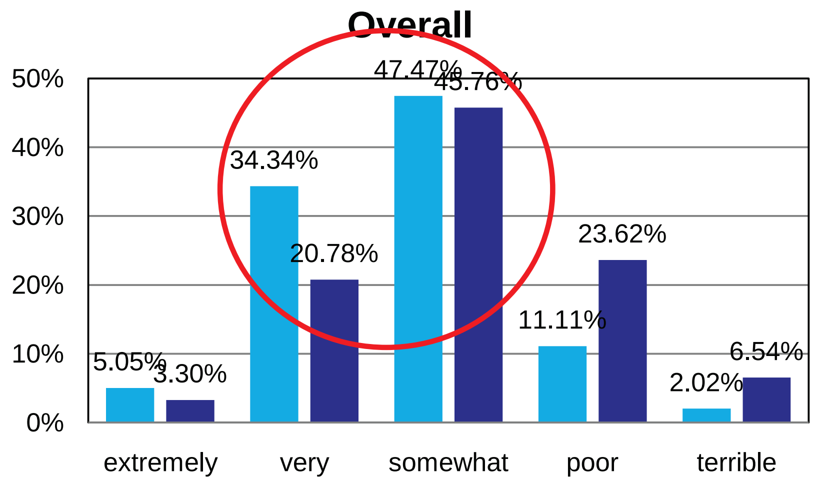
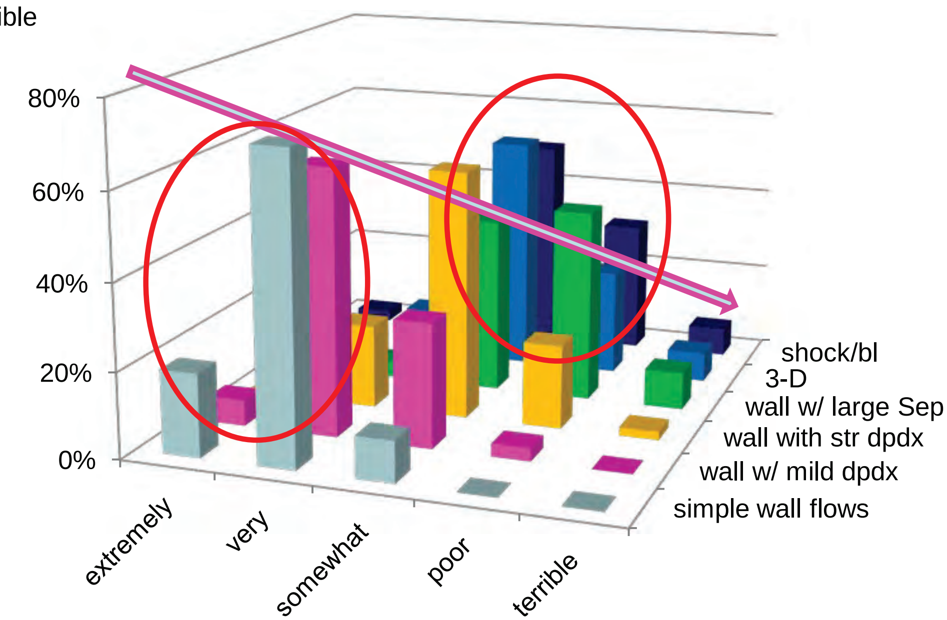
How critical is the accuracy of RANS to the success of CFD designs?

- Majority believe it is very critical.
- Most critical area is in detailed designs.
- A small fraction believe that it is not that useful in pre-design stages.

Are today's RANS sufficiently accurate?

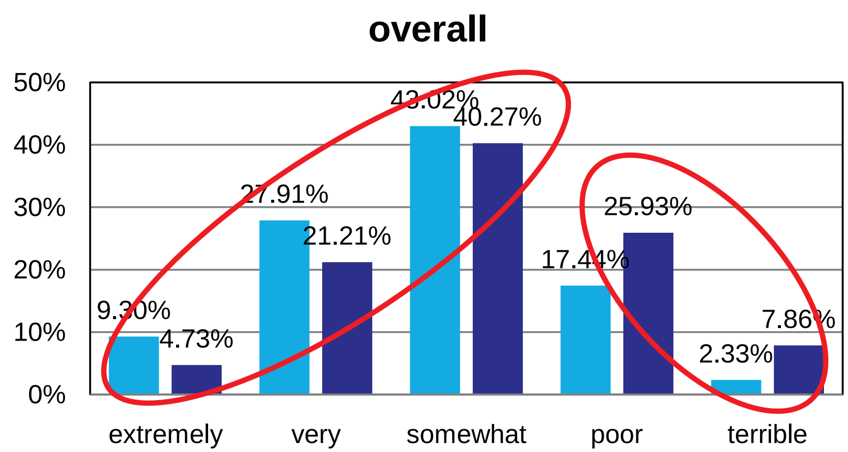


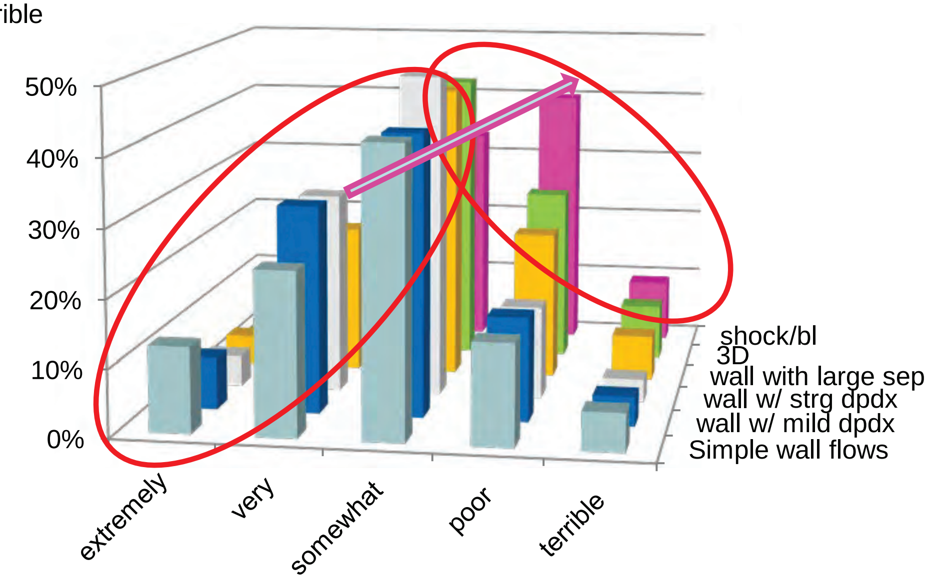


Are today's RANS sufficiently accurate?

- Most are not unhappy about RANS.
- Most have confidence for simple flows while are less so for complex flows.

Have RANS models been improved in the past 10 years?

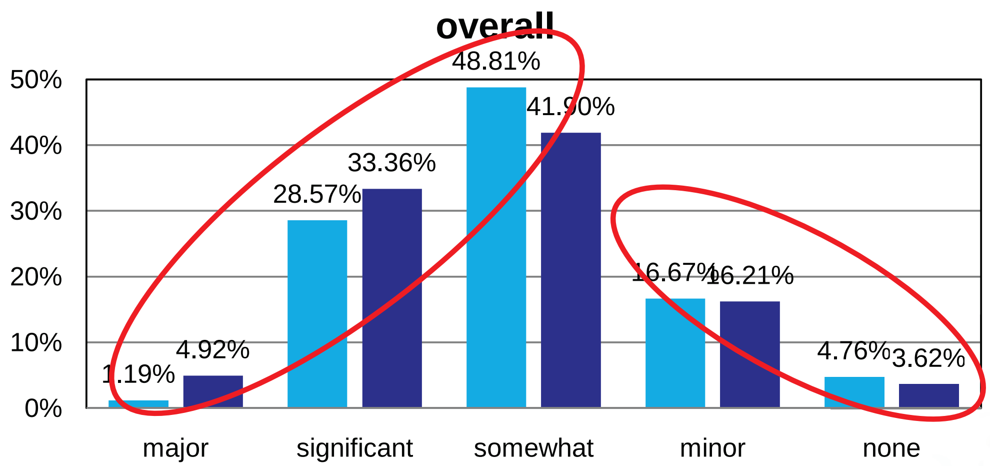


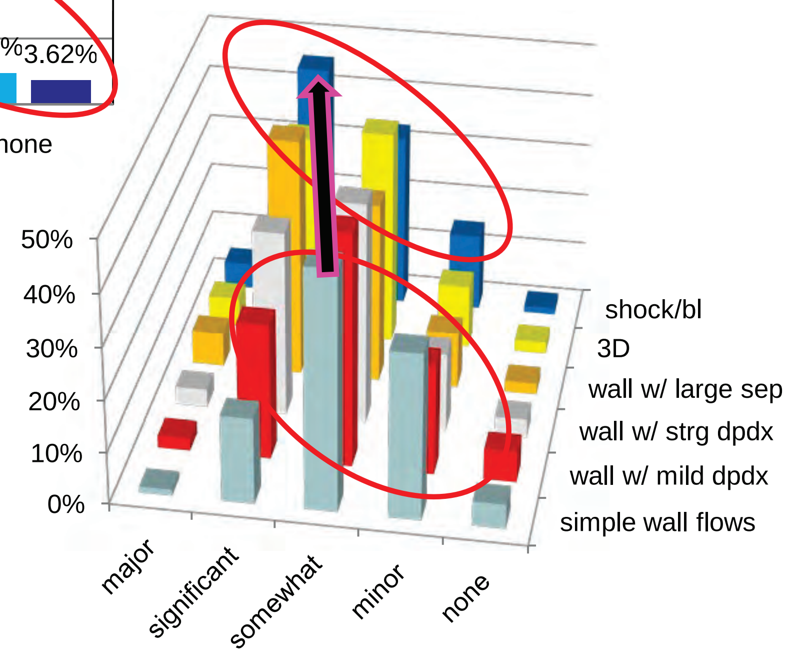


Have RANS models been improved in the past 10 years?

- Most believe between very and somewhat.
- But more so in simple flows than in complex flows.

Can RANS models be improved in the next 10 years?





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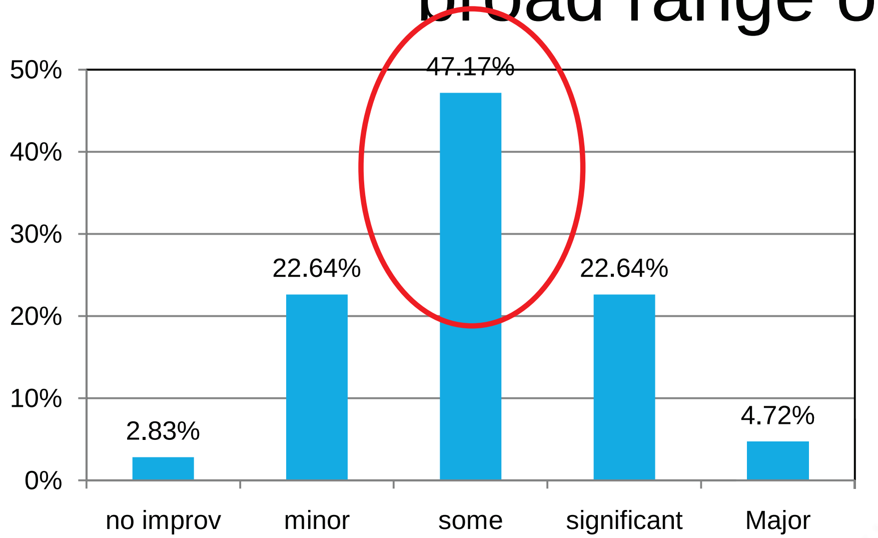
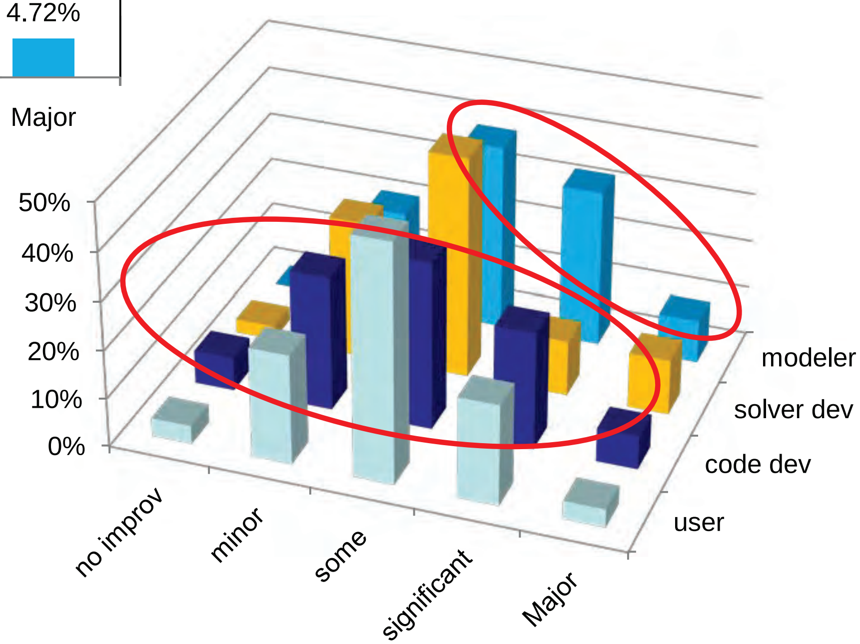
Can RANS models be improved in the next 10 years?

- Most believe the same scale of successes they have observed for the simple flows in the past 10 years will apply to the complex flows in the next 10 years.

Can the accuracy of RANS be improved for a broad range of applications?

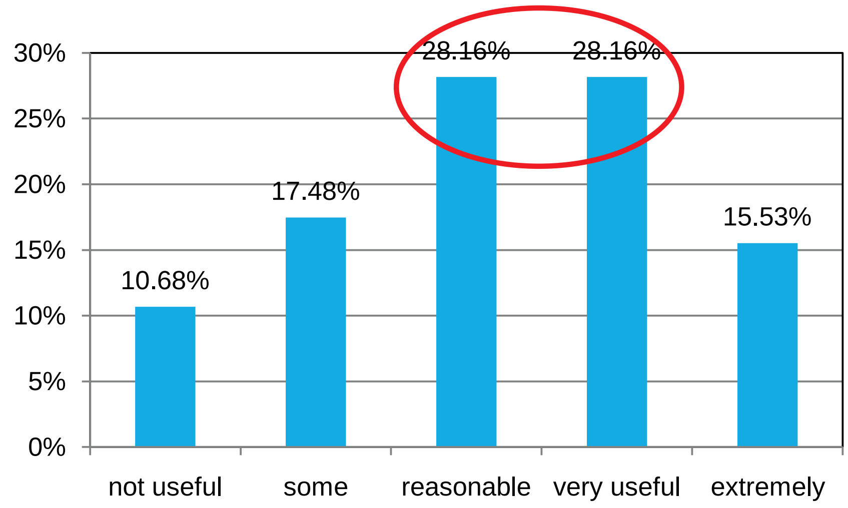


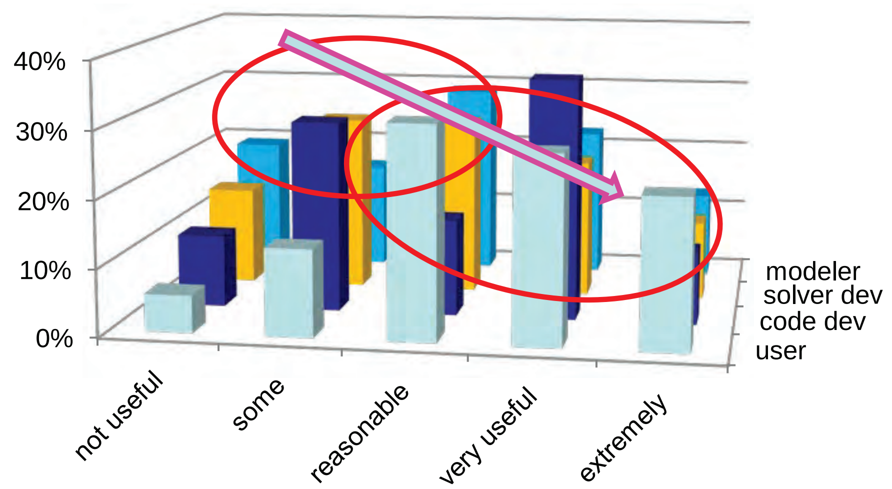


Can the accuracy of RANS be improved for a broad range of applications?

- Most are neutral to this question.
- However, the modelers are more hopeful than the rest groups.

Are wall functions useful today and in the next 5-15 years?

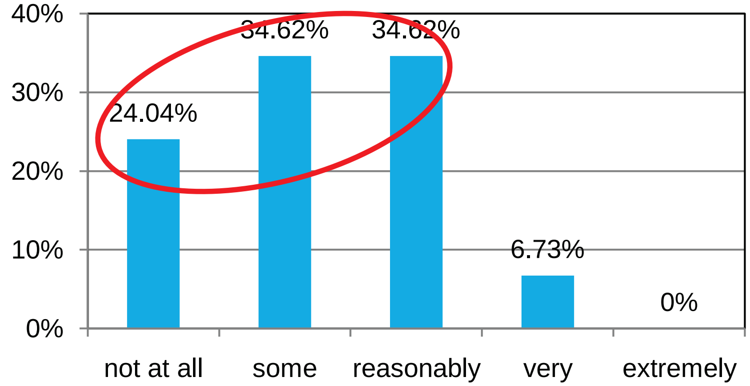


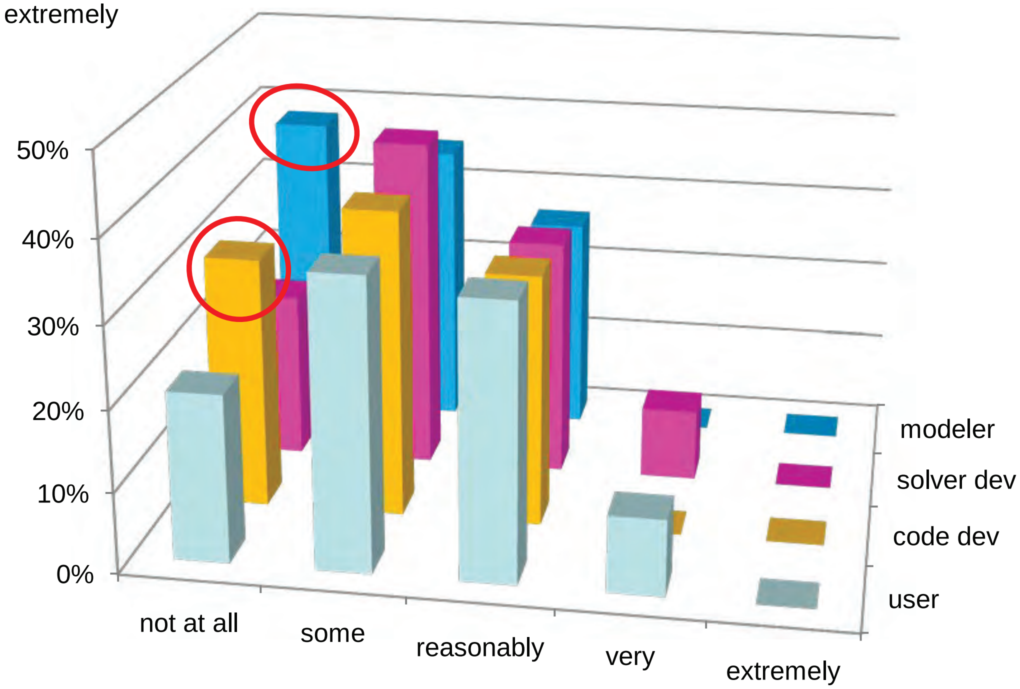


Are wall functions useful today and in the next 5-15 years?

- Majority will continue to use wall functions.
- Modelers tend to move away from using wall functions.

How confident are you on the turbulence model implementation in commercial and government codes?

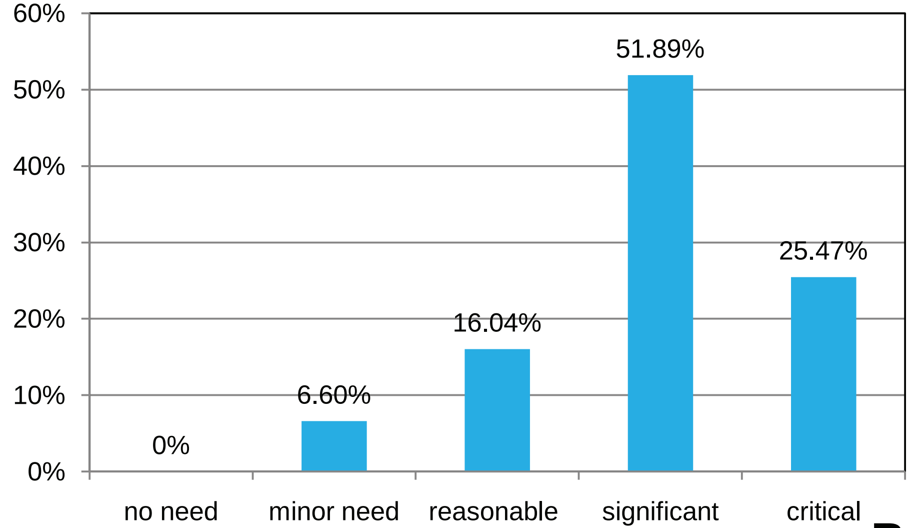




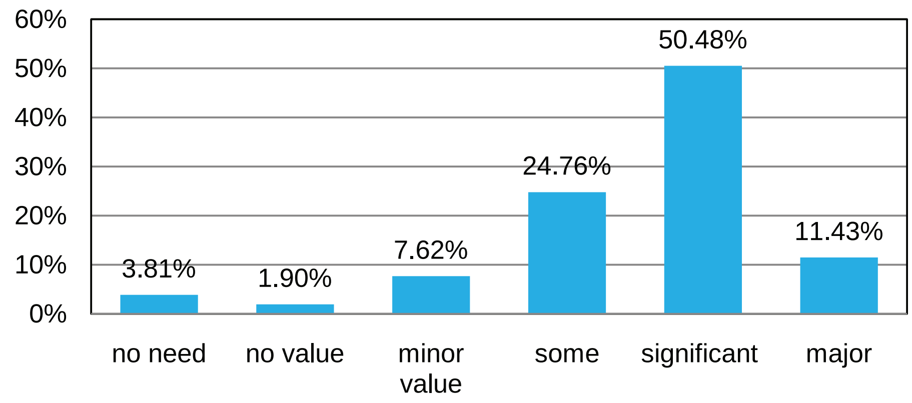
How confident are you on the turbulence model implementation in commercial and government codes?

- Most do not have confidence.
- Among them, a majority of non-believers are code developers and modelers!

Do we need to improve documentation and expand benchmarking of turbulence models?



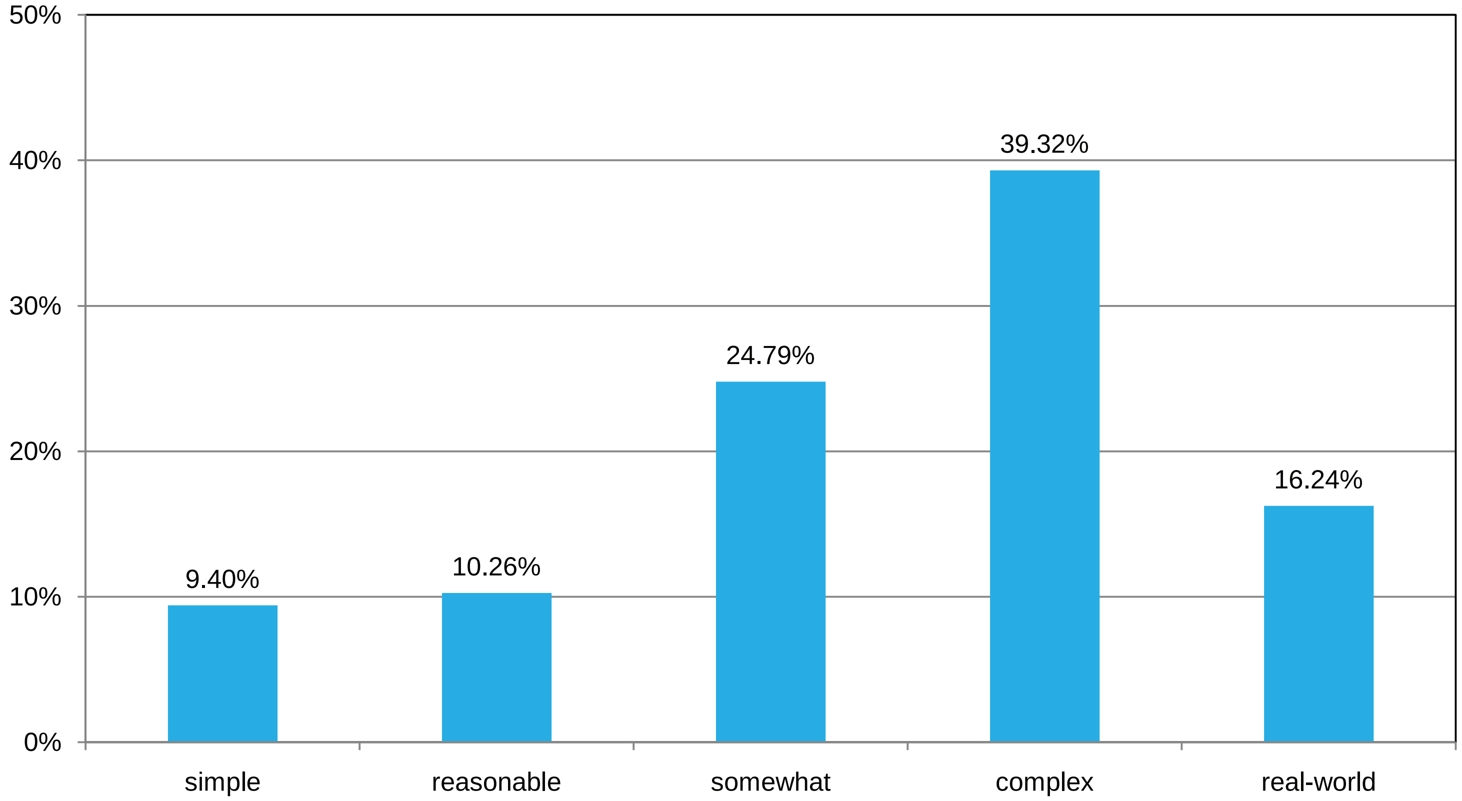
Benchmarking using multiple ppl and multiple code?



Do we need to improve documentation and expand benchmarking of turbulence models?

- Most believe it is very important.
- Most also believe benchmarking using different people with different codes is significantly important.

What types of flow cases should be the emphasis of a benchmark effort?



What types of flow cases should be the emphasis of a benchmark effort?

- Most believe there is a need to shift the emphasis from simple to complex flows.

NASA Turbulence Modeling Resource Website

- http://turbmodels.larc.nasa.gov
- Provide a central location where widely-used Reynolds-averaged Navier-Stokes (RANS) turbulence models are described and selected validation results given
- Provide simple test cases and grids, along with sample results (including grid convergence studies) from one or more previously-verified codes
- List accepted versions of the turbulence models as well as published variants
  - Establish naming conventions in order to help avoid confusion when comparing results from different codes
- Serve as forum for new turbulence model ideas

Verification cases and grids

- How to achieve consistency in turbulence model implementation?
  - Decided to create series of “verification cases”
  - Show how 2 or more independent codes with the same turbulence model go to the same result as grid is refined
  - Provide grids for others to use
  - Provide solutions for others to compare against
  - Simple, analytically-defined geometries, no separation, easy to converge fully
- Current verification cases:
  - 2D zero pressure gradient (ZPG) flat plate
  - 2D planar shear
  - 2D bump in channel
  - 3D bump in channel

Validation cases

- TMBWG decided to focus on 5 simple validation cases for the website
  1. 2-D incompressible ZPG flat plate
  2. 2-D incompressible NACA 0012 airfoil
  3. 2-D incompressible planar shear (Bradbury & Riley)*
  4. Axisymmetric incompressible APG separated flow (Driver)*
  5. 2-D compressible supersonic ZPG flat plate (van Driest)*
- Reasons for choosing simple cases:
  - Easier to ensure fully converged solutions
  - Easier for multiple codes to be employed on same problem
  - Easier to conduct thorough grid-convergence study
  - With complex flows, one is usually not sure whether disagreement is due to turbulence model or something else (insufficient grid density, poor geometric fidelity, BCs, etc.)

* = tentative

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Future expansion

- Model "readiness level" rating system (proposed)
  - Level 0: Well-Defined Model
  - Level 1: Single-Code/Single-User Verification
  - Level 2: Multiple-Code/Single-User Verification
  - Level 3: Multiple-Code/Multiple-User Verification

	Level 0	Level 1	Level 2	Level 3
Sponsor	✓	✓	✓	✓
Completely described and referenceable	✓	✓	✓	✓
In at least 1 CFD code		✓	✓	✓
Run on flat plate with grid study & results available		✓	✓	✓
In 2 or more codes - results agree as grids refined			✓	✓
Run on 2 or more verification cases & results available			✓	✓
At least one code from outside home organization				✓
Independently verified (committee or other designee)				✓

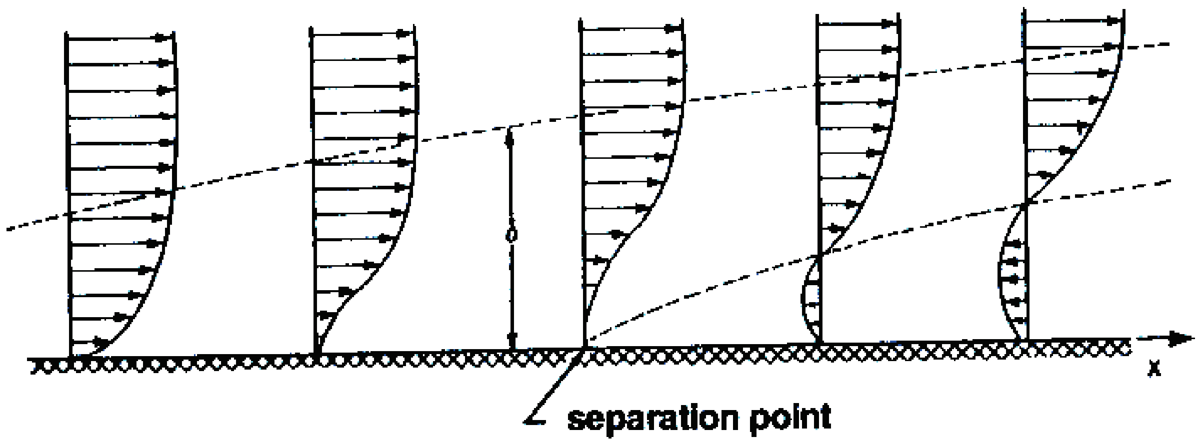
Other resources on the website

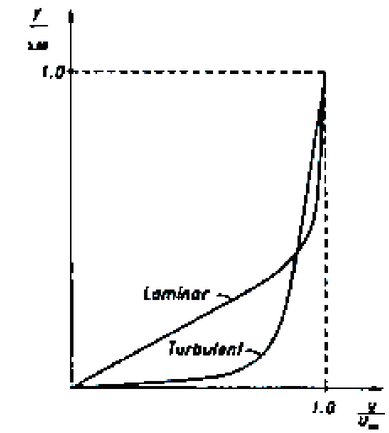
- Validation database archive
  - Turbulent flow experimental and simulation databases are included from Bradshaw, P., Launder, B. E., and Lumley, J. L., "Collaborative Testing of Turbulence Models," Journal of Fluids Engineering, Vol. 118, June 1996, pp. 243-247.
    - Incompressible Flow Cases from 1980-81 Data Library
    - Compressible Flow Cases from 1980-81 Data Library
    - More recent databases (courtesy P. Bradshaw) also included
- Collection of turbulent manufactured solutions
  - From "Workshop on CFD Uncertainty Analysis" series
  - Manufactured Fortran function files, courtesy Luis Eca, IST (Lisbon)
    - Spalart-Allmaras (SA-noft2), Menter one-equation, Menter BSL, standard k-epsilon, Chien k-epsilon, TNT k-omega

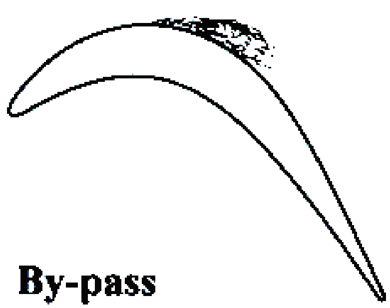
Future plans for website

- Expand number of turbulence models described / referenced
- Complete the set of 5 planned validation cases
  - Compute each with at least 2 independent CFD codes
  - Ensure that results agree when using the same model
  - Initial focus: Spalart-Allmaras and Menter SST models
- Expand verification & validation cases to include other turbulence models
- Additional verification or validation cases as need arises
- Include transition modeling efforts?

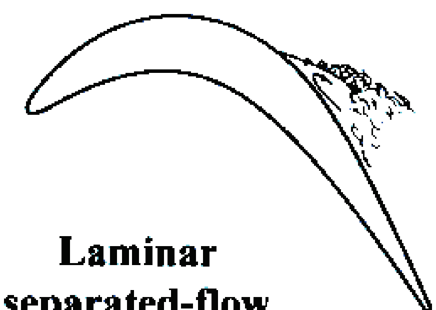
Interactions between transition and Separation





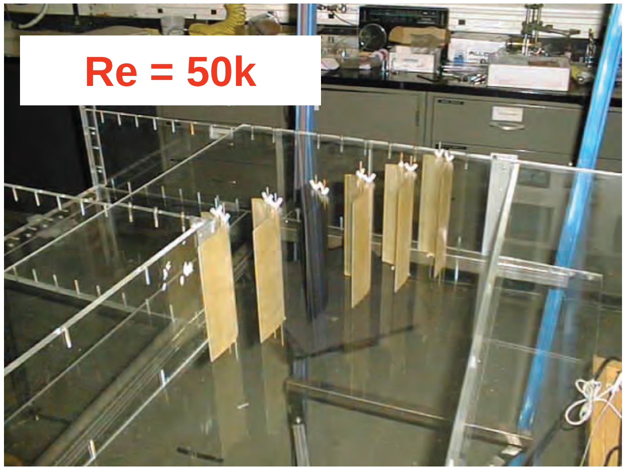


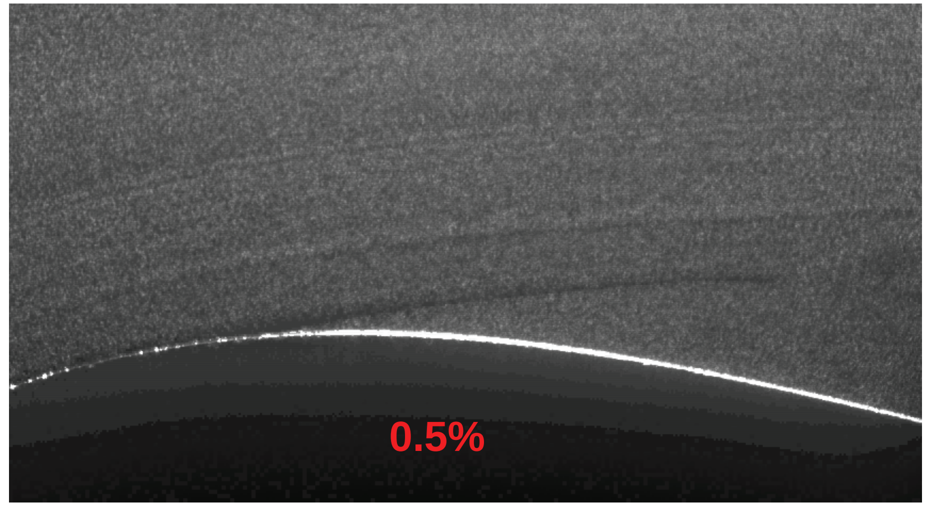
By-pass transition

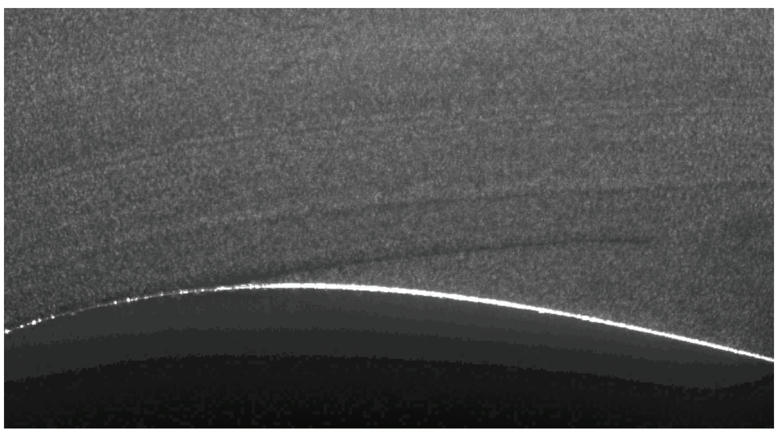


Laminar separated-flow transition

Attached- and Separated- Transition







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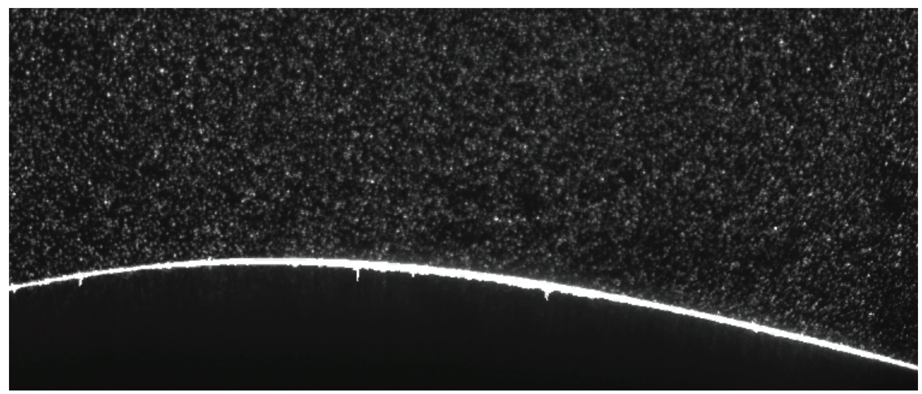

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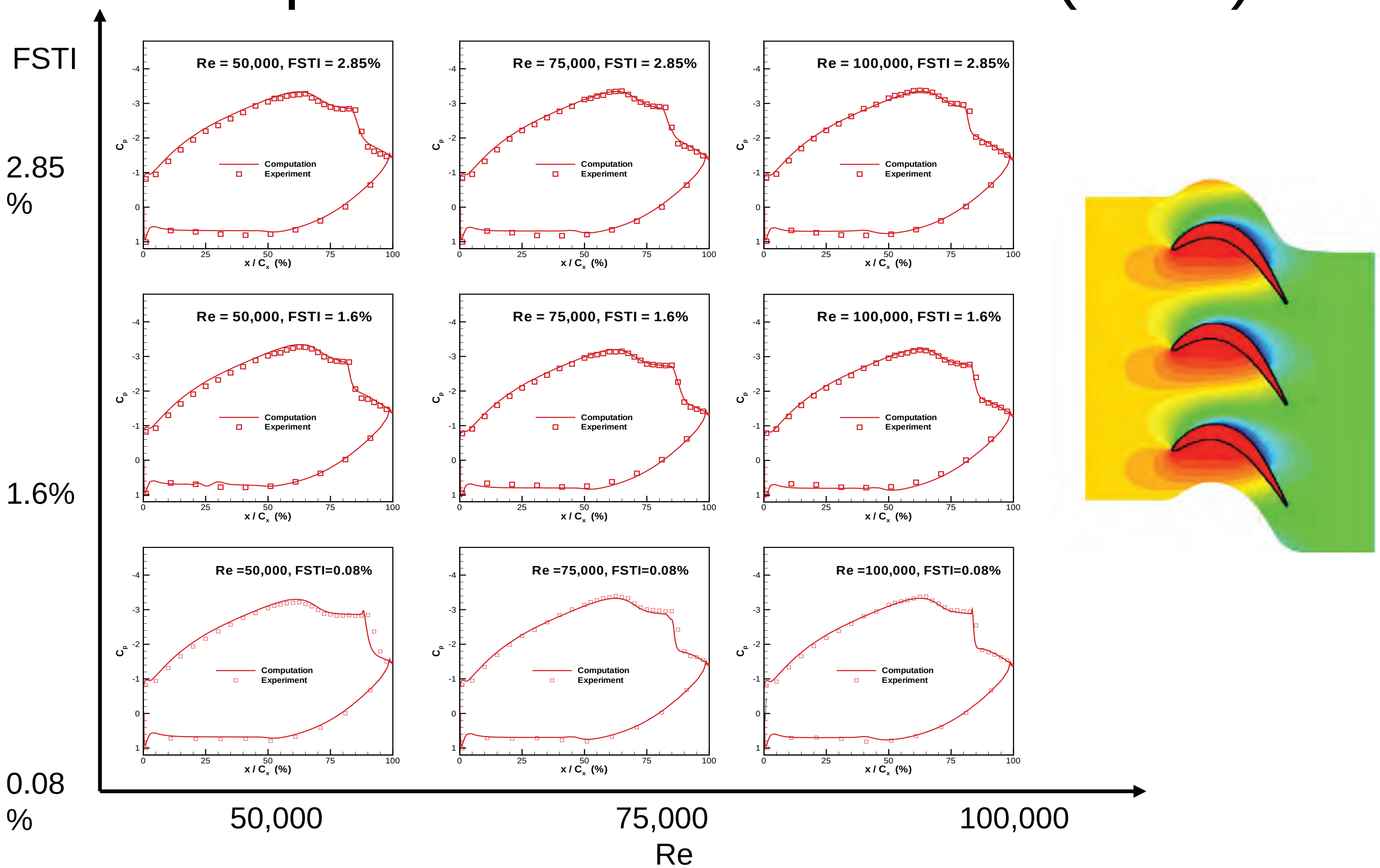
Experiments of Corke *et al*. (2002)



Test/Validation Cases

- **Flat Plate Experiments (Effects of Re, FSTI, dp/ds):**
  - ERCOFTAC Benchmarks, Coupland (1993)
  - Transitional Boundary Layer Separation Experiments of Hultgren and Volino(2000)
- **Cascade Experiments(Effects of Re, FSTI, dp/ds, Flow Separation):**
  - PAK-B blade experiments of Simon (2000)
  - PAK-B Cascade Experiments of Corke et al. (2002)
  - PAK-B Cascade Experiments of Lake et al. (1999, 2000)
  - PSU Compressor Cascade Experiments of Zierke and Deutsch (1989)
  - Genoa Cascade Experiments of Ubaldi et al. (1996)
  - VKI Cascade Experiments of Arts et al. (1990)
  - PAK-B Blade Passage Experiments of Volino (2002)
- **3-D experiments**
  - RGW compressor
- **Unsteady Wake/Blade Interaction Experiments (Effects of Unsteadiness):**
  - PAK-B Blade Passage Experiments of Simon et al. (2001)
  - T106A Cascade Experiments of Stieger (2001)
  - SSME Cascade Experiments of Schobeiri and Pappu (1997)
  - PAK-B Cascade Experiments of Schobeiri and Ozturk (2003)
  - TD106D-EIZ Cascade Experiments of Stadtmuller and Fottner (2001)

Conclusions

- There is a need to establish consistency in turbulence modeling across multiple codes in the CFD community

- Website http://turbmodels.larc.nasa.gov addresses consistency, verification, & validation
  - Documents model versions & establish naming conventions
  - Includes 4 verification cases, including full grid convergence studies (provides grids and solutions for easy reference)
  - Easily-accessible one-stop location that will document performance of various models for a suite of 5 representative validation cases (provides grids and solutions for easy reference)
- Do we need a separate website for LPT modeling?

Workshop Summary

Workshop Summary

Proceedings of the 2010 NASA—Industry Low Pressure Turbine and Power Turbine (LPT/PT) Efficiency Improvement Workshop, August 10–11, 2010

David E. Ashpis
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Introduction

This article provides an introduction, description, and summary of the NASA-Industry Low-pressure Turbine/Power Turbine (LPT/PT) Efficiency Improvement Workshop, that took place at NASA Glenn Research Center in 10-11 August, 2010. A review is provided of the background, motivation and workshop agenda. A summary of discussions and workshop recommendations are given. Citations of references are given and pertinent material are included in appendices.

1. Workshop Background

The workshop was organized by NASA in response to advocacy that originated outside NASA. A NASA-led Aerothermodynamics Technical Working Group (TWG) was established in March 2007. It consisted of technical experts from industry, university and government agencies. The group convened in May 2007 at the ASME Turbo Expo conference, and recommended generation of white papers to outline technology development needs in several areas of turbomachinery. A set of white papers was compiled by the TWG in 2008 (Ref. 1). The low-pressure turbine (LPT) was addressed in one the white papers. It was entitled “Highly Loaded Low Pressure Turbines” and authored by Howard Hodson (Cambridge University) and Om Sharma (United Technologies Research Center) (Ref. 2). A reprint is attached in Appendix A. Subsequent persistent advocacy lead mainly by Dr. Om Sharma included a series of meetings with NASA personnel, leading a breakout group at Minnowbrook VI workshop ((Ref. 3), reprinted in Appendix B, and (Ref. 4)), and dissemination of a post workshop article with Dr. J. Paul Gostelow (reprinted in Appendix C), lead to organizing the workshop.

The reason NASA Glenn Research Center (GRC) was expected to organize the workshop is its history of involvement with LPT research. Briefly reviewing this history, GRC was initially engaged in research problems associated with laminar to turbulent transition in turbines, mainly bypass transition (Ref. 5). A focused research program named Bypass Transition in Turbines was established in 1989 at the Turbine and Heat Transfer Branch, and was led by for several years by Fred Simon. (Refs. 6-7). The program conducted annual workshops, and in the

1993 workshop industry participants strongly recommended to redirect the effort to Low-Pressure Turbine problems (see, Simon, 1993, workshop summary document, Appendix D, and Simoneau, 1993, workshop notes, Appendix E). In response, NASA GRC established the Low Pressure Turbine (LPT) Flow Physics Program that was led by David Ashpis. A brief review of this program is included in Ashpis & Povinelli presentation in this workshop. In addition, NASA (jointly with AFOSR) had funded the Minnowbrook series of workshop, where LPT research was one of the main topics (Refs. 8-14). Based on this background it was natural for NASA Glenn to be the organizer and host of the present workshop. The workshop was organized under the auspices of the Subsonic Fixed Wing Project of the NASA Fundamental Aeronautics Program. This program was interested in reduced fuel burn and improved propulsion efficiency and therefore the subject fell under its areas of interest. The Subsonic Rotary Wing Project has started a program in Power Turbines (PT) research for future tilt rotor aircraft. The PT shares research challenges with the LPT and it was decide to include the PT in the workshop.

The first call for the workshop came out on March 2010. The workshop hosted about 65 participants from industry, academia, US Air Force, US Army and NASA. In particular the participation of international visitors from the UK, Spain, Germany, and Canada is acknowledged. The workshop took place at the Ohio Aerospace Institute at NASA Glenn Research Center. A small meeting room was chosen to encourage discussions and interactions. Keynote presentations were given in the auditorium. Discussions and socializing occurred also at breaks and at a group dinner.

2. Workshop Objectives

The motivation of the workshop was to address issues associated with efficiency of large commercial engines LPT. The aero-engine industry has moved towards design of high-lift airfoils, but encountered issues with efficiency. It seemed that high-lift airfoils were not producing expected level of performance in LPTs. The issue affected airline operations and was reported in trade magazine articles (Refs. 15-18). A paper by MTU Aero Engines AG, a leader in the area of LPT design, addressed aspects the problem (Ref. 19). A well designed LPT for commercial engine application should be operating at about 95.5% efficiency. Since the current LPTs are operating at best around 93.5% efficiency, the best path to specific fuel consumption (SFC) reduction is through an improvement in the LPT efficiency. The impact of LPT efficiency on the SFC is almost that 1% in LPT efficiency is equivalent to 0.8 to 0.9% in SFC for high bypass ratio engines.

The intent of the workshop was to understand the underlying issues, and discuss, on a pre-competitive basis, efficiency improvements of modern LPT/PT for reduced engine fuel burn and emissions. Technical issues associated with the unique flow conditions in LPTs were to include low Reynolds number effects, high freestream turbulence, wakes, separation, transition, 3D effects, endwall interaction, loss mechanisms, etc. Technical issues associated with variable-speed PTs were also be addressed. It was a specialists' workshop with discussions, on a fundamental flow-physics level, on theory, experiments, numerical modeling, and design. Diverse points of view was facilitated by participation from aero-engine industry, government, research institutes, and academia.

The expected outcomes were:
1) Comprehensive understanding of issues associated with flow and losses in modern LPT & PT
2) Understanding the barriers for efficiency improvements
3) Outline future research needs

3. The Agenda

The Agenda included presentations and ample time for discussions. The presentations included industry reviews, Keynote lectures and other presentations. It was anticipated that fundamental research areas will be addressed, therefore a set of keynote presentations and shorter presentations was chosen to address various issues and approaches to LPT and PT research. In order to directly address the issues, Industry presentations were scheduled for the start of the first day. It proved to be a good approach as the participants were immediately immersed in the issues at hand. Optional turbomachinery facilities tours were conducted at GRC for interested participants after conclusion of the workshop. The Turbomachinery and Heat Transfer branch researchers provided overviews and tours of their respective facilities.

3.1 Outline of Workshop Presentations

After welcome and opening remarks by NASA program managers the workshop motivation was put into focus by Om Sharma. A review of past NASA research activities in the LPT research area was given by David Ashpis and Lou Povinelli. The workshop proceeded with reviews by the aero-engine industry. Their presentations largely responded to advance request asking them to cover to the maximum extent possible the following topics: Description of the LPTs in various engines of their product line (size, weight, number of stages and number of airfoils), operational envelope (Reynolds number, temperatures, axial velocity, rotation speeds, turning angles), LPT airfoil design philosophy (mainly loading distribution), LPT design cycle, computational tools used, models used, experimental facilities used – rigs to flight tests, system studies showing benefits of improvements, maintenance considerations, cost considerations, structure and materials considerations, role of multidisciplinary, design, analysis, and optimization (MDAO), impact of the geared turbofan (GTF)/Open rotor/other concepts on LPT, power turbines, future trends and LPT challenges and opportunities. The presentations where by Rolls Royce (Frank Haselbach, UK), ITP (Raul Vazquez, Spain), General electric (Lyle Dailey), Pratt and Whitney (Thomas Praisner) and Honeywell (Malak Malak). The speakers were experienced leaders in turbine aerodynamics in their respective companies.

The workshop proceeded with topical presentations in relevant areas to LPT research by invited speakers from academia in the USA and the UK, corporations (ANSYS Germany & Canada), and government laboratories (US Air Force Research Laboratory and the Canadian NRC). Areas covered were experimental facilities, MDAO approaches, CFD approaches, and transition and turbulence modeling. The power turbine (PT) area was covered by review of work performed and GRC. The workshop participants did not engage in much discussion on the PT topic as it was felt that the power turbine, despite similarities to LPT, has its own unique challenges. The various presentations presented the state of the art in the various disciplines, reviewed selected work and addressed future challenges. The grouping of the talks, the speakers and their affiliations are evident from the table of contents that follows the workshop agenda and will not be reviewed here.

4. Workshop Recommendations

The main recommendation of the workshop was to conduct LPT rotating rig experiments. The requirements from the experiment are;

1. A geometry representative of high lift design.
2. A minimum of three stages.
3. Include purge, end-wall seals, and other design details.
4. The first test article will be a baseline geometry.
   Follow-up with a second test article with improved geometry.
5. Accompany experiments with CFD.

Experimental studies of fundamental mechanism in simplified facilities, (e.g., wind tunnels, linear cascades, annular cascade, single stage) was recommended as supporting experiments to the main rotating rig experiments. In addition, CFD and turbulence/transition model development was to accompany the experiments where experiments and computation augment and leverage each other.

The recommendation was to address Power Turbine issues separately as they were unique for these turbines and differ from the larger commercial engines LPTs.

A committee was formed to follow-up on these recommendations in post-workshop teleconferences and meetings.

The committee representatives were;

1. UTRC: Om Sharma
2. Rolls Royce: Frank Haselbach
3. IPT: Raul Vazquez Diaz
4. Pratt& Whitney: Shankar Maggee
5. GE: David Halstead
6. Honeywell: Malak Malak
7. NASA: Paul Giel, David Ashpis, James Heidmann

5. Summary of Workshop Discussions

The format of the workshop encouraged discussions during the presentations and in dedicated discussions time. A transcript of the discussions was deliberately not kept so to encourage uninhibited discussions.

One noteworthy opinion expressed at the workshop was that the higher than expected losses of the new generation of high-lift LPTs that were put into service are to be attributed to secondary flows, impact of purge flows, and interactions with hub an casing, aggravated by typically highly-sloped LPT casing.

The following summarizes selected comments made without crediting the content to specific individuals. Attempt was made to sort the largely free-flowing comments by topic. The summary is in verbal bullet style and is based on notes taken at the workshop.

5.1 Topical discussions:

- <u>Secondary flows</u>
  - We don't have a good understanding of secondary losses. We should explore that design space.
  - Endwall divergence is important. Disagree with some audience comments seemed to suggest it was not so important.
  - Diverging endwalls results in 2 times higher losses than with a straight law. Why? This is a potential experiment
  - Question is how LPT diverging end-walls affect the losses
  - Very little is known about the effect of Re in secondary flows, need to have better testing, understanding
  - To tackle secondary losses need to test experimentally then explore CFD
  - Is it unsteadiness, radial effects, or both?
  - Endwall profiling is hard because a lot of these flows can be transitional even in the endwall region. Have seen it in turbine rigs both upstream and downstream of passage lift-off line. It can be laminar in purge flows. Endwall flows go in the direction of favorable pressure gradient.
  - Endwall profiling is not general enough.

- If you can predict secondary flows accurately, you can do endwall profiling.
- More experiments are needed to more data so that we can model it better. The predictive system needs to capture these effects.
- Systematic study, flat wall, divergent wall
- Is it possible to release a generic endwall for computation and experiments

- Passage vortex
  - How the endwall flow looks in the absence of the inlet vortex.
  - In a purge flow, the chances of a horseshoe vortex are small.
  - We covered 30% of the pitch with a suction, and the passage vortex developed just the same.
  - When we eliminated the passage vortex, we increased the efficiency by a factor of 3 or 4.
  - The passage vortex does not exist. We did PIV, and there was not a vortex in any single picture. When the pictures were averaged, we saw the vortex. You have to think about scale.
- Thick vs. Thin LPT airfoils
  - IPT has run thin and thick airfoils – both are needed, but hard to discriminate where losses are produced
  - Proposed to run thin airfoil in a rig, change out to a thicker airfoil, test and compare.
  - Since we don't understand streamwise vorticity well, best way we'll understand is to put a thick and thin airfoil in a cascade
  - Some participants feel cascade studies should be done first to compare blade thickness, learn fundamentals to get started then move to a rig test.
  - There was argument if cascade testing is really needed.
  - What's wrong with a cascade? The endwall separation is significant.
  - In endwall boundary layer; thick and thin boundary layers are prevalent
  - Commonality between thin and thick blading and pressure-side separation of VSPT take-off condition
- HP/LP interaction
  - Include Transition duct
  - Include EGV
  - Understand aggressive transition duct which impacts LPT
- Misc. Flow physics
  - Pressure side separations – fundamental separation – how do you do a fundamental experiment
- Test program
  - We need a test program that changes one thing at a time to understand each effect individually.
  - Consensus that a rotating rig is needed
  - Lower speed rotating facilities.

- It’s hard to make measurements in rigs. Do we need to build special rigs keeping in mind measurements?
- Can you measure details well enough to be able to verify a CFD code?
- We get bulk measurements from the rotating rig and detailed measurements from CFD.
- There are old measurements that we should look at
- We need to ensure appropriate inlet boundary conditions to the LPT. Probably the only way to do that is to have an HPT stage upstream feeding the LPT, which is a real challenge because of the dual spools.
- In selecting the rig facility, an error analysis should be conducted to ensure the ability to measure efficiency accurately at the low pressures associated with low Re operation. Hope to be able to run at Re as low as 30,000 to 40,000 range.
- I think having input from each of the engine manufactures for this baseline rig will ensure that the rig represents all of our needs.
- More real geometry and leakage in the rig in later years.
- There are not enough experimental PhDs with careful, systematic backgrounds. That’s what we need in experiments

- <u>Differences from rig to engine</u>
  - Worse performance observed in an engine than in a rig
  - Steeper Reynolds Number fall-off in rig
  - Off-design had bigger delta in engine
  - Get details right
  - Hot to cold conversion
  - My experience is that our results from the rig are not the same as those in the engine, especially for off-design conditions.
  - We can usually get similar deltas in the rig and in the engine. We might be getting the right answers, but not necessarily for the right reason.
- <u>Engine testing</u>
  - Proposed to map out boundary layer in engine to get a basic physical understanding of what’s going on in an engine environment.
  - We should map out the boundary conditions in the engine, including incoming turbulence
- <u>3D rig vs. 2D cascade testing</u>
  - When we have 2D flows with similar unknowns, we can predict the differences between engines pretty well. It’s when we move between rigs where we have trouble. We don’t know the turbulence, purge flows, flow angles.
  - There is a fundamental problem with pressure side separation in 2D. In a 3D rig, that flow tends to centrifuge. How do you design an experiment to separate the centrifuge? Can we get the understanding from a 3D rig?
  - We need cascade as a benchmark to understand what’s happening in the rig.
  - It’s difficult to tell where the losses are coming from in a 3D rig.

- We don't have a good understanding of secondary losses. We should explore that design space.
- Diverging endwalls results in 2 times higher losses than with a straight law. Why? This is a potential experiment.
- Endwall divergence is a very important item to consider in the baseline rig.
- Is it unsteadiness, radial effects, or both?
- Do we want a rotating rig test? If so, we could write a white paper to get funding.
- You should send the old paper out so we can update it.

- CFD and modeling
  - We have to be careful about how we use CFD codes. They have to be used with caution and we have to understand the limitations. We need basic physical understanding in order to improve efficiency. We have talked about Re effect. You have been able to predict it, but you don't understand it.
  - Lack of CFD standard. Example was given of using the same model but getting two different solutions.
  - Perform optimization in multi-stage environment
  - RANS is not a good framework for incorporating transition and endwall. If that's the case, what is the next step? Do you think that at low Re, LES would do a better job?
  - The code is not capturing the observed effects.
  - RANS is pretty reliable for simple flows, but they don't have much confidence in it for complex flows. The problem with RANS is that it is a very general term. There are several different models. Even two k-epsilon models can be implemented differently. We need to set a standard. There can be errors in the code that are blamed on the model.
  - Note AIAA survey of RANs (modelers, developers, users, applications): RANS considered a major workhorse. RANS has been progressing to be more reliable (SA and SST); feeling next 15 years will see more development on complex flows. Need to establish a standard
  - LES notoriously bad at transition.
  - LES is not going to help that much with predicting transition. LES is not going to be ready until 2045. Some understanding can be gained from LES and it can be used to improve RANS.
  - LES is important in some situations. Computing power is growing fast.
  - LES Applicability? Argument that there is too many option, gets to be confusing
  - LES can't do predicting transition, but it can do wall bounded flows.
  - Are there benchmark problems that we don't understand where we could apply LES?
  - Need to distinguish between benefit of including deterministic unsteadiness in calculations and steady (RANS vs. URANS) vs. LES
  - Hybrid RANS-LES could let us incorporate transition.
  - It would be good to have a tool that would tell you that one airfoil is better than the other

- A simulation without leakage flows will have a much different result at the endwall.
- Is it worth it to do the work to capture all the small effects in CFD?
- Let's not forget that LPTs are running at 93%, but we need 95%. Even with a toolbox that could predict everything, do we know exactly how we want the flow to behave?
- Is it possible to release a generic endwall for computation and experiments?
- We should work on that.
- If I were a tool developer and I developed a code that would give the right answer, would I be able to solve the problem of predicting the differences between a small engine and a large engine.
- Can you measure those things well enough to be able to verify the code?
- A simulation without leakage flows will have a much different result at the endwall.
- My experience is that our results from the rig are not the same as those in the engine, especially for off-design conditions.
- We can usually get similar deltas in the rig and in the engine. We might be getting the right answers, but not necessarily for the right reason.

- <u>CFD role in experiments</u>
  - Pre-test predictions
  - Post rig test CFD
  - A participant was successful using CFD to interpolate experimental data. Use experimental data to anchor CFD and use CFD to see detailed areas in rig.
- <u>Test cases</u>
  - Industry provided test cases: explore leakage and endwall profile
  - Is the data from Notre Dame available? Yes, final data is being formatted. Will be available to US.
- <u>Core noise</u>
  - Becoming more important, if testing multistage need to get acoustic measurements
  - Noise regulations are going to get more restrictive. The design trends we have been discussing will lead to stronger noise sources, less attenuation, and stronger interactions effects. We should do the 4 stage rig and take measurements.
  - The last stage is believed to be the noisiest.
  - We would put a duct after the turbine and measure the pressure distribution. We can do a modal decomposition on it for tonal noise.

5.2 Summary of action plan discussions:

- Need for multistage testing
  - Multistage test increases difficulty in facility, due to increased pressure ratio
  - Need understand effect of tips, gaps, end-wall, and 3D issues
  - Need to understand differences between high and low speed
  - Need to characterize the disturbance environment and understand its role

- Use proper instrumentation, there are challenges, need smaller sensors. Can we apply pressure on manufacturers?
  - Use the data to compare to simulations.
  - Low speed or high speed testing?
  - One problem with low speed is that most CFD is done with compressible flow.
  - In the test, we change the pressure to change the Re
- Conduct simplified lab testing complementary to rig tests. We might not be able to get the best measurements in the full rig, but we could compare to the fundamental experiments.
- There's a spectrum of research. Universities need to take on simpler projects that look at a specific issue.
- CFD resource requirements could significant in personnel and computing time
  - Pre-test predictions
  - After selecting a geometry, let the CFD predict the flow, and use that information to plan the instrumentation needed for the experiment. Then build the rig and do the experiment. That's what Sandia Labs does
  - Post rig test CFD
- Geometry – consider E^3 or relevant blading.
  - Common geometry available to all
  - How aggressive a design?
  - Need a SoA LPT baseline as reference for improving efficiency
  - Everyone would have to agree that the baseline is representative of what we have today.
  - We need a 3 stage minimum rotating rig. You don't reach a fully developed flow at the 2nd stage. We know that 3 is different from 2, and we have some evidence that 4 is different than 3.
  - What if we can't get 4 stages? Do we sacrifice number of stages or speed? There is not that much difference in building cost, just running cost.
  - Establish set of test cases
  - Decision needed: Low speed vs. reduced number of stages
  - Scaling down makes measurements harder.
  - Are we worried about Mach number effects? Cannot assess importance, but best to focus on the most important features.
  - We should consider including a HPT and transition duct. At least the exit guide vanes.
- CFD Needs:
  - Well established boundary conditions
  - Turbulence intensities at inflow at every inlet
  - Static pressure profile for every exit
  - Flow rates for leakage flows
  - Unsteady data
  - Pressure distribution
  - Hot running conditions, geometry, clearance
  - Surface temperature distributions
  - Transition and separation locations
  - Turbulence level & scale inter blade rows

- o Flowfields, e.g., via optical measurements
  - o Spanwise profiles
  - o Different information for different types of simulations, e.g., midspan vs. endwall
  - o Need unsteady measurements
  - o It's really hard to get unsteady measurements since the scales are so small
  - o Using a website database for verification
- Direction headed towards
  1. Establish geometry
  2. CFD performing pre-test predictions to define requirements
  3. Rotating rig test
- Value of investment
  - o How much is 2% efficiency worth to industry? Billions. 5-10 million cost of a program should be an easy sell
- Power Turbine
  - o PTs could be much harder because they go so far off design.
  - o We should separate PT research from LPT

<u>List of recommended action items</u>:

- o Establish post-workshop subcommittee
- o Asses potential LPT designs for baseline geometry rig test
- o Asses capabilities and availability of potential experimental facilities
- o Capture relevant design parameters
  - o Reynolds Number
  - o Loading
- o Initial input due 9/8/2010
- o NASA Report on LPT workshop

6. Post-Workshop Committee Discussions

The purpose of this paragraph is to briefly report on the post workshop committee discussions. These discussions were conducted for several weeks after conclusion of the workshop. The committee has convened by teleconference and the following conclusions resulted. The issue was forwarded for decision by project management. Unfortunately no funding allocation was made to pursue the proposed project.

It was agreed that NASA GRC's new warm turbine rotating rig W-6 is the best facility to conduct the experiments.

1. The W-6 rig need modifications to accommodate low Reynolds number flows.
2. A three-stage minimum is required for the test article.

3. After examining several possibilities, it was agreed that the Prat & Whitney Energy Efficient Engine (E^3) LPT design (Ref. 20) is appropriate as baseline design for the test article.
4. Based on past experience, cost of constructing the experiment was estimated to be in the order of $4-5 Million. It is a rough order-of magnitude estimate that t includes rig modification, instrumentation, complete design of test article, and fabrication of the test article.

7. Conclusion

The workshop received positive reviews and was considered successful. Due to budgetary and programmatic priorities there were no subsequent activities conducted by NASA in this area.

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Appendix A

Reprint of:

Howard Hodson, University of Cambridge and Om Sharma, United Technologies Research Center, “Highly Loaded Low Pressure Turbines,” in: Heidmann J., et al. “Aerothermodynamics Technical Working Group: 2008 Turbomachinery Technology Assessment and Recommendations,” NASA/TM—2020-220219, pp. 19–27.

7.0 Highly Loaded Low-Pressure Turbines[2]

7.1 Part I: Profile Design

7.1.1 Description of Problem

The low-pressure turbine (LPT) powers the fan and, in some cases, the booster stages. It is constrained to rotate at the same speed as the fan unless a gearbox is provided. However, a gearbox is not usually used in an aeroengine because of the weight penalty and cooling required for such a large structure. The outer diameter of the LPT is also constrained by the presence of the bypass duct and stress limitations on the materials used. The combination of a low rotational speed and limited diameter means that LPTs usually operate at blade-relative exit-flow Mach numbers in the range 0.6 to 0.9. Transonic LPTs are rarely seen in aeroengines. The work output for a given stage is limited because the blade speeds and flow Mach numbers are relatively low. Because the majority of the thrust is produced by the fan in high-bypass-ratio engines, there are many stages in the LPT. This means that the LPT is heavy, accounting for about 20 to 30 percent of the engine's weight, and is expensive to manufacture. The engine weight and cost can be reduced if each airfoil can be made to carry a greater aerodynamic load, thereby reducing the number of airfoils. The efficiency of the LPT strongly influences the SFC of an engine, where a 1-percent increase in LP polytropic efficiency improves the fuel consumption by 0.5 to 1 percent. With efficiency levels already much greater than 90 percent, there would appear to be little scope for improving this aspect of performance without a step change in technology.

A typical LPT has blades with large aspect ratios, which are usually in the range of 3:1 to 7:1. Because of this, the profile loss is by far the largest single contributor to the total loss of efficiency in these blades. Because the blades have relatively thin trailing edges, the magnitude of the profile loss depends mainly on the development of the airfoil boundary layers, particularly those on the suction surfaces. The Reynolds number (Re) of an LPT blade ranges from about 0.5×10^5 in the final stage at high altitude in small business jet applications to about 5×10^5 at sea-level takeoff in the first stage of the largest turbofans. Between takeoff and cruise altitude, the Re might fall by a factor of between 3 and 4. Given these Re values, boundary-layer transition and separation play important roles in determining engine performance at different operating conditions.

Low Re values mean that an inability to accurately predict how the boundary layers undergo transition from laminar to turbulent flow limits the degree of certainty associated with a given design. For example, increasing the lift coefficient or decreasing the Re is likely to cause the growth of laminar separation bubbles on the rear part of the suction surface. This is one of the main sources of the suction-side loss. In the past decade, by using incoming wakes from upstream blade rows to periodically promote transition in the suction-side boundary layer, it is possible to increase the lift on each blade and therefore reduce the number of blades and weight of the engine without reducing the efficiency. In some cases, it has actually been possible to raise the efficiency.

The introduction of unsteady wakes into an LPT with separation bubbles has three effects: (1) the wake interacts with the separation bubble to produce a high-loss turbulent flow associated with a rolling up and breakdown of the shear layer (a significant source of increased loss), (2) turbulence-induced attached flow follows this vortex, and (3) the so-called calmed period that follows. During this time, the boundary layer has not yet reseparated from the surface, and the losses remain at typically attached laminar levels. This is a truly unsteady effect. The effect on the overall loss is governed by the

[2]Lead authors: Howard Hodson, University of Cambridge, and Om Sharma, United Technologies Research Center.

balance between the reduction in the bubble-generated losses in the calmed period and the high-loss turbulent regions generated before this.

Below a Re of 100,000, the profile losses of airfoils tend to follow a laminar trend (loss scales with $Re_C^{-0.5}$, where Re_C is Reynolds number based on axial chord and exit velocity). This indicates that in the low-Re regime, the large suction-side separation bubble dominates the overall loss production. Thus, the introduction of unsteady wakes beneficially suppresses the separation, causing a reduction in the boundary layer loss. Increasing the reduced frequency tends to reduce the loss further. At Re values above 200,000, they are more likely to follow a turbulent trend (loss scales with $Re_C^{-0.2}$). This indicates that at high Re values, the bubble is small or nonexistent and the loss generated in the turbulent boundary layer downstream of reattachment dominates.

For a given amount of deceleration over the rear part of the suction surface (usually quantified by a diffusion factor), moving the peak velocity forward on the surface reduces the rate of deceleration. This tends to reduce the bubble-generated losses, at the cost of increasing the extent of the turbulent boundary layer. Front-loading therefore improves the low-Re performance, where bubble-generated losses are more significant, at the expense of the high-Re performance, where turbulence-generated losses are more dominant. Conversely, moving the peak velocity further aft has the opposite impact, reducing loss at high Re values at the expense of low-Re performance. This also helps in reducing the development of secondary flows and improving the tolerance to incidence, which is useful because increasing the lift tends to have the opposite effect.

The LPT of the NASA Subsonic Fixed Wing (SFW) Project is likely to have Re values in the range 70,000 to 200,000 at cruise conditions. Understanding and, crucially, being able to predict the unsteady separated and transitional suction-side boundary layer is essential in developing airfoils with increased lift that retain the already high levels of efficiency. Unfortunately, increasing the lift beyond today's levels represents an even greater challenge, especially as a reducing core size means that the Re is also reducing. There is also evidence that without a step change in technology, the lift cannot be increased without a reduction in efficiency. Recently, boundary-layer flow control has shown some promise in this direction, particularly when it is used in conjunction with the incoming wakes.

Today, the majority of advanced LPTs are still designed using two-dimensional (2D) steady codes. Yet, it is well known that unsteady flow is necessary for the efficient operation of many LPTs. Indeed, the MISES code of Drela and Giles seems to be almost universally employed. MISES is a 2D solver that couples an integral boundary-layer solver to an inviscid free stream. The correlations used for modeling transition onset in attached and separated flows are often adapted by its users. Though these correlations are simple, they are the mainstay of many transition predictions, and their exact details are closely guarded. In some cases, these have been adapted to allow some consideration of the effects of the unsteady flow. It should also be noted that these correlations are only applicable to 2D, often incompressible, boundary layers.

There are many reasons why 2D steady codes are still the mainstay of LPT design. One reason is that no practical alternative currently exists. Many of the better codes rely on using the integral parameters to define the onset location via correlations and then employ a low-Re turbulence model to predict the growth of the transitional flow. But even 2D URANS (unsteady Reynolds-averaged Navier-Stokes) codes are currently unable to predict the entire range of possible transition mechanisms in the LPT with sufficient fidelity, even for a single stage. However, most implementations are technically flawed because they do not acknowledge the fundamental rules governing the growth of unsteady transitional flow. Prediction of multimode transition (i.e., transition which at certain times occurs in a separated shear layer and at other times in attached flow), prediction of the speed at which the transitional flow regions grow and move along the surface, as well as prediction of the size and duration of the calmed period remain a particular difficulty. There are no high-fidelity 2D multistage transitional calculations.

7.1.2 Overview of Proposed Research

The efficiency, cost, and weight of the LPT are critical to the success of the NASA SFW Project. The proposed research should focus on three areas. First, simultaneous data are required concerning the disturbance environment and boundary-layer behavior in multistage machines. Second, methods must be developed that can properly and efficiently model this flow. Third, methods of supplementary flow control are required.

Though a handful of measurements have been made in LPT test rigs, these data are very sparse and inadequate, and the geometry is unavailable to the research community.

7.1.3 Research Activities

Proposed research will include the following areas.

7.1.3.1 Profile Development

A large body of research already exists studying the effects of wakes on suction-side boundary layers of LPT airfoils in the 2D cascade (or single-stage) environment. These data have been successfully used to improve LPT designs in the past. This approach should continue, using low-speed as well as high-speed (transonic) facilities to develop and demonstrate new approaches to designs. These cascades must be fitted with upstream wake generators to simulate the primary source of unsteadiness in the LPT.

In the first instance, cascade facilities should be developed or upgraded to include wake-generating mechanisms. In the case of transonic facilities, this will require considerable effort. The first studies should focus on determining the style of velocity and pressure distributions appropriate to profiles with an increased lift. Since this is likely to lead to a forward loading of the airfoil, the effects of incidence must also be studied in detail. This is a significant omission from many studies. New profiles can then be prepared based on the outcome of this research. The effects of high peak Mach numbers also require special consideration as these may exceed unity. The initial part of this study should take no more than 2 years.

The most successful studies of this type have taken place in universities, and this is likely to continue to be the case.

7.1.3.2 Multistage Test Vehicle

Although there is much information available from cascades, there is almost no information on the behavior of the suction-side boundary layers in multistage LPTs, apart from a small number of surface shear stress measurements. These have shown that although the first few blade rows behave in a manner that is similar to those in cascades fitted with upstream wake generators, the rising level of unsteadiness through succeeding blade rows creates a confusing picture of the behavior of the boundary layers. The next generation of experimental research must include a detailed study of the multistage environment, including measurements of both the boundary layers and the disturbance environment. Without this basic information, it will be impossible to validate the necessary method developments.

An LPT test vehicle should be developed to enable the measurement of the disturbance environment and the development of the blade surface boundary layers. The same experimental test vehicle can also be used to validate new LPT designs and to assess novel methods of flow control. A program of this type is expensive and time consuming, requiring at least 3 if not 5 years to bring to completion. Industry should be encouraged to provide the test vehicle, but universities and other research organizations should be enlisted to support the development of the advanced instrumentation that will be required.

7.1.3.3 Transition and Flow Control Devices

Flow control has not yet been used in LPTs, although some data exist from cascade studies that suggest that low-Re operation can be improved using simple passive systems such as surface roughness or trips that enhance the transition process between the wakes. In addition, active techniques, such as vortex generator jets, could be advantageous at very high lift coefficients and/or very low Re values. A two-part program of work is envisaged, which is aimed at exploiting flow control in very high lift situations. A combination of experimentation and large Eddy simulation (LES) and direct numerical simulation (DNS) calculations is envisaged:

(1) In the first part, fundamental studies of the effects of passive and active systems should be studied in depth to provide information on how these systems work and for the development of suitable prediction methods. These studies must include an accurate assessment of the impact of the flow control on the SFC.

(2) In the second part, passive and active systems should be developed that can be applied in the LPT in practice. It should be sufficient, on the first instance, to demonstrate these technologies using a representative 2D cascade that is fitted with upstream wake generators. Should this prove practical and worthwhile, the system can then be demonstrated in the multistage LPT described above.

Universities and other research organizations are best suited to the first part. The second part requires a close collaboration between these groups and industry. This program is expected to last for up to 10 years.

7.1.3.4 Model Development

Calculating transition in 3D unsteady flows presents a severe challenge today. Very little data and even fewer suitable models exist for relevant 3D flows. Compromised methods do exist for 3D URANS equations, and these are used, but with limited success. LES and DNS do offer a greater possibility of success, but not within the next 5 years. These methods can, however, be used to enhance experimental databases. No methods exist that have been successfully applied to the calculation of LPT boundary layers when using supplementary methods of control.

The prediction of the transitional behavior of boundary layers in the unsteady multistage 3D environment cannot continue to be based on correlations developed originally for integral boundary-layer solvers. Nor can it ultimately rely on 2D methods: to do so denies the three dimensionality of the unsteady flow in the LPT. Nevertheless, 2D methods will continue to be required for preliminary design. Therefore, the development of an entire hierarchy of computational methods is required, which deliver consistent results of increasing fidelity as the complexity of the model increases. These methods must acknowledge the peculiar aspects of unsteady multimode transition, the importance of the disturbance environment (which may include transition control devices), and be capable of use in 3D simulations. Most existing RANS methods are not capable of the required extension. It is expected that the methods will range from 2D URANS through 3D LES with zonal DNS. The timeframe for the development of such a complete set of tools would be in excess of 5 years. Universities would be best suited to this development role.

The development of a high-fidelity 2D (with streamtube height variation) computational method based on URANS/LES is of the highest priority.

7.1.4 Outcomes

Immediate results include a determination of whether or not it is likely to be able to increase the lift, whether or not control devices are required to achieve this, a description of the 3D unsteady flow field in the LPT, high-fidelity 2D URANS methods, and a roadmap for model development. Long-term results include a demonstration of very high lift technology; successful flow control devices, if viable; methods for use in design; and the development of a hierarchy of transition models for use in LPTs that includes the effects of periodic unsteadiness, turbulence, roughness, and other flow control devices.

A 1-percent reduction in direct operating costs is approximately equivalent to a 1-percent increase in component efficiency, an 8-percent reduction in engine cost, and a 17-percent reduction in engine weight.

The greatest risk is that it will not be possible to develop an LPT with increased lift and a substantially unchanged efficiency even when using flow control.

7.2 Part II: 3D Design

7.2.1 Description of the Problem

The design of modern LPTs is a compromise between efficiency, cost, and weight. Increasing the 2D profile loading of LPTs reduces the cost and weight, but risks compromising the efficiency of each blade section. This is because each blade carries a greater aerodynamic load, and this tends to increase the net aerodynamic loss generated within the blade surface boundary layers, even though there are fewer blades. This aspect of LPT design has received much attention in recent years, and considerable progress has already been made. However, increasing the blade loading also increases the so-called cross-passage pressure gradient as the difference between the suction and pressure side pressures increases. This gradient leads to the development of secondary or 3D flows close to the hubs and tips of the LPT blades.

Several features, including the overturning of the endwall boundary layers and the formation of the passage vortex, identify the secondary flows. The cross-passage pressure gradient that turns the mainstream flow also affects the endwall boundary layer, which contains slower moving fluid and is therefore overturned. In addition to the cross-passage pressure gradient being increased when the profile loading is increased, local streamwise pressure gradients are also increased. As a result, local flow reversal can occur, and this serves to increase the magnitude of the secondary flows and associated losses still further. This problem is exacerbated in low-Re flows because laminar flows, which are then more prevalent, will withstand only small adverse pressure gradients before separating. When solid, thin—as opposed to hollow—blade sections are used to reduce the cost and weight of the LPT, increasing the loading can lead to the formation of a very long (typically 30 to 50 percent of the chord length) separation bubble on the pressure side. The flow within the separation bubble can interact with the secondary flows on the endwalls and lead to a further increase in the strength of the secondary flows and losses. This is a result of the spanwise (radial) pressure gradients.

There is an opportunity to alter the spanwise loading, reaction or vortex design in LPTs. As a consequence, a more optimal balance between the profile and secondary-flow losses may be obtained. This is suggested because the secondary-flow losses are traditionally thought to deteriorate less as the core size, and therefore the Re, is reduced. This may be because, as has recently been shown, the boundary layers on the endwalls of multistage LPTs can begin as laminar and progressively become more turbulent as they develop. This transitional behavior has been observed in the case of the boundary layer upstream of the leading edge and in the new boundary layer that develops inside the blade passage as a result of the cross-passage pressure gradient. Given that some HPT cascade studies have revealed transitional boundary layers at much higher Re values, this behavior in LPTs is likely to be common. Furthermore, it has been shown that the state of the incoming endwall boundary layer has a significant effect on the development of the secondary flows, and it is likely that the effectiveness of 3D designs will also be dependent on this state.

The secondary flows and losses in LPTs have many similarities to those in HPTs. As a result, LPTs can be controlled using features such as endwall profiling, lean, and sweep, which are beginning to be found in HPTs. However, additional care must be taken when using these geometrical features to control the near-endwall static pressure field and therefore, the secondary flows. This is because the endwall flow can change dramatically when steps and leakage flows are introduced into the annulus line. This is partly related to the transitional nature of the flows, as the laminar flows are less robust. These steps and leakage flows occur because stationary and rotating parts are encountered in the turbine, and this implies the existence of gaps. At the hub, hot gas-path flows can enter the disc cavities, causing thermal fatigue. To prevent the ingestion of hot gas, relatively cold air from the compressors is directed to the turbine discs. The effect of this air is to cool the disc cavities and to avoid the ingestion of hot gas due to the pressure difference between the cooling air and the mainstream. At the casing, flow leaks over the shroud of the turbine rotor. Exactly how this leakage of cooling air is introduced into the main gas path leads to the aforementioned steps.

7.2.2 Overview of Proposed Research

The effect of features such as steps, leakage flows, and endwall profiling can be predicted with some success. However, computations of the flow associated with the real LPT geometry are rare, and the transitional nature of the endwall flow has yet to be addressed in experimental or computational studies. Furthermore, in an engine the general pattern of endwall flows will be affected by the unsteadiness associated with the vortices and wakes from upstream blade rows and the potential fields of upstream and downstream blade rows. The presence of tip leakage and hub leakage flows will also influence the endwall flow structures, possibly through several stages. In addition, potential interactions and the presence of radial pressure gradients will modify the structures of the endwall flows and their interactions with the mainstream flow. Whether a flow is laminar, transitional, or turbulent, and whether it is separated or attached, will affect the success of particular design choices.

7.2.2.1 Endwall Flow Studies in Cascades

A limited number of studies of the 3D endwall flows and losses already exist for conventional and high-lift LPTs. This work requires extension to higher lift and needs to cover a wide range of Re values. Fundamental studies, using CFD and experiments, of the individual and combined effects of the style of velocity and pressure distributions appropriate to profiles with an increased lift, annulus line changes, endwall profiling, shroud and hub leakage paths, blade lean, and blade sweep are required. Much of the experimental work can probably be carried out in low-speed cascades, with the extension to high-speed flows being performed using CFD calculations. The effects of high peak Mach numbers require consideration as these may exceed unity.

The most successful studies of this type have taken place in universities, and this is likely to continue to be the case. A timeframe of 3 to 5 years is envisaged.

7.2.2.2 Multistage Environment

A multistage test vehicle has been proposed for the research related to high-lift profile design. It is proposed to use this same vehicle for an in-depth analysis of the 3D flows within the engine environment. Steady as well as unsteady fast response measurements are required. Prior to this study, 3D design of LPTs should be examined computationally. This study should extend to the optimization of the leakage paths, the endwall profiles as well as fundamental studies of blade loading, reaction, and vortex design. A limited number of unsteady analyses should also be performed.

A program of this type is expensive and time consuming, requiring at least 3 if not 5 years to bring to completion. Industry should be encouraged to provide the test vehicle and to perform the design studies but universities and other research organizations should be enlisted to support the development of the advanced instrumentation and computational methods that will be required.

7.2.2.3 Transition, Separation, and Reattachment

The 3D endwall flows in actual LPTs have recently found to be transitional. Separation and reattachment are also features of endwall flows. Unfortunately, there is very little data available concerning transition in highly skewed boundary layers, which are subject to severe favorable and adverse pressure gradients, such as those found on the endwalls of the LPT. A three-part program of work is envisaged that is aimed at improving this situation.

In the first part, fundamental studies of 3D skewed boundary layers in controlled pressure gradients is required. This will assist in the physical understanding of the transition mechanisms and quantify the relative importance of the pressure gradients, skew, and free-stream disturbances.

In the second part, cascade models would be used to verify the findings of the fundamental studies and to provide validation data for CFD codes.

In the third part, models are required to be developed that are capable of predicting these flows. LES and DNS should be used to enhance the experimental database. The required methods must acknowledge the peculiar aspects of the unsteady 3D endwall boundary layers, including the leakage flows themselves. The timeframe for the development of such model is likely to be in excess of 5 years. Universities and other research organizations are best suited to this research.

7.2.3 Outcomes

Immediate results include a determination as to whether or not the secondary-flow losses will limit or enhance the ability to increase the lift of the LPT and whether or not endwall flow control will be successful. Long-term results include a demonstration of very high lift technology; successful flow control techniques, if viable; and methods for use in the design and development of transition models for use in 3D endwall flows such as those found in LPTs.

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Appendix B

Reprint of:

Efficiency Considerations in Low Pressure Turbines, Minnowbrook IV LPT Discussion Group Summary (NASA/CP—2010-216112, pp. 601–604).

NASA/CP—2020-220327

Efficiency Considerations in Low Pressure Turbines

Discussion Group Topic

Minnowbrook VI Workshop

8/24 -26/09

NASA/CP—2020-220327

Discussion Group List of Participants

Ravikanth Avancha (GE Research)
John Clark (AFRL /RZTT)
Paul Gostelow (NRC Canada & University of Leicester)
Howard Hodson (Cambridge University)
Inga Mahle (MTU)
Lou Povinelli (NASA GRC)
Om Sharma (UTRC)
Ken Van Treuren (Baylor University)

Issues & Topics Discussed

- **Aviation Week reported shortfall In LPT efficiency due to the application of "high lift airfoils"**
- **Progress in the design technologies in LPTs during the last 20 years**
  - **Application of RANS based CFD codes**
  - **Integration of recent experimental data and modeling of LPT airfoil specific flows into design methods**
- **Opportunities to further enhance LPT efficiency for commercial aviation and military transport application and to impact emissions, noise, weight & cost**

Recommendations

- **Hold a workshop with participation from the aviation propulsion industry in USA & EU to benchmark status and opportunities to improve SFC and reduce the emissions through enhancements in LPT performance**

- **Focus the LPT research effort to align with the Environmentally Responsive Aviation initiative**

Appendix C

J. Paul Gostelow, University of Leicester, and Om Sharma, United Technologies Research Center, “Post Minnowbrook VI Summary,” August 2009.

Summary - Following Minnowbrook VI Workshop, August 2009 (NASA/CP-2010-216112)
J. Paul Gostelow & Om Sharma

Low pressure turbine (LPT) efficiency falls off between sea level take-off and altitude cruise conditions due to a halving of Reynolds number. Workshops were convened twenty years ago to address this issue and high-lift turbine blading was conceived in the process. NASA initiated research programs on this topic and funded the first Minnowbrook workshop. Considerable effort was invested in attempts to understand boundary layer behavior on turbine airfoil surfaces dominated by unsteady transitional flows. The attendant research generated the good interaction between industry and universities that resulted in high lift turbine blades. The major engine companies have deployed these with significant benefits in engine cost and weight reduction but it has proved difficult to maintain high efficiencies. Although the reasons for the discrepancy between the expectations and results are not fully understood, it is thought that current design procedures have not adequately addressed issues such as secondary flows, purge flows and tip clearances; these are known to be principal contributors to loss.

It is recommended that a workshop be held with participants from the aircraft engine industries in the USA and the European Union to benchmark status and to identify opportunities to improve the specific fuel consumption and reduce emissions through the enhancement of low pressure turbine performance. The LPT has a larger impact on the fuel consumption of the engines used in commercial aircraft than other components. If the LPT efficiency is improved by 1%, then the fuel consumption for the engine is reduced by 0.7 to 0.95%. An improvement in the efficiency for HP compressor, HP turbine and fan yields reductions in fuel consumption of about 0.6%, 0.6% and 0.8% respectively. It is important to improve the performance of all components but incentives for the LPT are particularly high.

It is further recommended that the low pressure turbine research effort be re-focused to align with the NASA's Environmentally Responsive Aviation (ERA) initiative. To reduce carbon dioxide signature, emissions and noise the best return on investment will be gained by improving the LPT efficiency; this can be raised from 93% to 95%, yielding a 1.8% reduction in fuel consumption for aircraft engines. NASA is investing funding in the ERA program and this is one of the areas in which NASA can be supported to achieve its objectives.

Considerable progress has been made over the last two decades as a result of LPT-related research. Robust design systems have been developed and it has been demonstrated that high performance turbines can be designed for large engines by companies other than OEMs. It has also been demonstrated that highly loaded turbines can be designed with relatively low loss in performance. It has, however, not yet been possible to design very high performance turbines with high lift (reduced blade count) airfoils. Currently, increasing the lift beyond today's very high lift levels results in a loss of efficiency. It is not clear whether, or not, that is a necessary evil of such lift coefficients. Although, over the last twenty years, substantial improvements in weight and blade count have been achieved, the race is now on to regain, and improve, the efficiency sacrificed in the process. On both economic and environmental grounds our future effort needs to be focused on achieving this goal.

Appendix D

Frederick Simon, NASA Glenn Research Center: Bypass transition workshop summary document, 1993.

November 24, 1993

TO: David Bowditch/Chief Technologist/2000

FROM: Fred Simon/2630

SUBJECT: 5th Annual Bypass Transition Workshop(11/18-19/93)

The subject workshop was held in 215 of the Administration Building. In attendance at the workshop were representatives from Case Western Reserve, University of Minnesota, University of Texas, University of Toledo, Texas A&M, Dynaflow,Inc., Pratt & Whitney, GE Aircraft Engines, Allison Gas Turbines, Textron Lycoming, NASA/Ames, NASA/Langley, NASA/Lewis, and NASA-ICOMP. A list of the Attendees is attached.

The purpose of the workshop is outlined in the attached handout. The workshop provides an opportunity for government and university researchers to present a status of the Bypass Transition work supported by the Heat Transfer Branch(2630) of IFMD. This year a request was honored to include our customers from the aircraft engine companies. This was done in the spirit of the new NASA agenda with the objective of "Working together to establish consensus and partnership on research critical to the national agenda" - see attached Robert J. Simoneau handout. It was also felt that phase one of the effort had been achieved and that input was needed from the users of this technology to plan future efforts.

As indicated in the attached agenda, the first part of the workshop was a status summary by the researchers in the areas of experiments, modeling and computations. This work was also summarized in a recent Transition Workshop sponsored by Syracuse University (TM 106278 - enclosed). The research was well received, with respect to its technical progress. However, our industrial partners questioned the applicability of our research to their design needs. The application of our transition efforts to the design of high pressure turbines was not seen as great need. They believe that the arena of interest should shift to the low pressure turbine. Presentations were made of loss in performance issues of a LP turbine for take-off and cruise conditions and the need to establish a consistent design approach. Their response and recommendations was expressed in the second part of the workshop. Their response is represented by the following quotes:

* "Majority of transition work not of value to design of turbines......"

* "Transition in attached flows can be reasonably well simulated for design...."

* "There is a need to work the right problem together"

* "There is a need to apply our resources to such issues as - **Improving Design Methodology and Consistency of LP Turbines Using an Agreed Upon Standard Approach"**

The engine companies see transition as having a relatively small impact on heat transfer and performance of film cooled turbines. They requested help in the area they label "Enabling Technologies". They are no longer in a position to impact this area to the extent they once did.

The above issues were discussed friday morning as means of planning the future direction of our efforts in transition, as applied to turbine vanes/blades and possibly compressors and fans. The discussions were fruitful and positive. There was general consensus of all the points discussed. The university people said that they were not aware of the needs of the engine companies and that they are very willing to work the research issues of interest to the companies. It was stated that these type of discussions with industry "need to happen more often". A summary of the discussions and recommendations will be prepared by Fred Simon and Bob Simoneau for distribution to the workshop participants for their comments. A final document will form the basis for a cooperative effort with the aircraft engine industries.

The key recommendations given at this workshop are as follows:

* Broaden the focus of the Bypass Transition Program to include LP Turbine effects.

* Reference the research to a standard LP turbine and conditions

* Strong endorsement is given to use low pressure turbine results of the E^3 program as the standard

cc: R. Simoneau

Appendix E

Robert J. Simoneau, NASA Glenn Research Center: Bypass transition workshop discussion notes document, 1993.

Notes from Transition Workshop Discussions

These notes are simply my recollections of the discussions on Thursday afternoon and Friday morning on Phase II directions for the by-pass transition program, more or less in the order the discussion occurred.

I. Thursday Afternoon

The Thursday afternoon discussion began with input from our invited industry partners and focused on their assessment of where the need exists (and doesn't exist). This discussion was facilitated by John Adamczyk.

John Adamczyk (NASA LeRC): John reported that he, Tony Strazisar, and a small group of invited industry and academia members held a workshop approximately a year ago on key issues in unsteadiness in turbomachinery. They produced a "white paper" and one of their conclusions was that much of the vast body of work on transition was not of great use to the turbomachinery community. (The high disturbance - by-pass - work was not included in this criticism.)

John emphasized the need to do turbomachinery specific work, especially for low pressure turbines. His agenda was to gather industry and get their input - recommendations, commitment and partnership.

Dave Wisler (GE): Dave introduced his input with a scaled down (and somewhat revised) version of the talk he had given at the WINCAT Meeting at Purdue. He later gave us a copy, which we have. (Should we attach it?) The main, and most important, revision to the Purdue version was the addition of the "Enabling Technologies" column in his "levels of interest" charts regarding various technical areas in turbomachinery unsteadiness. His main message was that the aircraft engine industry has embarked on a fundamentally - and permanently - different way of doing business. The industry is downsizing by about a factor of two.

Following that, Dave discussed the specific agenda, which we requested - transition and its importance (or lack of importance) in turbomachinery. His pitch was that the area for the potentially biggest payoff was the low pressure (LP) turbine. There is an approximately 2-point penalty in efficiency in LP turbines at altitude cruise (i.e. low Reynolds Number). There also seems to be an effect in compressors, but not as dramatic and probably something that can be engineered around. Much the same comment applied to high pressure (HP) turbine heat transfer. In discussing an agenda, re: b.l. transition, Dave recommended the following in rank order:

1. Effect of RE on LP turbine performance
   a) Efficiency studies
   b) Airfoil design methodology
   c) boundary layer transition studies
2. Transition in high pressure compressors

Dave's bottom line was, "Unless you can tell me how to bend the metal differently, it is all academic."

Larry Junod (Allison): Larry urged that in our plans we don't forget about the use of computationally simple techniques - especially in optimized or iterative processes (e.g. "tuning" the airfoil shape). The idea was that sometimes you don't need the absolute answer; you need to know how things change.

Larry agreed that there was not much interest in transition with regards cooling high pressure turbines. Industry tends to design to a worst case and wouldn't trust less. Film cooled surfaces are generally treated as turbulent throughout.

He said there was a strong interest at Allison in laminar blading for compressors. (This was seconded by Wisler.)

Rick Bozzola (Lycoming): Rick pointed out that small engines tend not to go to such high altitudes, as the large engines (implying a smaller Reynolds Number change).

Lycoming has an engine (T-55?) and an altitude test capability to go to 31,000 ft. They can run it, but they can't instrument it (money, I think). He offered it as a possible candidate for the program.

He also observed that what is not well-known is the conditions of the external flow. (?)

It was also observed (not sure who said this, but everyone agreed) that engineers are pretty smart people, who can work their way around things they don't understand. (Again, the implication was that you don't have to understand everything.)

Eli Reshotko (CWRU): Eli tended to agree with the last observation and said he could only cite one instance in his experience where that was not true and where design depended on fundamental knowledge - the ballistic missile reentry problem.

Eli commented that industry needs to make their problems known to the wider community (and sooner).

Sharma responded that he had a paper on the low Reynolds Number problem in the 1990 Reno meeting. John Adamczyk commented that MTU had instrumented an LP turbine (not sure whether this was published or something he and Tony saw on their trip to Europe).

Dave Halsted Iowa State/GE): Dave presented some of his dissertation work done at GE in the large low speed turbine show the Reynolds Number effect on transition. It is very nice work. It was a little unclear as to what details would be released in the thesis and subsequent paper.

Ohm Sharma (P&W): Ohm began by prioritizing Mike Crawford's "Future" chart (the hand written last chart in Mike's briefing): Item 1 - suction side high Re transition modeling - No. Item 2 - Adapt Transition models to minimal grid N-S solutions - Priority 2. Item 3 (a) - high dp/dx - No; (b) film cooling - ?; wake disturbances - ?; separation bubbles - **Priority 1**; (e) roughness - No.

Ohm's key point was that industry needs rules and guidance. They need consistency from design to design. This is more important now than ever, since they have less people. He went to say he saw this as opportunity - not disaster. They want understanding, not correlations, from the experts on key problems.

John Adamczyk (NASA LeRC): John posed the question whether industry would be willing to work with NASA to design an advanced two stage LP turbine to share around. (No answer in my notes.)

Dave Wisler (GE): Dave commented that there is a disconnect between industry and university that doesn't exist in industry. (Not sure I got this right, where it comes from, or where it fits in the conversation?)

Eli Reshotko (CWRU): Eli commented and asked whether it was possible to get together on the time scales (i.e. the urgency of industry needs vs. the normal PhD gestation time). He also commented that he was pleased that industry was coming forward with important problems.

II. Friday Morning

Fred Simon (NASA LeRC): Fred opened the discussion with a couple summary charts. He observed that from the previous day's discussion he drew the conclusion that transition in either the HP turbine or the HP compressor was not a "show-stopper." This observation did not imply that we understood or could predict transition in these machines; it just meant we could work our way around it.

John Adamczyk (NASA LeRC): John repeated and wanted to emphasize that we should not drop existing work, which is good. We should take on the new problem - the LP turbine. The question of whether we needed a multistage activity came up. John said he believed we did need a multistage activity and that his observation was that MTU felt the same way.

Bob Simoneau (NASA LeRC): In general, I did not take notes while I was on my feet, but I did jot down a couple things. I initiated a discussion on what the group felt the key variables (parameters) where. My notes say the response was: 1) Reynolds Number, 2) pressure loading, 3) embedded stage effects, 4) structure of the disturbances. I also initiated a discussion on whether the E3 LP turbine would be a good "generic" machine (as opposed to designing a new one, as proposed earlier). The consensus was that it would be; however, Ohm Sharma had already left, so we were going to confirm it with him. (Note: In subsequent discussion between Adamczyk and Sharma, Ohm said agreed personally, but wanted to run it through his management.)

Dave Wisler (NASA LeRC): Dave wanted to clear up some important terminology that he felt we were using loosely. He said industry is very careful to distinguish between "design practice/methodology" and the codes, models, etc. which help "design practice". His point was that each company has an official, written down, legal (or at least semi-legal) "design practice" which is their bible and which is carefully guarded. They would not invite outsiders into that arena. They will invite outsiders into the enabling technologies, which support "design practice".

Larry Bober (NASA LeRC): Larry requested that, when the "generic" LP turbine is selected, a 2D section also be agreed upon. This was to allow work in aero-elasticity.

Man-Mohan Rai (NASA LaRC): Man asked if it was essential that the work be in an embedded stage? (The obvious point was that this was certainly computationally impossible for DNS, at least now.) John Adamczyk said that in his opinion the answer was yes; but, that he had some ideas on how Man could simulate it and would talk off-line with him about it. (Note: In later discussions with Ian Jennions, John was brought to the thinking that maybe the first vane row was also important.)

Bob Simoneau (NASA LeRC): I was on my feet during all of the above discussion. I had made a discussion agenda chart (attached) and we returned to it. Some people where concerned about the use of the expression Phase I plateau, implying we had level off at the top. When I explained that I meant leveling off at some intermediate, but definitive, point, the group relaxed and agreed that we could make some recommendations. However, they deferred this to some later date.

The second question was on the group response to the industry assessment of needed enabling technologies (also the not needed ones). In general there was enthusiastic response to the proposed problem. This was particular led by Eli Reshotko.

The third question was where we were the right folks to do this (i.e. was the by-pass transition program the right foundation)? The group seemed to agreed that this was the right background.

The final question on the definition of the program was deferred as not appropriate for the morning - other than agreeing on the use of E3 geometry.

John Adamczyk (NASA LeRC): John put up a chart on his thoughts. I didn't take notes. we need to get his chart.

Dave Wisler (GE): Dave put up a picture their large low speed rigs and made the observation that working with the universities was essential, both from a technical and financial perspective. He offered their rigs and support to the university community, if the universities wanted to play by their (GE) rules. This generated a discussion on how? how many? technology transfer (publication)? etc. It was agreed that there was wide variation from school-to-school on this and that it would have to be an individual negotiation; however, the was sufficient precedent that it could be done (Halsted/Iowa State for example).

John Adamczyk (NASA LeRC): John specifically asked Man Rai whether he would be willing to work this problem. Man replied that he wanted to think about it, but, yes, he thought he would like to do it. It would probably be a year before he could start.

John then turned to Eli Reshotko and asked how he felt. Eli's response was that he thought it was the proper - but not necessarily exclusive - direction in which to go. Mike Crawford agreed.

Fred Simon (NASA LeRC): Fred and Bob Simoneau will "draft" a "white paper" and circulate the draft to the group for comment. The target was before Christmas.

Terry Simon (U. Minnesota): Terry observed that we still need further discussion on how this program will flesh out.

Finally, I have a note which say a single face forward is being replaced by a double face forward. Darned if I know what it means or who said it. I suspect it means we now have industry and the universities marching together to attack a problem.