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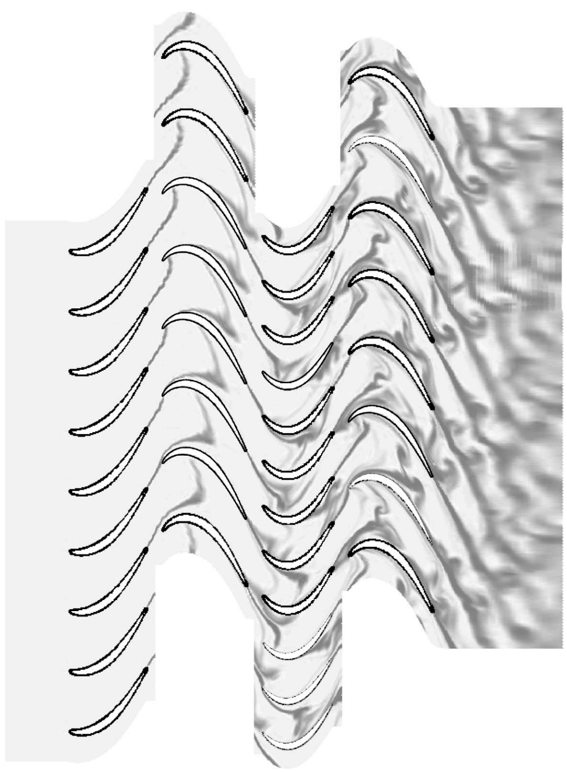
Minnowbrook III
2000 Workshop on Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows



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Minnowbrook III
2000 Workshop on Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows

John E. LaGraff and David E. Ashpis, editors

Proceedings of a workshop
held at the Syracuse University Minnowbrook Conference Center
Blue Mountain Lake, New York
August 20–23, 2000

National Aeronautics and
Space Administration

Glenn Research Center

April 2002

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The workshop co-chairs would like to express their appreciation for financial support given to the workshop and to participants by the following groups and individuals:

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Proceedings

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PREFACE

On August 20–23, 2000, over 40 attendees participated in a workshop entitled "Minnowbrook III—Workshop on Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows."

Workshop co-chairs were
John E. LaGraff, Syracuse University, Syracuse, New York, U.S.A.
Terry V. Jones, Oxford University, Oxford, U.K.
J. Paul Gostelow, University of Leicester, Leicester, U.K.

The sessions were held at the Syracuse University Minnowbrook Conference Center in Blue Mountain Lake, New York, and followed the theme, venue, and format of two earlier workshops held in 1993 and 1997. Earlier themes focused on improving the understanding of late-stage (final-breakdown) boundary-layer transition. The specific engineering application of improving design codes for turbomachinery was encouraged by the attendance of representatives from gas turbine manufacturers.

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

The workshop proceedings are arranged in form of a booklet and an accompanying CD-ROM. The booklet includes abstracts and transcripts of the plenary discussion and the summary session. The CD-ROM contains all the viewgraphs presented as well as the materials in the booklet. The materials are organized according to the workshop sessions. The workshop summary and the plenary-discussion transcripts clearly highlight the need for continued vigorous research in the technologically important area of transitional and unsteady flows in turbomachines.

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

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SUBTRANSITIONS REVISITED

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Bangalore, India

There are a number of situations where the intermittency distribution within the transition zone shows evidence of a relatively abrupt departure from the standard 2-D distribution.[1] Two situations in which such changes have been observed and are reasonably well documented are those concerned with the flow past an aligned circular cylinder,[2] and flows with strongly varying pressure gradients.[3] In the former case the mechanism is relatively easy to understand. A spot that forms at any point on the surface of the axisymmetric body will in general wrap around the body after propagation for a certain distance downstream[4]. Downstream of the point where this wrapping occurs there is a turbulent sleeve on the body. The length of this sleeve will increase as it propagates downstream, but its width is limited by the circumference of the body. This leads to a change in the regime of the intermittency distribution, from a 2D like law to a 1D like law.[2]

In the second case rapid changes in the pressure gradient can lead to a situation where spot propagation characteristics can also change correspondingly. It is well known for example that an adverse pressure gradient tends to increase the spot spread rate dramatically;[5] similarly a sufficiently strong favorable pressure gradient or a relatively low Reynolds number can suppress spot growth.[6] It is of course possible that such changes will occur continuously, but an interesting observation is that, at least in certain situations, the changes are relatively rapid, and may be related to a quick shift from subcritical to supercritical states or vice versa in the stability characteristics of the boundary layer.[6]

These different regimes in the transition zone may be said to be separated by *subtransitions*. The evidence for the occurrence of such subtransitions in both flow types mentioned above is reviewed. In flows with pressure gradient, a particularly clear case is presented in Figure 1.

In addition, a detailed analysis of results can be made of the experimental results on a heated axisymmetric body in water reported by Lauchle & Gurney.[7] These measurements provide strong evidence for subtransition: a gradual increase of intermittency in the initial 2D region is followed by a sharp and rapid increase downstream (Figure 2). Taking the possibility of subtransition into account, a model has been formulated[8] for the variation of intermittency with flow Reynolds number at a *fixed* station on the body, as in the experiments. The transition *onset* Reynolds number (corresponding to the location where intermittency begins to depart from zero), inferred from the data on the basis of this model, shows a continuing increase with the temperature overheat, a trend in close agreement with stability theory; but the axisymmetric body geometry results in a very short transition zone, countering in part the benefits of the appreciable transition delay that does occur due to heating. The analysis incidentally reveals that there can be two spot-wrapping scenarios, one involving a single spot and the other a cluster. Earlier conclusions that results were not in agreement with stability theory were based on identifying the (intermittency = 0.5) point with transition onset. The culprit in the disagreement is sub-transition, not stability theory.

The analysis predicts that heating becomes more attractive at lower Reynolds numbers and on plate-like bodies (i.e., those with blunter noses), because both encourage the singleton spot-wrapping scenario.

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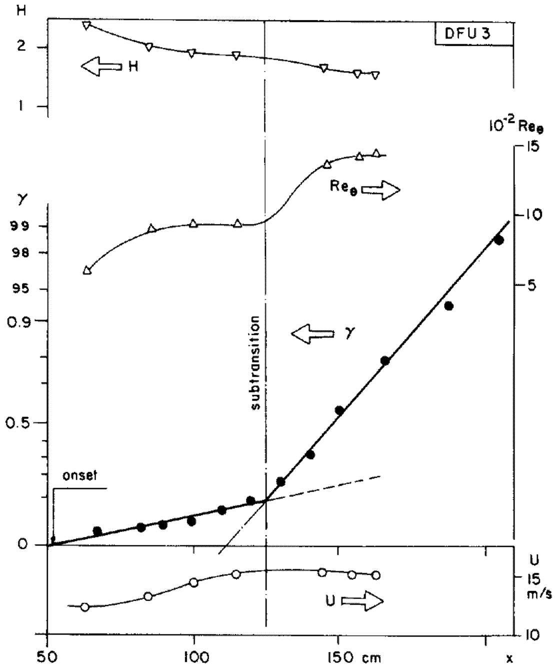

Figure 1: Subtransition in boundary layer subjected to a varying favourable pressure gradient. The figure shows, from the top: the shape factor, the momentum thickness Reynolds number, the intermittency (on a scale that makes the usual 2D distribution a straight line[1]), and the free stream velocity. Note the kink in the intermittency distribution and the sudden rise in Reynolds number, marking the location of subtransition.

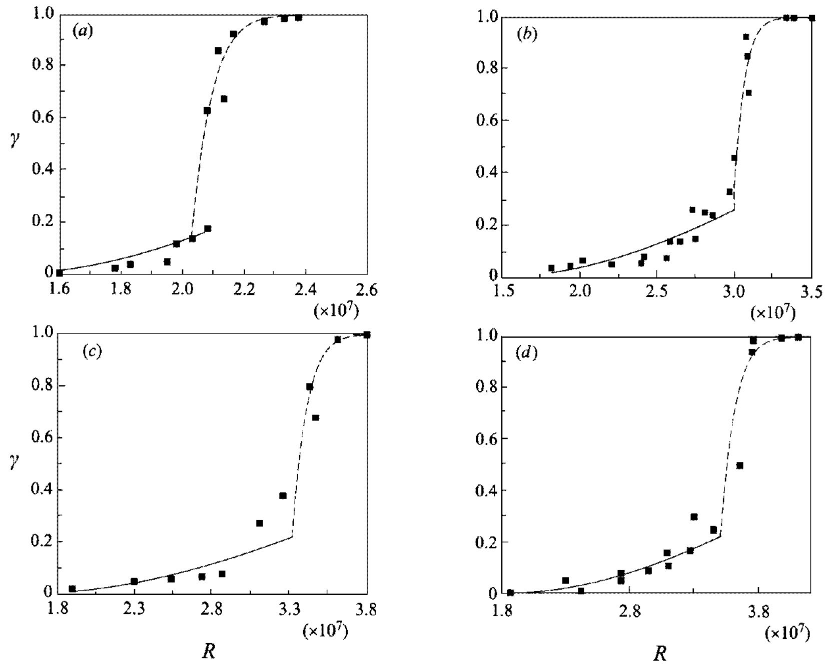

Figure 2: Comparison of the Govindarajan and Narasimha[8] model with the experiments of Lauchle and Gurney[7]. Note the strong evidence provided by the measurements for subtransition: a gradual increase of intermittency in the initial 2D region is follow ed b y a sharp and rapid increase downstream.

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SUBTRANSITIONS REVISITED

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with at various times

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of the Indian Institute of Science/Jawaharlal Nehru Centre
Bangalore, India

with partial support (since 1998) from the Naval Research Board
Government of India

Presented at the Minnowbrook III 2000 Workshop on Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows

WHAT IS A SUBTRANSITION?

A relatively abrupt change in the nature of the intermittency distribution within the transition zone

(presumably as a consequence of)

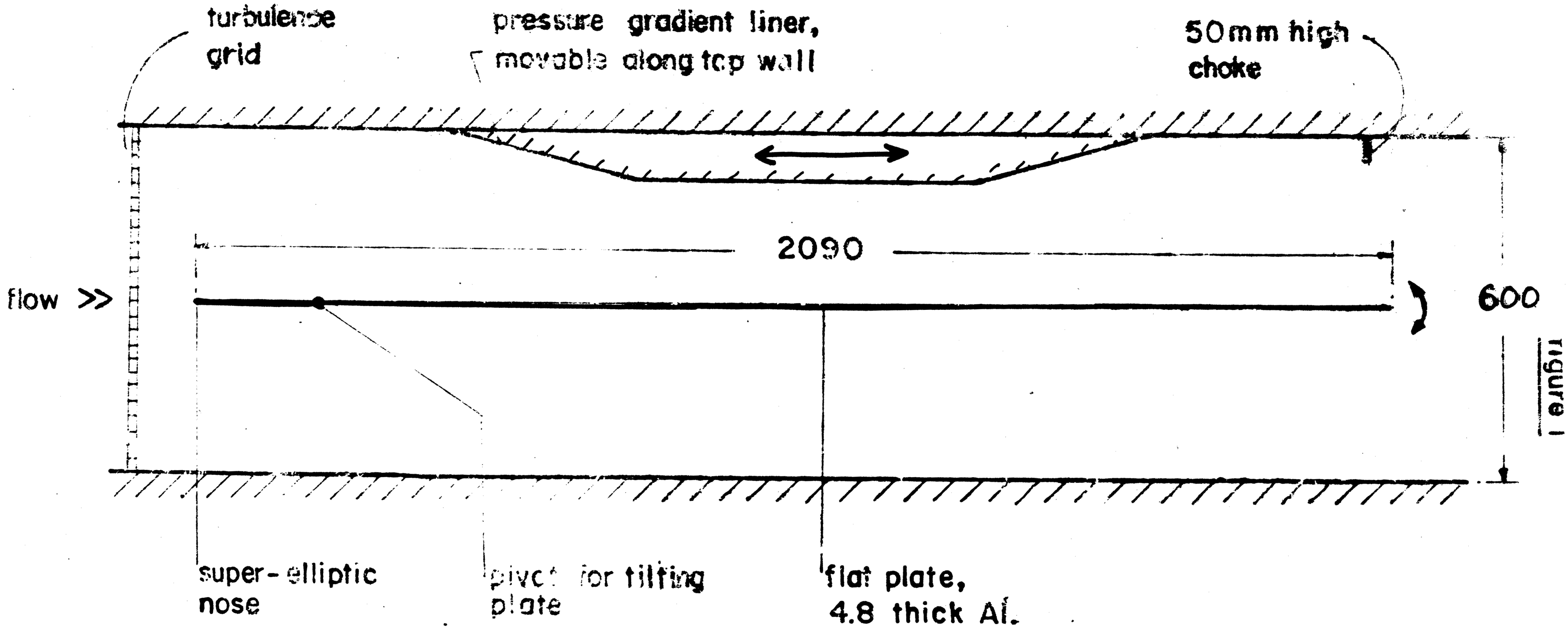
Similarly abrupt changes in the propagation characteristics of turbulent spots / slabs / patches...

(which changes may occur because of)

Either	GEOMETRIC	} causes,
or	DYNAMICAL	
or	BOTH.	

THE EVIDENCE → POSSIBLE MECHANISMS, MODELS → CONCLUSIONS

Devasia et al. 1984



all dimensions in mm

figure 1

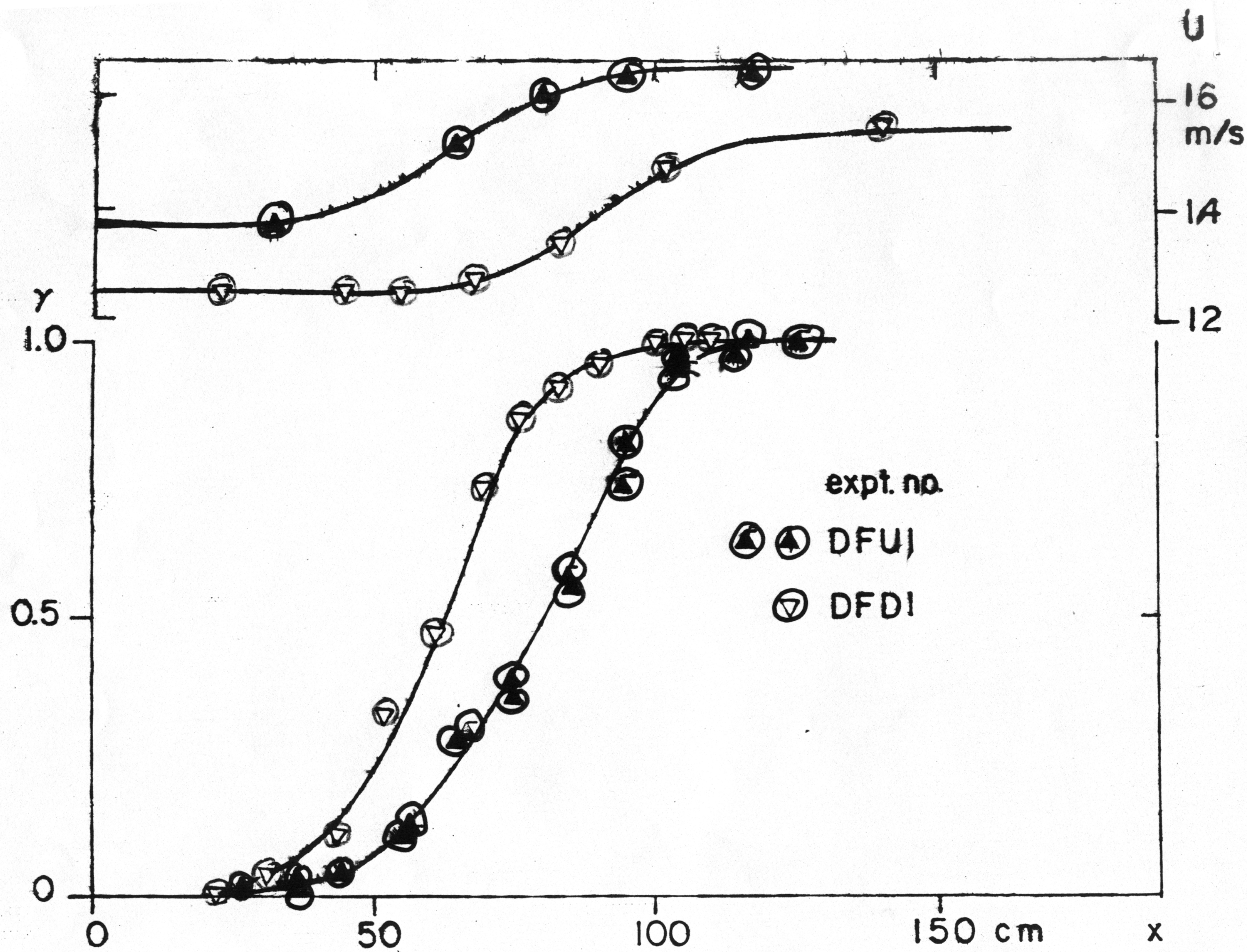
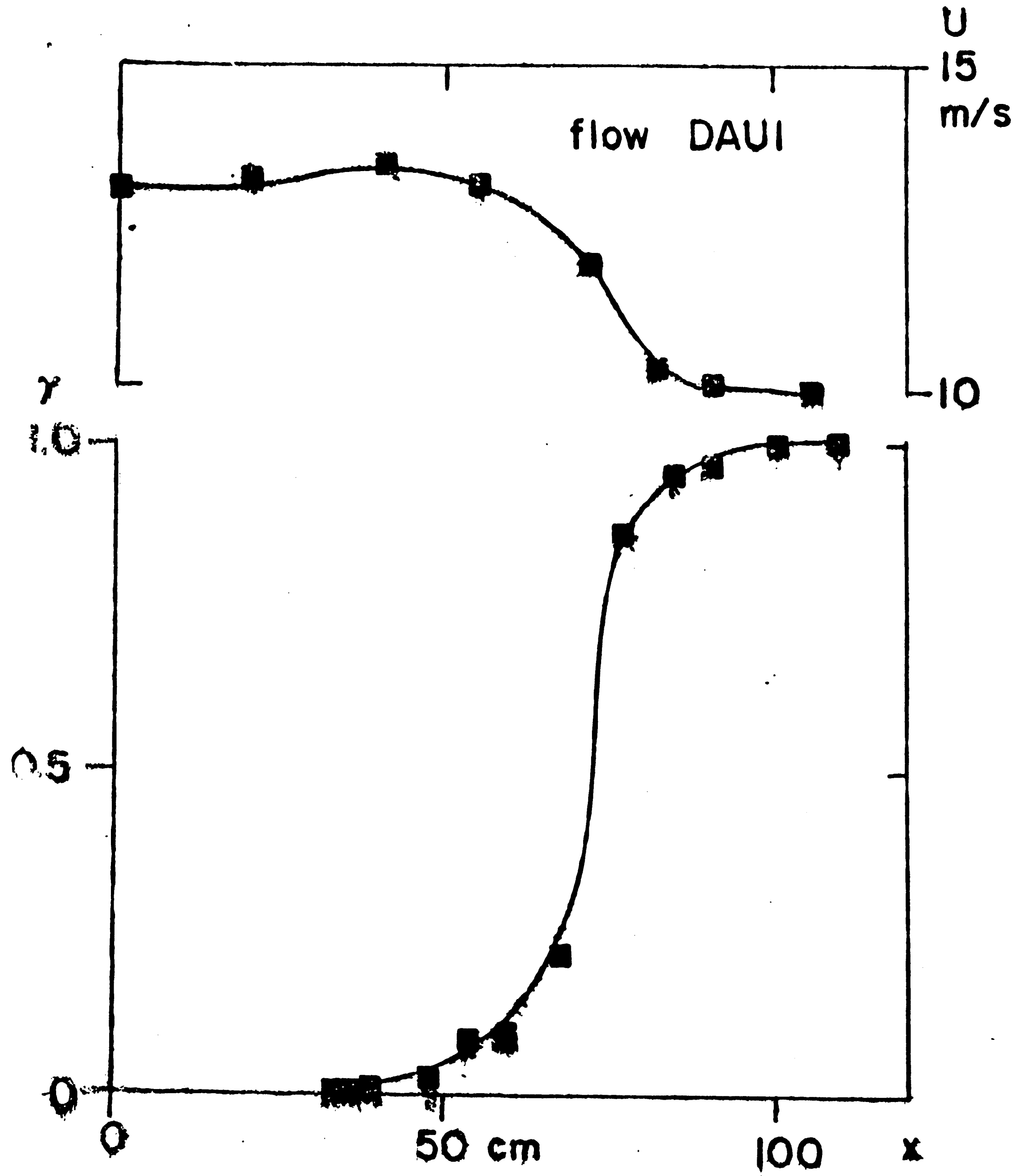


figure 5

figure 8



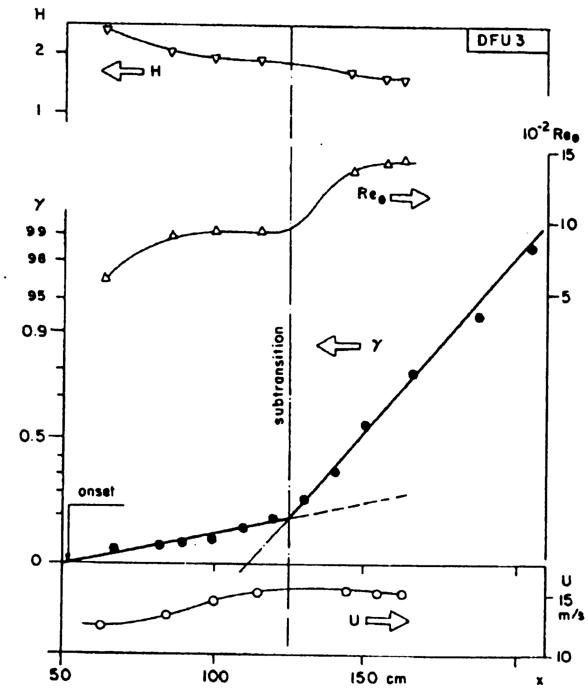


Figure 1: Subtransition in boundary layer subjected to a varying favourable pressure gradient. The figure shows, from the top: the shape factor, the momentum thickness Reynolds number, the intermittency (on a scale that makes the usual 2D distribution a straight line[1]), and the free stream velocity. Note the kink in the intermittency distribution and the sudden rise in Reynolds number, marking the location of subtransition.

The Transition Zone on a Heated Axisymmetric Body

OR

Is Transition on an Under-water Vehicle Delayed Less with More Heating?

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Supported by the Naval Research Board (Government of India)

BACKGROUND

Linear 2D stability theory for boundary layer on under-water surface (Wazzan, Okamura & Smith 1968):

ΔR_{cr} (b.l. thickness) ~ overheat ΔT.

But experiments* of Lauchle & Gurney (1984) (JFM 144: 79-101) suggest saturation of heating effect.

* Axisymmetric body in water tunnel
* Intermittency measured at fixed station, as tunnel speed varied
* Transition Reynolds number indicated by

$$R_{0.5} \equiv \frac{U_{ref}(\gamma_s = 0.5) \cdot s}{\nu}$$

s — arc length to measuring station

U_{ref} — Tunnel reference velocity when intermittency $\gamma(s) = 0.5$

Lauchle & Gurney 1984

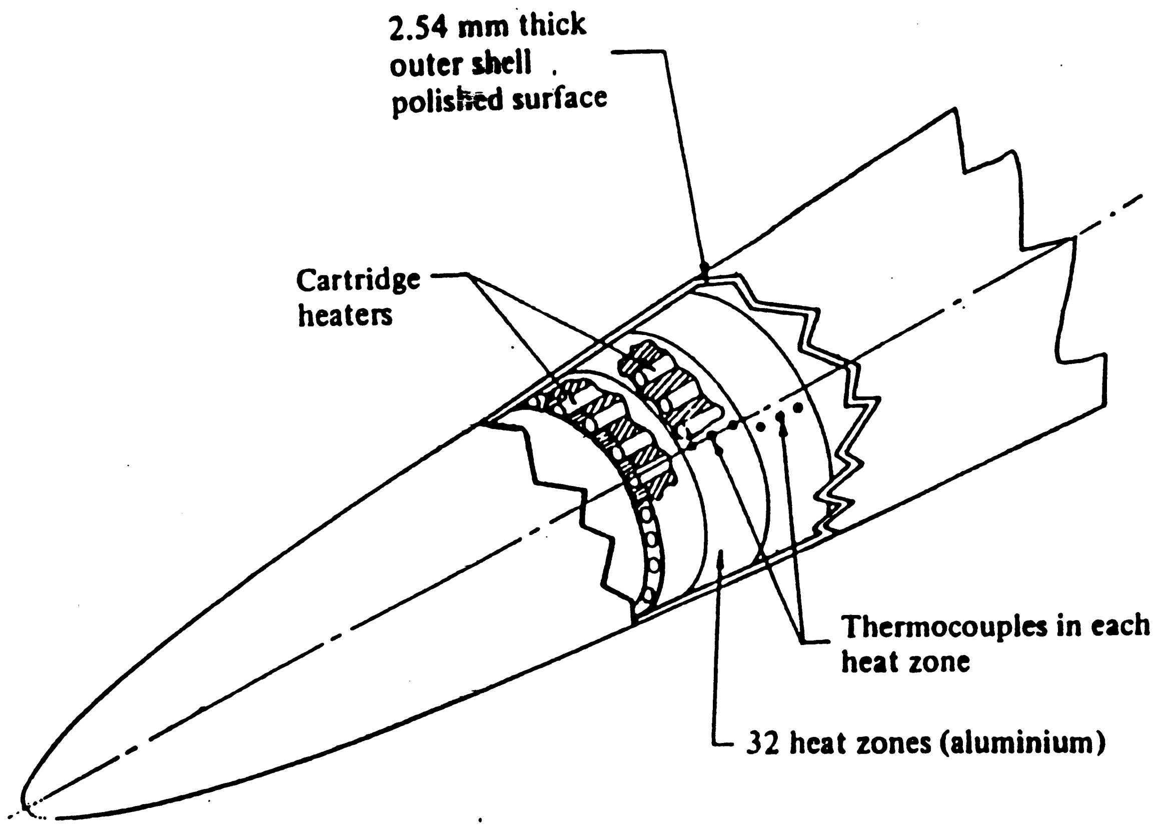

FIGURE 3. A schematic view of the heated body.

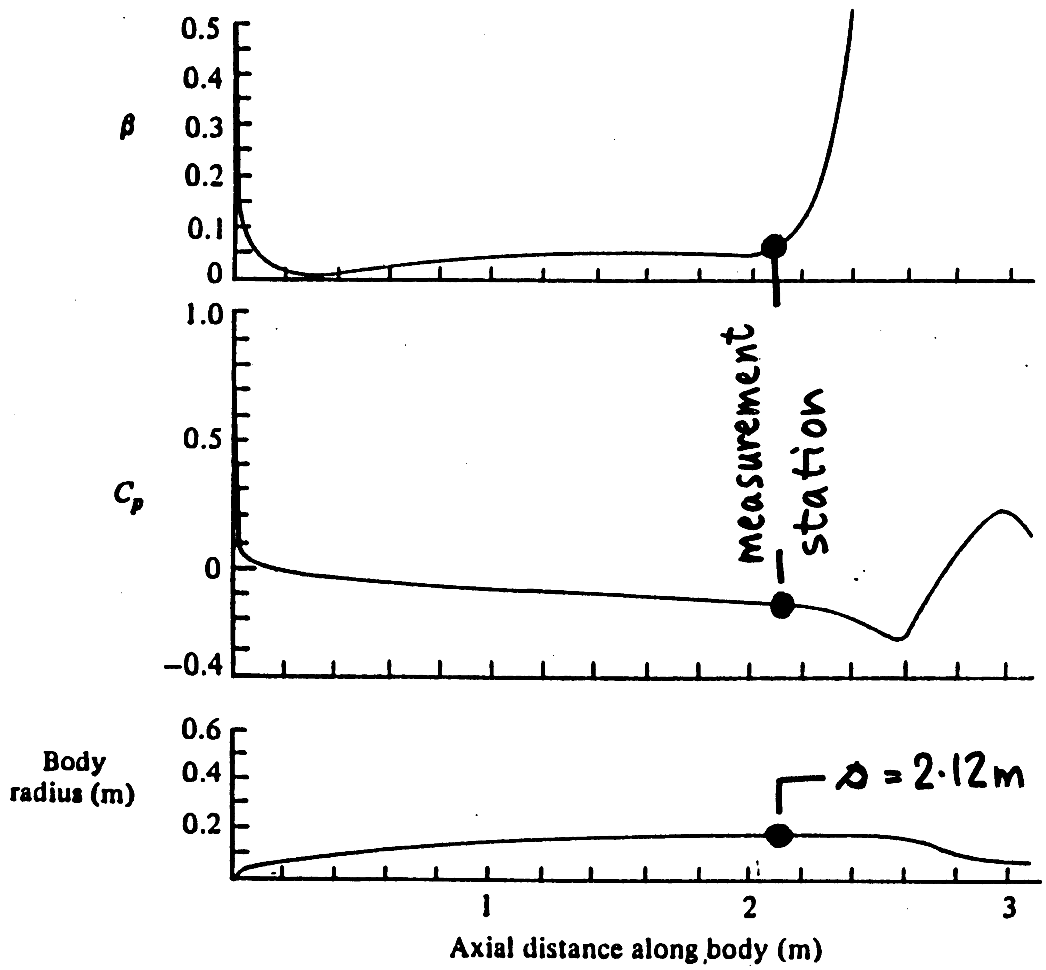

FIGURE 2. Potential-flow calculations of pressure coefficient and pressure-gradient parameter for the heated body including wall effects.

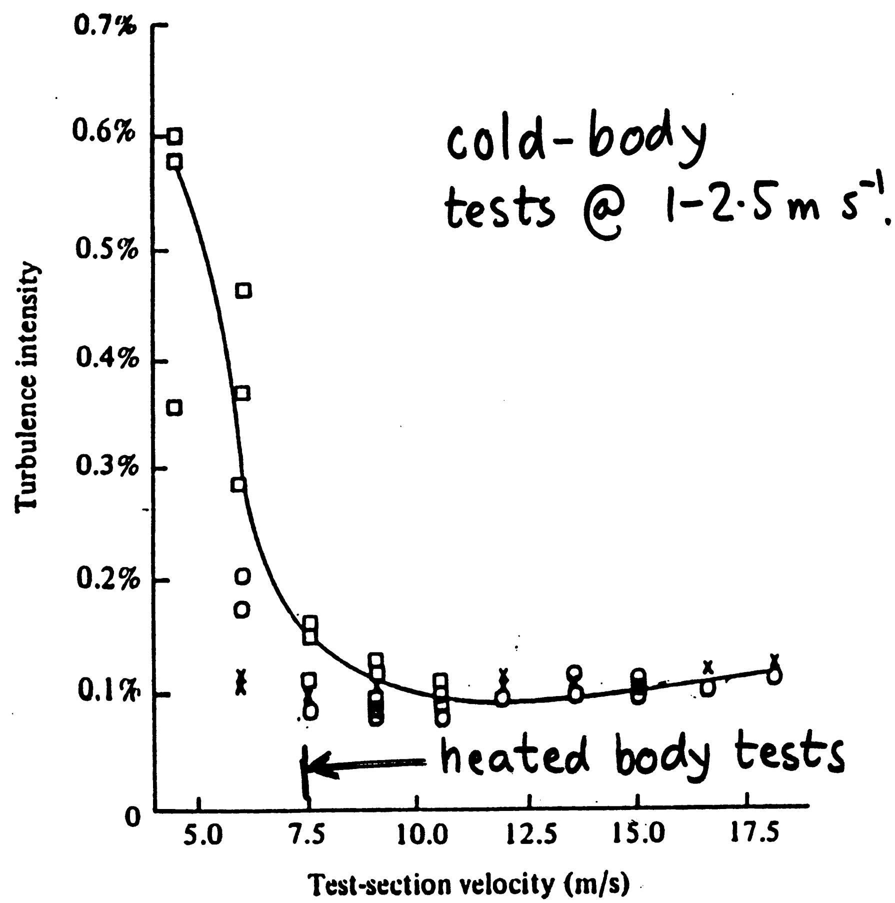

FIGURE 1. Test-section tubulence intensity as measured in the 1.22 m diameter water tunnel by Robbins (1978): ×, □, measured in the test section; ○, calculated from levels measured in the settling section.

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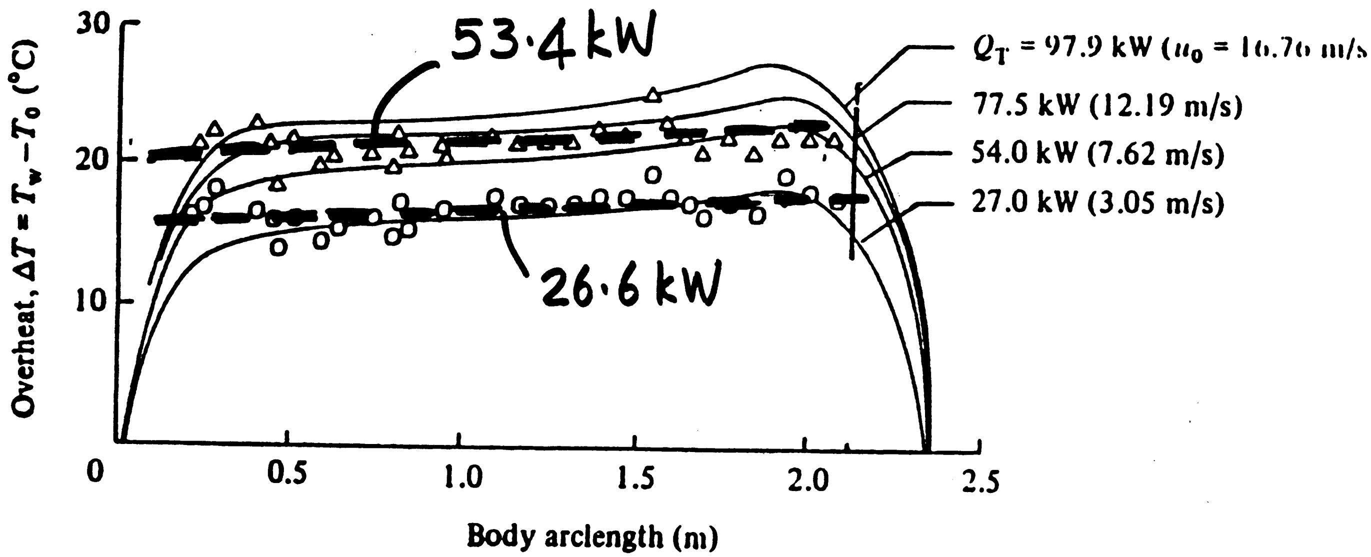


FIGURE 8. Predicted and measured wall-temperature distributions for the heated body: —, theoretical predictions; ○, measured at $Q_T = 26.6$ kW, $u_0 = 3.05$ m/s; △, $Q_T = 53.4$ kW, $u_0 = 7.62$ m/s. $T_0 = 25.6$ °C (78 °F).

L&G 84

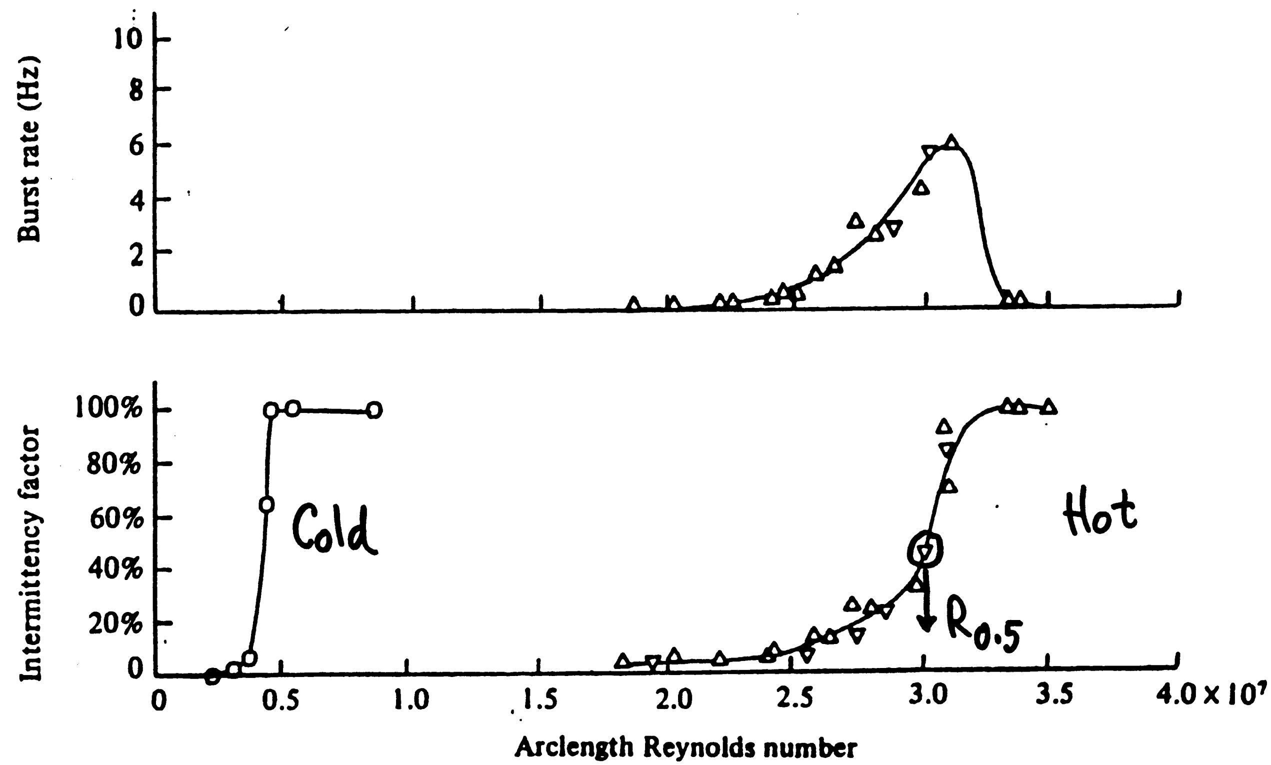


FIGURE 12. Variation of turbulence intermittency and burst rate with Reynolds number for baseline conditions and $Q_T = 53.4$ kW: ○, cold body; △, increasing u_e; ▽, decreasing u_e. $T_e = 26.7$ °C (80 °F), $P_0 = 241.3$ kPa (35 p.s.i.a), $\alpha_0 = 1.21$ p.p.m.

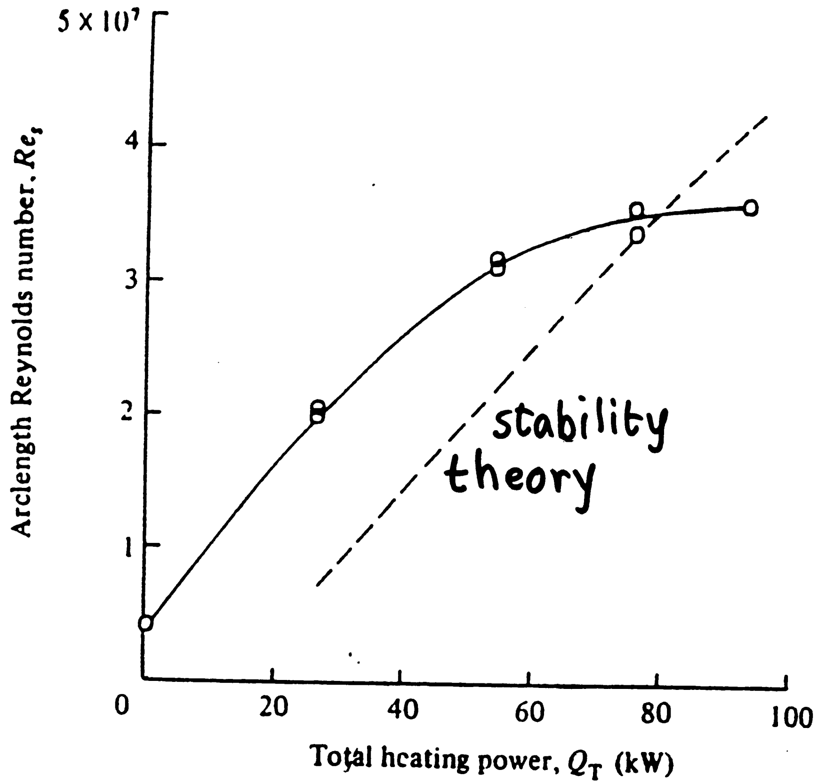


FIGURE 15. Comparison of experimentally determined transition Reynolds numbers with theoretical critical Reynolds numbers: O, measured; ---, theory.

RELATIONS BETWEEN R_{cr}, $R_{0.5}$ AND R_t (at onset)

> Not simple

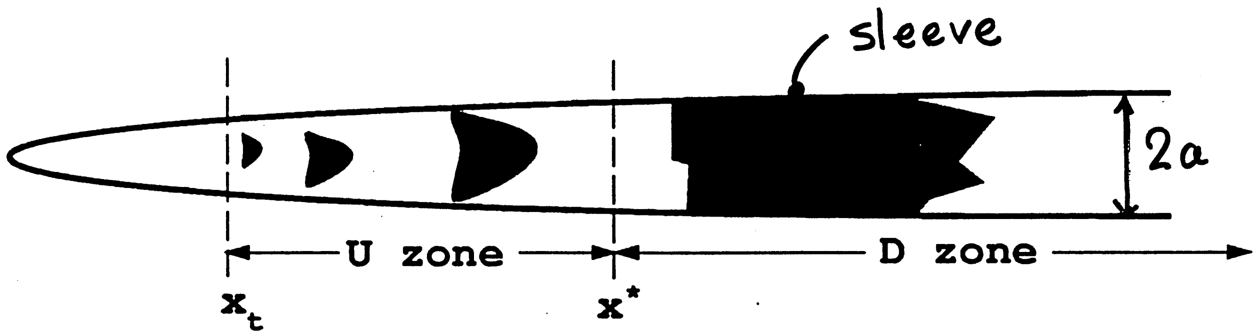
> $R_{0.5}$, R_t related through "Transition Zone" model:
> $s(\gamma = 0+)$ to $s(\gamma = 1-)$
> $s = s_t$, "onset location" → $R = R_t$.

> Transition zone on axi-symmetric body DIFFERENT from that on 2D surface (RN '84), because:

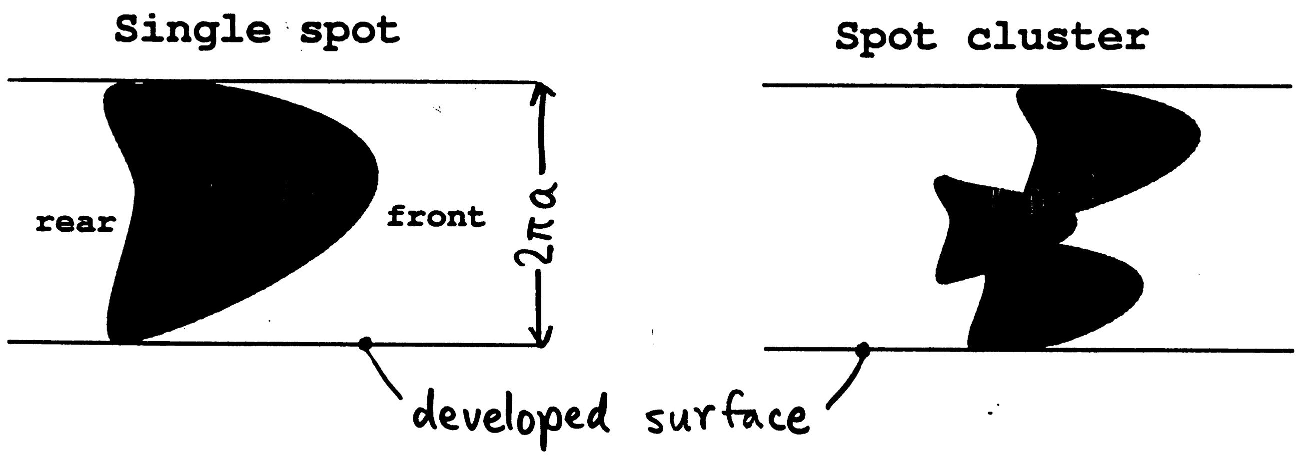
> 2D ("Emmons") spot can wrap around body into a (1D) turbulent "sleeve"; resulting in:

> "Subtransitions" within transition zone; at any rate, it is

> More meaningful to compare R_t (not $R_{0.5}$) with R_{cr}.



Spot wrapping scenarios:



Patch of turbulence in D zone:

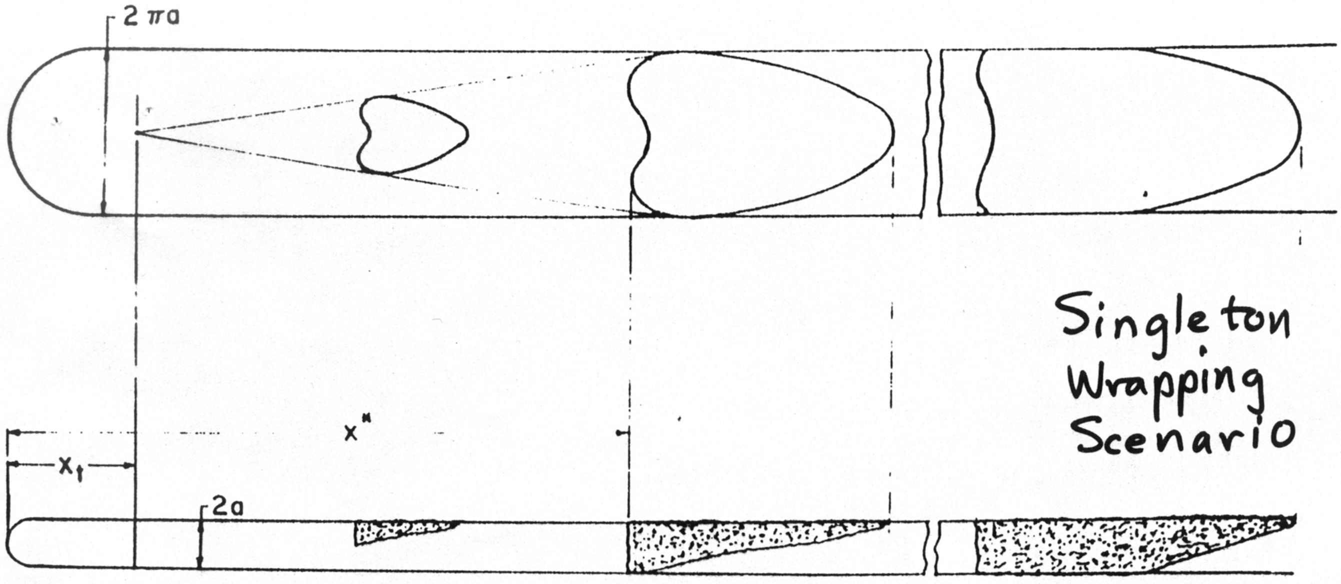


FIG. 20. Development of spot in axial flow past a circular cylinder (after Rao, 1974).

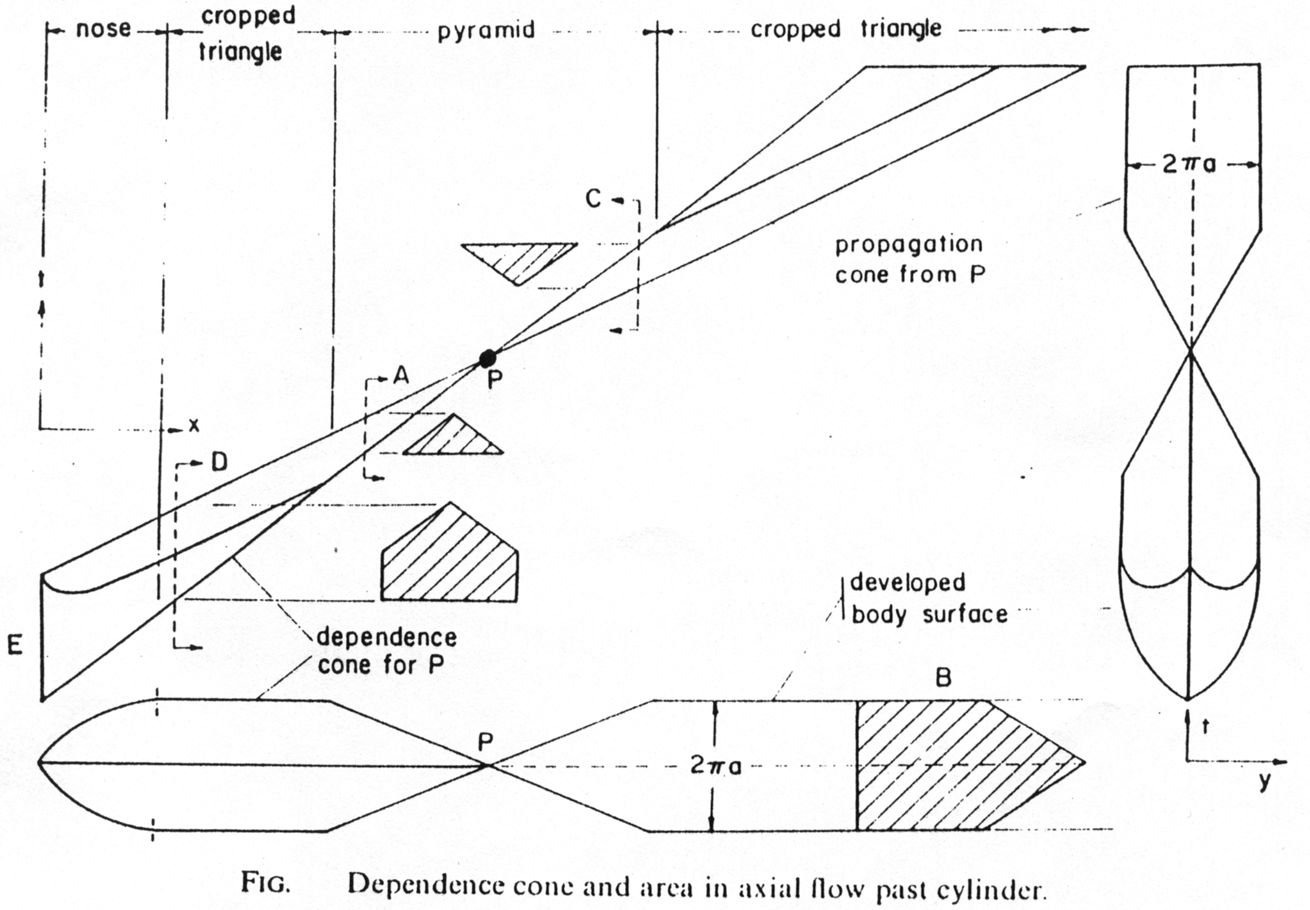
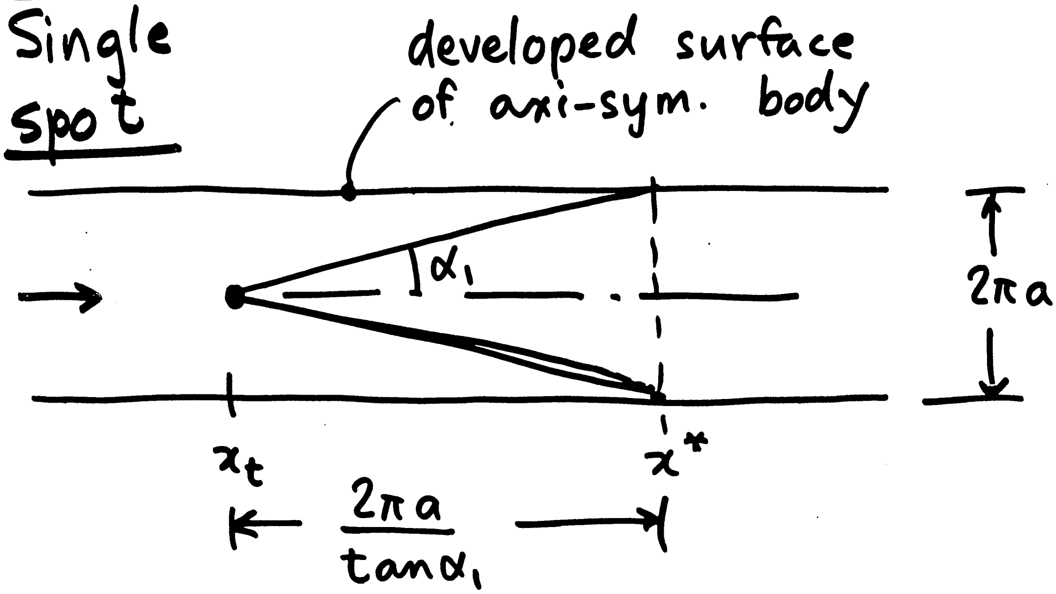


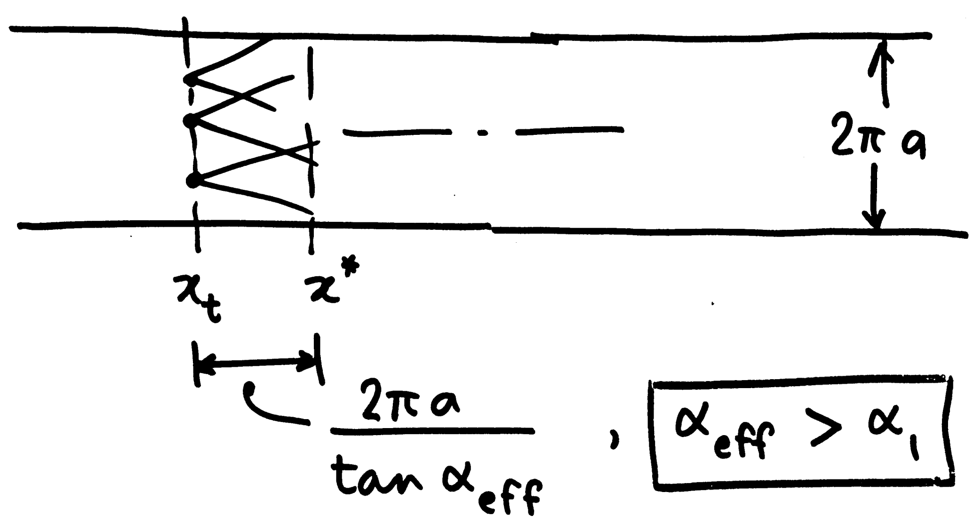
FIG. Dependence cone and area in axial flow past cylinder.

SPOT-WRAPPING SCENARIOS

Single spot



Spot cluster



CRITERION FOR SPOT WRAPPING SCENARIOS

Let

$T_w \equiv$ spot wrapping time

$= \dfrac{x^* - x_t}{k_r U}$, $k_r U$ = velocity of t.e. of spot

$T_s \equiv$ mean time interval between formation of successive spots at x_t, $= (2\pi a_t n_2)^{-1}$

Introduce "merge parameter"

$$M \equiv \frac{T_w}{T_s} = \frac{2\pi^2}{k_r \tan\alpha} \frac{n_2 a_t^2}{U}.$$

"Low" M ⟶ Singleton scenario

"High" M ⟶ Cluster scenario

Rao 74: M = 0.95, 0.55, 8.24, 1.66 ~ 'low' M. (S)

L&G 84: M = 124, 262, 292, 247 ~ 'high' M. (C)

INTERMITTENCY DISTRIBUTIONS

Assumptions:
- No strong pressure gradients
- Linearly propagating spots / sleeves ...
- Concentrated breakdown at "onset" location, x_t

2D: Emmons spots on flat surface:

$$\gamma(x) = 1 - \exp - \frac{n_2 \sigma_2 (x - x_t)^2}{U}$$

where n_2 = spot formation rate at x_t, $m^{-1}s^{-1}$

σ_2 = spot propagation parameter (non-dim.)

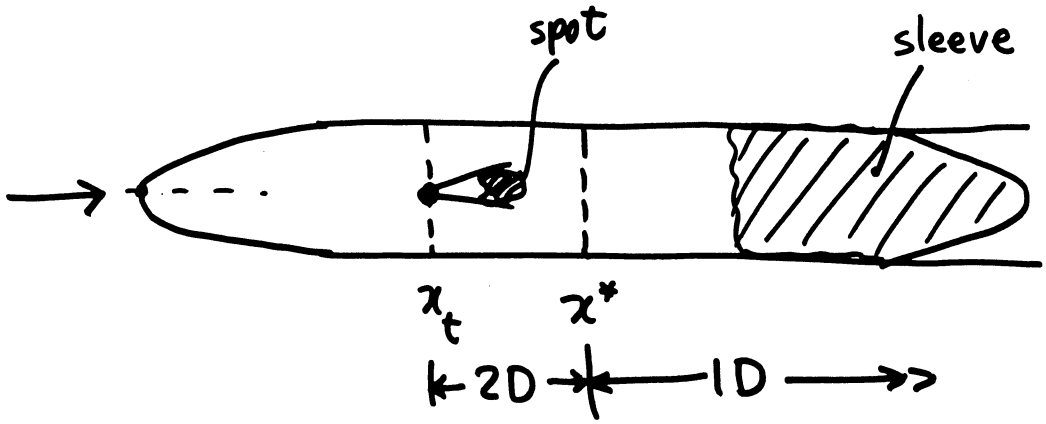
1D: e.g. Reynolds 'flashes' in pipe (internal flow), turbulent 'sleeves' on (cylinder-like) axi-symmetric bodies:

$$\gamma(x) = 1 - \exp \frac{-n_1 \sigma_1 (x - x_t)}{U}$$

where n_1 = spot formation rate at x_t, s^{-1}

σ_1 = spot (/sleeve) propagation parameter (non-dim.)

TRANSITION ZONE ON (CYLINDER-LIKE) AXISYMMETRIC BODY



$$\gamma(x) = 1 - \exp - \frac{n_2 \sigma_2}{U}(x - x_t)^2 \quad , \quad x_t < x \leq x^*$$

$$= 1 - (1 - \gamma^*) \exp - \frac{n_1 \sigma_1}{U}(x - x^*), \quad x^* \leq x$$

[based on hypothesis (RN 84) that turbulent sleeve consists of:
an unchanging 'head' or 'nose',
a linearly growing base whose width = circumference, length increases with time].

→ 'SUBTRANSITION' AT x^*.

Supported by measurements of Rao (74)

INTERMITTENCY AT FIXED STATION AS FLOW REYNOLDS IS VARIED

Assumptions:

> No strong pressure gradients

> Free-stream turbulence level q approx. constant

> Spot formation rate parameter, 'crumble'

$$N \equiv \frac{n_2 \sigma_2 \theta_t^3}{\nu}$$ (non-dim

approx. constant

⟹ R_t, R_λ constant ⟶
[$\lambda \equiv x(\gamma = 0.75) - x(\gamma = 0.25)$ is measure of transition zone length in 2D flow]

> R^* constant

FINAL RESULT

$$\gamma(R) = 0, \quad R \le R_t, \quad \text{(lam. flow)}$$

$$= 1 - \exp\left[-N(R-R_t)^2\right], \quad R_t \le R \le R^*, \quad (2D)$$

$$= 1 - (1-\gamma^*) \cdot \exp\left[-\frac{N_1 R(R-R^*)}{R_t^3} \cdot \frac{a_t}{s}\right], \quad R^* \le R, \quad (1D)$$

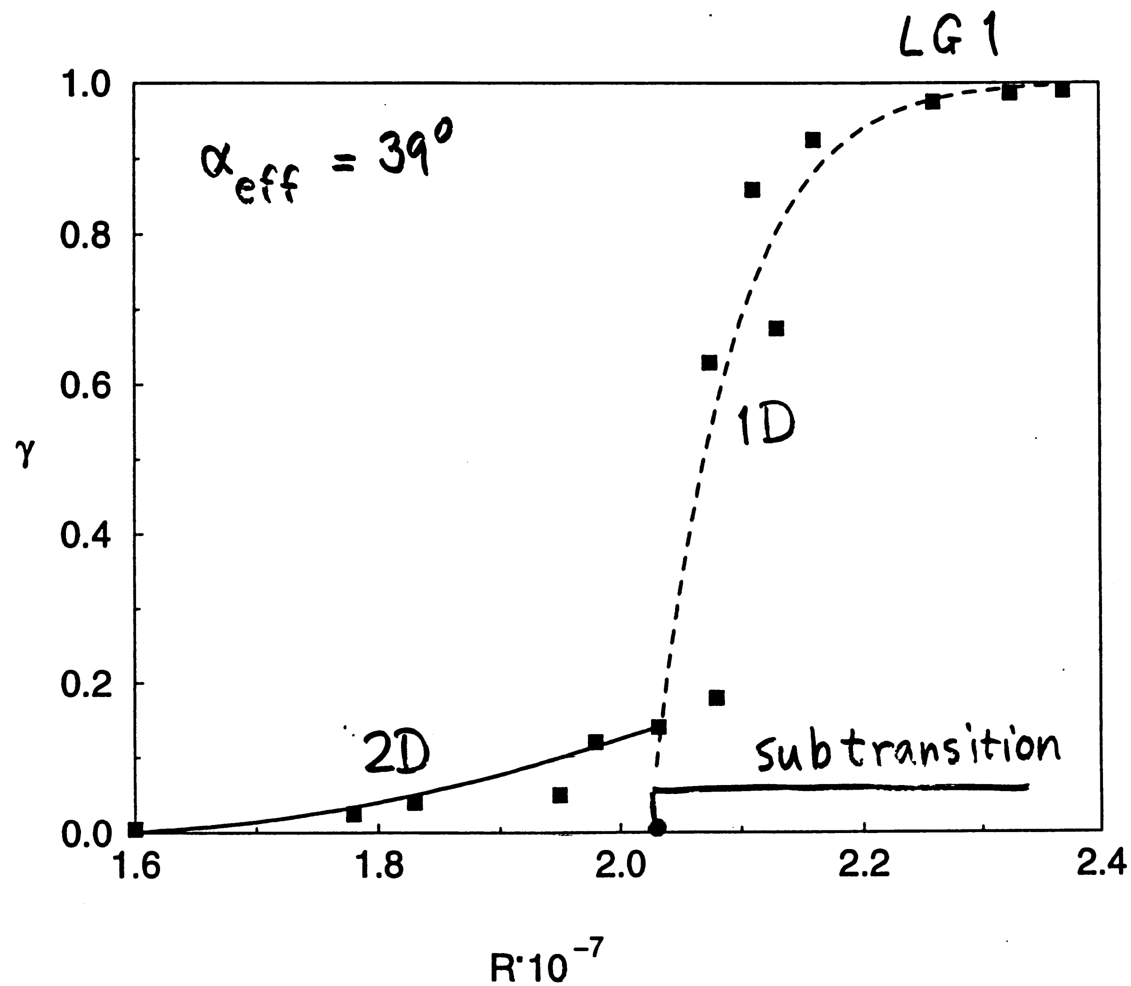
where $\gamma^* \equiv \gamma(R^*)$,

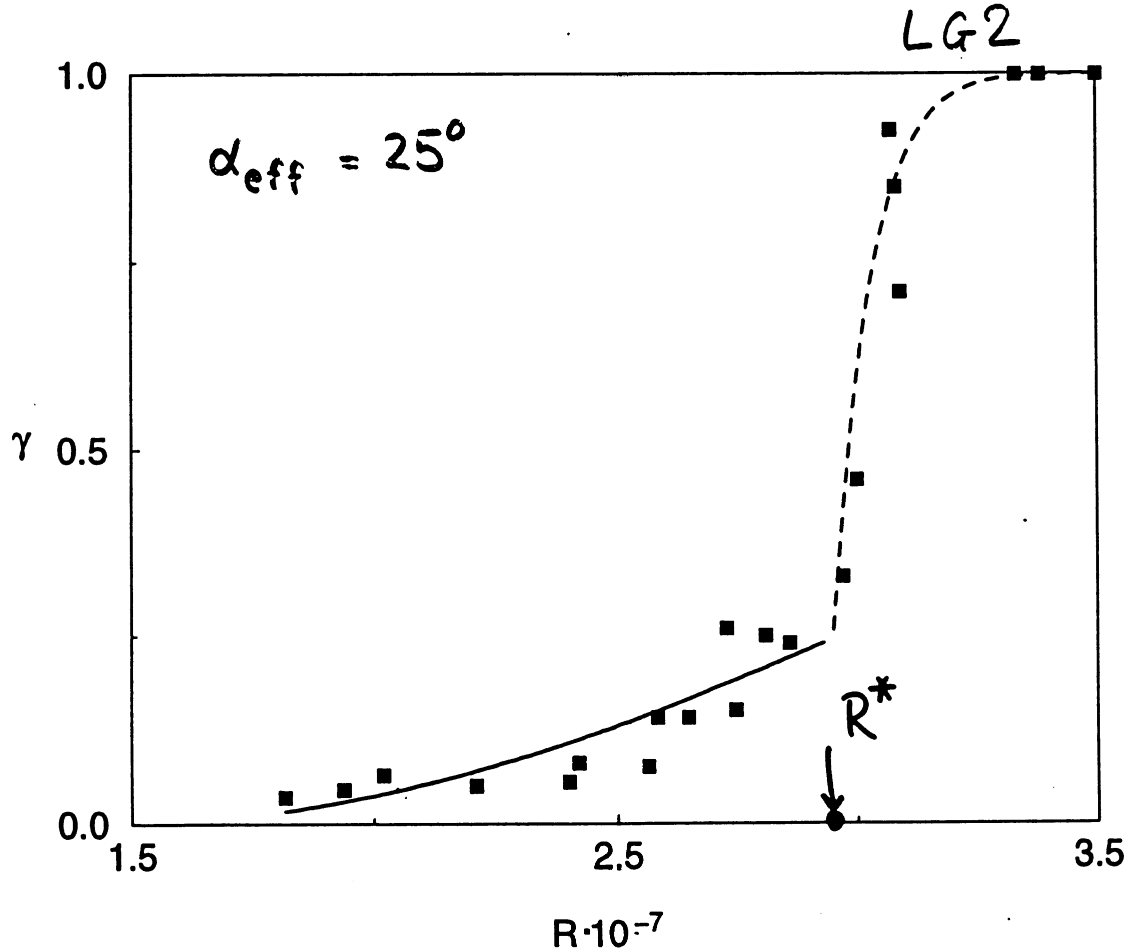
= intermittency at subtransition.

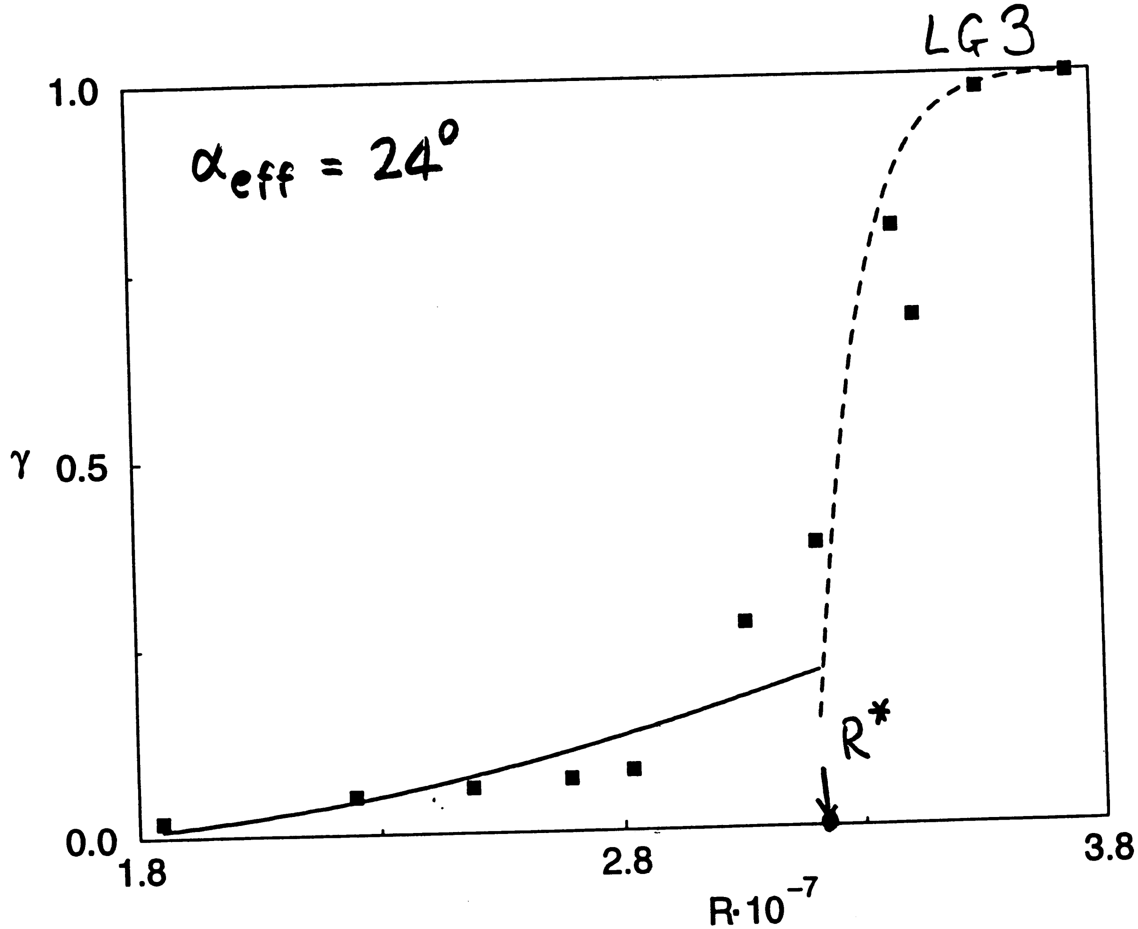
NOTE steep rise in γ near R^*:

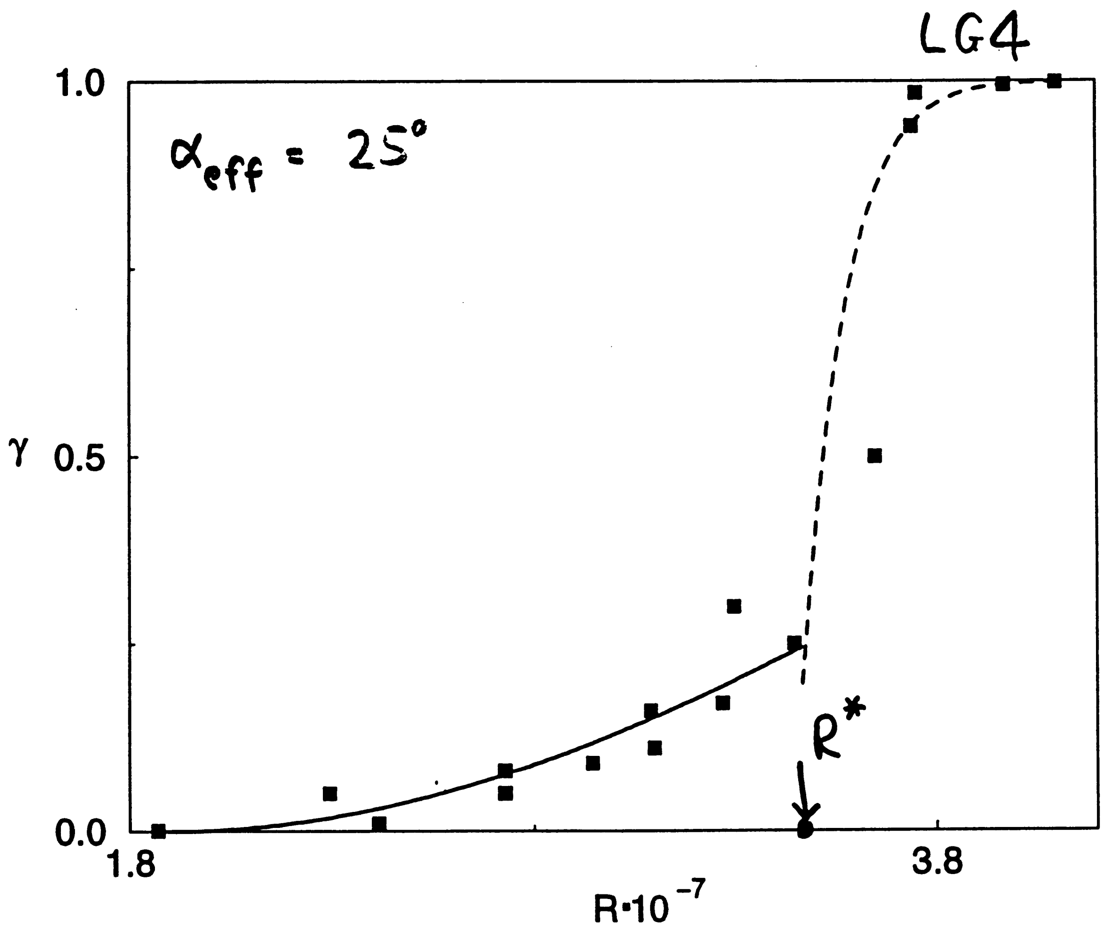
for $R = R^*+$,

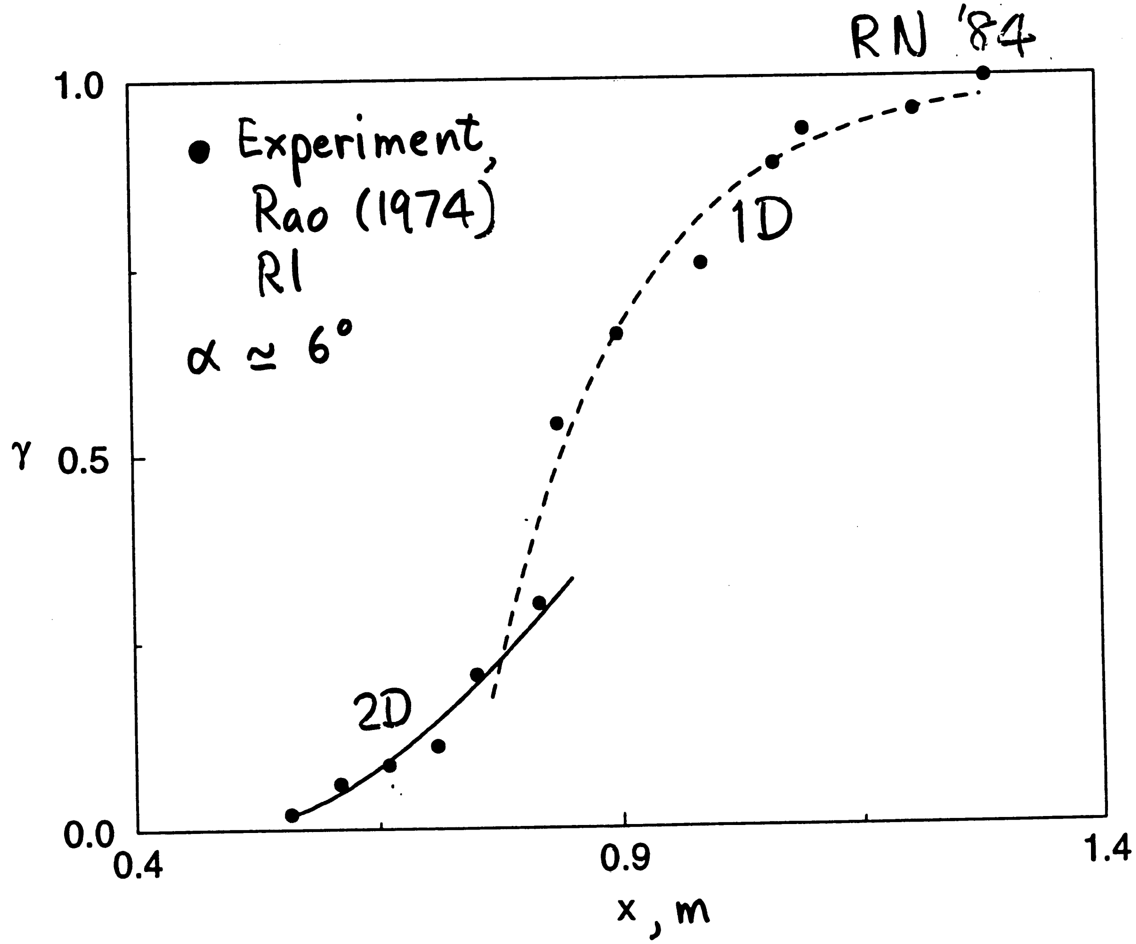
$$\gamma \simeq \gamma^* + \text{const} \cdot (1-\gamma^*) \underbrace{(R-R^*)}_{\text{linear}}$$

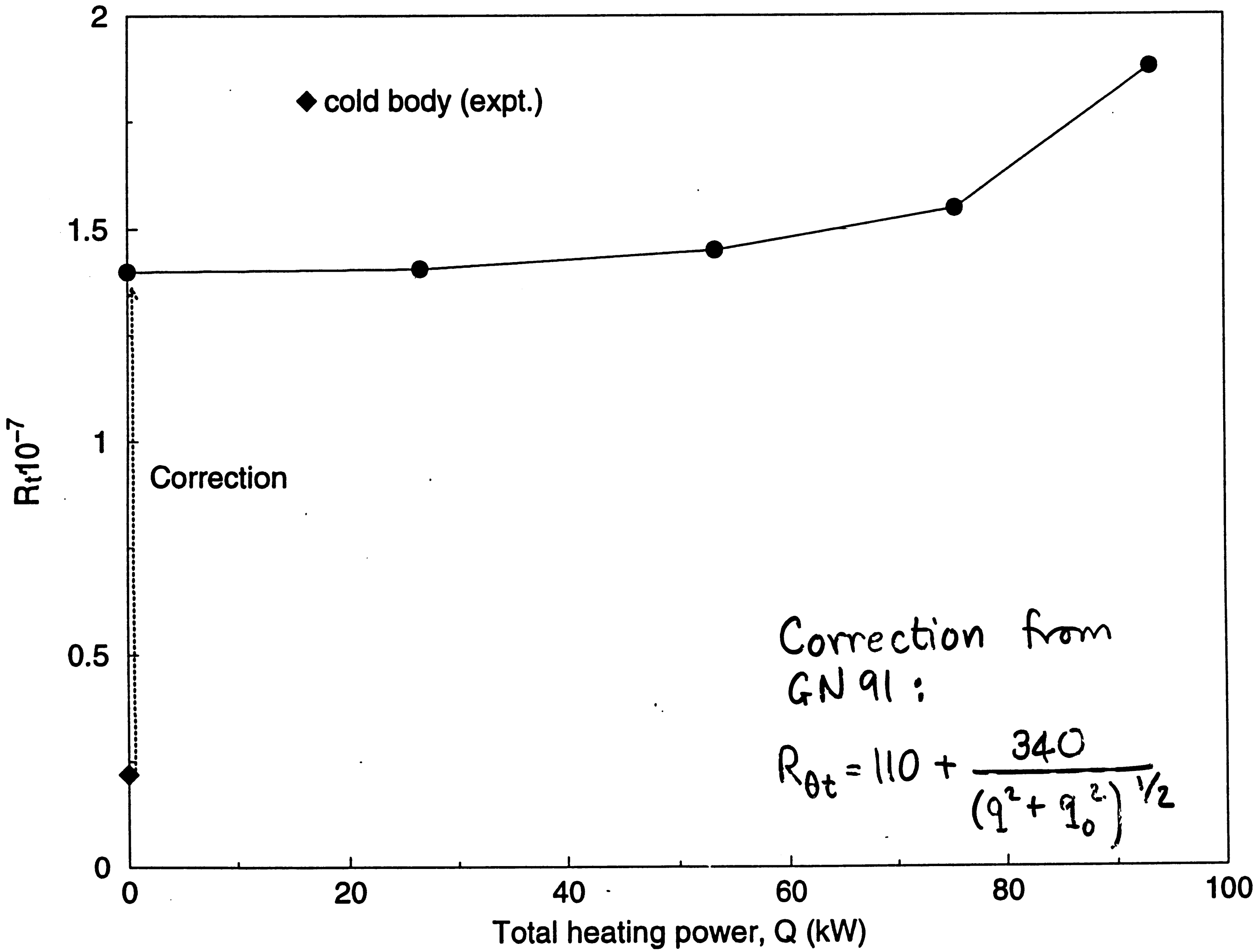

LG 1
1.0
0.8
0.6
0.4
0.2
0.0
1.6
1.8
2.0
2.2
2.4
γ
α_eff = 39°
1D
2D
subtransition
R·10^-7


LG2
α eff = 25°
1.0
0.5
0.0
γ
1.5
2.5
3.5
R·10⁻⁷
R*


LG3
α_eff = 24°
1.0
γ 0.5
0.0
1.8
2.8
3.8
R·10^-7
R*


LG4
α_eff = 25°
1.0
γ 0.5
0.0
1.8
3.8
R•10^-7
R*


RN '84
1.0
0.5
0.0
γ
• Experiment,
Rao (1974)
R1
α ≃ 6°
1D
2D
0.4
0.9
1.4
x, m


cold body (expt.)
Correction
Correction from GN 91:
$R_{\theta t} = 110 + \frac{340}{(q^2 + q_0^2)^{1/2}}$
$R_t 10^{-7}$
Total heating power, Q (kW)

CONCLUSIONS

> In complex flows, transition zone can look peculiar

> This is generally associated with changes in spot behaviour, due to:
  - pressure gradient
  - surface curvature

> In most cases, changes relatively sudden, can be viewed as "subtransitions".

> Recognition that subtransitions are possible can often explain strange behaviour

> Modelling still has problems

CONCLUSIONS

1. Transition onset on LG under-water body IS delayed more with more heating ; and this
2. Trend IS in agreement with linear stability theory (Wazzan + 68) ; but
3. Gains from delayed onset are partially offset because of the shrinking of the transition zone on the axisymmetric body, caused by
4. Early subtransition, as spots quickly merge into sleeves.

[CULPRIT IS SUBTRANSITION, NOT STABILITY THEORY]

PREDICTIONS

Heating becomes more attractive

- at lower Reynolds
- on plate-like bodies (blunter noses)

because both encourage

single spot-wrapping scenario.

HIGH LIFT LOW PRESSURE TURBINES

H.P. Hodson and R.J. Howell
University of Cambridge
Whittle Laboratory
Department of Engineering
Cambridge, U.K.

In aircraft engines, chord-based Reynolds numbers of the order of 0.5-5x10^5 are found in the low pressure turbines. Given that many component efficiencies are above 90 percent, improving the efficiency has become progressively more difficult. Consequently, a reduction is component count is now a common goal. Reducing the number of airfoils in a turbine inevitably leads to an increase in the blade loading. This increases the possibility of laminar separation in these low Reynolds number flows. Conventional (steady flow) wisdom dictates that the efficiency decreases as the laminar separation bubble grows. This perception has limited the development of low pressure turbines for many years.

In practice, the flow in turbomachines is unsteady due to the relative motion of the rows of blades. The combined effects of random (wake turbulence) and periodic disturbances (wake velocity defect and pressure fields) will affect the transition processes in low Reynolds number turbomachines. Research has shown that patches of transitional/turbulent flow can be created during the interaction of the upstream wakes with laminar boundary layers. These patches will reduce the efficiency. Fortunately, the so-called calmed regions, where the flow relaxes back to the laminar state, that follow the transitional/turbulent flow can withstand the deceleration much better than steady flow laminar boundary layers. Consequently, in high lift applications, attached laminar-like flow can be made to persist downstream of the steady flow laminar separation line, possibly as far back as the trailing edge. Most importantly, the calmed region represents an increase in efficiency as it is essentially laminar in nature and it is attached. Thus, there are two opposing mechanisms at work in the interactions between wakes and the boundary layers. As the frequency of wake-passing changes, so does the balance between these mechanisms.

This presentation will describe progress in understanding the details of the flow and the loss generation processes that arise in LP turbines. Particular emphasis will be placed on the unsteady separating flows, and how their effects may be exploited in controlling the laminar-turbulent transition processes that has allowed the successful development of ultra high lift low pressure turbines.

High Lift Low Pressure Turbines

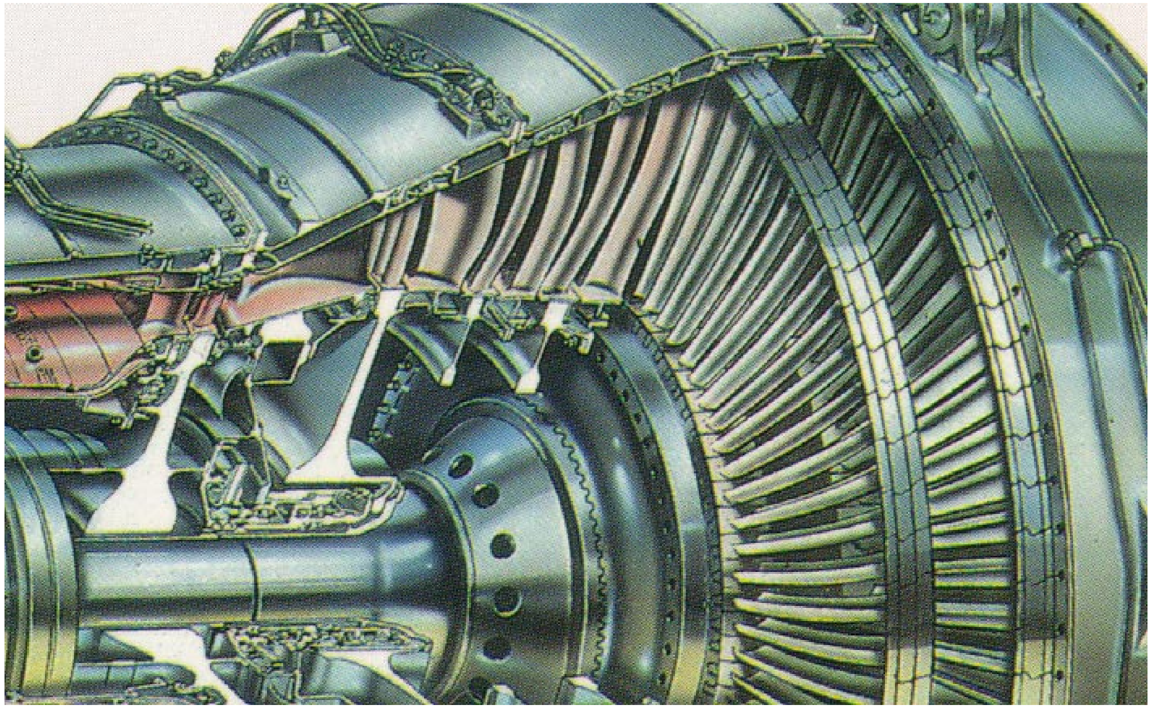
HP Hodson and RJ Howell
Whittle Laboratory
University of Cambridge

Overview

- LP Turbines
- Main features of unsteady flow
- Wake-induced transition
- Management of transition using unsteady transition
- The calmed zone
- Intermittency based modelling
- Conclusions

Rolls-Royce Trent 800 LP turbine

- Re = 1.2 - 4.5x10^5
- Mach 0.6 - 1.0
- 5 stages
- 900 airfoils
- Low lift
- Large Span
- 2-D flow



Technology Drivers

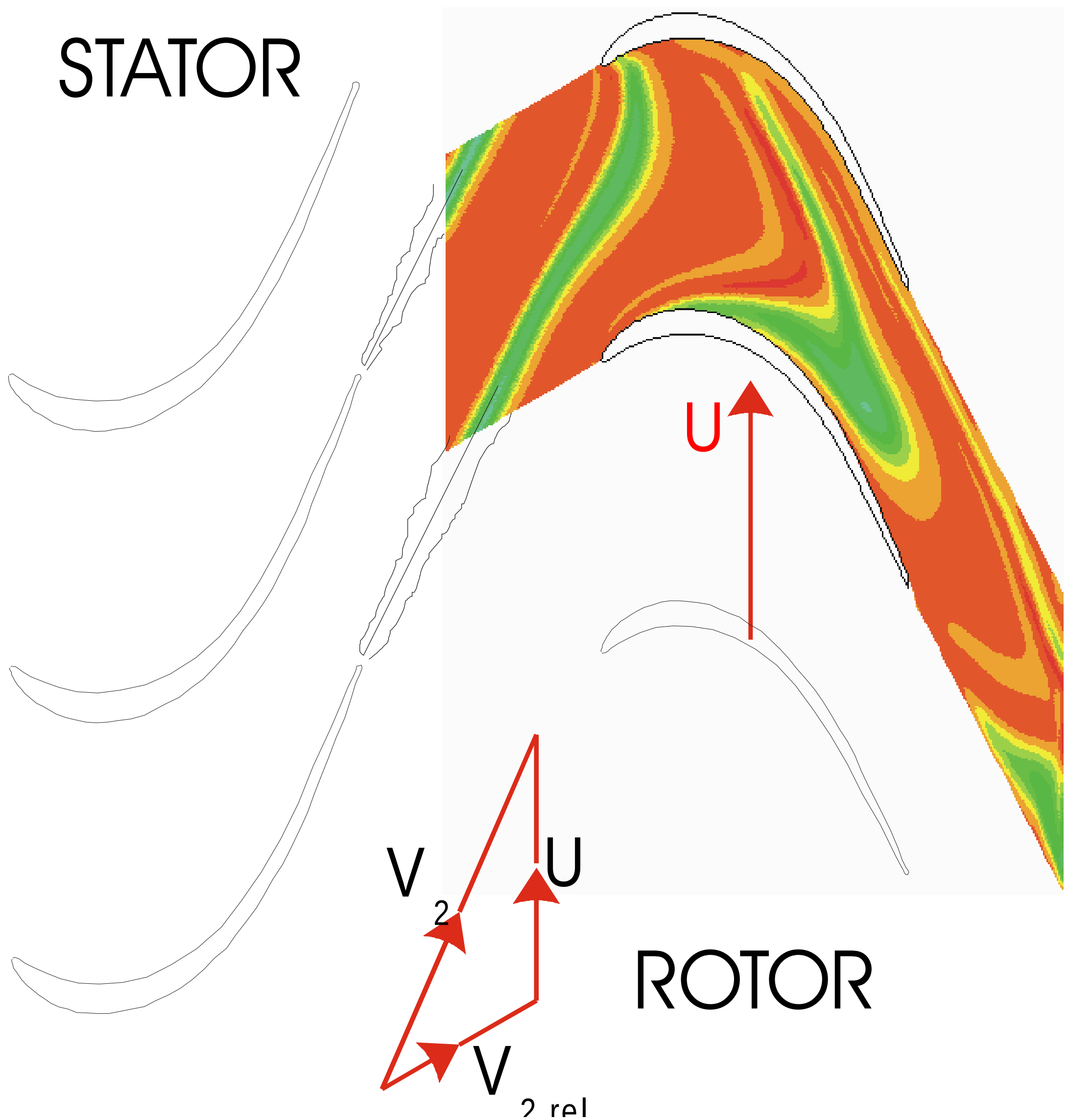
A 1% reduction in direct operating costs (DOC) is equivalent to

- $200,000 per aircraft per year

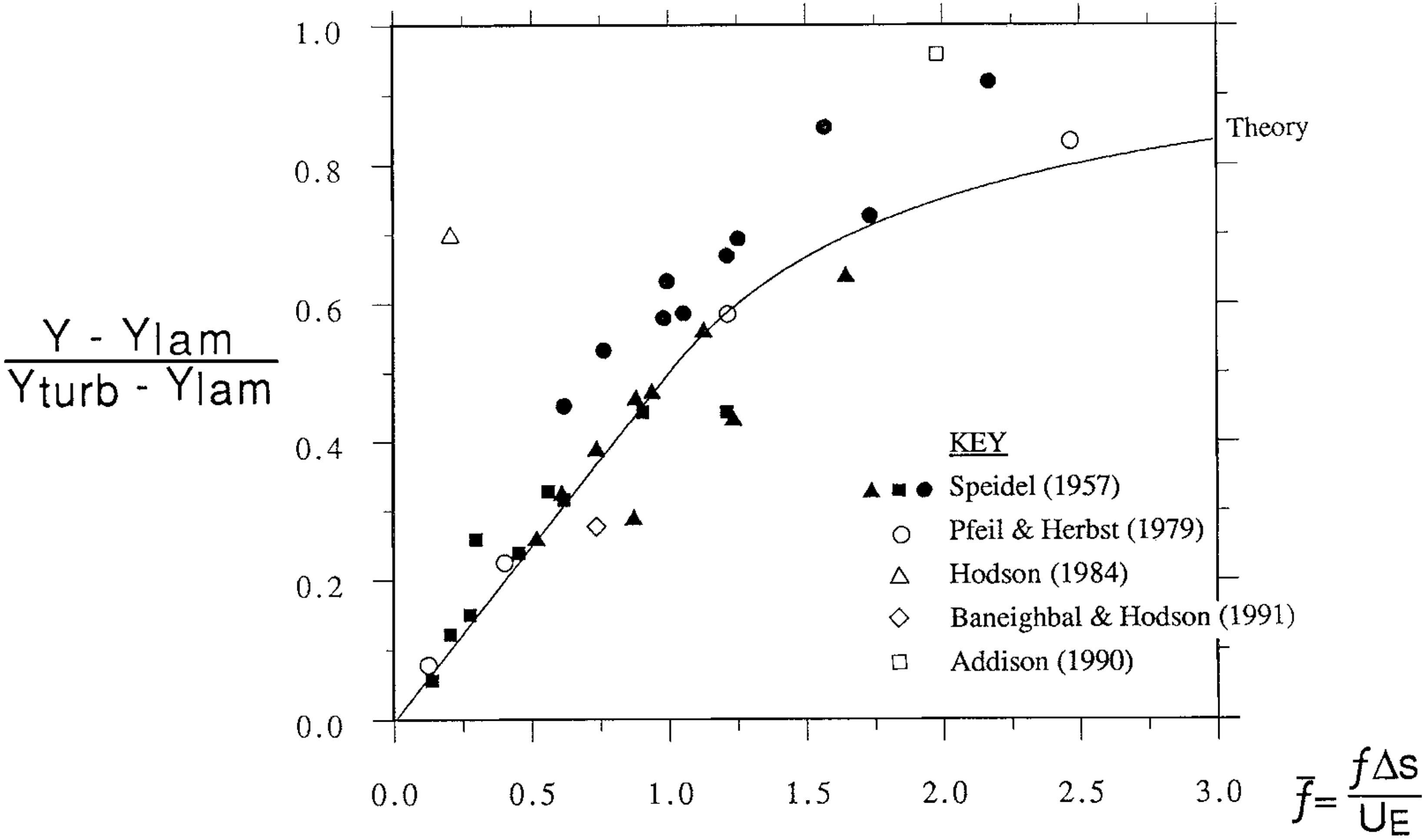
It requires

- 1% increase in component efficiency or
- 8% reduction in engine cost or
- 17% reduction in engine weight or

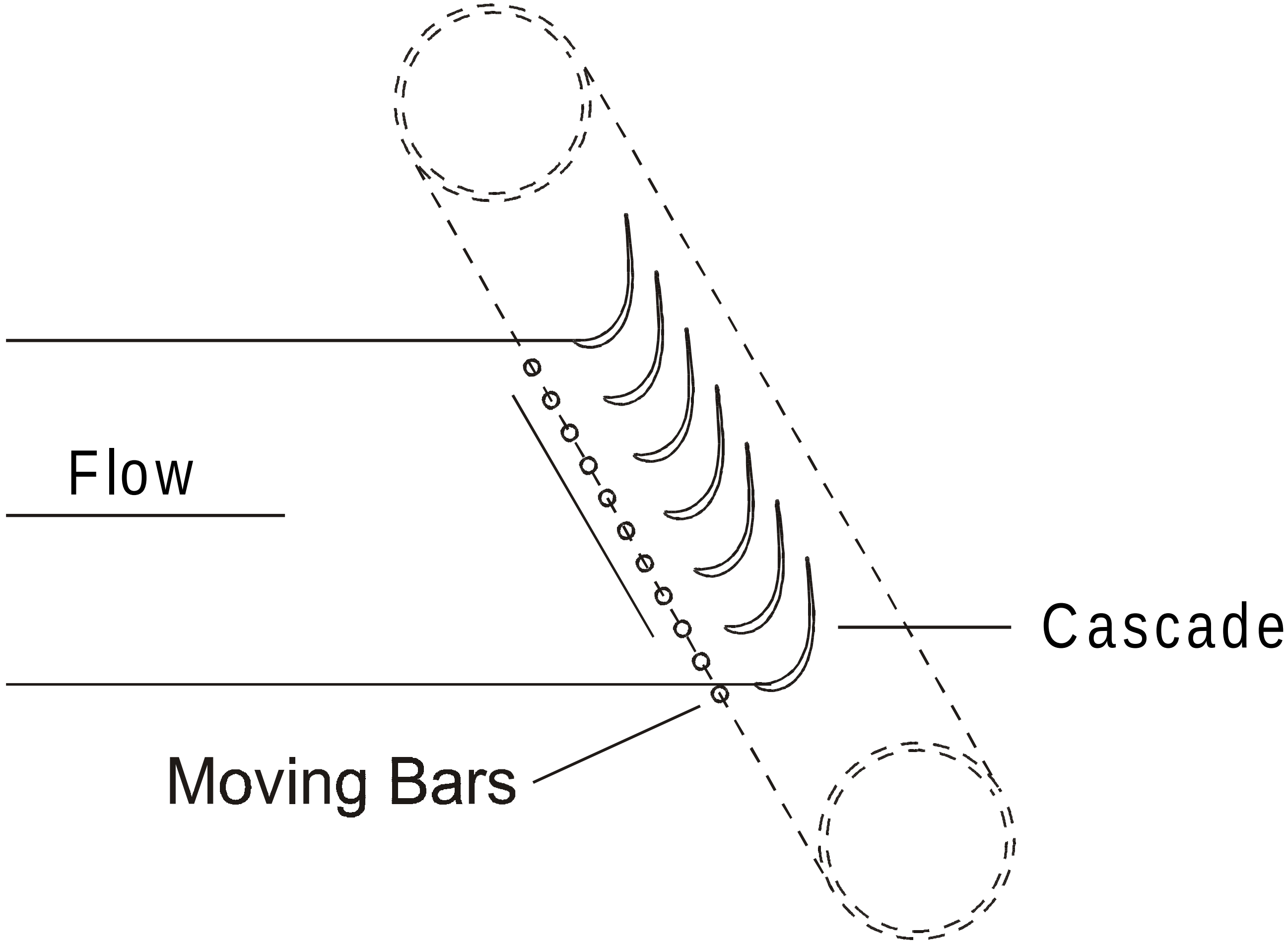
Wake-blade interactions in LP turbine



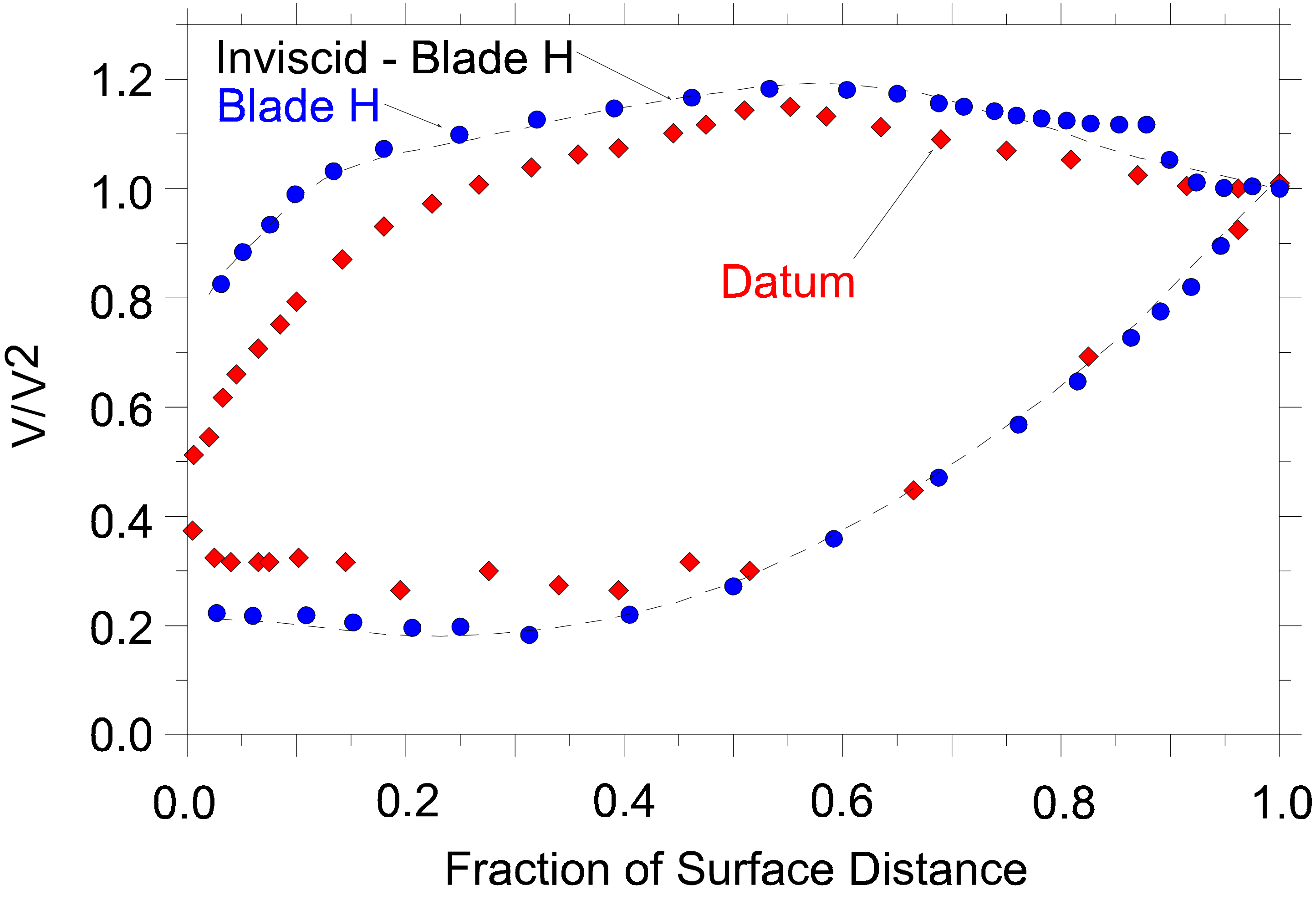
Effect of wakes on loss for attached flows



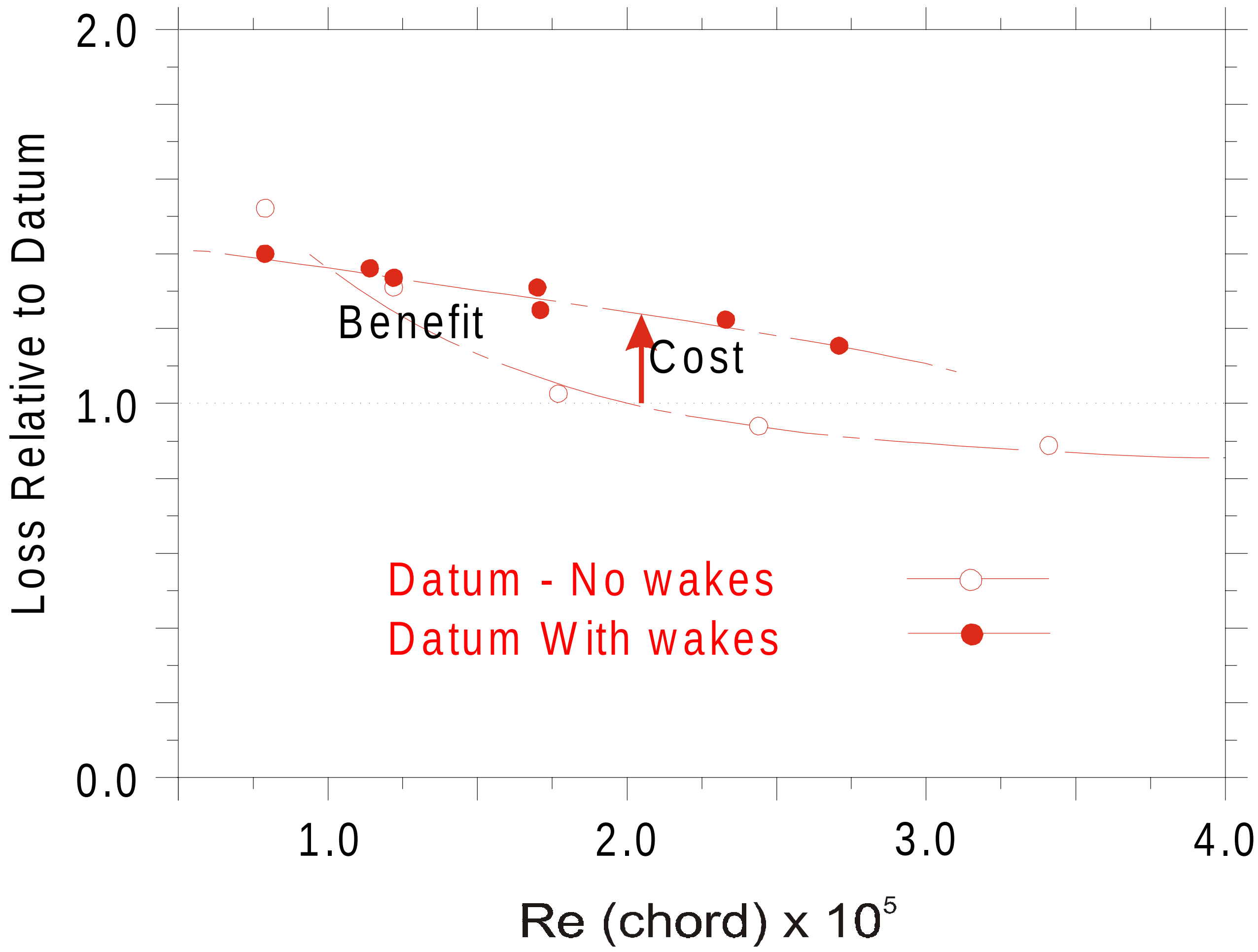
Single stage simulations: the Moving Bar Cascade



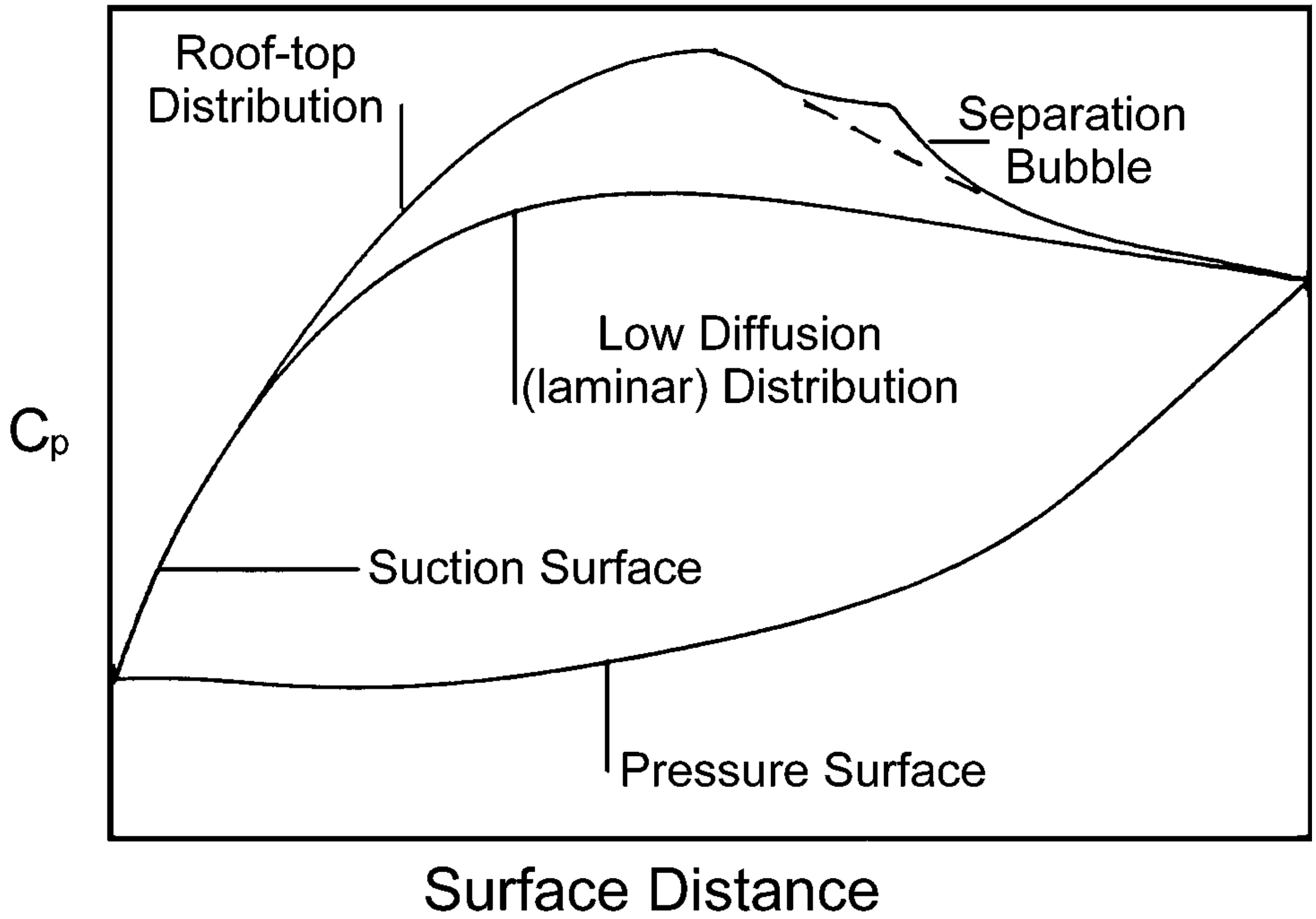
Two LP turbines: low (0.87) and high (1.04) lift coeffs.



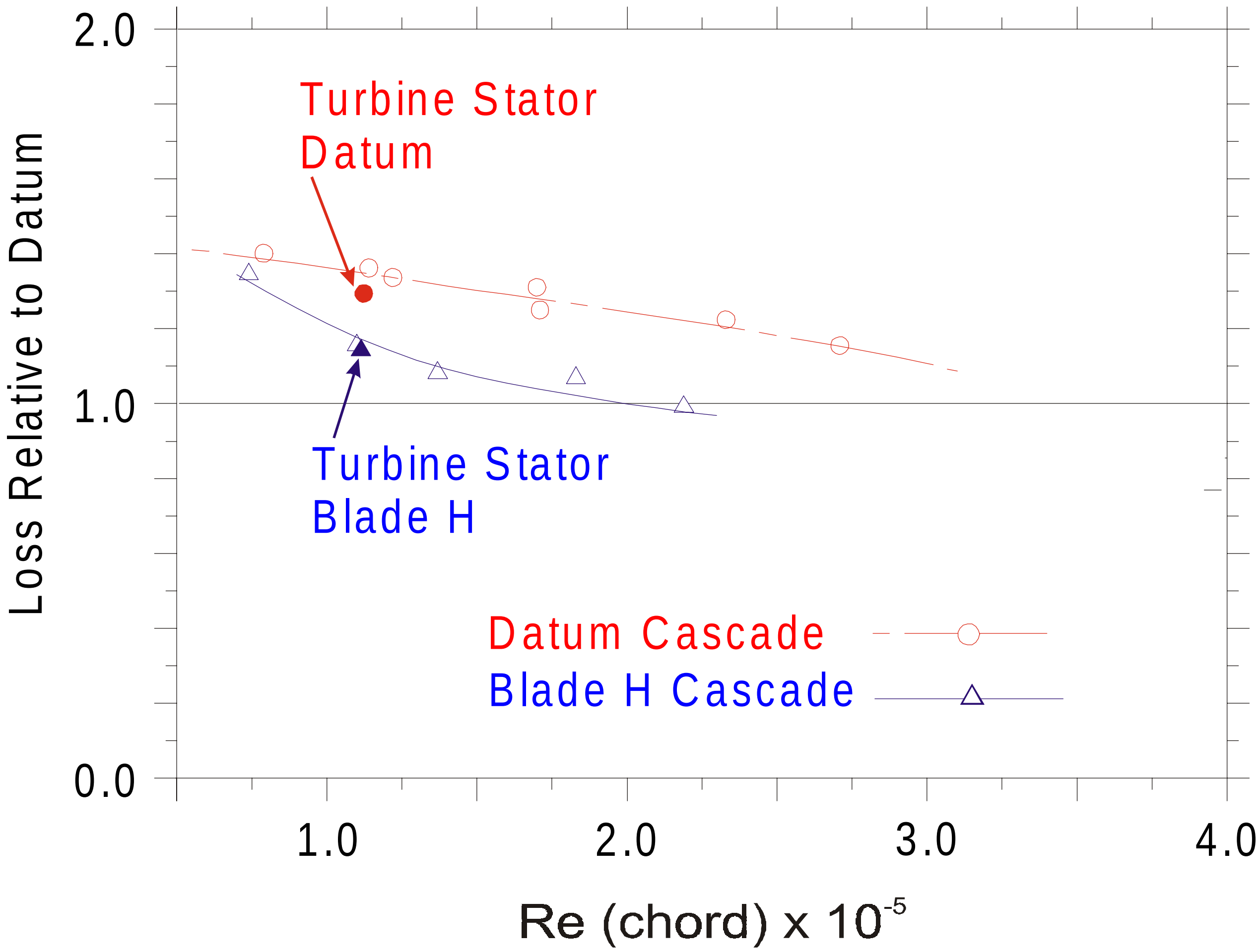
Effect of incoming wakes on profile loss – low lift



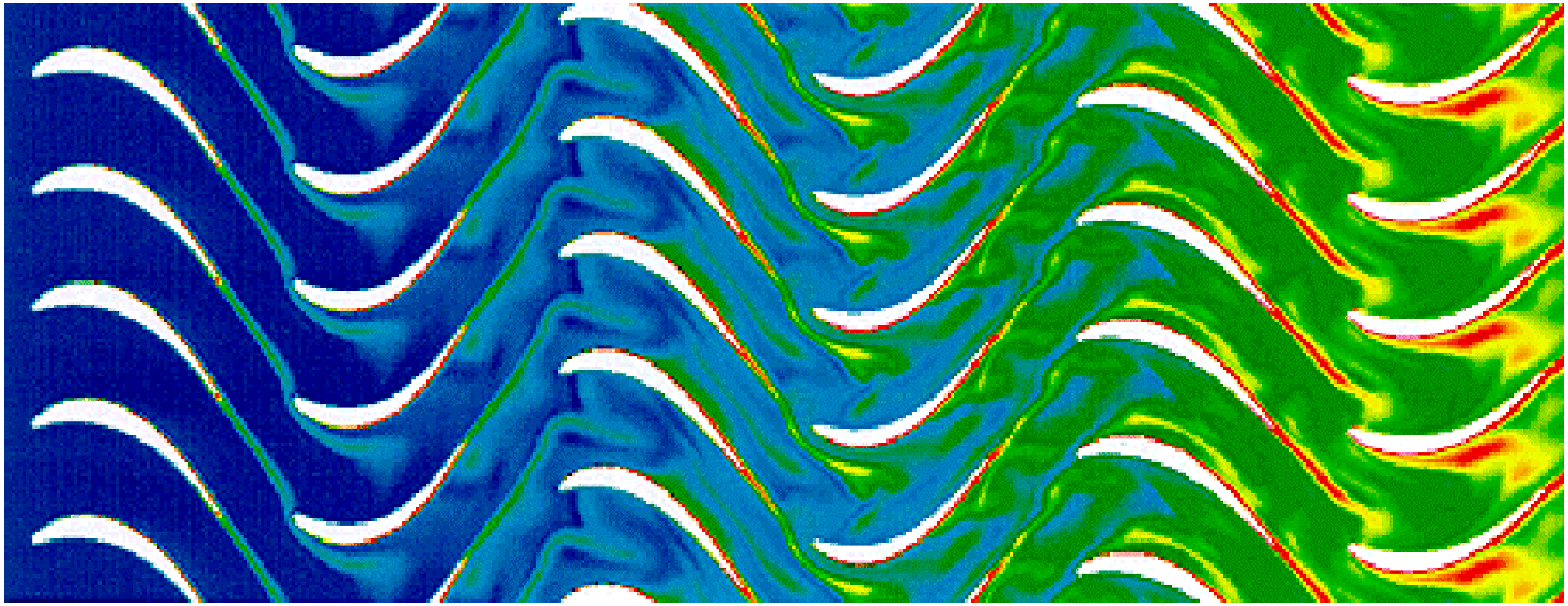
Generic pressure distributions for two LP turbines



Effect of wakes on profile loss – low vs. high lift



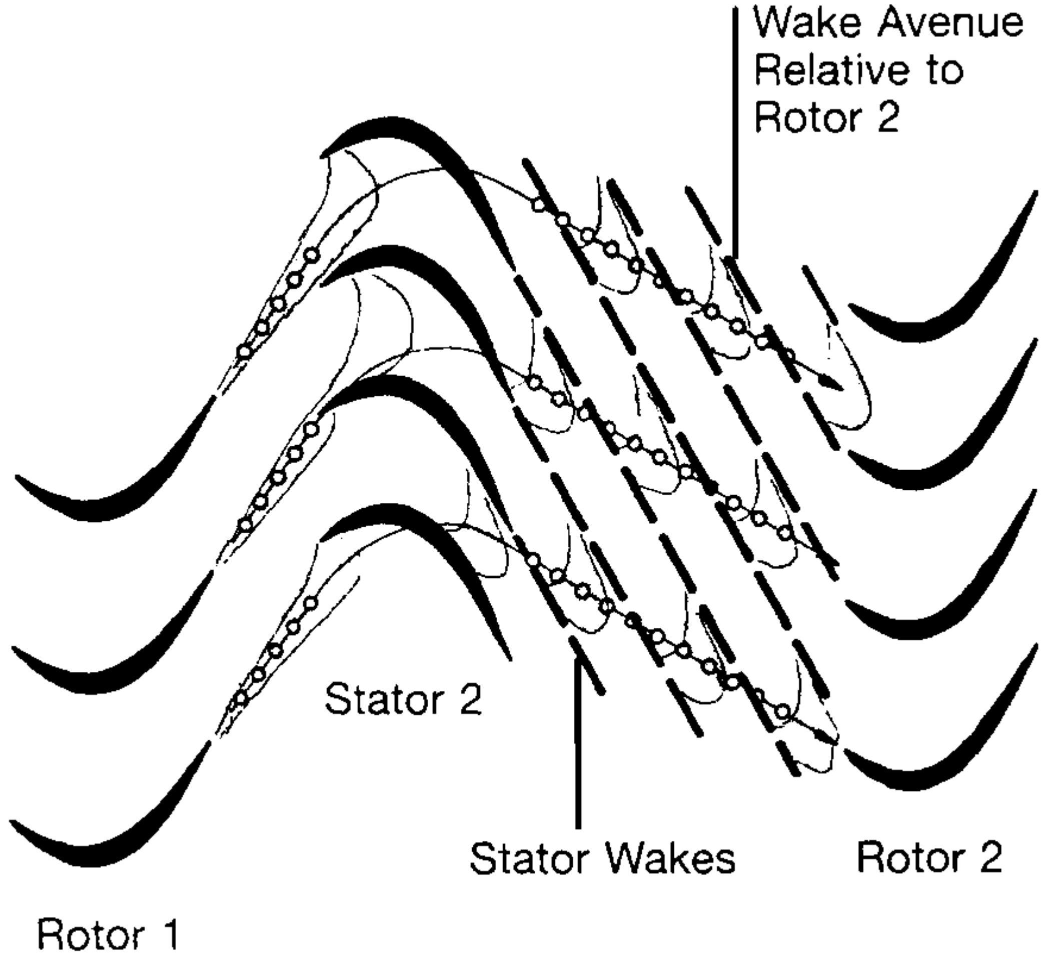
Multistage Interactions



Predictions of Arnone et al

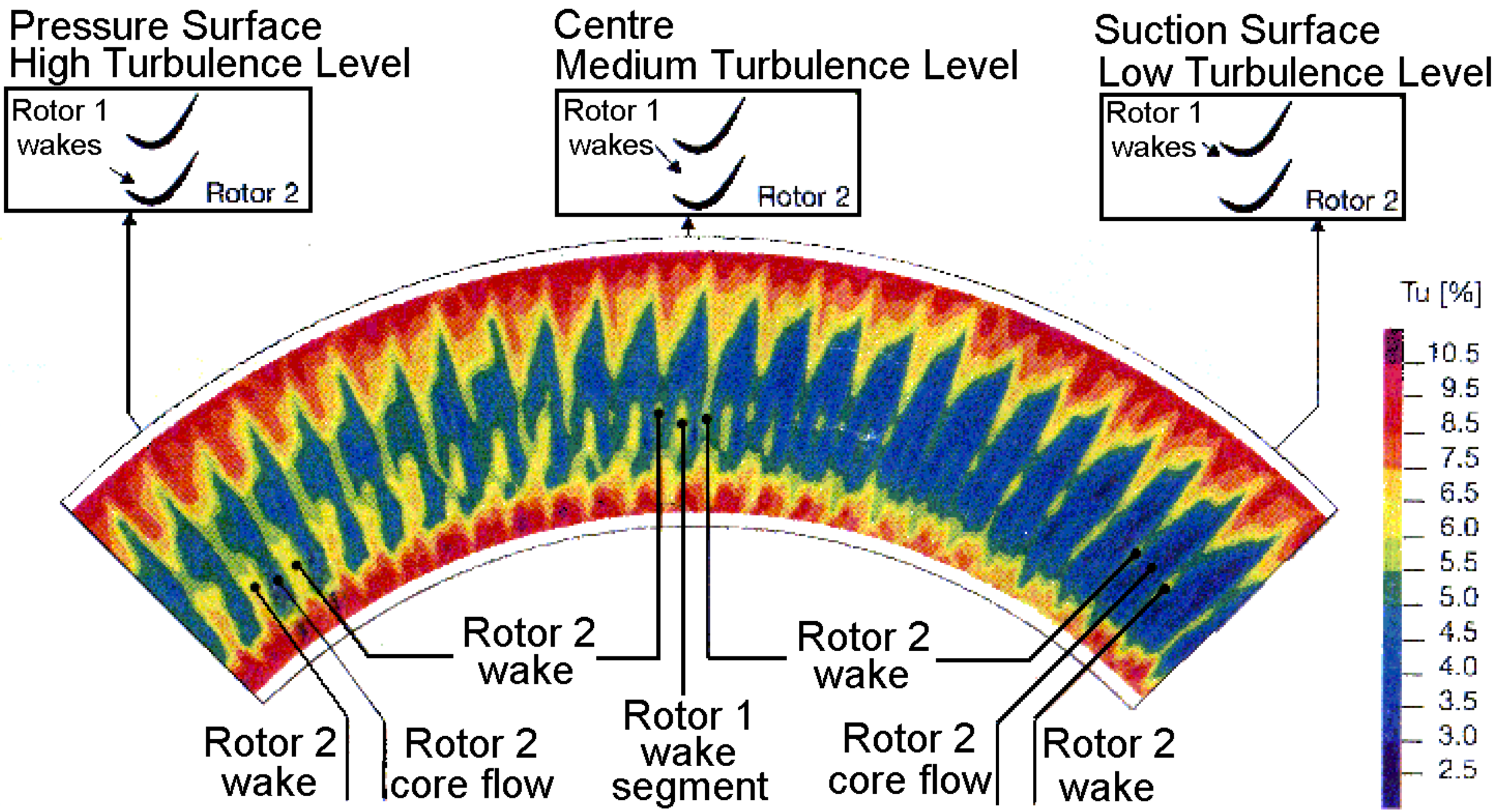
In engines many stages exist - increases complexity?

Schematic of wake avenues in multistage turbine

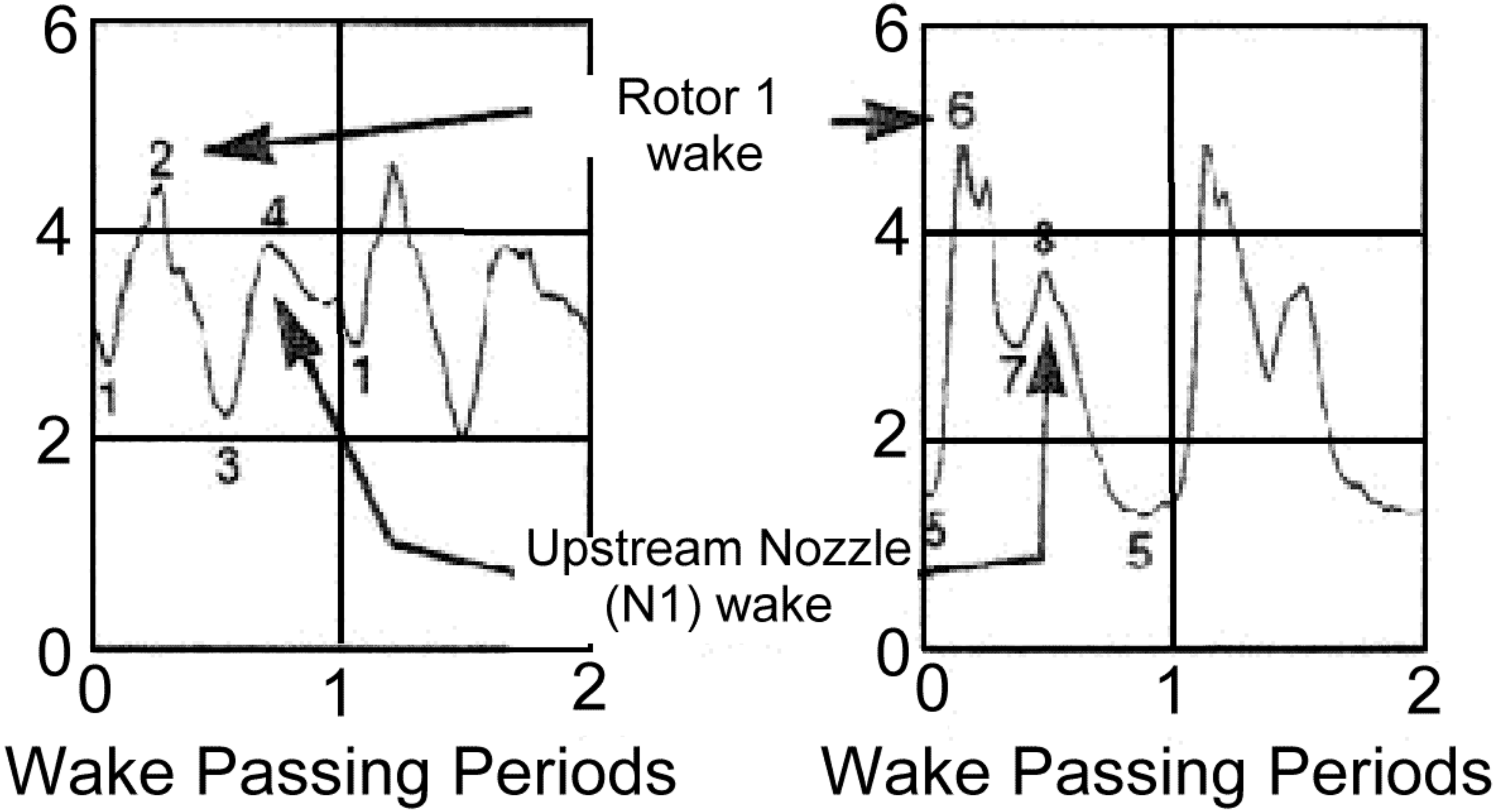


From Binder et al

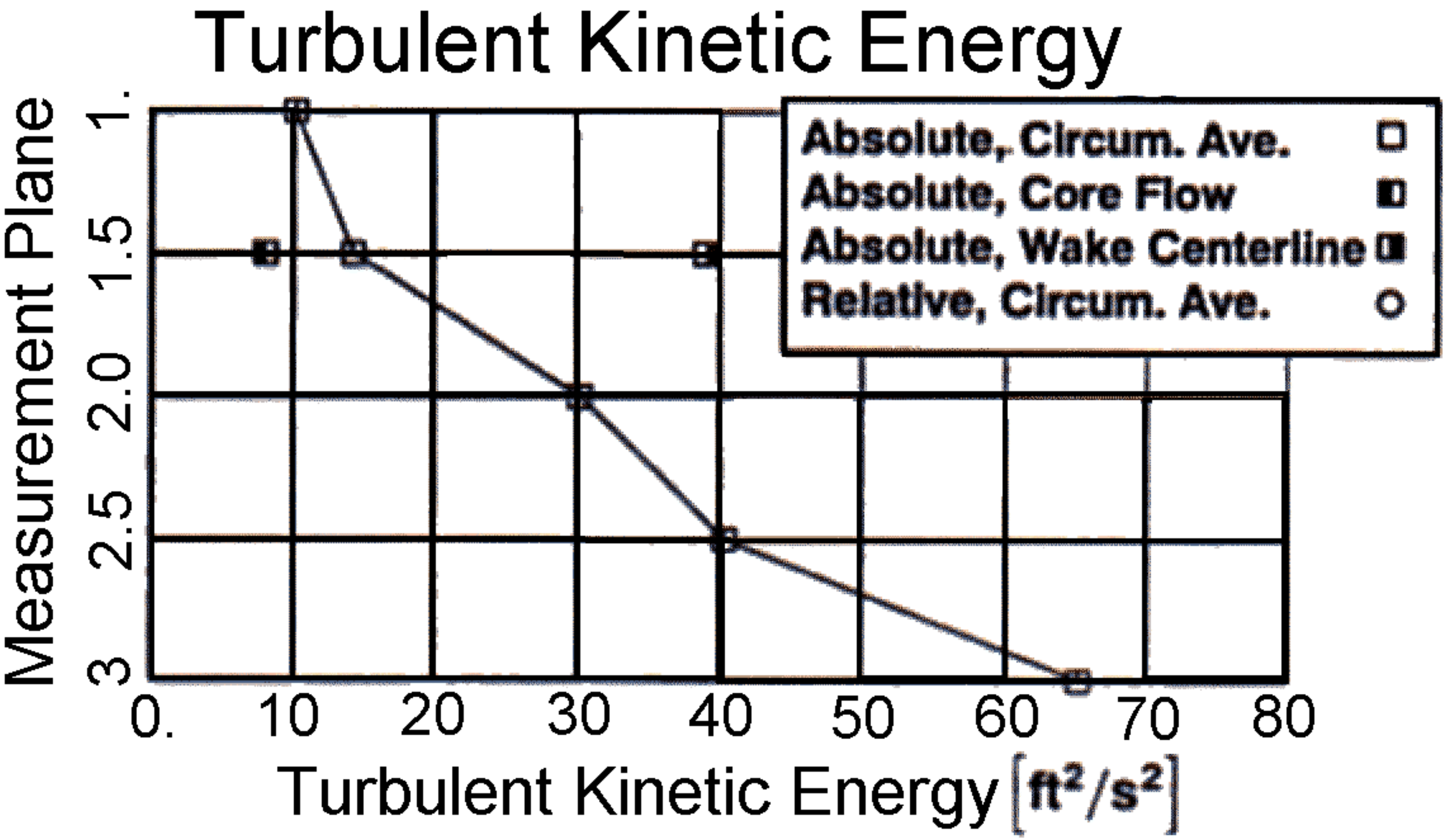
Variation with time of the turbulence intensity at inlet to stage 3 (Schröder)



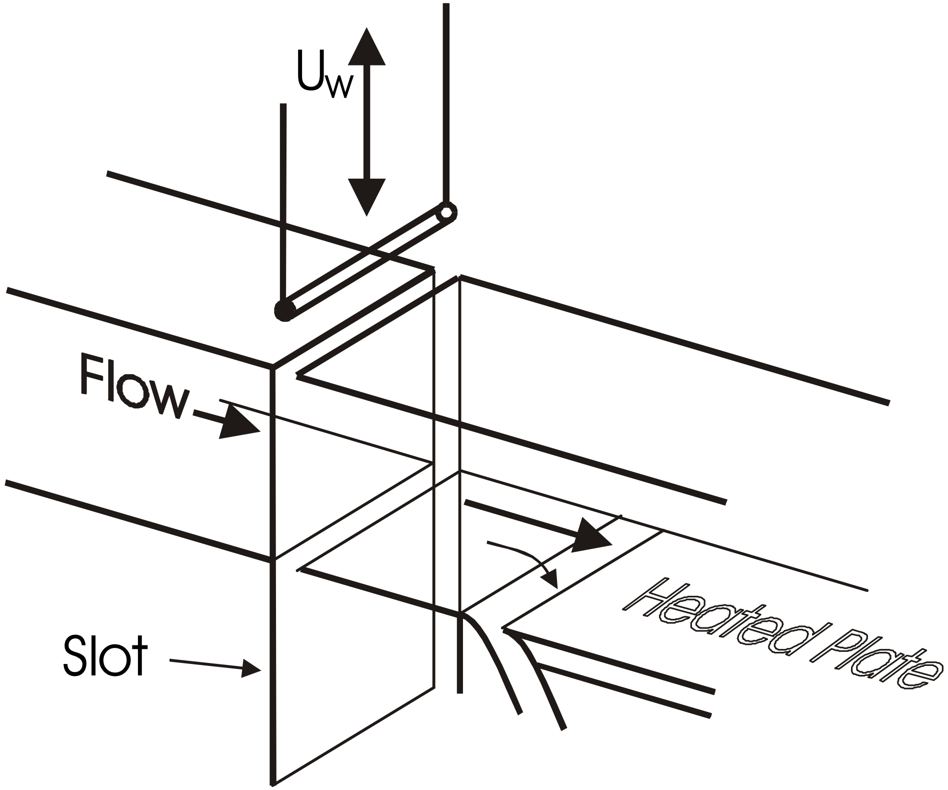
Variation with time of the turbulence intensity at inlet to stage 3 (Halstead)

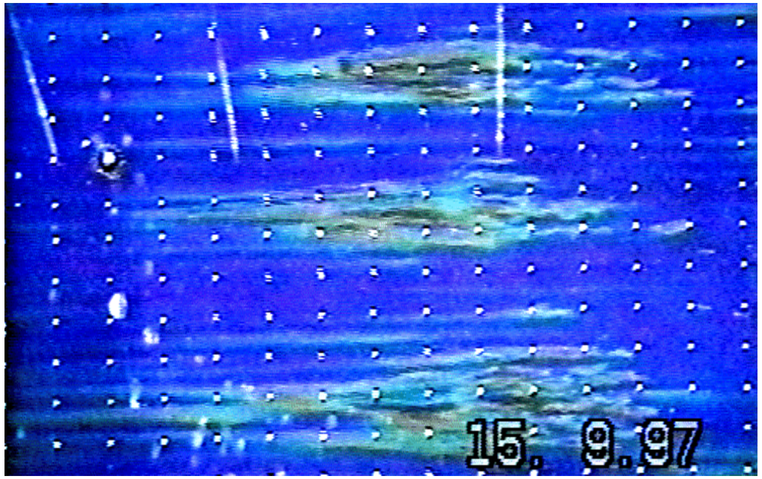


Pitchwise –average, time-mean disturbances in an LP turbine (Halstead)



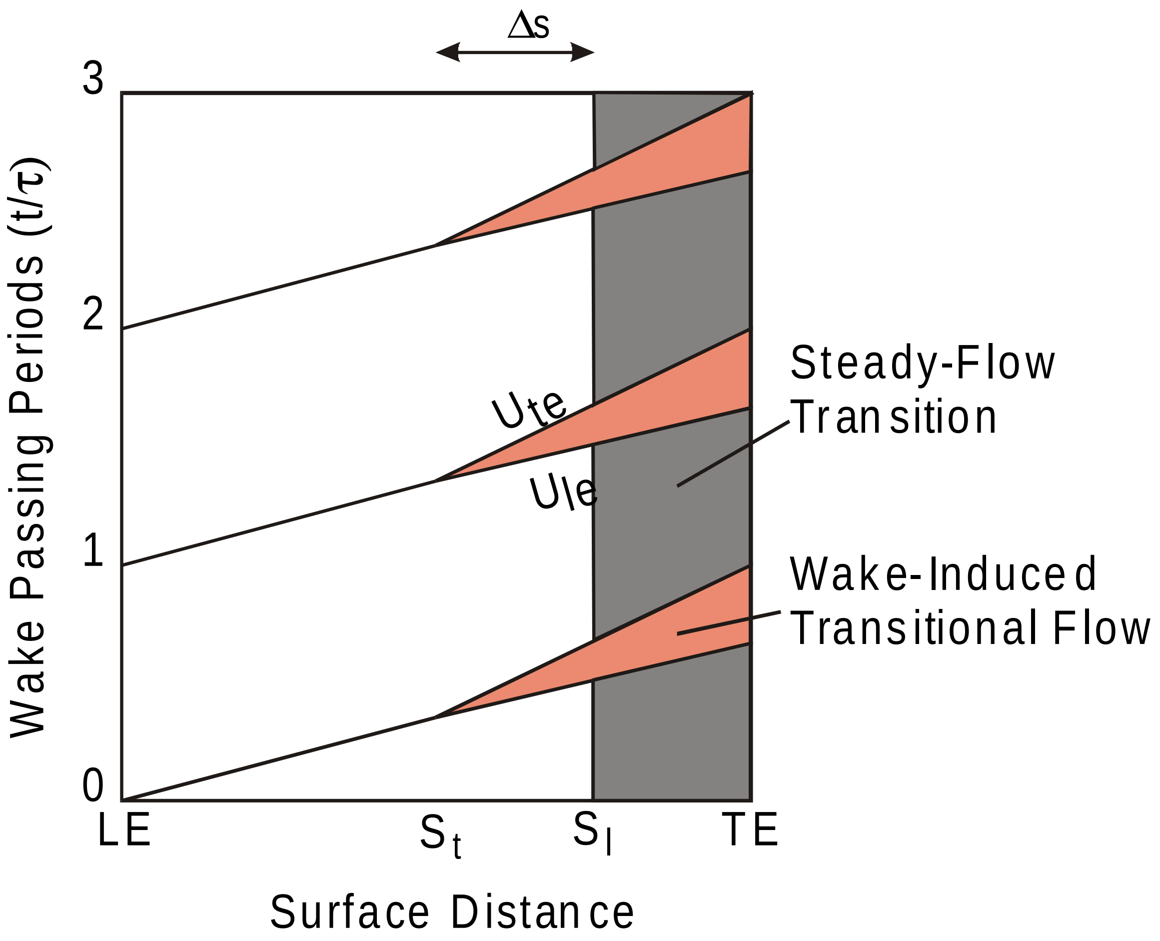
Wake-induced transition – attached flow



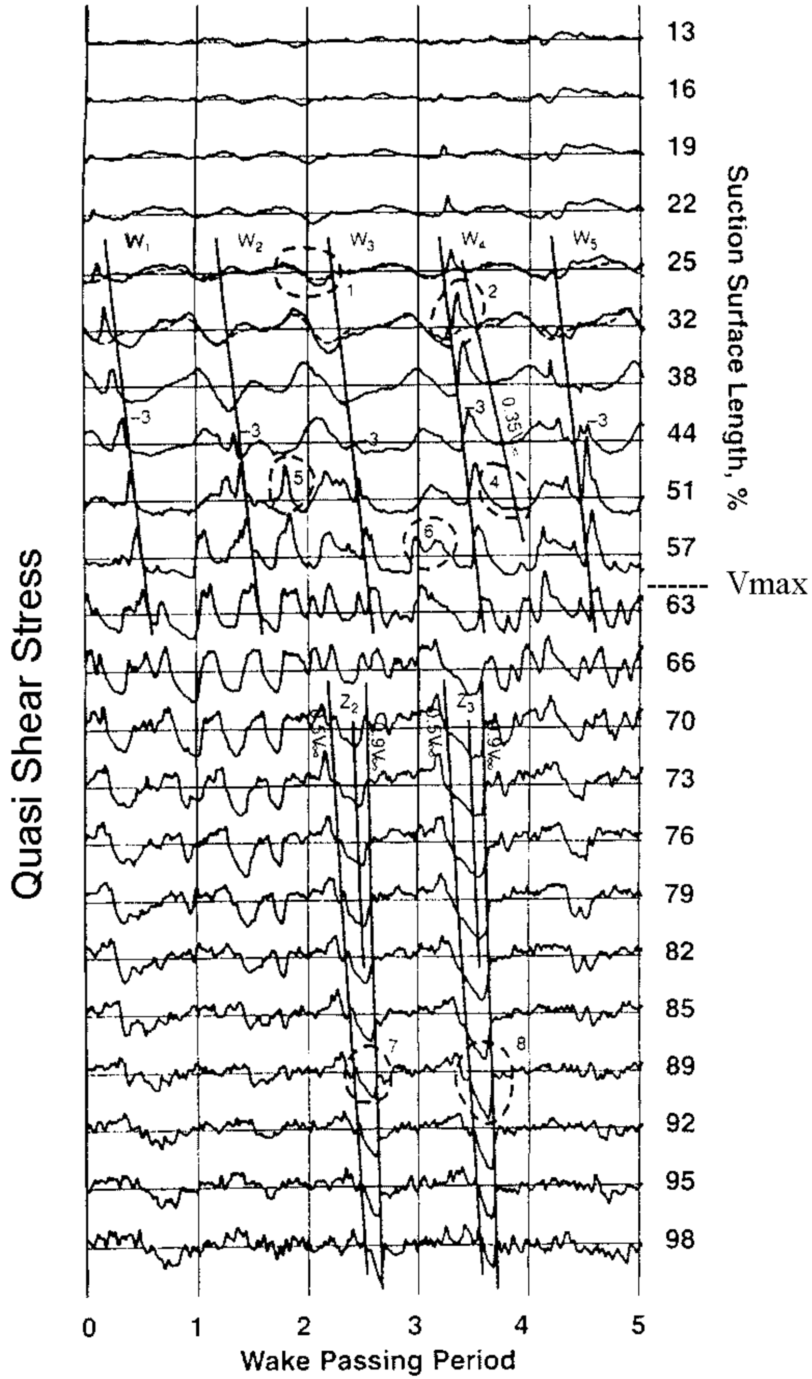


Visualisation of wake induced transition on a heated plate using liquid crystals

Schematic ST diagram of wake induced transition



Raw hot film traces for the baseline test case of Halstead at al (1995)

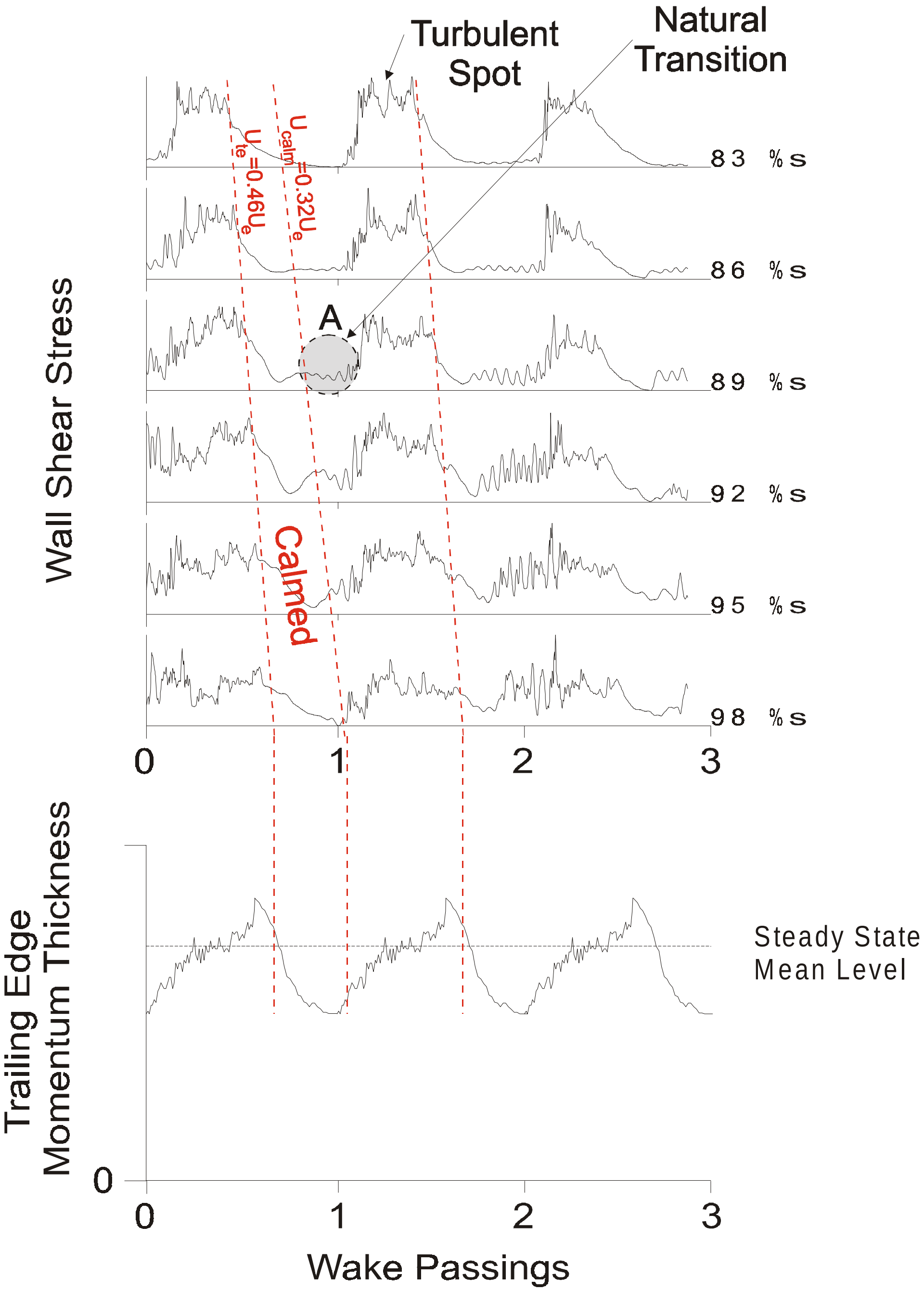


Low Lift Profiles

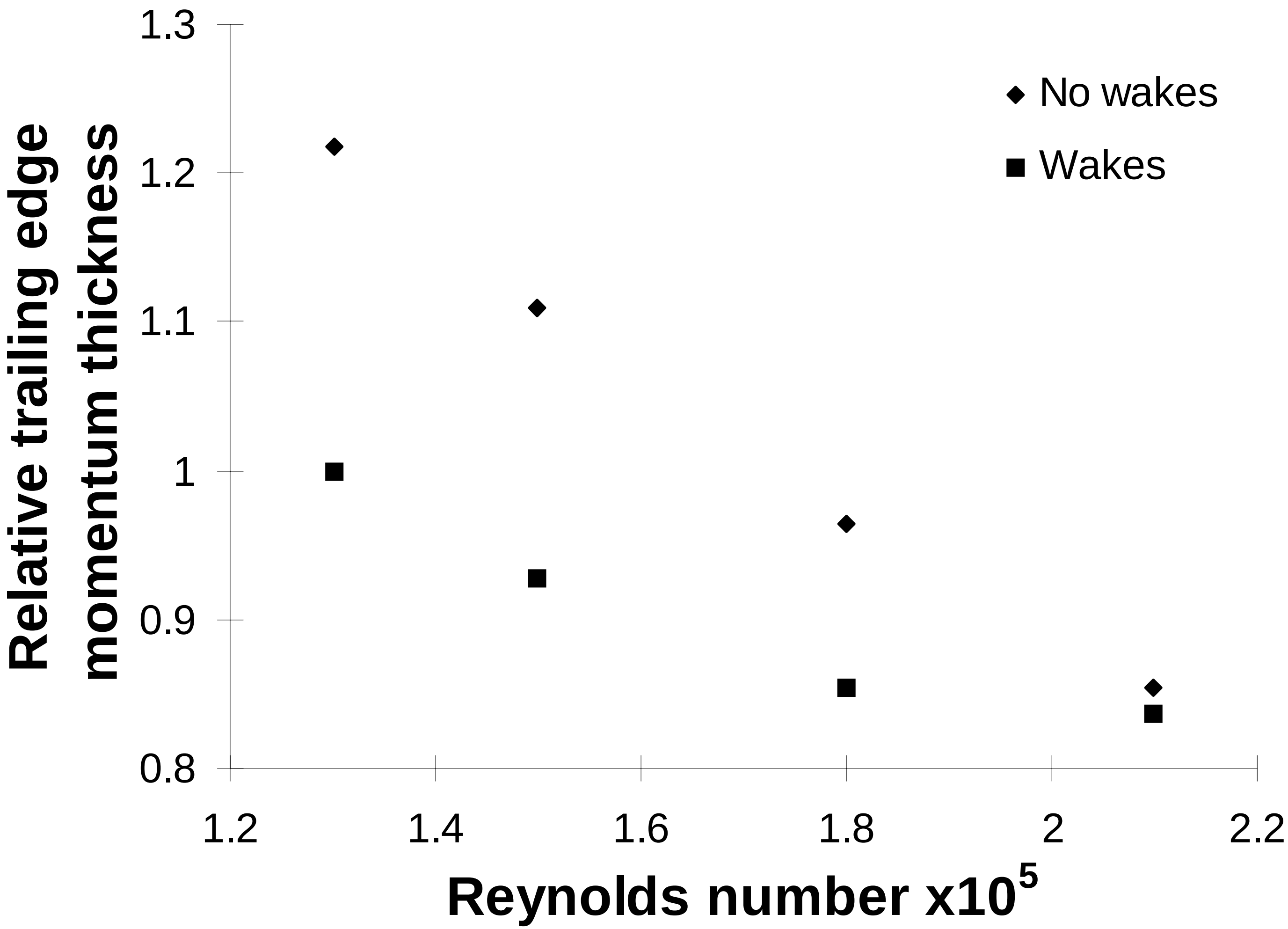
In single stage and multistage LP turbines

- wake induced transition proceeds via formation of turbulent spots
- wakes from bladerow immediately upstream dominate
- hence unsteady cascade experiments used to develop new profiles
- Calmed regions
    - ➢ exist in highly disturbed multistage environment
    - ➢ can persist as far as trailing edge.

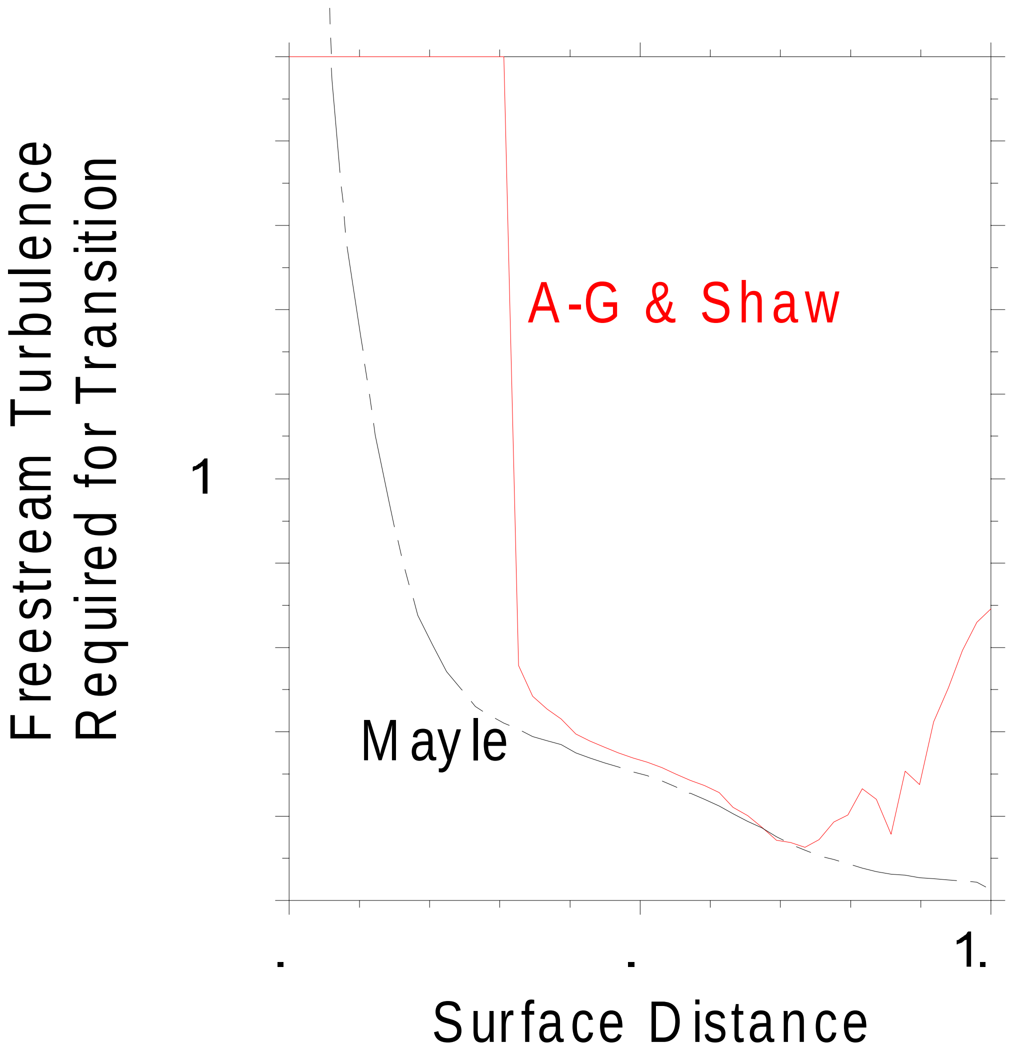
Effect of wakes on high lift cascade



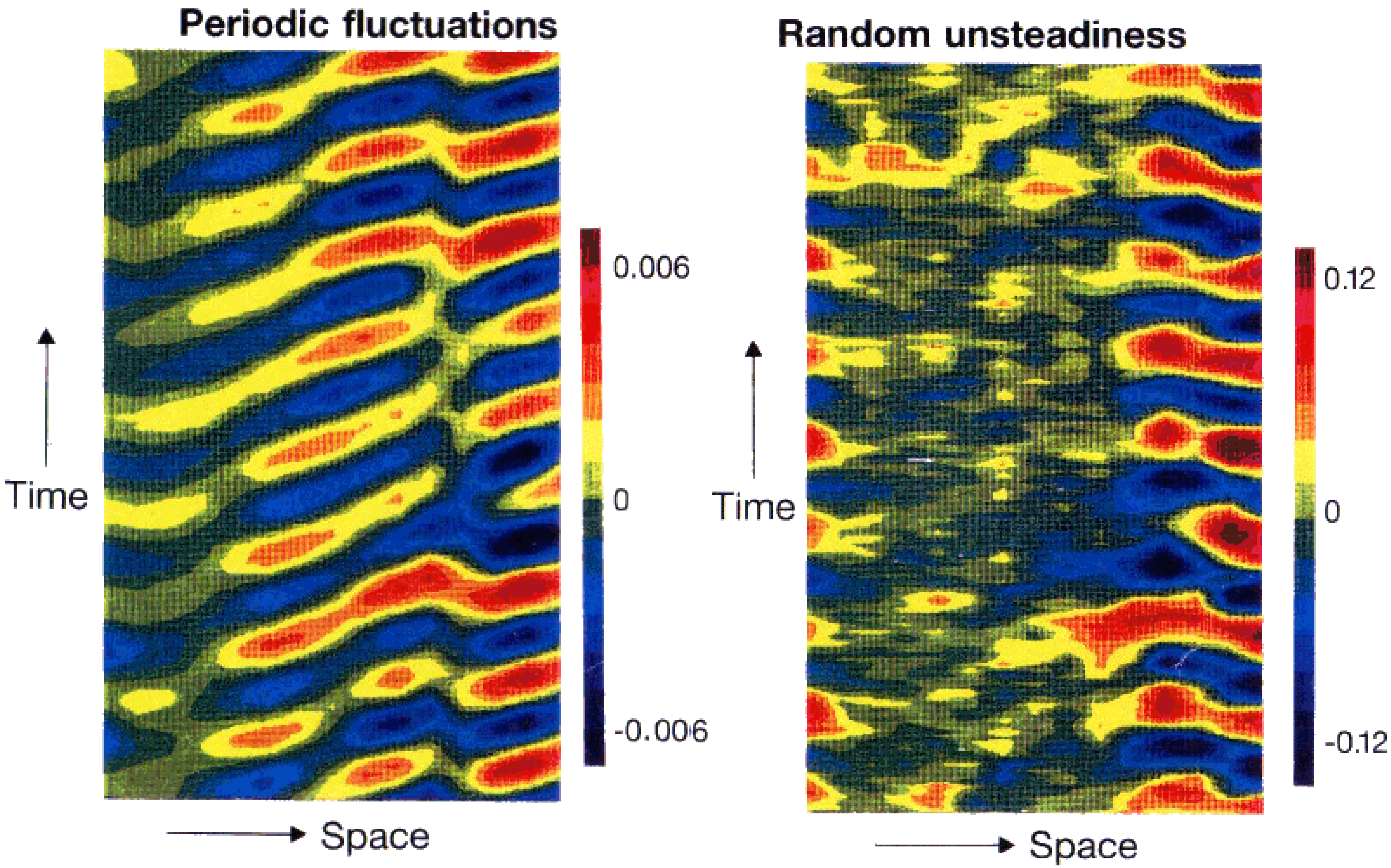
Suction side boundary layer loss vs. Reynolds number - high lift



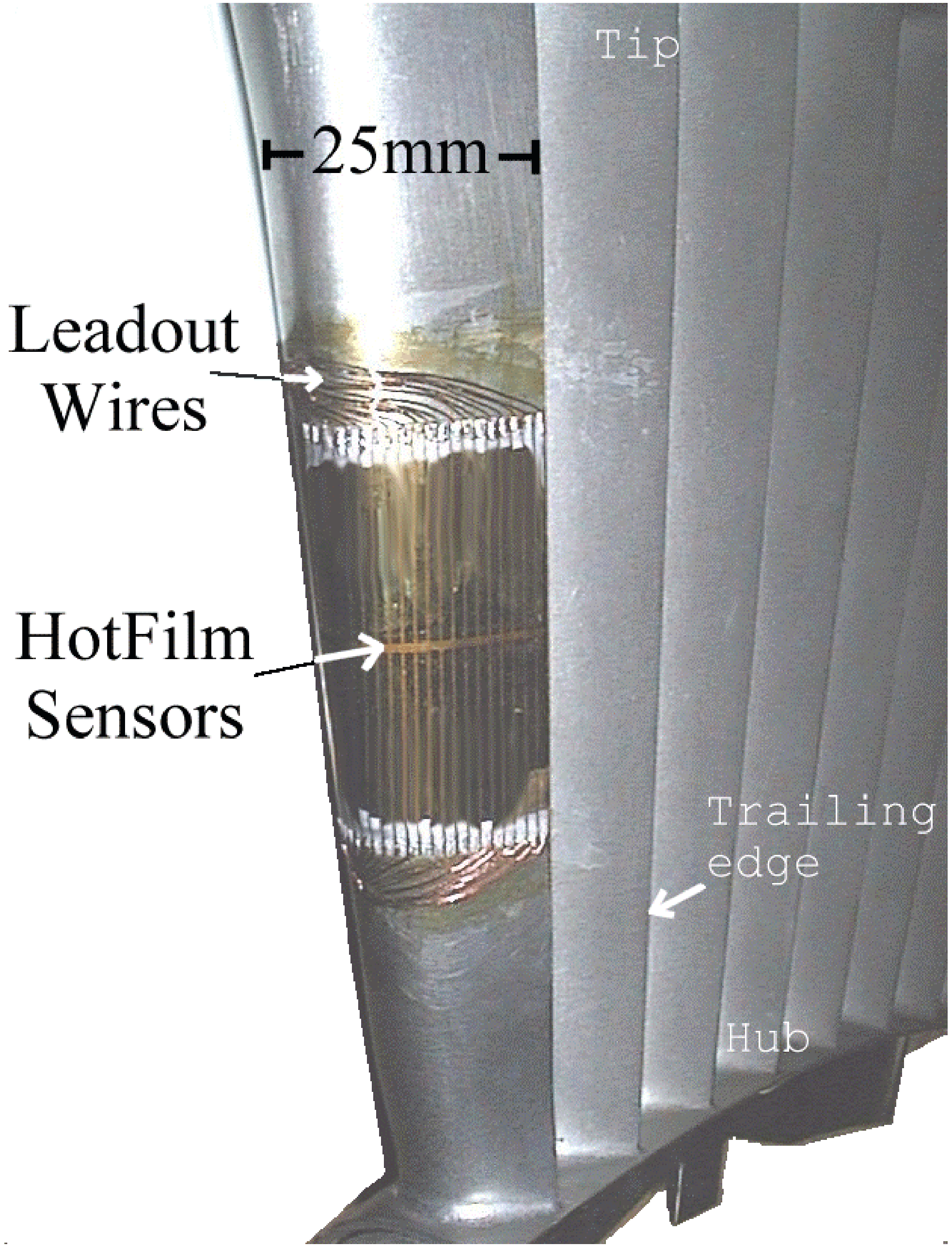
Freestream Tu required to cause transition



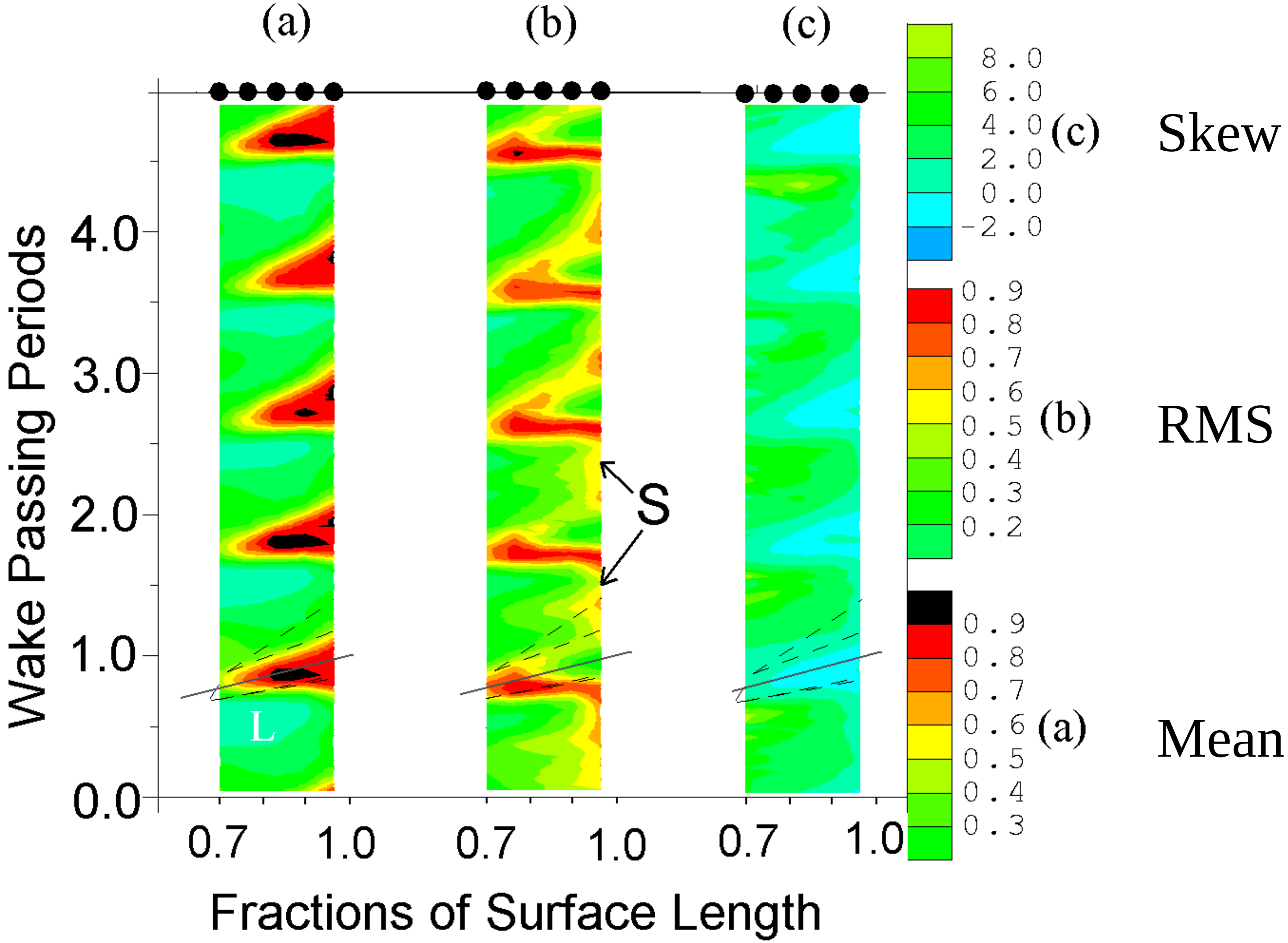
ST diagrams of hot film data from NGV5 of the LP turbine (Schröder)



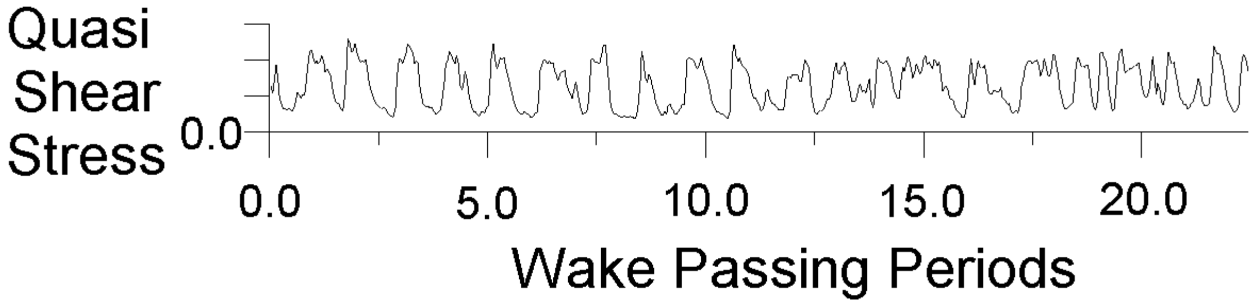
Surface mounted hot film anemometry on BR715 LP Turbine NGV3



Hot film data from NGV2 of BR715 LP turbine



Raw hot film data from NGV2 of BR715 LP turbine



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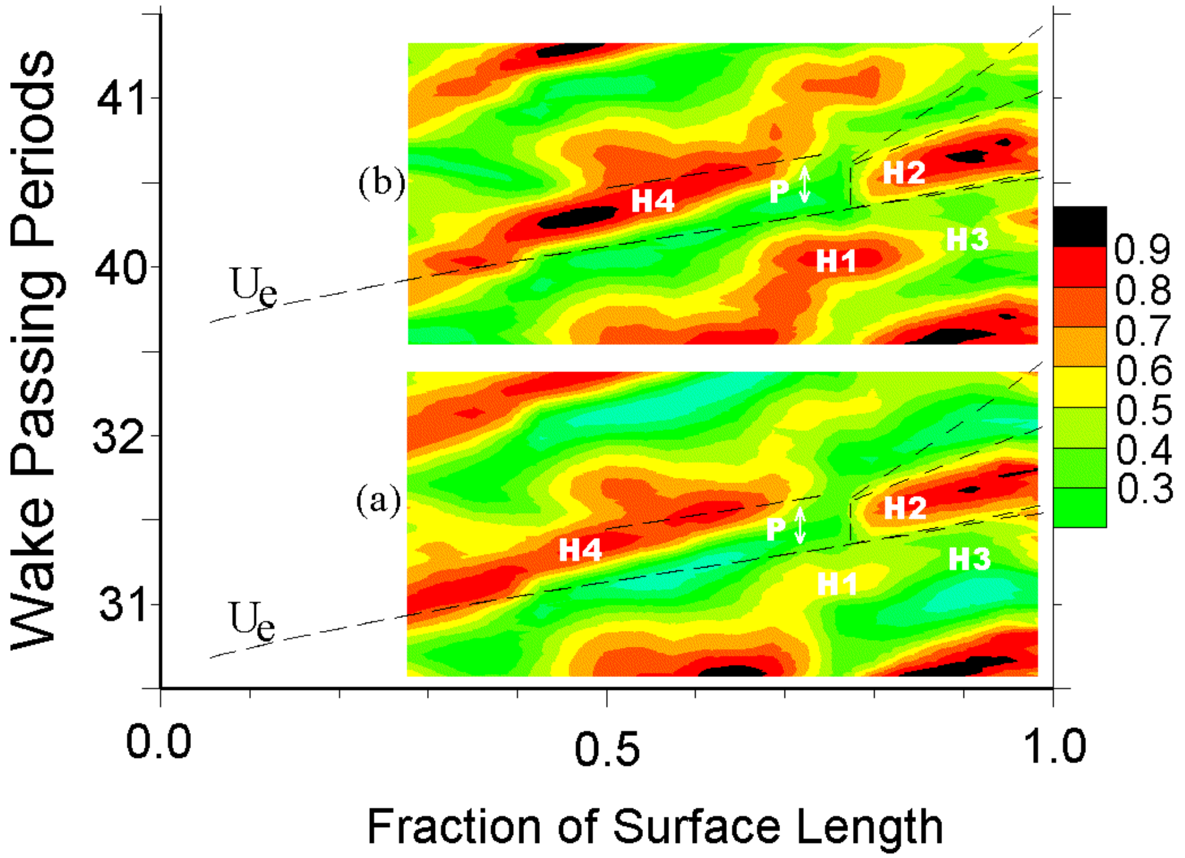
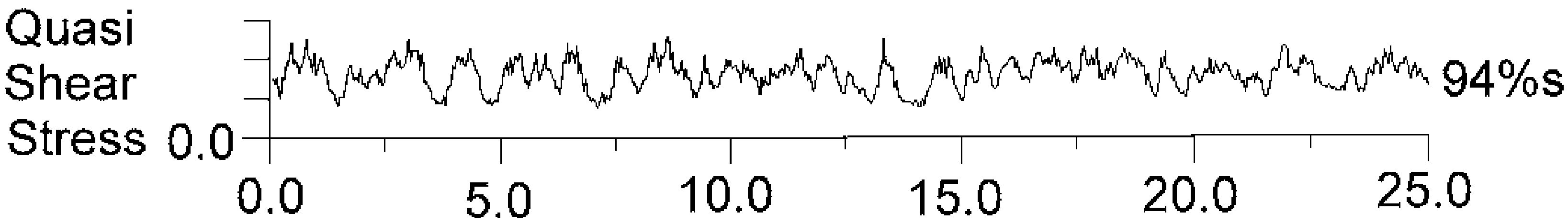
Ensemble-mean τ_w on NGV3 of BR715 LP turbine

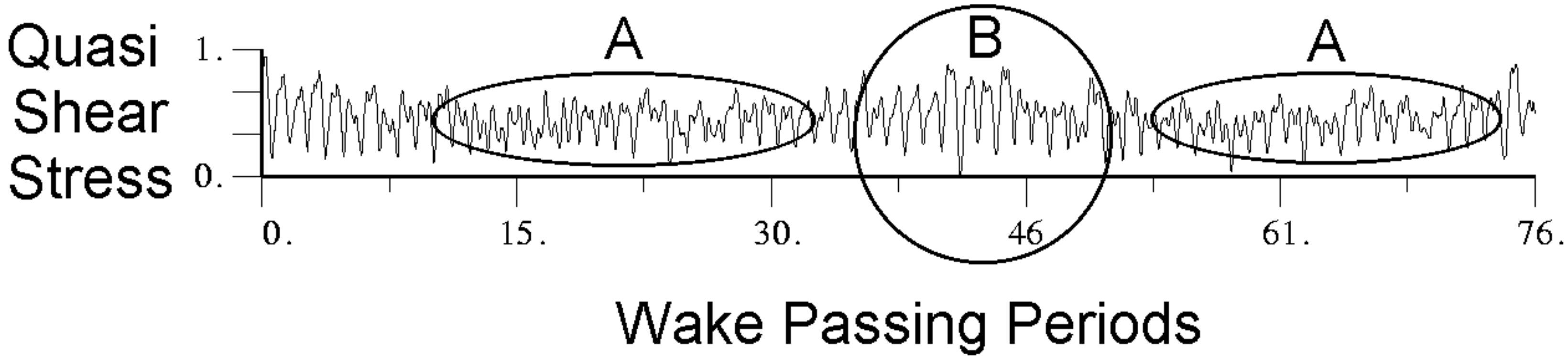


From stator 3 of the BR715 LP turbine. Reynolds number (90,000).

Raw hot film data from NGV3 of BR715 LP turbine



Ensemble-mean τ_w on NGV3 of BR715 LP turbine for one revolution of rotor 2

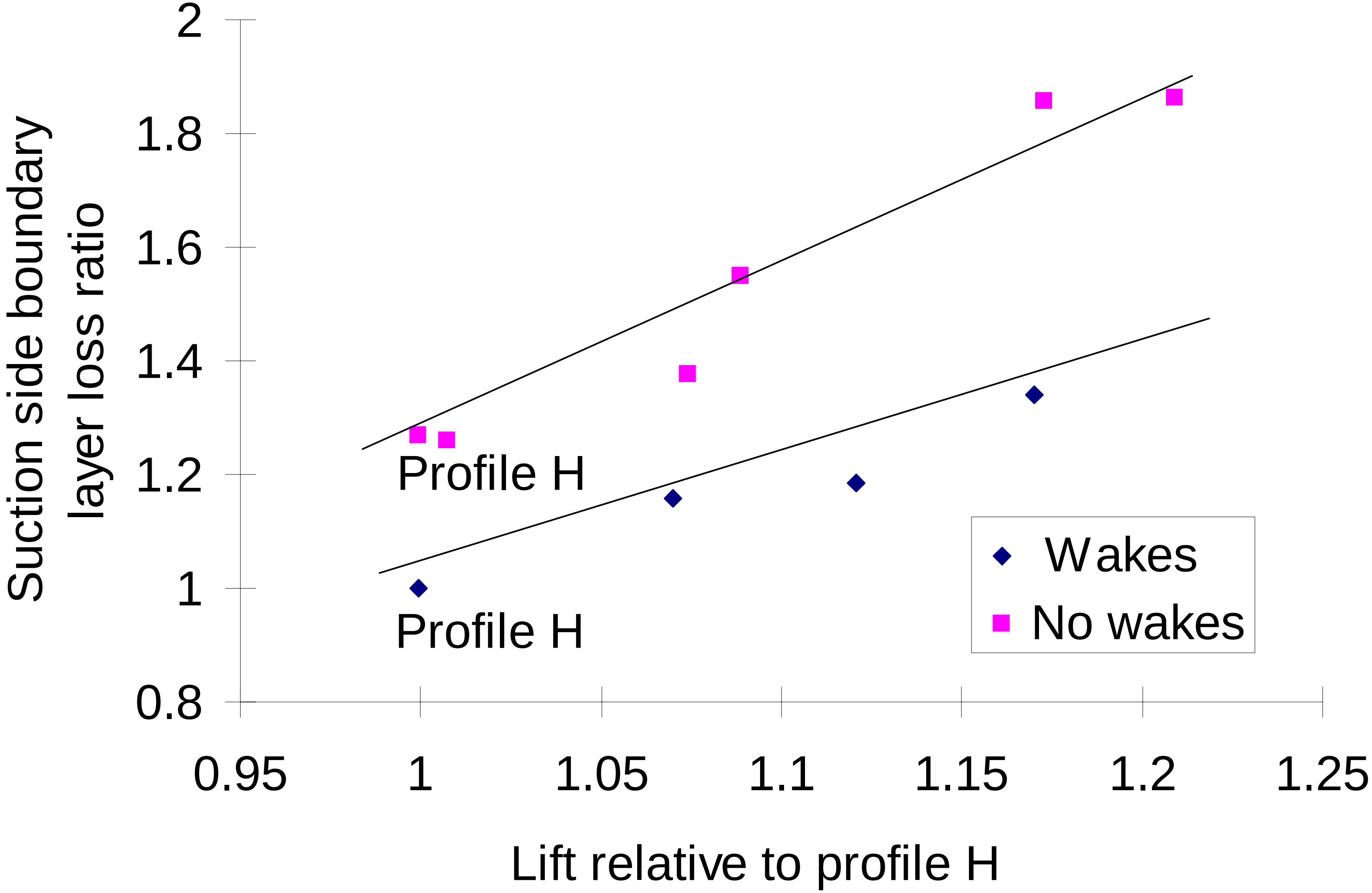


High Lift Profiles

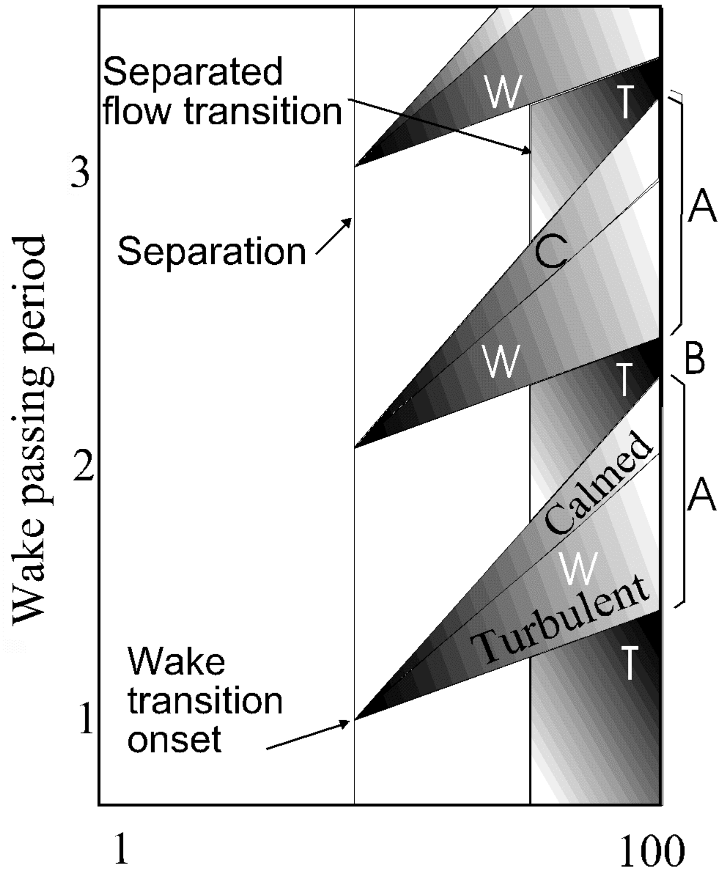
In the high-lift turbines

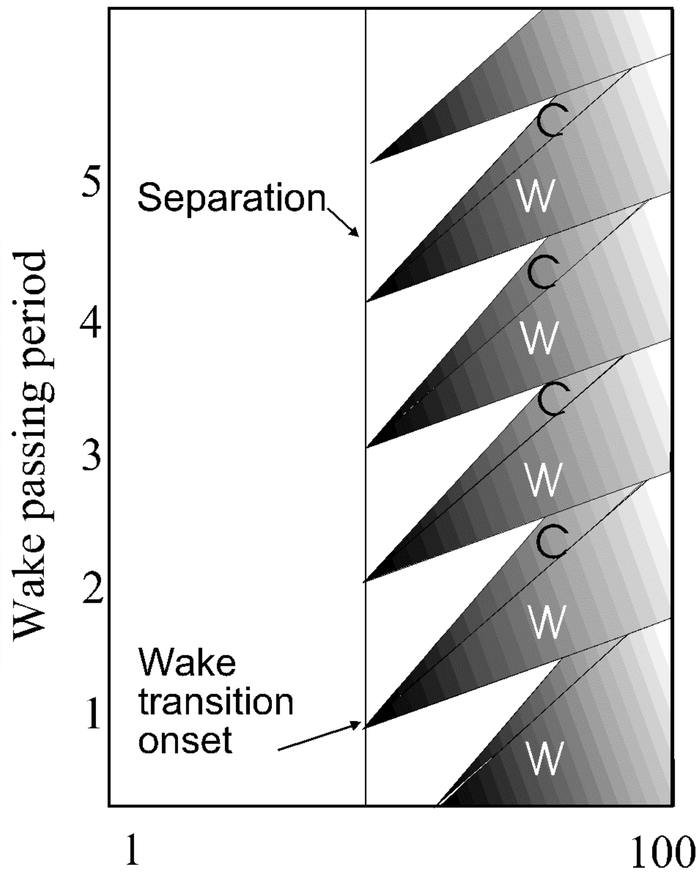
- evidence of rotor-rotor interactions
- no real evidence that rotor-rotor interactions impact on transition process
- calming visible at trailing edge
- benefits greatest at lower Reynolds numbers and higher lift
- no loss penalty due to increased lift

Effect of lift on loss – max velocity at $0.55s_{max}$



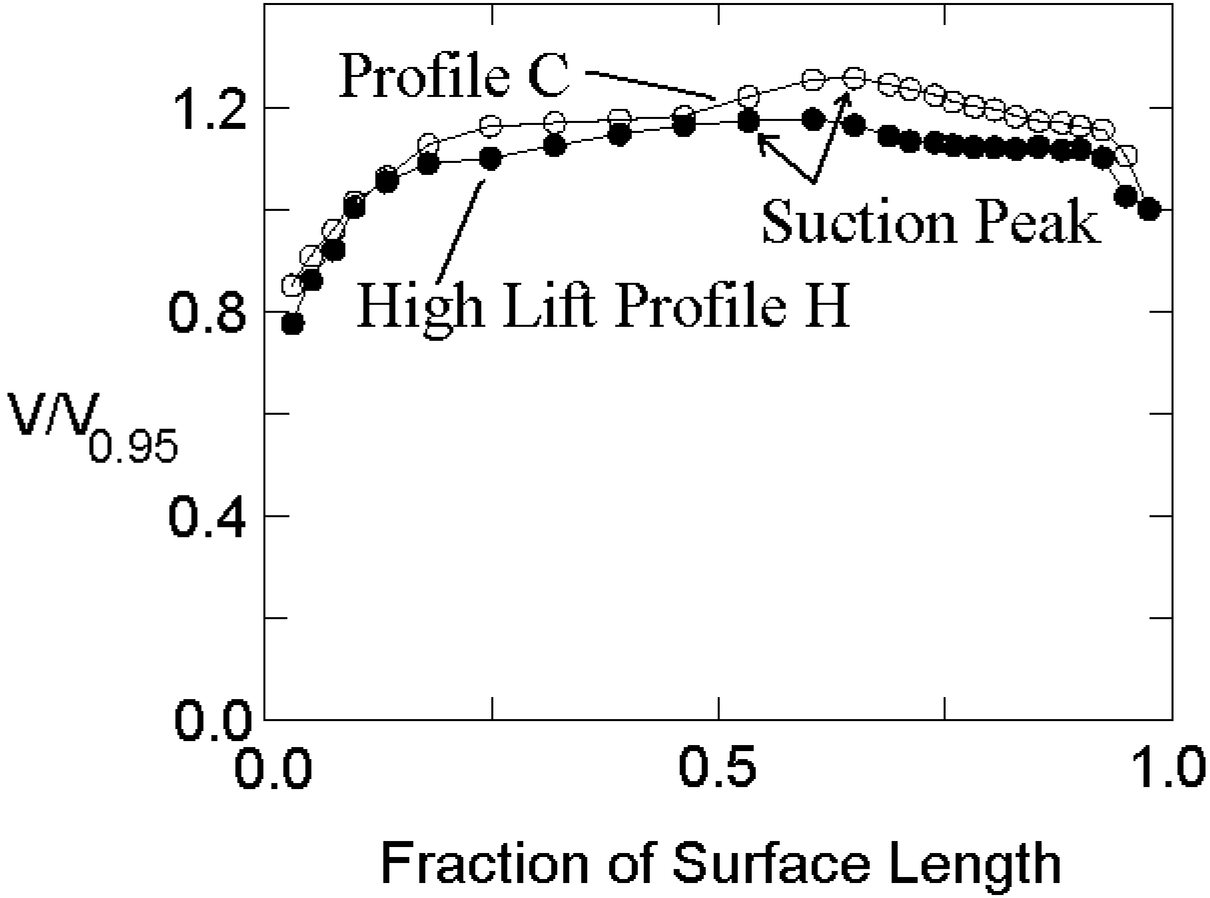
Effect of frequency on transition





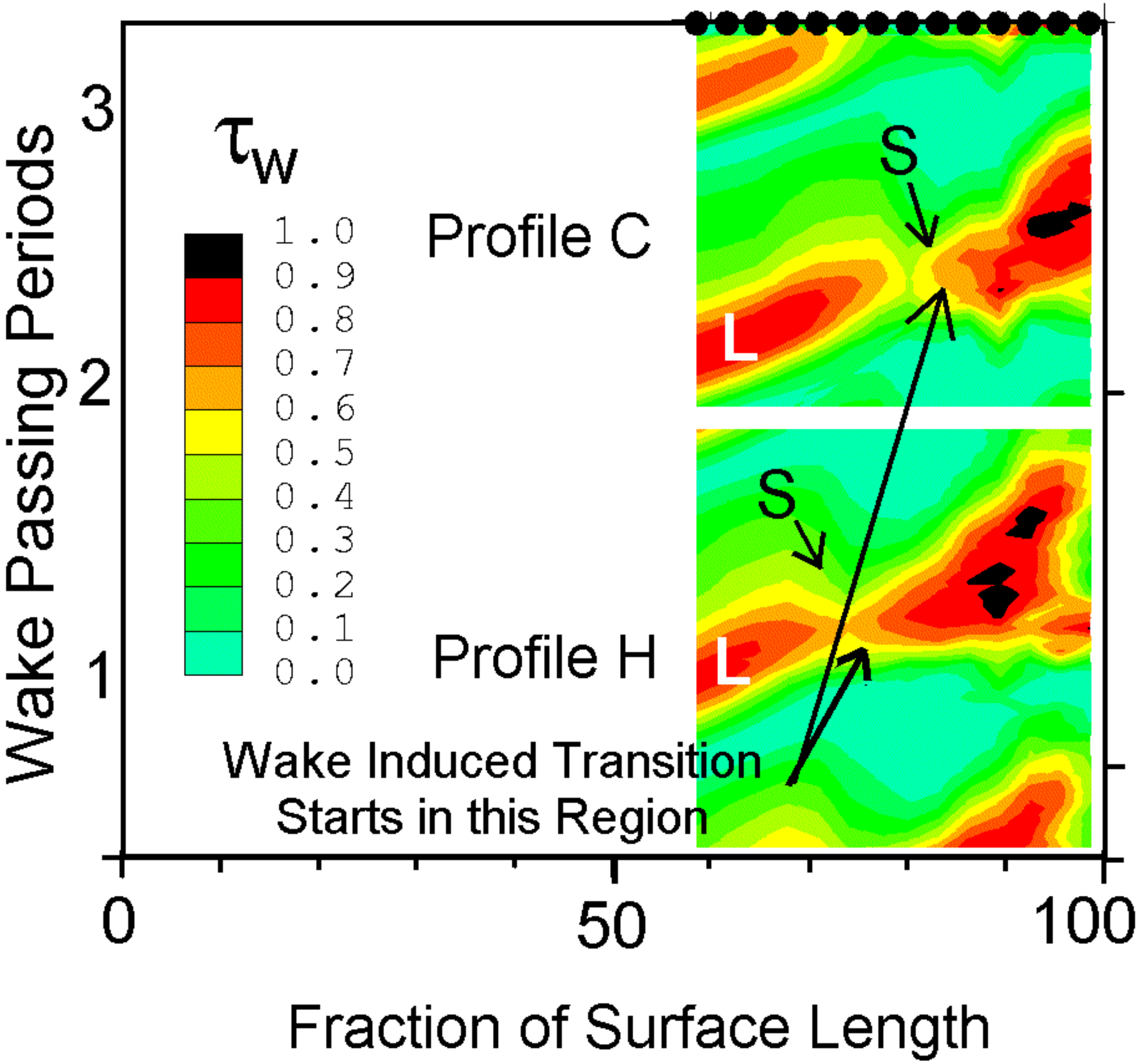
Aft loading removes turbulent boundary layer from wakes and separation bubble

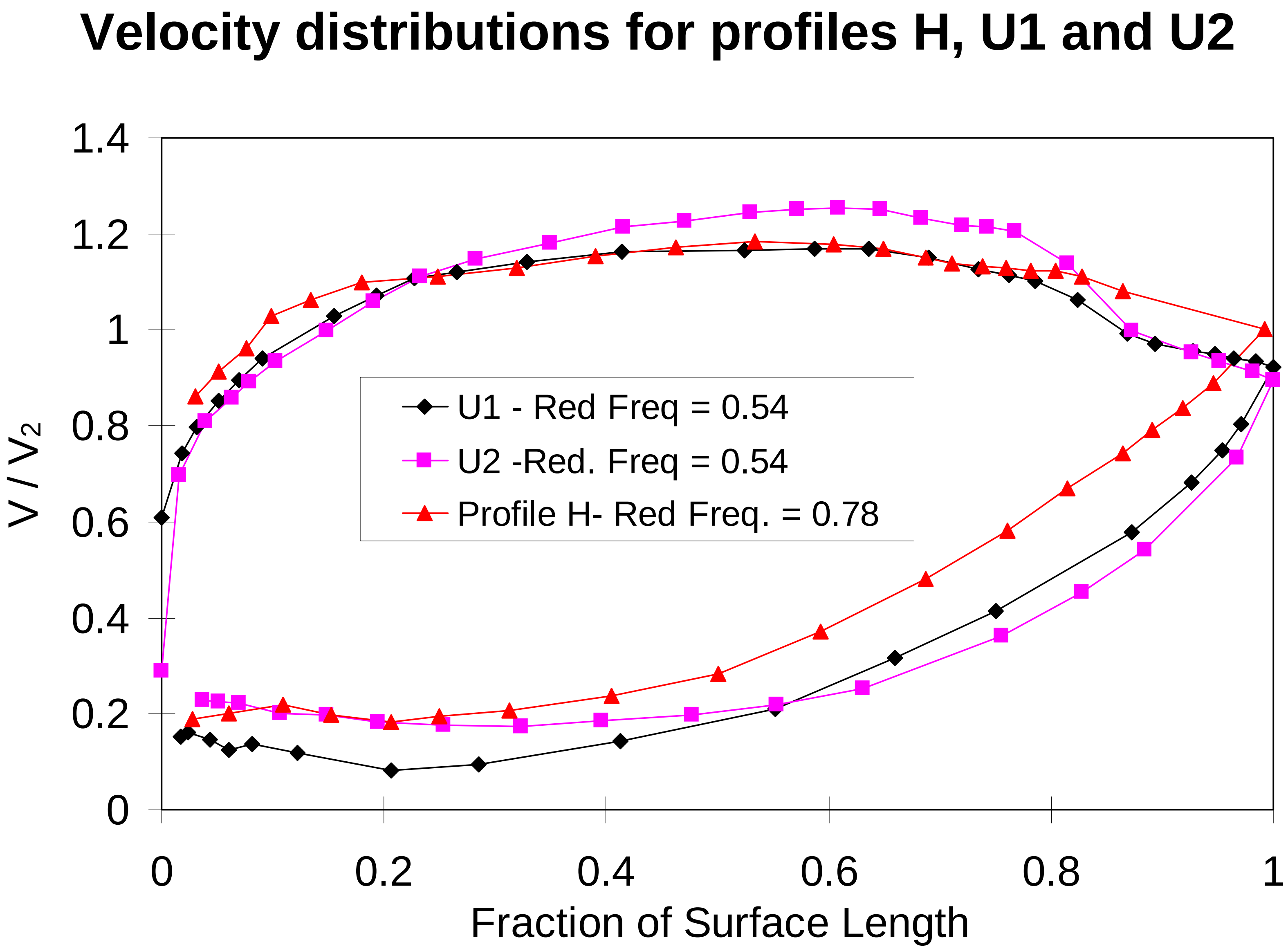
Aft loaded and ultra high lift pressure distributions



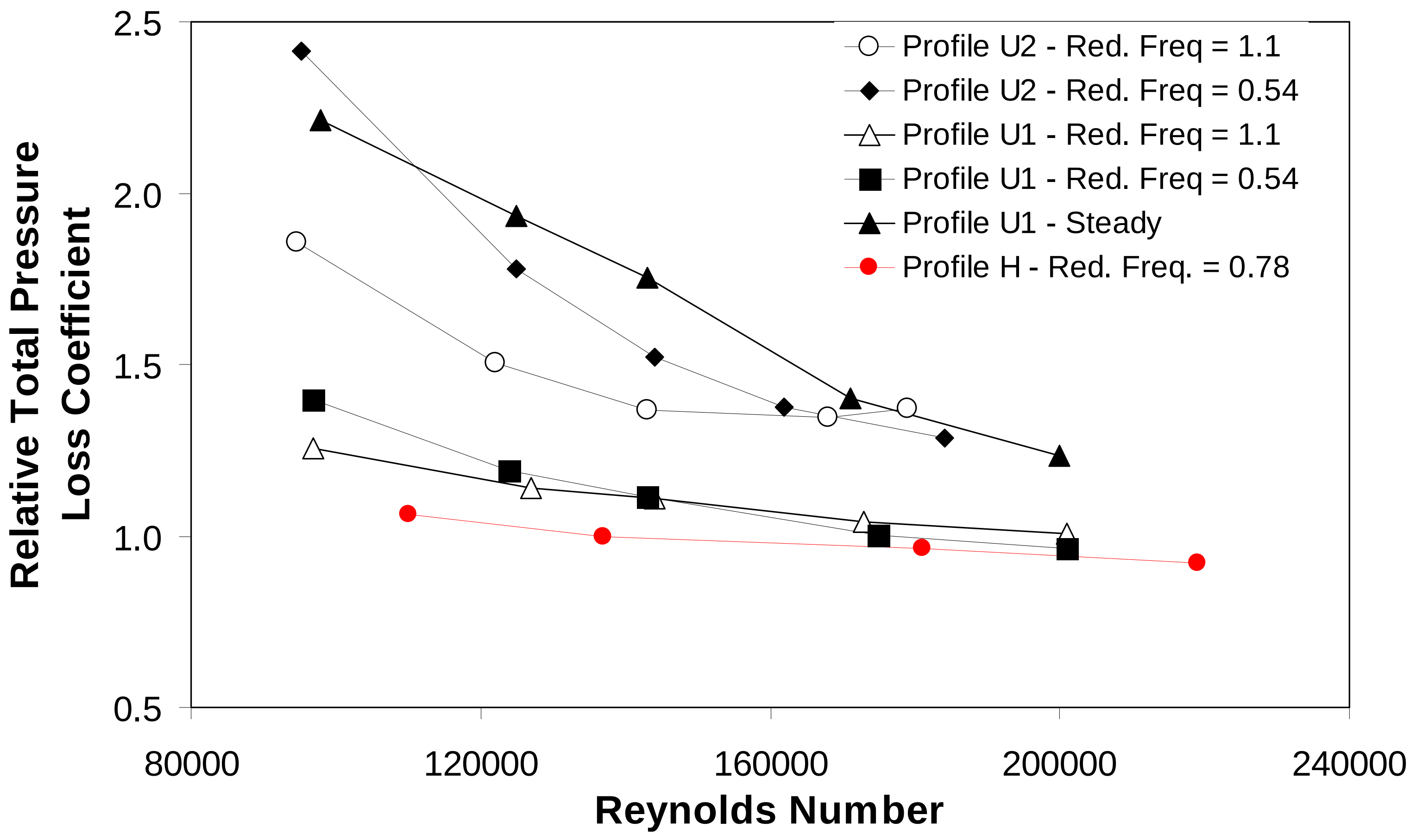
- Losses are same with wakes

Ensemble-mean τ_w for profile H and profile C

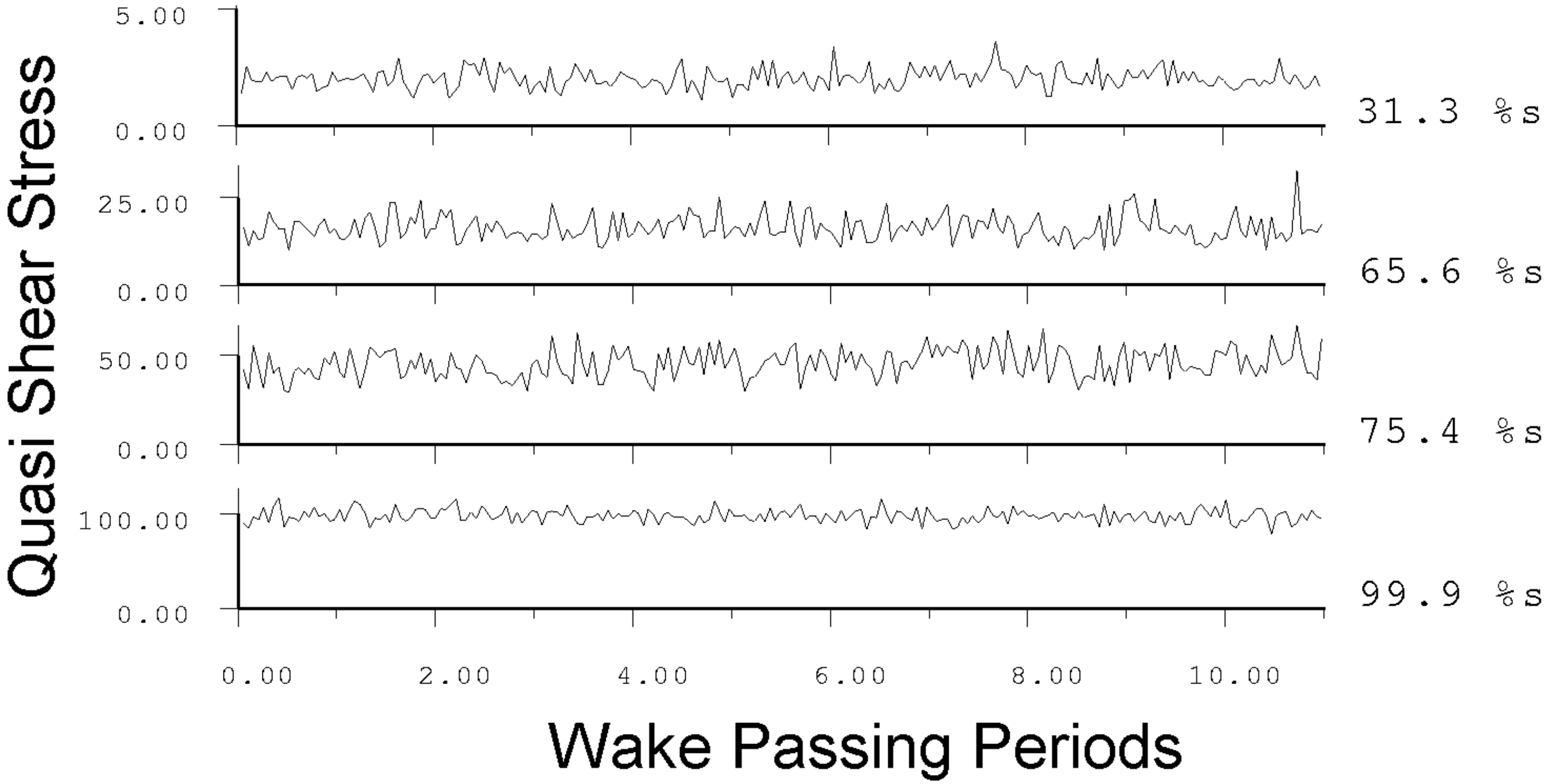



Velocity distributions for profiles H, U1 and U2
V / V2
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
Fraction of Surface Length
U1 - Red Freq = 0.54
U2 -Red. Freq = 0.54
Profile H- Red Freq. = 0.78

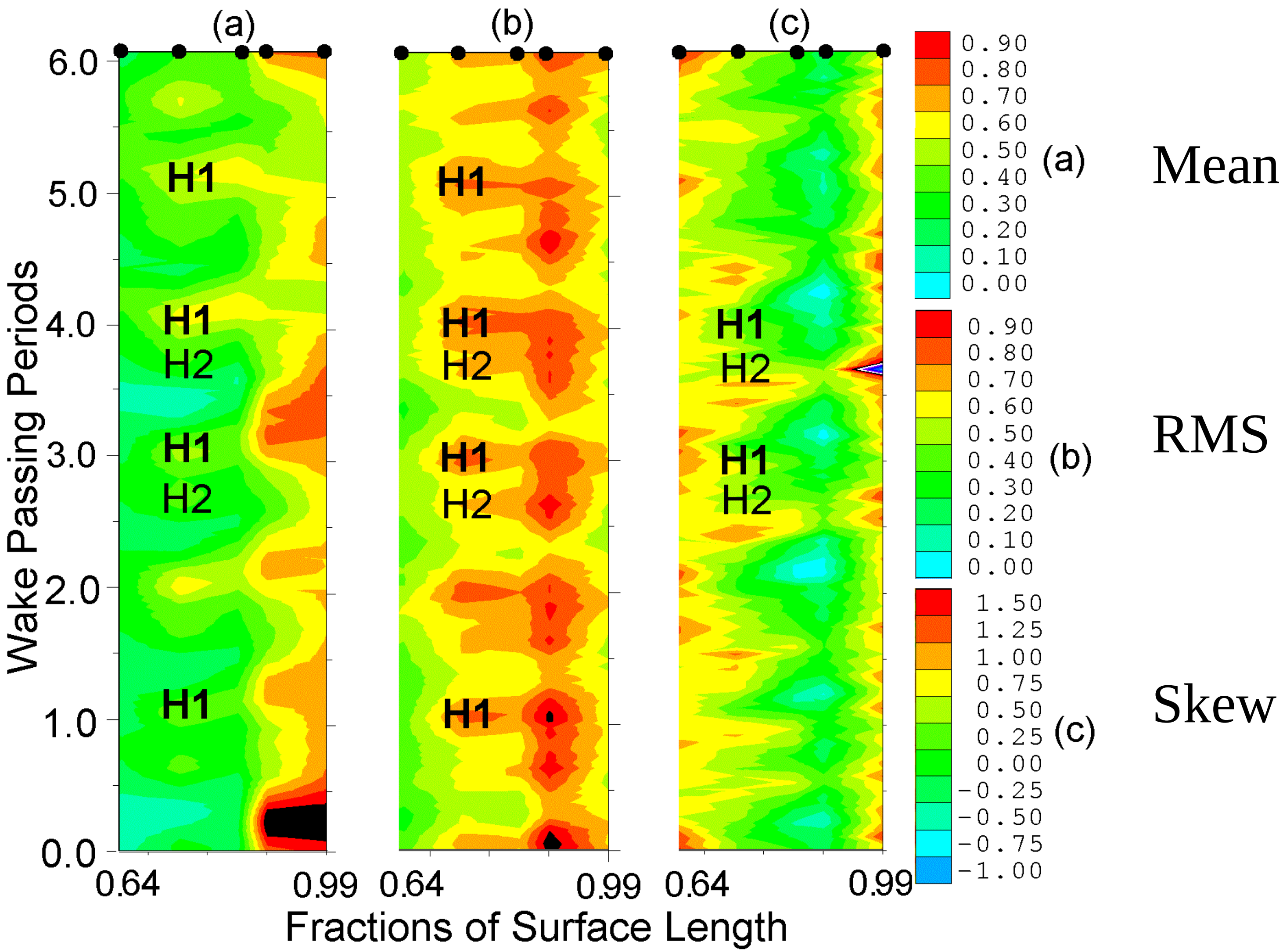
Variation of Loss with Reynolds number: high & ultra high lift cascades



Ultra High Lift and Aft Loaded Profiles: BR715U



Wall shear stress data from NGV3 of the BR715U LP turbine



Ultra High Lift

Ultra high lift profiles

- have been validated using cascades and turbine tests,
- have 15% more lift than high lift profiles
- have 38% more lift than datum profiles
- still rely on wake-induced transition
- probably represent limit of achievement

Conclusions

In low Reynolds number flow, i.e. in LP turbines

- wakes have profound effect on losses generated by suction side boundary layer on highly loaded LP turbine blades
- wakes create strips of bypass transition
- calmed region trail turbulent spots/strip
- calmed region is a laminar-like with very full velocity profile
- calmed region associated with low losses cf steady inflow
- benefit depends on Re, reduced frequency & velocity distribution

LOW PRESSURE TURBINE REYNOLDS NUMBER EFFECTS: SMALL ENGINE PERSPECTIVE

Greg Heitland
Honeywell Engines and Systems
Phoenix, AZ

The research work on low pressure turbine (LPT) performance lapse rate has been focused on the conditions for the large engine class size. This makes sense considering the majority of people travel via commercial airlines and the impact of additional fuel is directly felt on fares. The small engine class size that support business jet travel incur larger performance penalties due to the higher cruise altitude. Military high altitude applications, such as UCAV, result in LPT Reynolds number levels that are extremely low; the sturdiest turbine aerodynamicist will wobble at these operating conditions.

The turbomachinery industry carries a confusion factor when discussing Reynolds number; that is the length term. The classic boundary layer equations point to the use of surface length, for turbine airfoils the typical selection is the suction surface length. The suction surface length is what researchers tend to use for presentation of experimental/computational results. The various turbine engine companies use different length terms; axial chord, true chord, mean camber line length, and throat width. A review of available turbine rig tests shows Reynolds number variation data collapses best with the use of throat width. A blade row loss schematic is presented to support the use of throat width.

Boundary layer management methods, passive and active, are being developed to control low Reynolds loss in turbines. Honeywell has teamed up with University of Arizona and Arizona State University to research the low Reynolds issue based on a recent low pressure turbine airfoil design. A low speed cascade test rig with wake generator device will be used to collect the data, CFD modeling and enhanced near wall schemes will complement the rig data.

There are a several items that need to be addressed to close the gap between research and industry, two will be discussed here. One is the turbulence intensity level discrepancy between the test rigs and the actual engine environment. A second issue is the appropriate simulation of the upstream blade row wakes in cascade testing, the popular approach to date is cylindrical bars.

NASA/CP—2001-210888

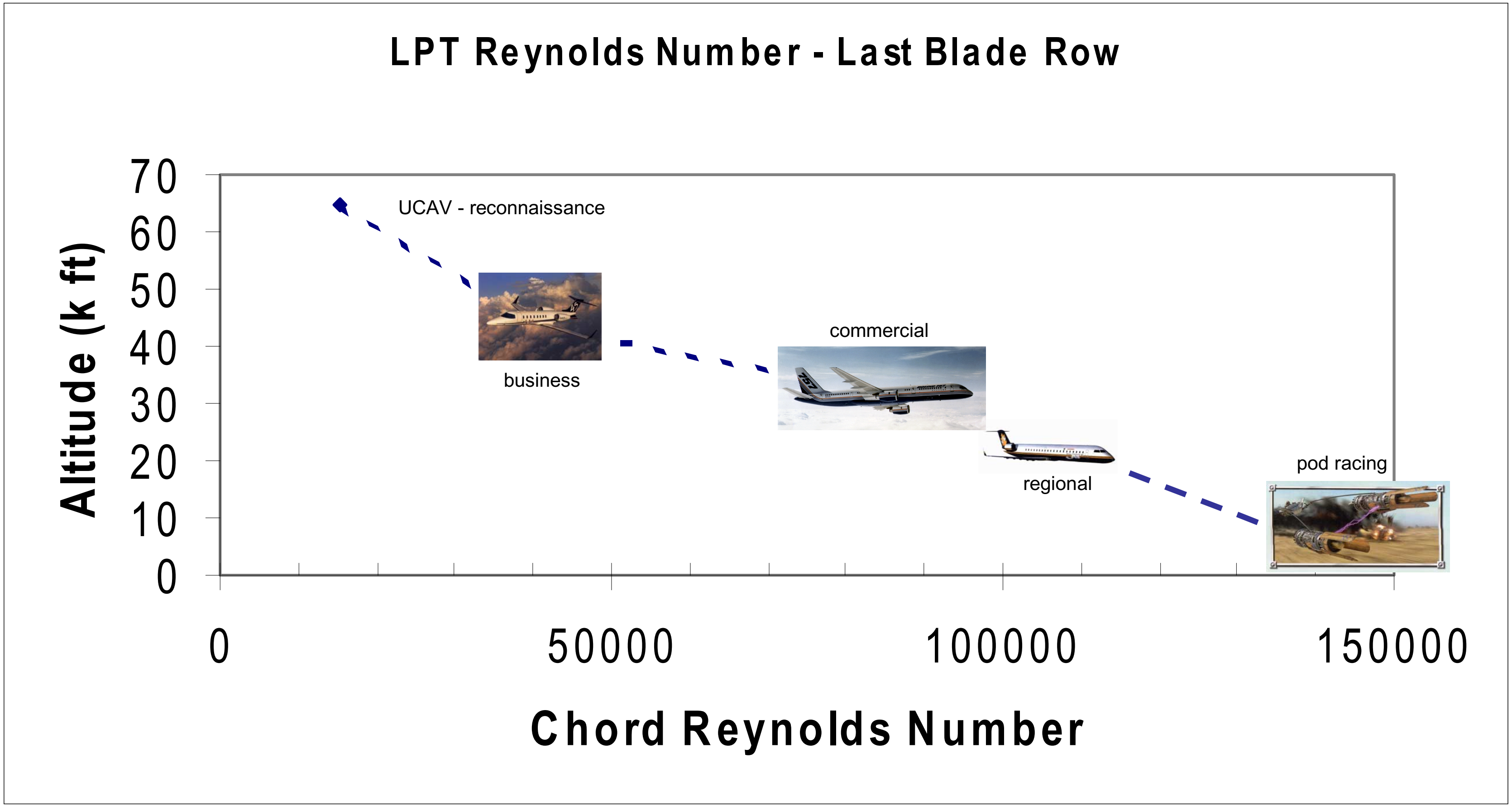
Minnowbrook III

Workshop on
Boundary Layer Transition
and
Unsteady Aspects of Turbomachinery Flows

Session 1 - Turbomachinery Disturbance Environment

Low Pressure Turbine Reynolds Number Effects: Small Engine Perspective

Greg Heitland
Principal Engineer
Turbine Aerodynamic Design and Technology
Honeywell Engines and Systems



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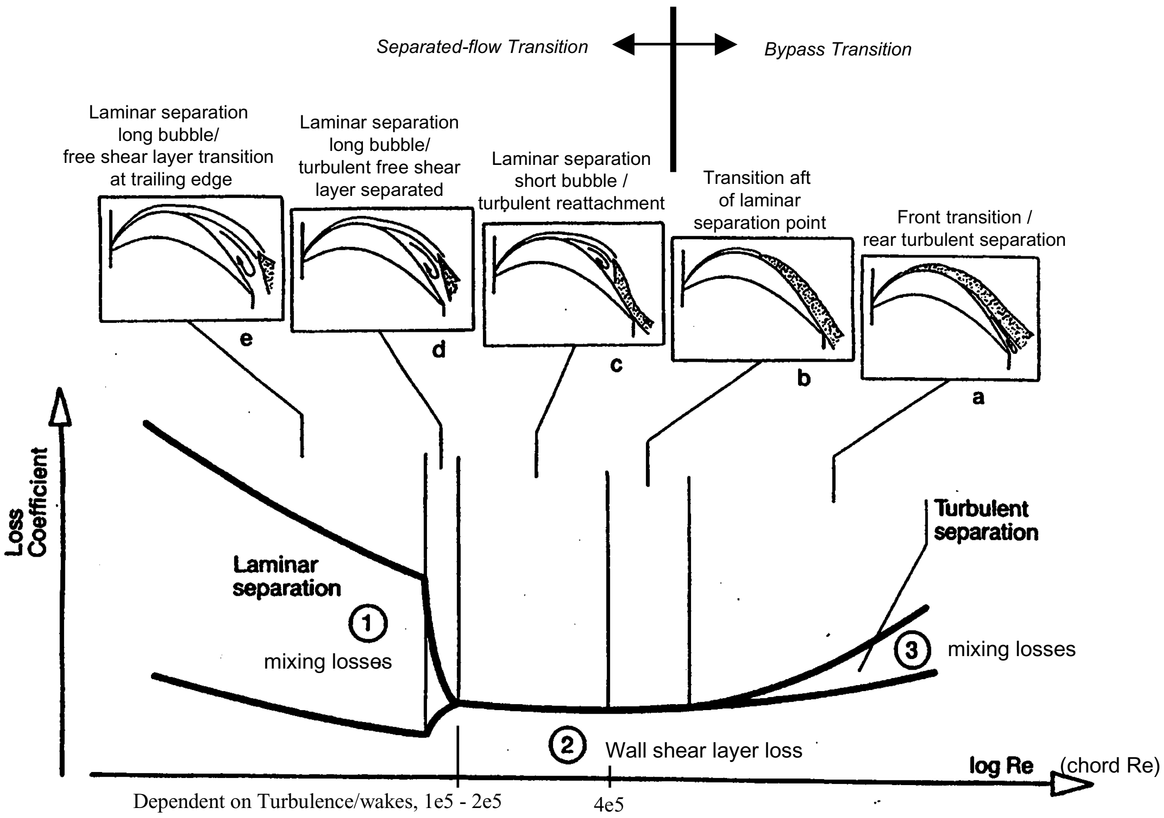

Reynolds Number Effects on Turbine Cascade Performance (Hourmouziadis)

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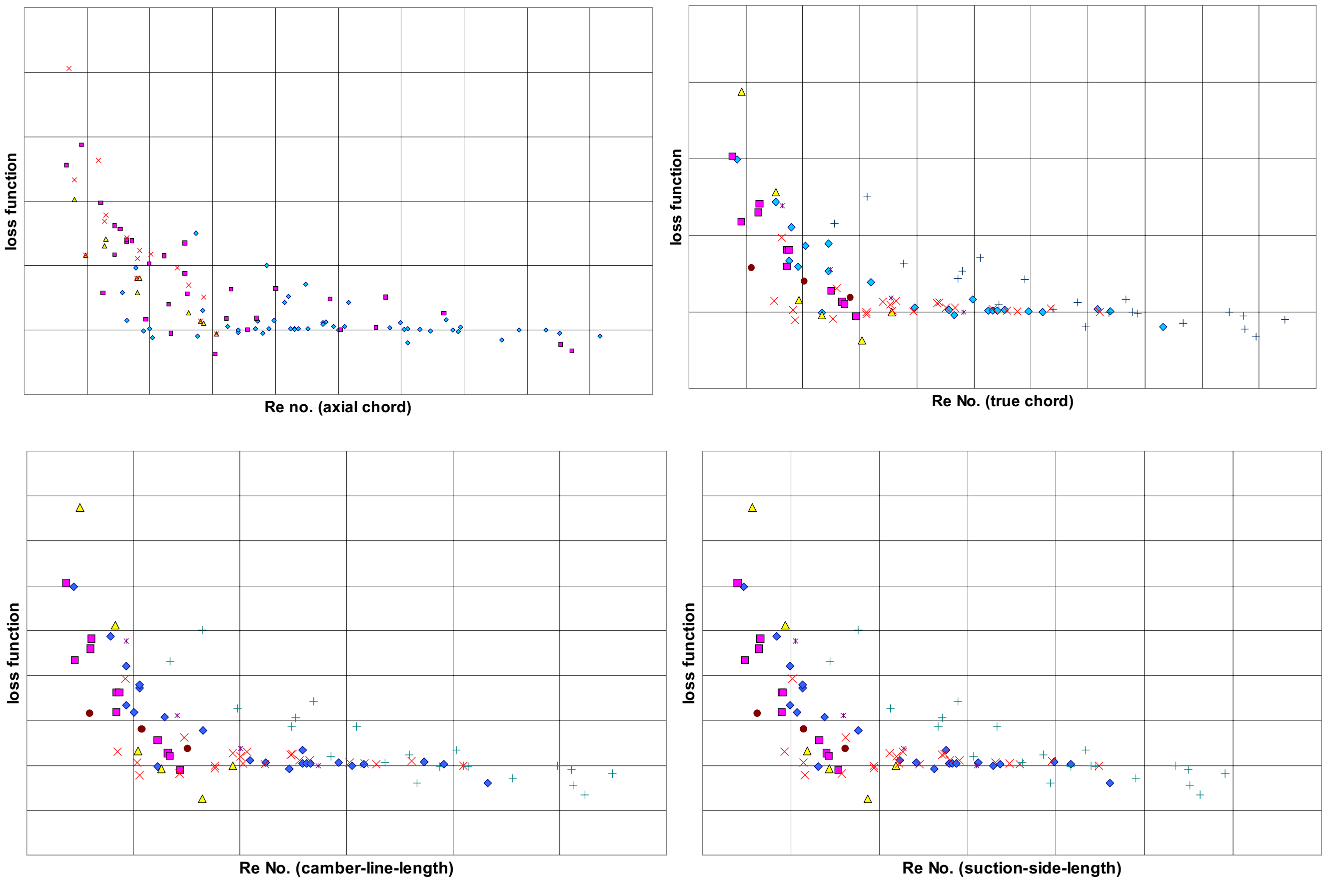
What is the appropriate length scale for a turbine Reynolds number?

- Classic boundary layer theory and research is surface length



Several length parameters were used in the Reynolds number definition to evaluate turbine test data;
- axial chord
- true chord
- backbone length
- suction side length

and ......

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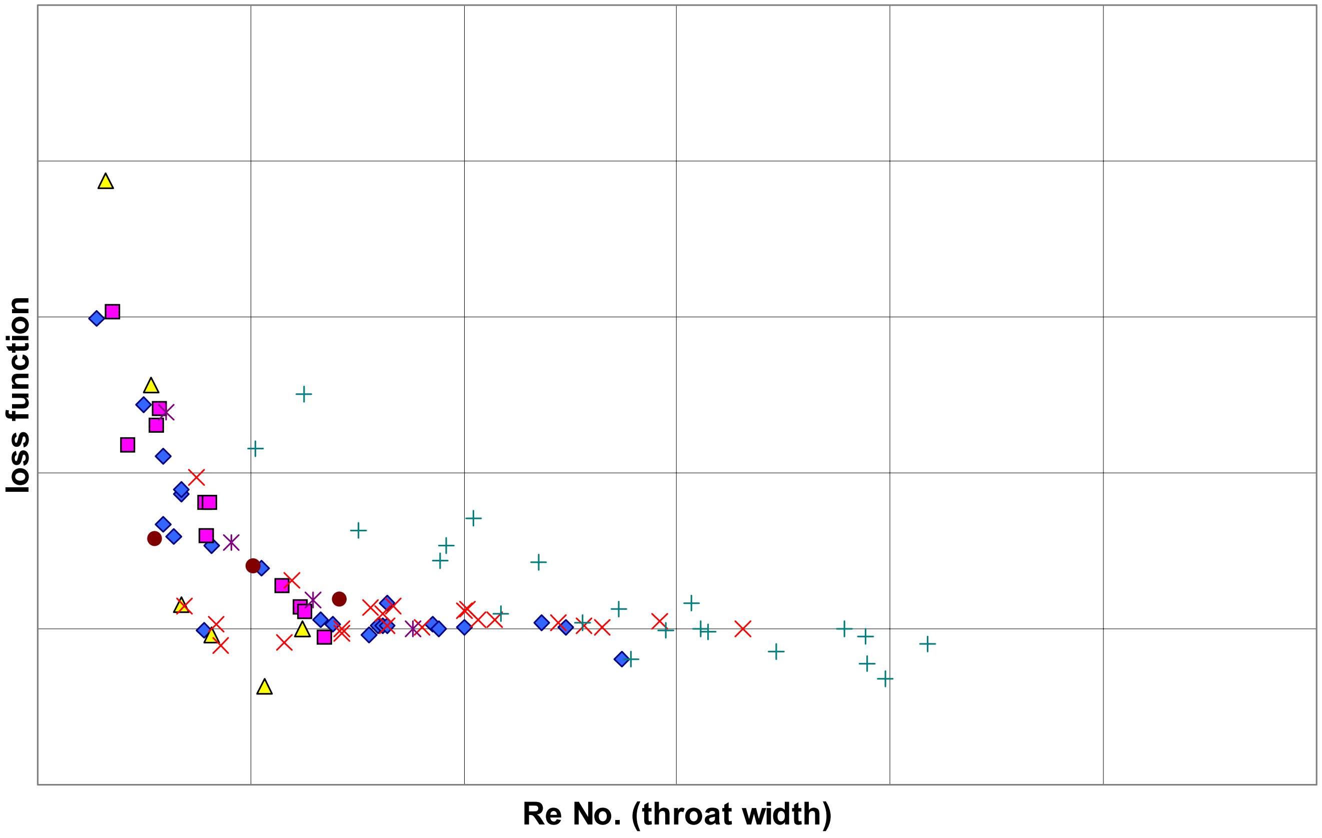
What is the appropriate length scale for a turbine Reynolds number?

The data best collapsed with the use of throat width as the characteristic length.
An interesting note is throat width is used by Craig&Cox loss model and GE.



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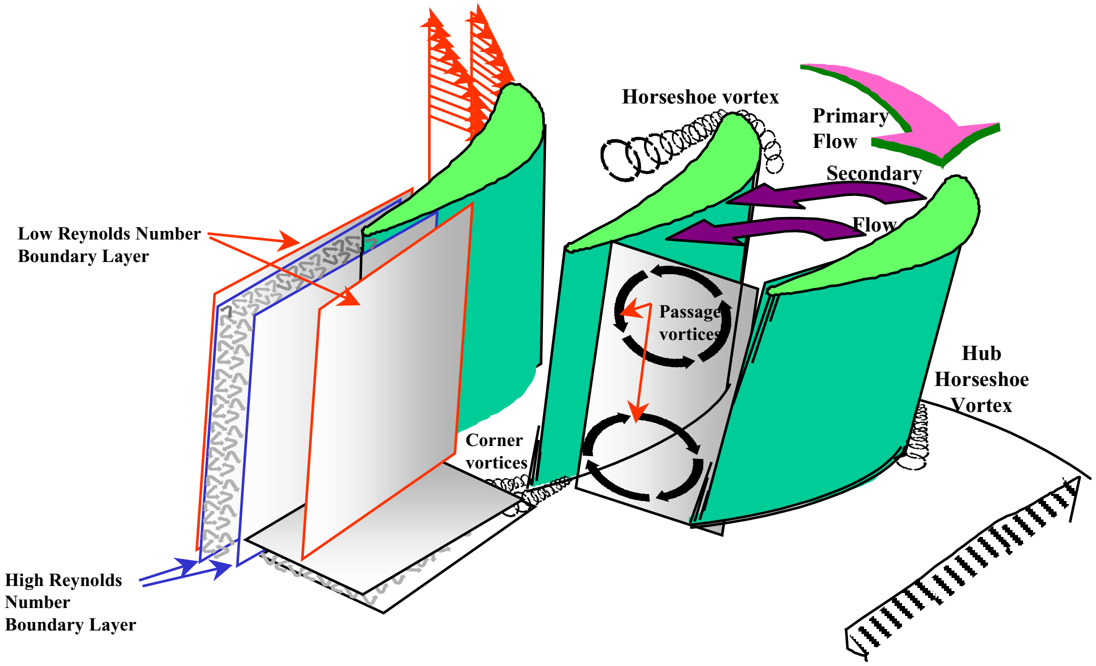
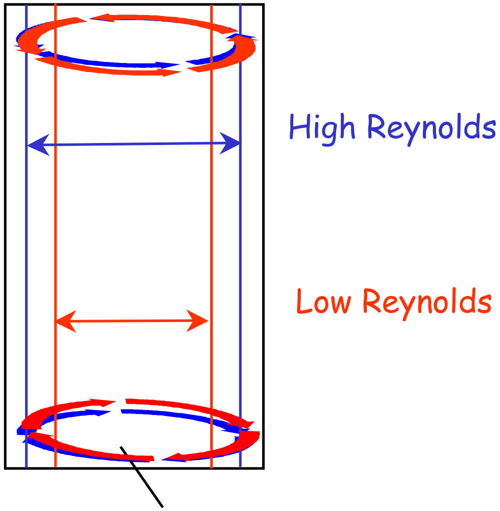
Throat width is an appropriate length for Reynolds Number

Bladerow loss models are made up of profile and secondary loss functions. For the high aspect ratio LPT blade rows (AR>3), the profile loss is significantly larger than the secondary loss. This information coupled with profile loss being related to boundary layer growth shows that the throat width is a logical selection for the Reynolds number characteristic length.





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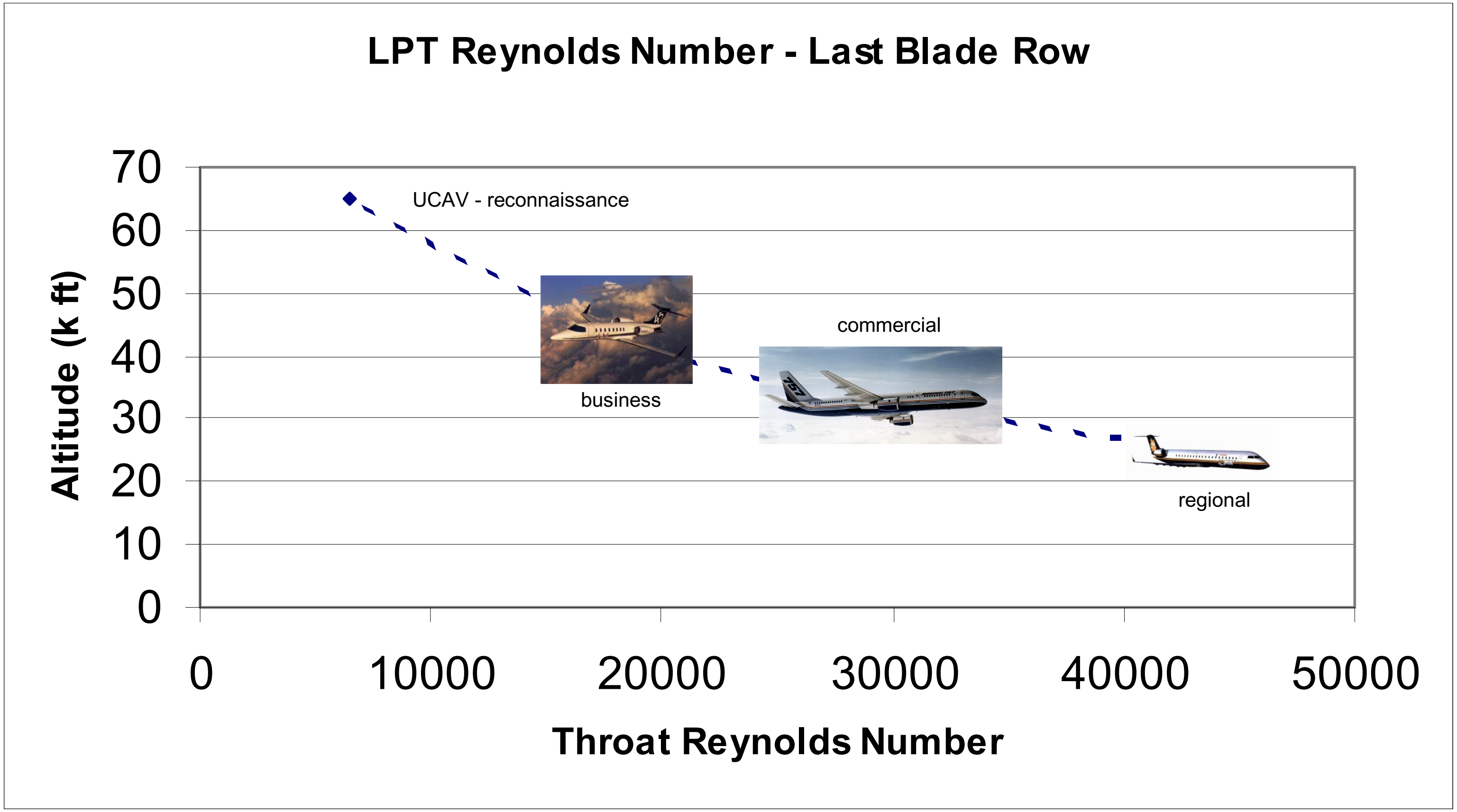

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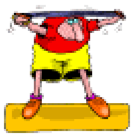
So, the low Reynolds number loss at altitude is a big probleemo ….. Can Reynolds number value be increased and will the overall loss be reduced?

Options:

increase characteristic length

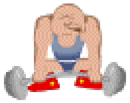


- increase chord
  - -- increase engine length, weight, and wetted surface area
- increase throat width by lower solidity
  - -- increase airfoil loading and diffusion

increase velocity

- increase through flow parameter
- frictional loss trade-off
- exhaust loss trade-off

increase density by adding secondary "heavy" fluid



- reduced aircraft payload
- safety

decrease viscosity by adding secondary "slippery" fluid

- reduced aircraft payload
- safety

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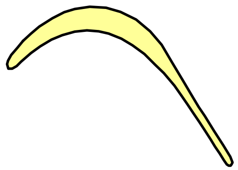
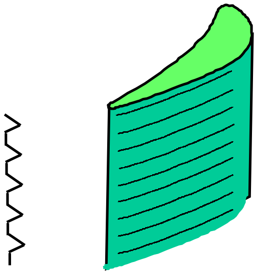
O.K., for the time being we are stuck with the low Reynolds number level ….. The approach being worked is Boundary Layer Management. The goal is to control laminar-transition-turbulent regions and the associated losses at low Reynolds number.

Two directions are being researched:

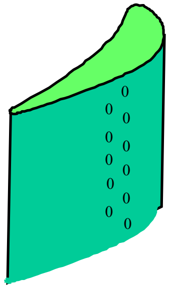
<u>Passive</u>



reflex airfoil design (Liebeck)

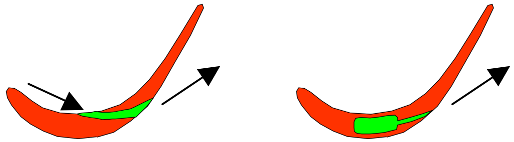


V-groove on suction side
(AIAA 00-0738)

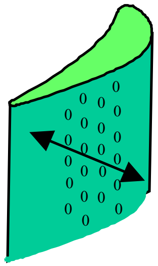


dimples on suction side
(AIAA 00-0738)

<u>Active</u>



aspiration or VGJ (vortex generator jets)
(2000-GT-0262)



airfoil surface fluctuation

Important to both of these areas is the unsteady wake passing / becalmed effect and the freestream/near wall turbulence intensity level and length scale.

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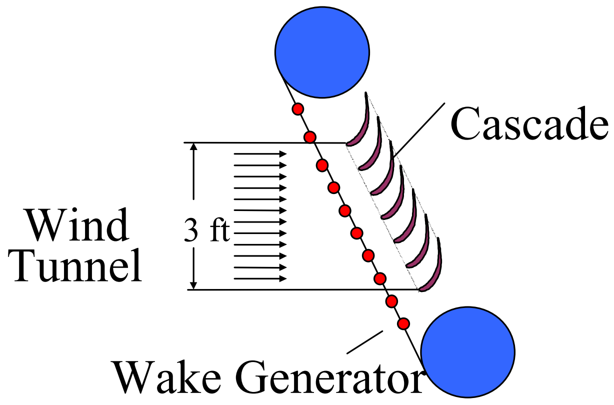
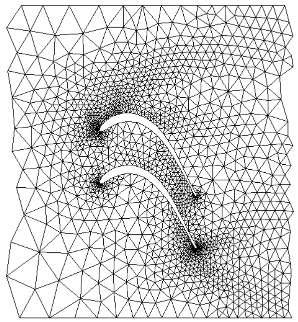
Honeywell research is focused on a low speed cascade test at the University of Arizona under the guidance of I. Wygnanski and A. Ortega with principal investigator Z. Wang.

- based on latest Honeywell LPT airfoil design
- Test program will include
  - 20000. < Reynolds number < 150000.
  - 2% < Turbulence Intensity < 20%
  - upstream wake simulation
  - airfoil loading variation



And CFD modeling of the low speed cascade at Arizona State University under the guidance of H. Reed with principal investigator J. Monttinen.

Problem Characteristics
- Low Reynolds number
- Strong viscous effects
- Turbulence modeling not a valid approach
  - Direct Numerical Simulation
    - High computational cost
- Complex geometries
  - Unstructured grid
    - Finite Element solver



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The industry needs to come to a consensus on a few items;

- LPT turbulence intensity

wake

rig	vs	*engine*
5 - 7 % (95-GT-463)		16 - 23% (Sharma, MinnowbrookII)

freestream

rig	vs	*engine*
4 - 8 % (88-GT-79)		11% (Sharma, MinnowbrookII)
2 - 5 % (95-GT-463)		12 - 15% (industry partners)

level discrepancy

And very little attention has been given to length scale

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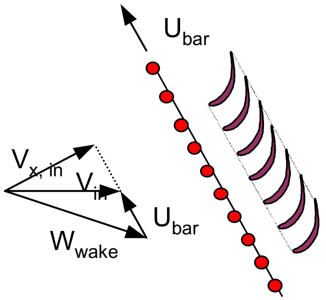
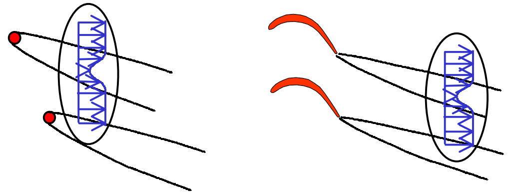
Industry consensus (cont); Wake Generator - how appropriate are cylindrical bars?

Wake Generator Velocity Diagram



Cylindrical Bar Wakes



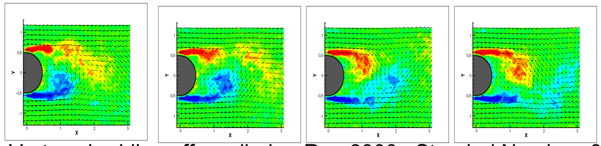
Far downstream (l/d>80) cylindrical bar wake width and amplitude(footprint) is representative of an airfoil wake when the pressure loss is matched (Pfeil & Eifler). As a reference, the Cambridge rig has l/d around 40.

Wake Turbulence Intensity

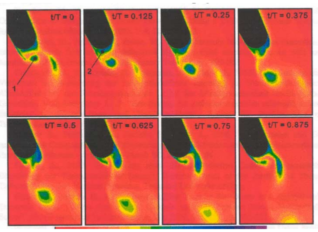
- Cambridge crew show wake velocity and TI (10-14%) are representative of turbine airfoils in the low speed cascade rig.

- GE LSRC show"high" wake TI of 16%.
- length scale ????

Near Body Vortex Shedding



Vortex shedding off a cylinder, Re= 3900., Strouhal Number=0.21
PIV measurements by Shih, Florida State University



… but the vortex structure should be mixed out for typical airfoil spacing.

Vortex shedding off a airfoil, MN=0.7, Strouhal Number=0.2 to 0.3
Unsteady simulation, 2000-GT-0434

What are the critical wake features and where do we go from here?

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FREE STREAM UNSTEADINESS AND TURBULENCE—WHAT IS THE DIFFERENCE?

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Berlin University of Technology
Berlin, Germany

Boundary layer transition on the blading of turbomachinery is dominated by three phenomena:

- periodic unsteadiness
- high levels of free stream turbulence
- very often separated shear layers

The latter have been well known for several decades now and are usually accounted for empirically in design systems. Periodic unsteadiness has received increasing attention since the presentation of the investigations in the General Electric low speed compressor at the ASME Gas Turbine Conference 1995.

Working with unsteady boundary layers gives rise to a variety of questions concerning the physical understanding of the transition process. It even leads to doubts about traditional interpretations in steady flow. The following problems will be offered for discussion.

- Using an order of magnitude analytical approach, an amplitude-weighted Strouhal-no. is identified as a significant similarity parameter. Using this parameter and the Reynolds-no. a classification of unsteady flows is performed.

- Blade passing in turbomachinery and classical shear flows are classified in this framework.

- With the amplitude-weighted Strouhal-no. turbulence is resolved into a continuous spectrum of discrete frequency intervals. This model is used to classify the response of turbomachinery boundary layers using typical spectra from low speed and high speed full size experiments.

Minnowbrook III
Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows

Free Stream Unsteadiness and Turbulence - What is the Difference

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Classification of Boundary Layer Flows

- Dimensional order of magnitute analysis
- Identification of similarity parameters
- Wake and boundary layer flow classification
- Classification of discrete and continuous (turbulent) spectra in turbomachinery

Incompressible Flow

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + \frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{\mu}{\rho}\frac{\partial^2 u}{\partial y^2} = 0$$

Normalize to Order of Magnitude 1

$$x^* = \frac{x}{L}\ ;\ y^* = \frac{y}{\delta}\ ;\ t^* = t \cdot f_{ch}\ ;\ u^* = \frac{u}{\overline{u}_\infty}\ ;\ v^* = \frac{v}{\overline{u}_\infty}\frac{L}{\delta}\ ;\ p^* = \frac{p}{\overline{p}_\infty}\ ;\ \rho^* = \frac{\rho}{\rho_\infty} \equiv 1$$

Normalized Momentum Equation

$$Sr\frac{\partial u^*}{\partial t^*} + u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} + \frac{\partial p^*}{\partial x^*} - \frac{1}{Re(\delta/L)^2}\frac{\partial^2 u^*}{\partial y^{*2}} = 0$$

$$Sr = \frac{f_{ch}L}{\overline{u}_\infty}$$

$$Re = \frac{\overline{u}_\infty L}{\mu/\rho}$$

Weiliang Lou
Jet Propulsion Laboratory, Aerospace Institute, Berlin University of Technology
Desertation (Ph.D Thesis), 6.2000

TU Berlin

Boundary Layer
Normalized Momentum Equation

Strömungsmechanik
166 / 21.7.2000 J. Hourmouziadis

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Technische Universität Berlin

Assessment of the Unsteady Term from the Main Flow Characteristic

$$\mathbf{u}_\infty^* = \frac{\overline{\mathbf{u}}_\infty + \mathbf{u}_\infty'}{\overline{\mathbf{u}}_\infty} = \mathbf{1} + \frac{\mathbf{u}_\infty'}{\overline{\mathbf{u}}_\infty} \quad ; \quad \mathbf{u}_\infty^* = 1 + \sum_{\mathbf{n}}^{1,\infty}\left[\frac{\mathbf{u}_{\infty\mathbf{n}}'}{\overline{\mathbf{u}}_\infty}\,\mathbf{sin}\left(2\pi\mathbf{n}\mathbf{t}^* + \phi_\mathbf{n}\right)\right]$$

$$\frac{\partial \mathbf{u}^*}{\partial \mathbf{t}^*} \approx \frac{\partial \mathbf{u}_\infty^*}{\partial \mathbf{t}^*} = \sum_{\mathbf{n}}^{1,\infty}\left[\frac{\mathbf{u}_{\infty\mathbf{n}}'}{\overline{\mathbf{u}}_\infty}\,2\pi\mathbf{n}\cdot\mathbf{cos}\left(2\pi\mathbf{n}\mathbf{t}^* + \phi_\mathbf{n}\right)\right] \le 2\pi\sum_{\mathbf{n}}^{1,\infty}\left[\mathbf{n}\,\frac{\mathbf{u}_{\infty\mathbf{n}}'}{\overline{\mathbf{u}}_\infty}\right]$$

$$\mathbf{Sr}\,\frac{\partial \mathbf{u}^*}{\partial \mathbf{t}^*} \le \mathbf{2}\pi\cdot\frac{\mathbf{f}_{\mathbf{ch}}\mathbf{L}}{\overline{\mathbf{u}}_\infty}\cdot\sum_{\mathbf{n}}^{1,\infty}\left[\mathbf{n}\cdot\frac{\mathbf{u}_{\infty\mathbf{n}}'}{\overline{\mathbf{u}}_\infty}\right] = \mathbf{ASr}$$

Amplitude Weighted Strouhal No.

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Desertation (Ph.D Thesis), 6.2000

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Boundary Layer
Assessment of Unsteadiness Effect

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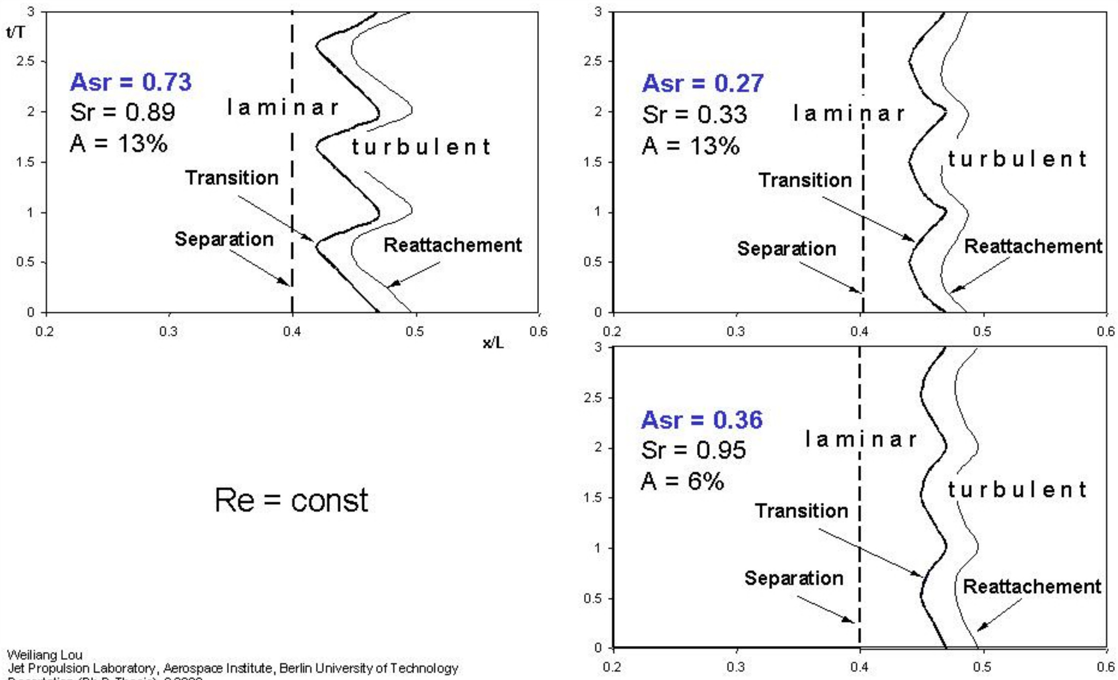

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Boundary Layer Similarity
with Amplitude Weighted Strouhal No.

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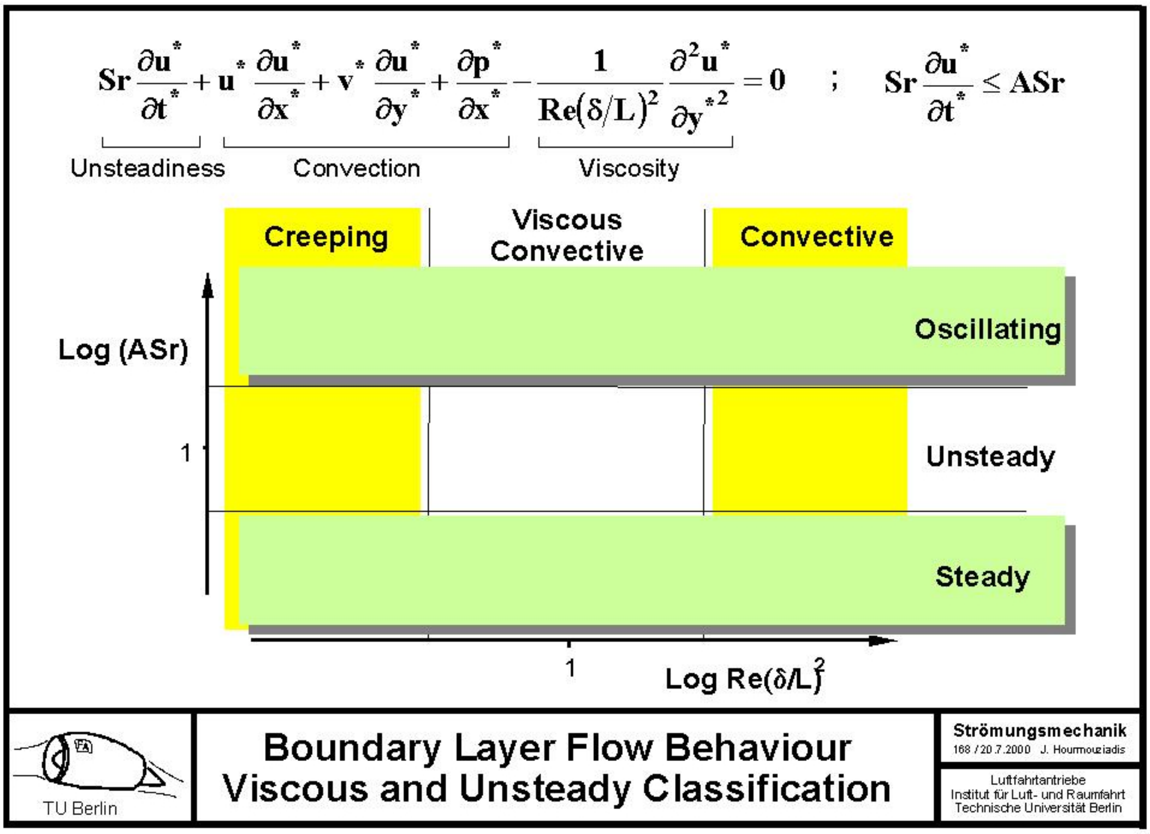

$$Sr\frac{\partial u^*}{\partial t^*} + u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} + \frac{\partial p^*}{\partial x^*} - \frac{1}{Re(\delta/L)^2}\frac{\partial^2 u^*}{\partial y^{*2}} = 0 \quad ; \quad Sr\frac{\partial u^*}{\partial t^*} \le ASr$$
Unsteadiness
Convection
Viscosity
Creeping
Viscous Convective
Convective
Log (ASr)
Oscillating
1
Unsteady
Steady
1
Log Re(δ/L)²
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Boundary Layer Flow Behaviour
Viscous and Unsteady Classification
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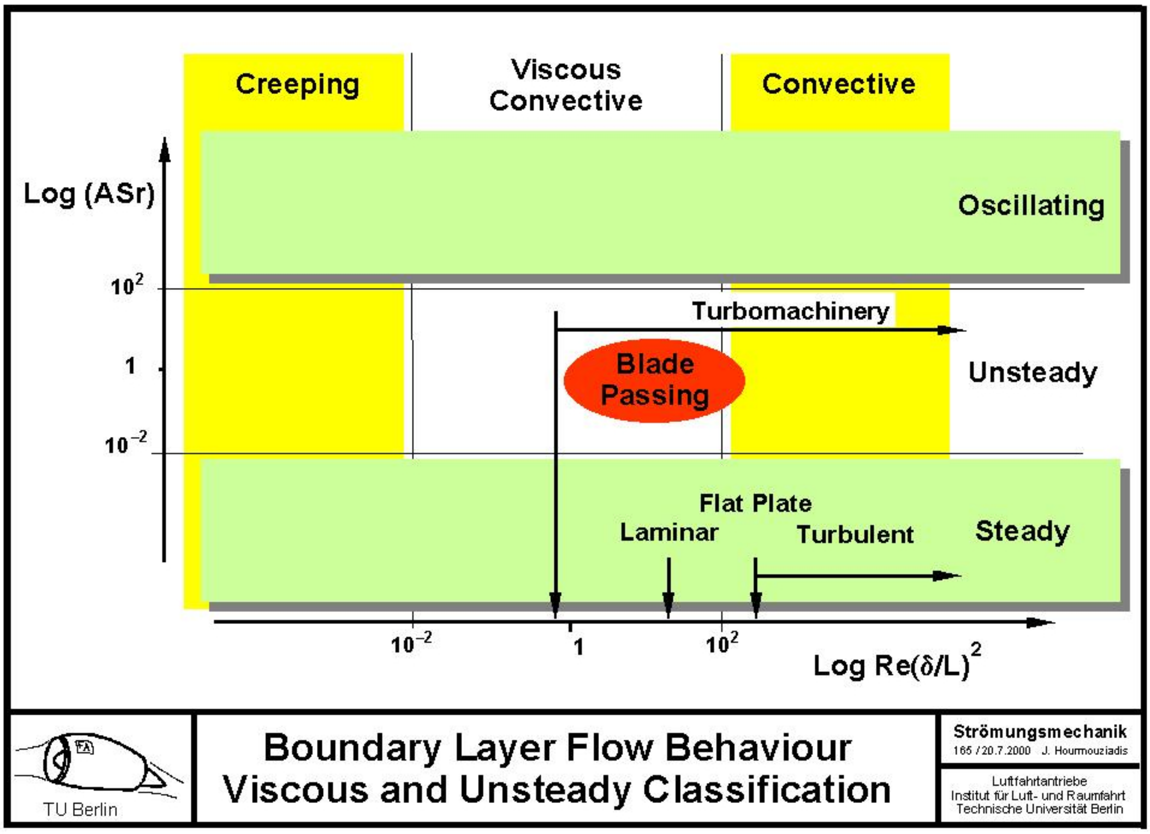

Creeping
Viscous Convective
Convective
Log (ASr)
Oscillating
10²
Turbomachinery
1
Blade Passing
Unsteady
10⁻²
Flat Plate
Laminar
Turbulent
Steady
10⁻²
1
10²
Log Re(δ/L)²
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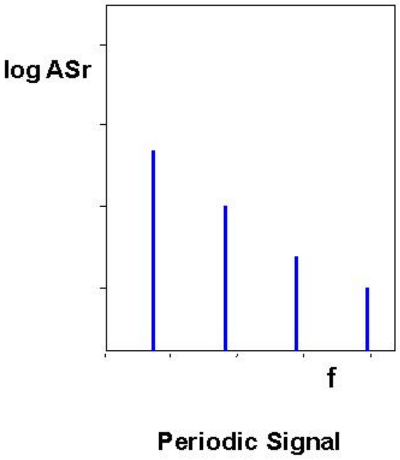
Amplitude Weighted Strouhal No.



$f_{fundamental} = f_{characteristic}$

$$\mathbf{Sr}\frac{\partial \mathbf{u}^{*}}{\partial \mathbf{t}^{*}} \approx \sum_{n}^{1,\infty} \mathbf{Sr}\frac{\partial \mathbf{u}^{*'}_{\infty n}}{\partial \mathbf{t}^{*}} \leq \sum_{n}^{1,\infty} \mathbf{ASr_n}$$

$$\sum_{n}^{1,\infty} \mathbf{ASr_n} = 2\pi\frac{f_{ch}L}{\bar{u}_\infty}\cdot 1\cdot\frac{u'_{\infty 1}}{\bar{u}_\infty} + 2\pi\frac{f_{ch}L}{\bar{u}_\infty}\cdot 2\cdot\frac{u'_{\infty 2}}{\bar{u}_\infty} + \dots + 2\pi\frac{f_{ch}L}{\bar{u}_\infty}\cdot n\cdot\frac{u'_{\infty n}}{\bar{u}_\infty} + \dots$$

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Boundary Layer Unsteadiness
Discrete Spectrum

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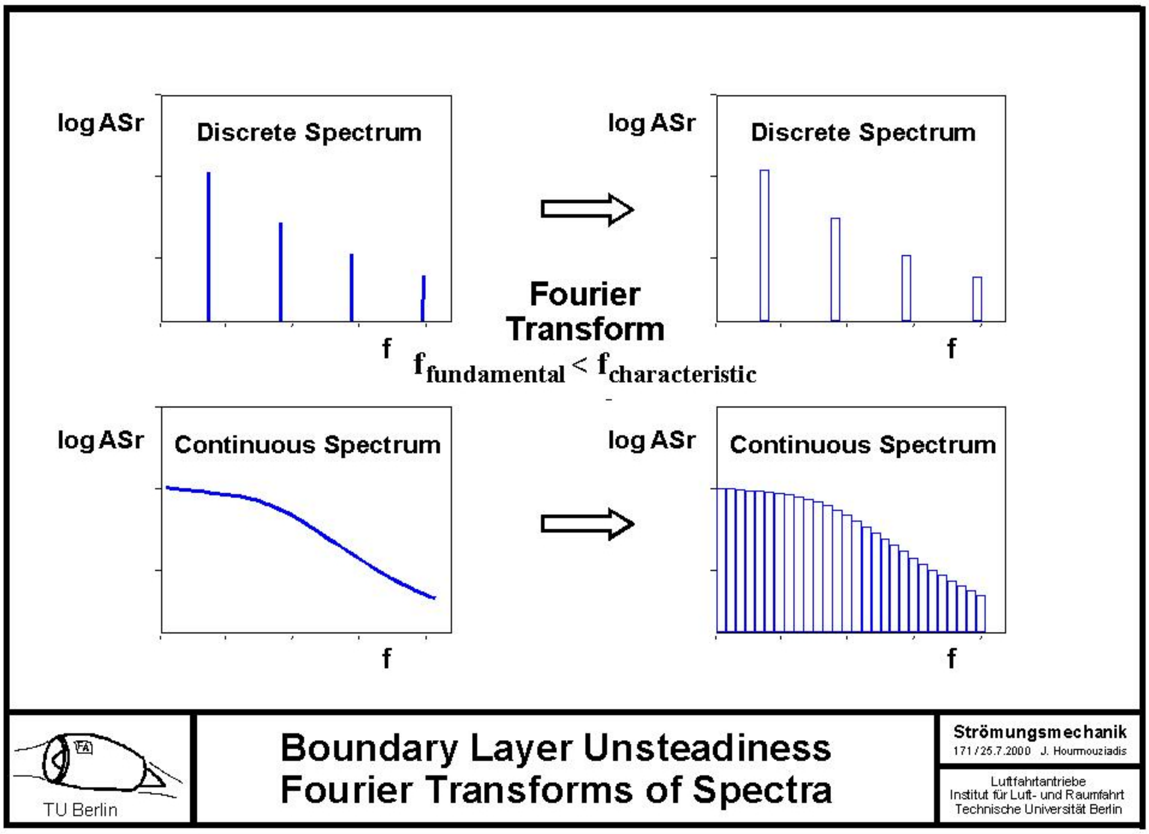
"Discrete" Treatment of Continuous Spectra

A discrete frequency spectrum has an amplitude-weighted Strouhal no. for every individual discrete tone.

The Fourier transform of a discrete spectrum is still a spectrum of individual discrete frequency intervals and has an amplitude-weighted Strouhal no. for every individual discrete frequency interval.

The Fourier transform of a continuous spectrum is a continuous spectrum of individual descrete frequency intervals and has respectively an amplitude weighted Strouhal no. for every individual discrete frequency interval.

This suggests a similar response of the boundary layer to periodic fluctuations and turbulence of the main flow.


log ASr
Discrete Spectrum
f
log ASr
Discrete Spectrum
f
Fourier
Transform
f fundamental < f characteristic
log ASr
Continuous Spectrum
f
log ASr
Continuous Spectrum
f
TU Berlin
Boundary Layer Unsteadiness
Fourier Transforms of Spectra
Strömungsmechanik
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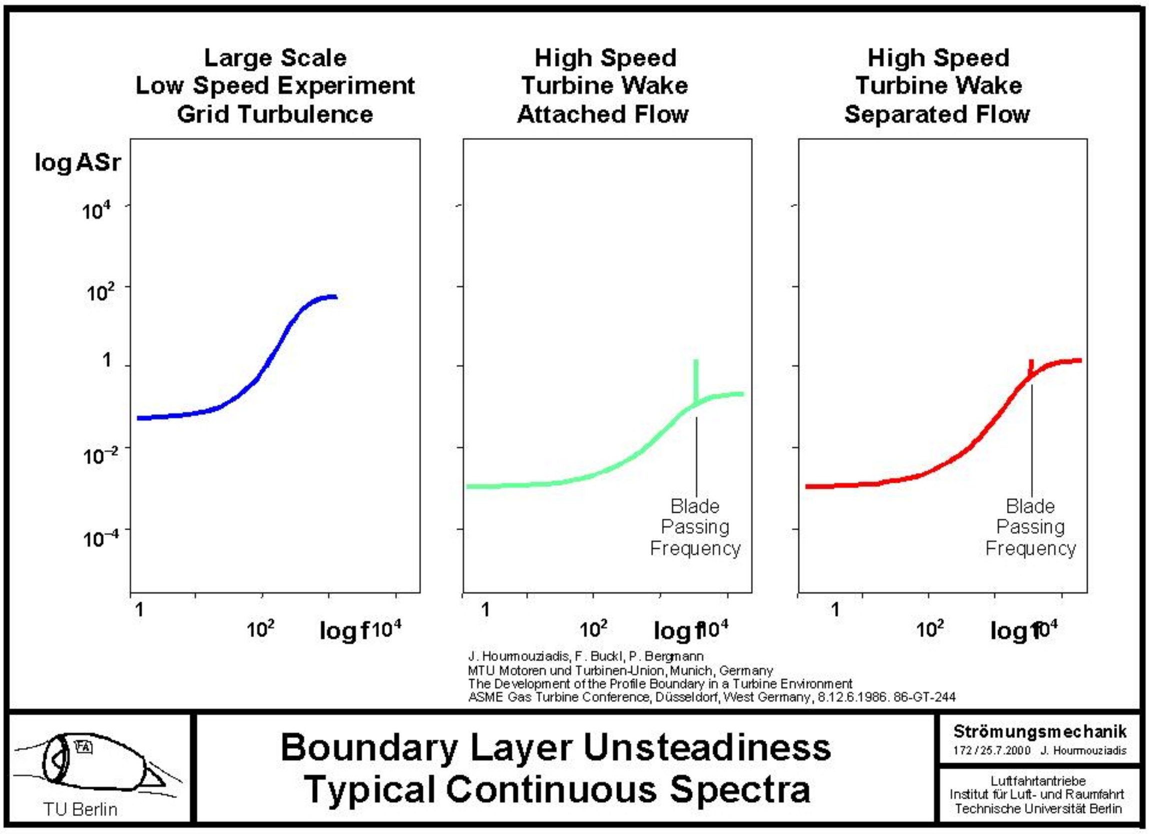
Large Scale
Low Speed Experiment
Grid Turbulence
High Speed
Turbine Wake
Attached Flow
High Speed
Turbine Wake
Separated Flow
log ASr
10^4
10^2
1
10^-2
10^-4
1
10^2
log f 10^4
Blade
Passing
Frequency
J. Hourmouziadis, F. Buckl, P. Bergmann
MTU Motoren und Turbinen-Union, Munich, Germany
The Development of the Profile Boundary in a Turbine Environment
ASME Gas Turbine Conference, Düsseldorf, West Germany, 8.12.6.1986. 86-GT-244
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Boundary Layer Unsteadiness
Typical Continuous Spectra
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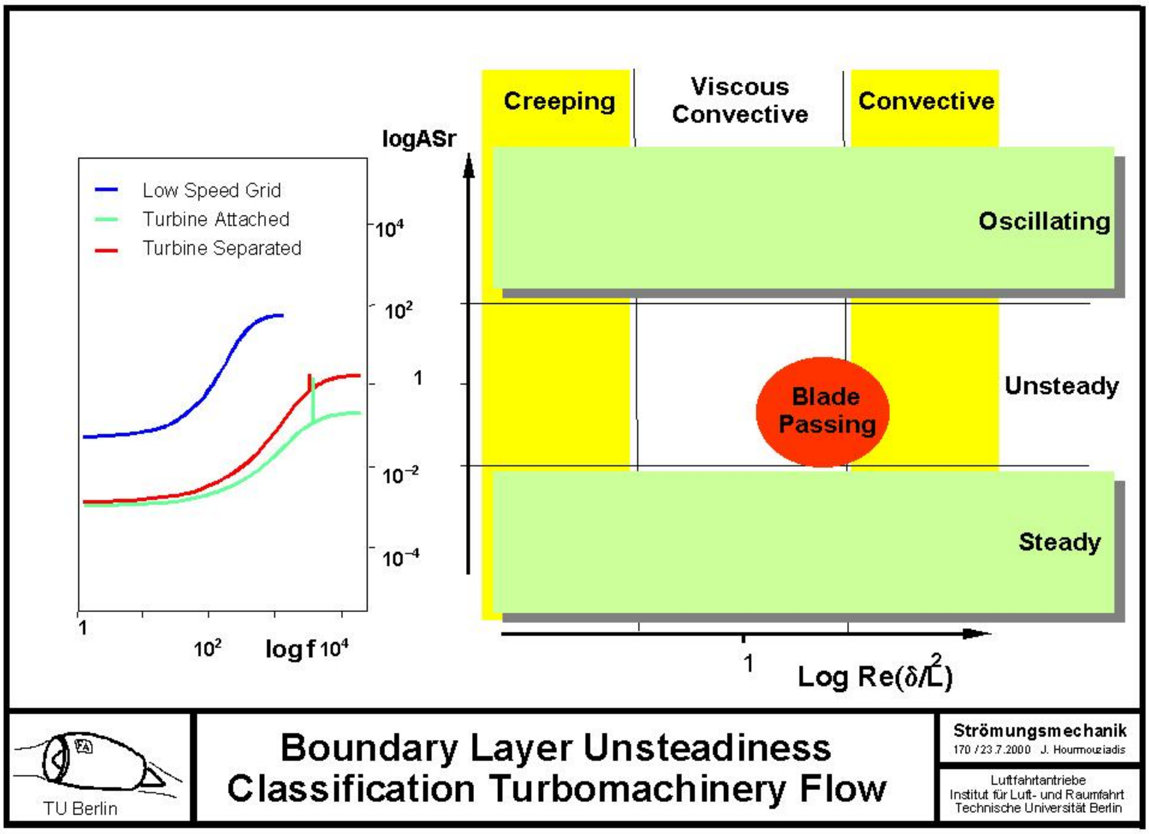

Conclusions for High Speed Turbomachinery

- The boundary layer responds quasi steady at a point in time for main flow turbulence with frequencies less than about 1000 Hz

- Blade passing effects lie in the predominantly unsteady domain.

- Main flow turbulence with frequencies greater than about 1000 Hz results in an unsteady boundary layer response.

- Convective effects are rather strong indicating that inviscid instability (Taylor) should be of significant importance.

NATURAL VERSUS BYPASS TRANSITION ON AXIAL COMPRESSOR BLADES—A NEED FOR REASSESSMENT?

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The transitional flow behavior on the outlet stator blades of a 1.5-stage axial compressor has been studied extensively using an array of surface hot film gauges covering both suction and pressure surfaces. Various techniques have been developed to identify flow regimes and individual events from fluctuations in quasi wall shear stress obtained form the surface gauges. Earlier work by Solomon and Walker was concerned with the evaluation of turbulent intermittency and the relaxation of flow following the passage of turbulent spots. The most recent studies by the present authors have involved the use of wavelet analysis to identify events characteristic of laminar instability waves.

Pitchwise average values of random inflow disturbance (free stream turbulence) experienced by the stator blades ranged from 2 to 3%, and ensemble average values were locally as high as 10% in passing rotor wakes. Despite theses elevated free stream turbulence levels there was an almost universal evidence of instability wave amplification prior to turbulent breakdown in decelerating flow regions on the compressor blade. Although the two-dimensional wave amplification stage was apparently bypassed, there was no evidence for direct production of turbulent spots within the boundary layer supposed within the turbomachinery community to be characteristic of bypass transition. Unstable laminar flow regions up to 20% chord in length were observed on the compressor blade in these investigations, both in the path of turbulent strips induced by passing rotor blade wakes and in regions between these wake-induced transition paths in the time-chordwise position plane.

The signatures of individual instability wave events and their subsequent breakdown observed by the surface film gauges closely resembled those of wave packets in basic experiments on artificially generated spots arising from weak localised initial disturbances. The wave packet events showed evidence of amplification prior to breakdown. This observation provides further justification for use of the modified e^N method of predicting turbulent breakdown in natural transition, which was successfully applied by Solomon et al. (1999) in a quasi-steady manner to predict temporal fluctuations in transition onset on the compressor stator blades. Interestingly, the values of exponent N typically required for the compressor blade boundary layers were roughly comparable with those for the non-linear amplification stage in natural transition with a very low level of free stream turbulence.

Wave activity both occurred in and originated from the calmed region following the passage of a wake-induced turbulent strip on the compressor blade. This activity could have arisen either from the attendant wave packets that occur in adverse pressure gradients (as with artificially generated turbulent spots) or from the turbulent perturbations within the wake-induced turbulent strip itself. The more stable flow in the ensuing “calmed region” clearly did not guarantee the total absence of instability wave activity.

The length of transitional flow along an individual disturbance path was also observed to reach 20% of chord on the compressor stator. Thus the total length of blade surface over which the flow was governed by natural transition phenomena (either directly through wave packet amplification or indirectly through determining the dominant Tollmien-Schlichting wave frequency which governs the turbulent spot inception rate) was as much as 40% chord.

The presentation concludes by inviting discussion on the following points:

- the need for a more precise definition of the term “bypass” in relation to transition on turbomachine blades, and the need for greater consistency in definitions of bypass transition used by researchers in the turbomachinery and transition physics communities;
- the desirability of complementary transition studies in accelerating flow, where bypass phenomena should be relatively more important, and the efficacy of zero pressure gradient (“flat plate”) studies which lie on the boundary of two significantly different regimes;
- remaining challenges for predicting turbulent breakdown on turbomachine blades.

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MINNOWBROOK III WORKSHOP

BOUNDARY LAYER TRANSITION IN TURBOMACHINES

Blue Mountain Lake, NY, USA

20-23 August 2000

NATURAL vs BYPASS TRANSITION ON AXIAL COMPRESSOR BLADES - A NEED FOR REASSESSMENT?

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SCOPE

- Outline disturbance environment in axial turbomachines and the morphology of transition behavior on the blade surfaces
- Describe recent observations of transitional flow on axial compressor blading
- Identify instability wave phenomena from compressor blade surface film data and compare with triggered turbulent spot experiments
- Review concepts of bypass and natural transition and the relevance of modified stability analysis for predicting transition on axial turbo-machine blades in the light of this evidence
- Discuss need for more precise definition of bypass transition and remaining challenges for predicting turbulent breakdown on axial turbomachine blades

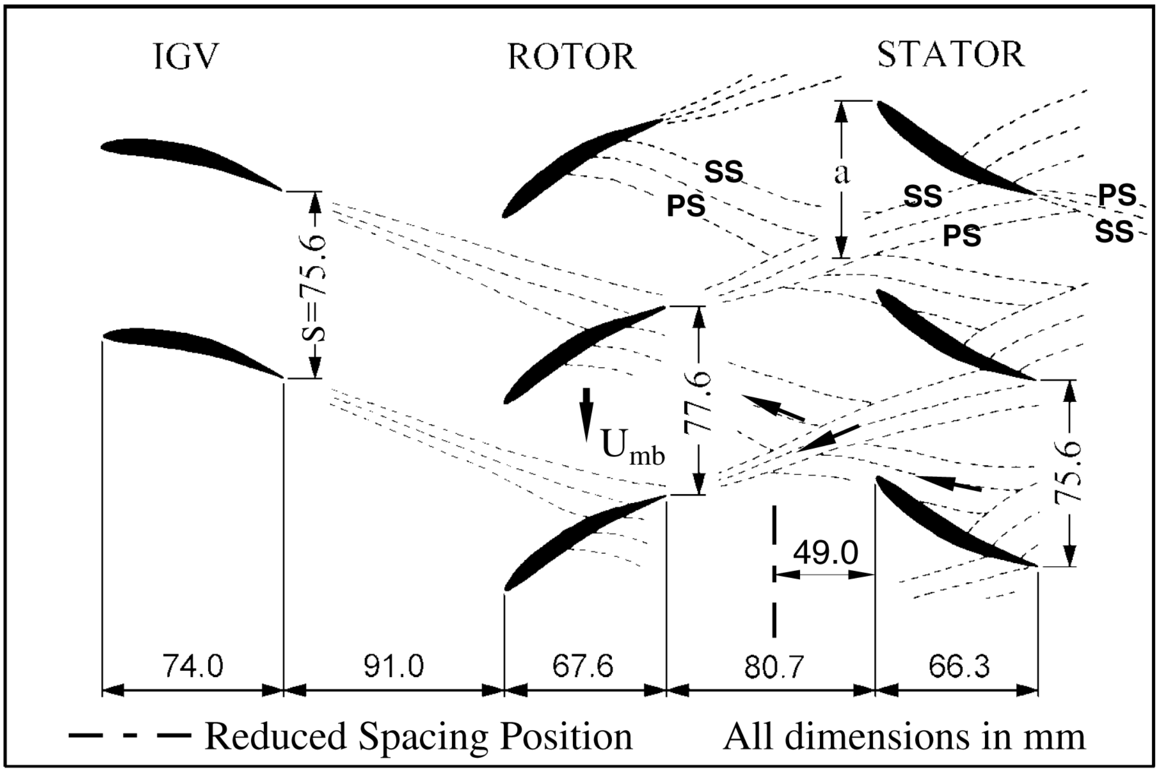
INTRODUCTION

Axial turbomachines (compressor or turbine)

- alternate moving and fixed blade rows (rotor and stator)
- airfoil section blades (low Re)
- approximately 2-D flow in LP stages outside endwall regions

Disturbance field dominated by

- moving pressure fields of adjacent blade rows
- periodic wake disturbances from blade row immediately upstream
- turbulence from all upstream blade wakes



Cross-section of 1.5 stage axial compressor showing typical instantaneous wake dispersion (schematic).

INTRODUCTION (cont.)

Typical disturbance field (Tasmania compressor)

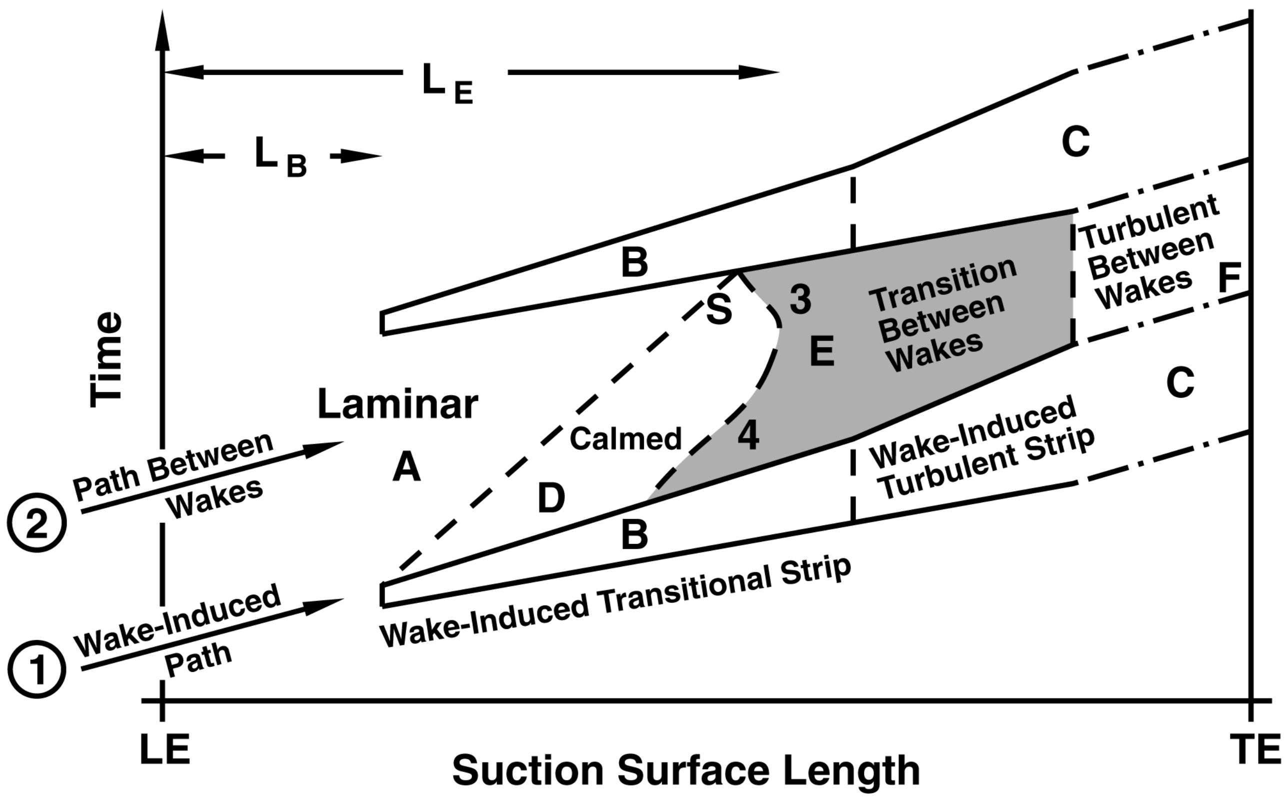
- random turbulence in wakes 12% peak
- background random turbulence 2.5-4.3%
- integral length scale ≈6.5 mm (8.6% chord)
- periodic unsteadiness 3.0-6.6%

MORPHOLOGY OF TRANSITION ON TURBOMACHINE BLADES

Transition on axial turbomachine blades

- Periodic wake-induced turbulent strips
- Calmed regions
- Transition by other modes

Morphology of transition on axial compressor and turbine blades described by Halstead et al. (1995)



Unsteady boundary layer development on an axial compressor blade (Halstead et al. (1995)).

TRANSITION PROCESSES IN TURBOMACHINES

Important modes as identified by Mayle (1991)

- Natural transition (T-S waves)
- Bypass transition
- Separated flow transition

Turbomachinery community view of transition

- the above modes are mutually exclusive
- bypass transition is instantaneous
- bypass transition will always dominate due to high free stream turbulence
- natural transition phenomena are irrelevant on turbomachine blades

NATURAL TRANSITION

Main regions of the Natural Transition process (low levels of freestream turbulence)

- A region of instability to small two-dimensional disturbances.
- The appearance of three-dimensional instability which produces periodic spanwise flow distortions. Rapid non-linear amplification of the spanwise waves into vortex loops.
- The initiation of turbulent spots through the appearance of high frequency fluctuations in regions of high shear near the heads of the vortex loops
- A transition zone in which turbulent spots merge to form a continuously turbulent flow

BYPASS TRANSITION

Bypass transition as described by Mayle (1991)

- "… is caused by large disturbances in external flow (such as freestream turbulence) and completely bypasses the T-S mode of instability"

Turbulent spots are then

- "… directly produced within the boundary layer under the influence of the freestream disturbances"

EXPERIMENTAL DETAIL

1.5 Stage axial compressor with IGV-Rotor-Stator

Hot film array at mid-span on outlet stator blade.

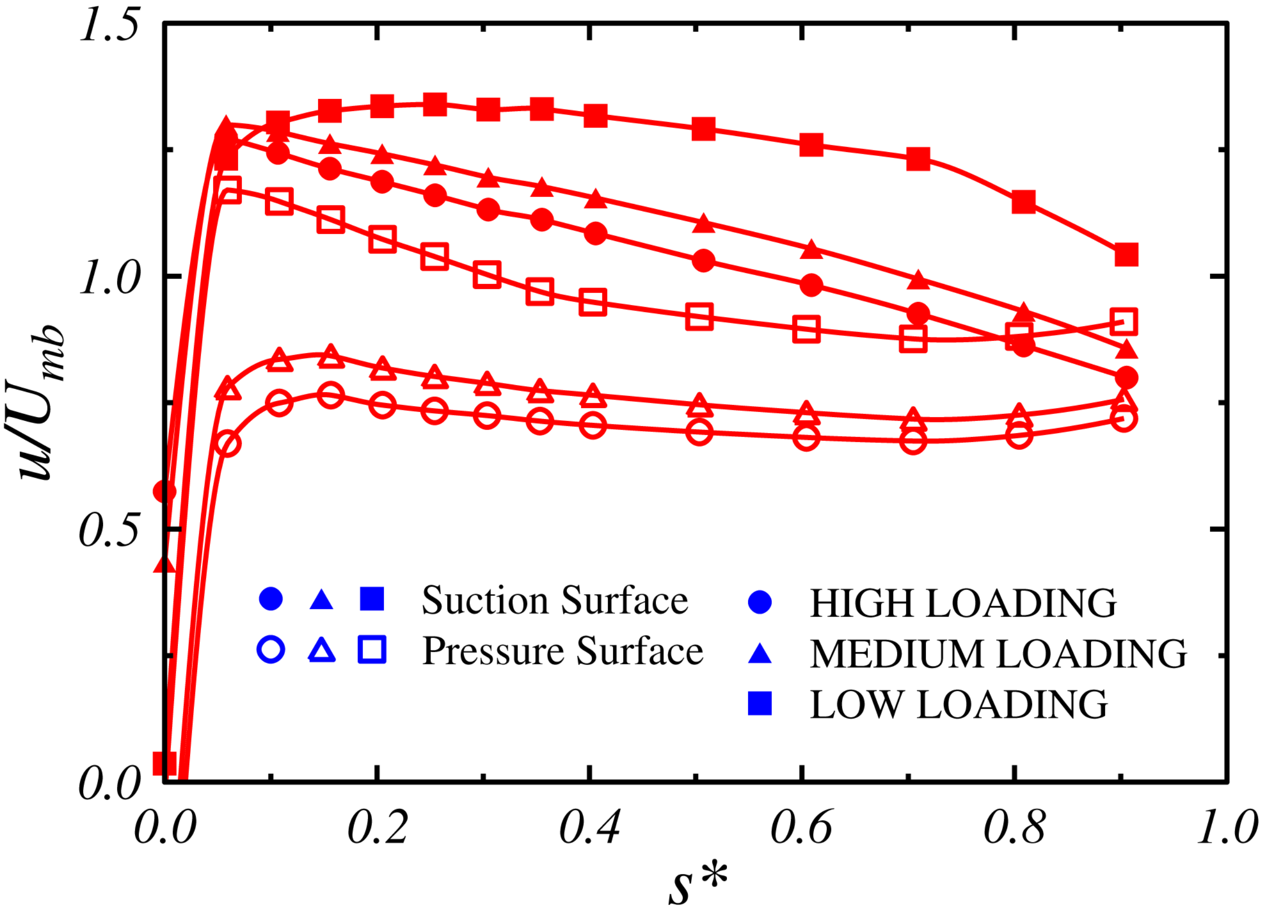
Simultaneous sampling of 5 surface film gauges to examine transition phenomena

Two IGV clocking positions

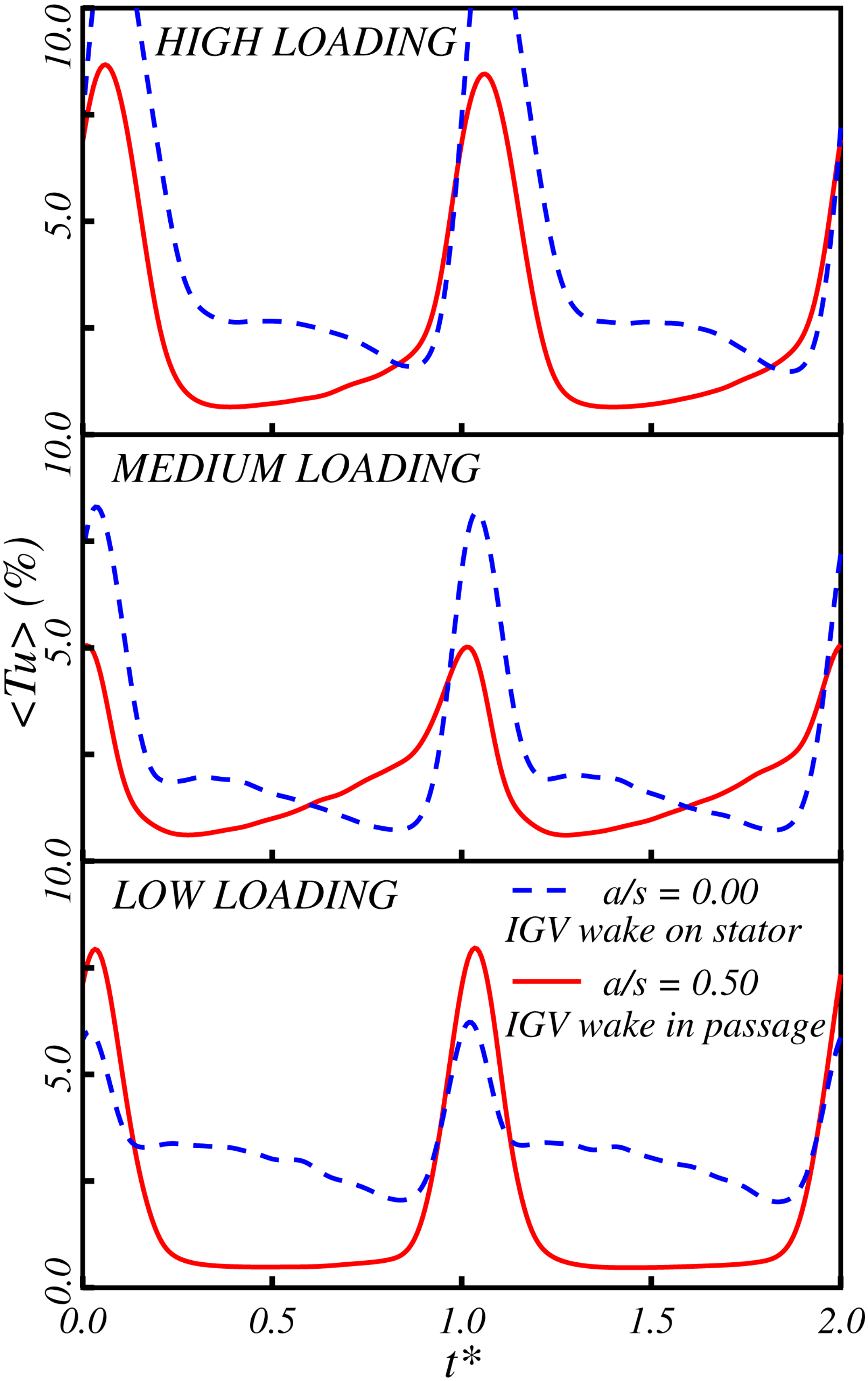
- $a/s = 0.00$
  IGV wake on stator
- $a/s = 0.50$
  IGV wake in passage

Three loading cases

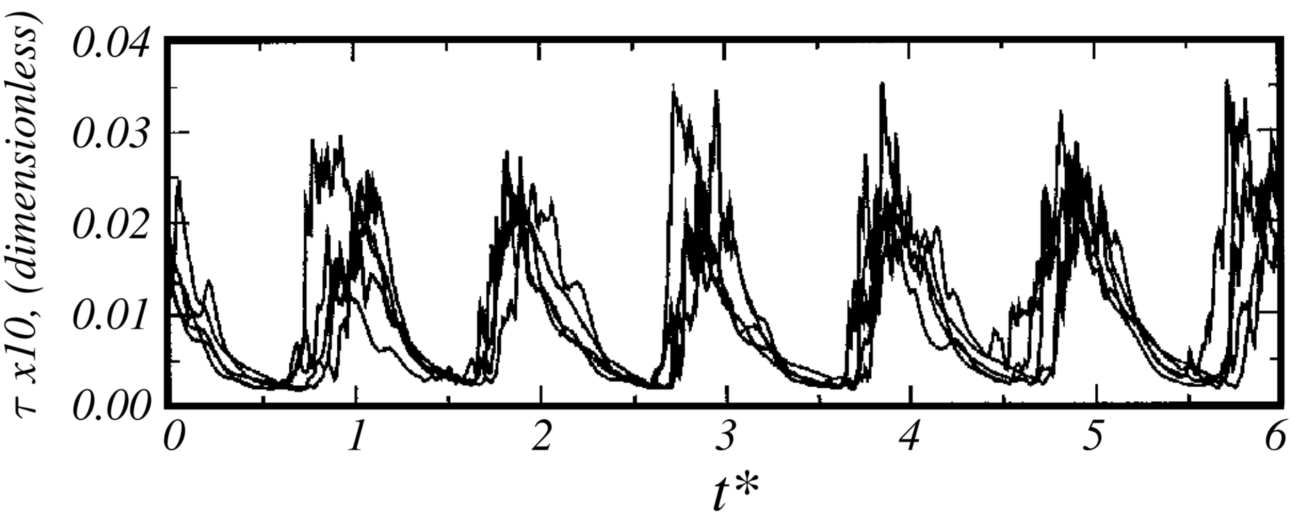
- High (near stall)
- Medium (design)
- Low (near max flow)



Variation of stator blade surface velocity distribution with loading at mid-blade height. Re_{ref} = 120000.



Temporal variation of ensemble average turbulence level <Tu> (%) on stator stagnation streamline at inflow measurement plane 55.7%c axial distance upstream of stator leading edge. Variation with stator loading and IGV clocking.

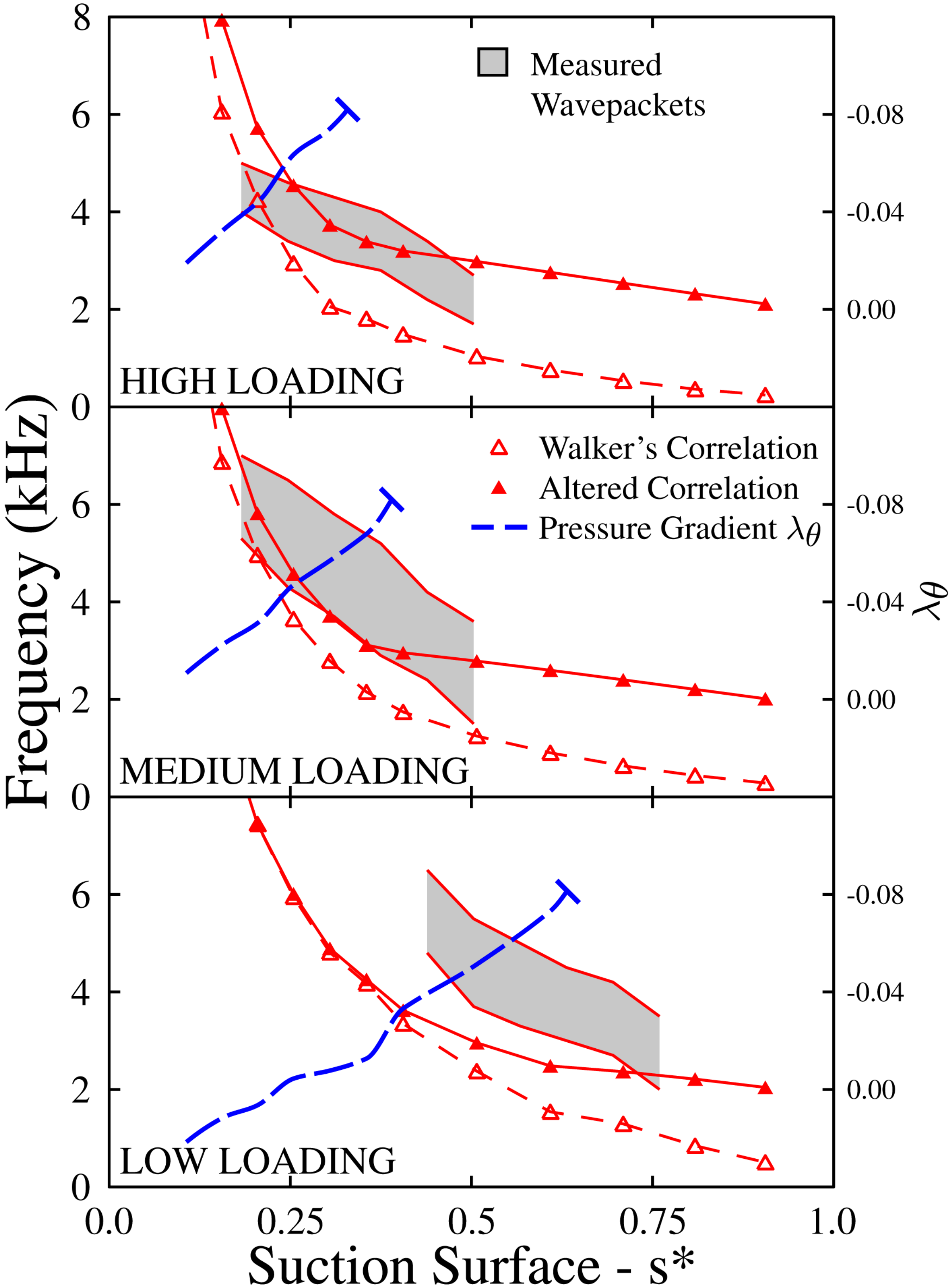


Five individual hot-film quasi-wall shear stress records at s* = 0.60 on the suction surface. Re_{ref} = 120 000: ϕ= 0.675.

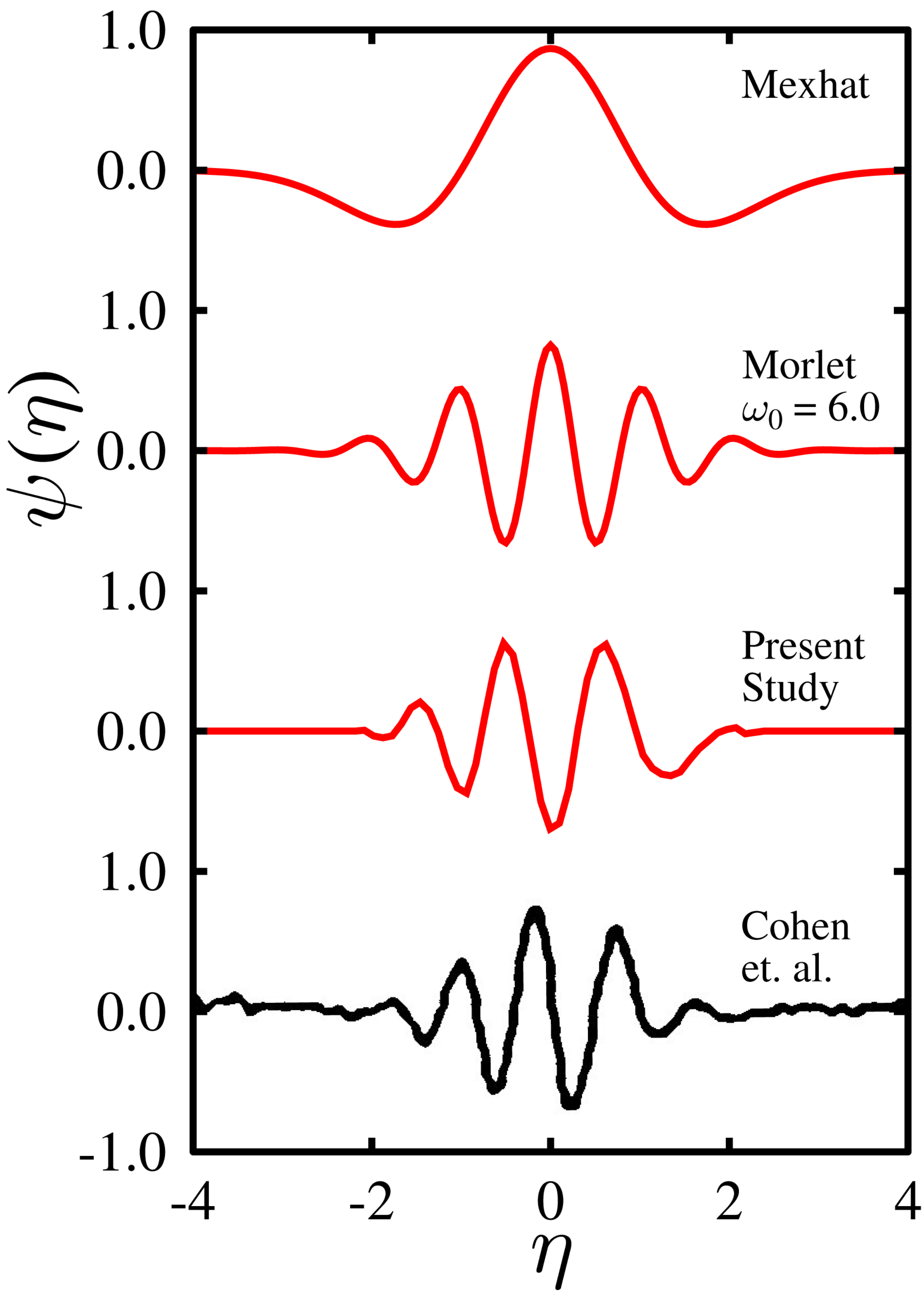
T-S WAVE DETECTION

T-S wave detection algorithm

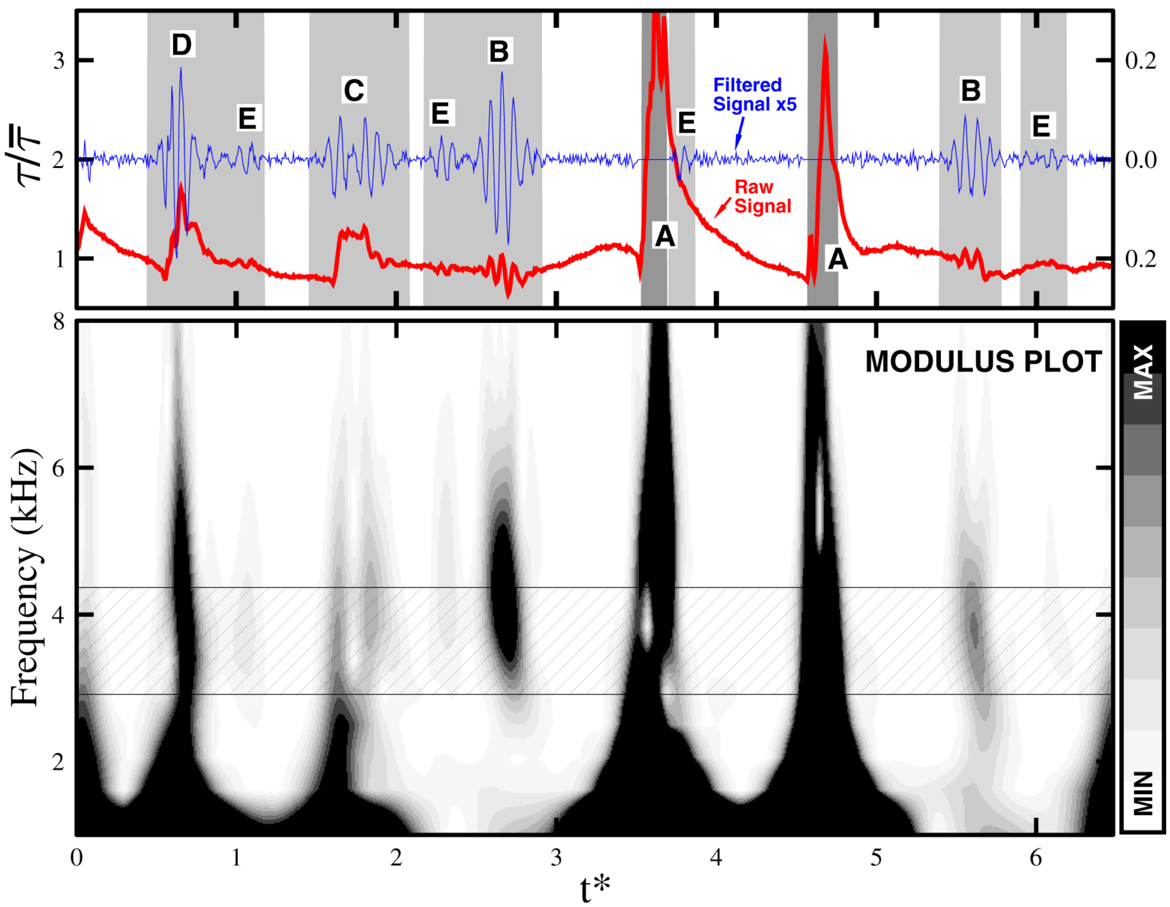
- Estimation of local T-S wave frequency
- High-pass filtering of the hot-film signal
- Wavelet transform of the filtered signal
- Exclusion of turbulent flow regions
- Identification of instability waves in the laminar flow



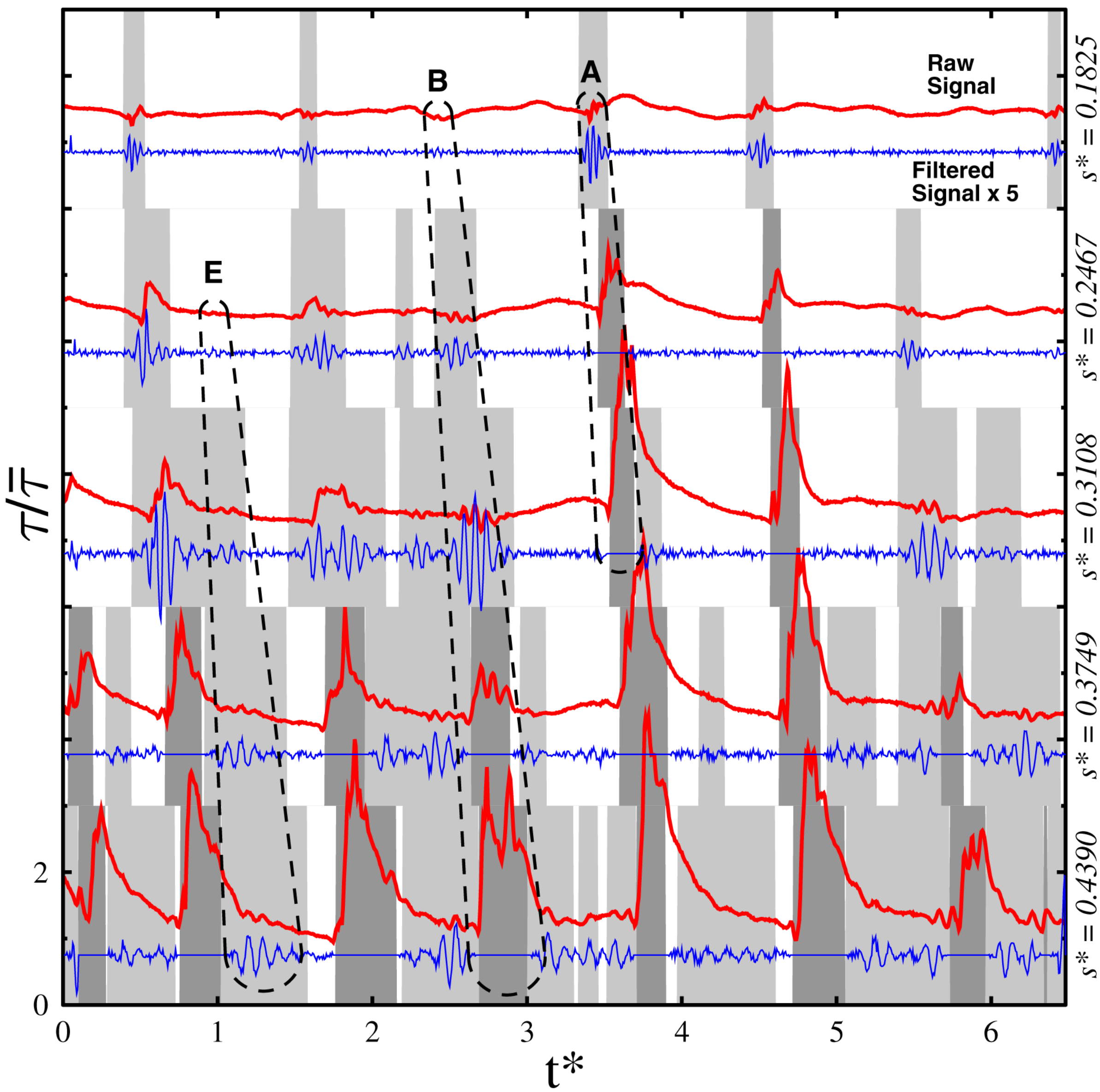
Comparison of predicted T-S wave frequency and measured instability wave packet frequency.



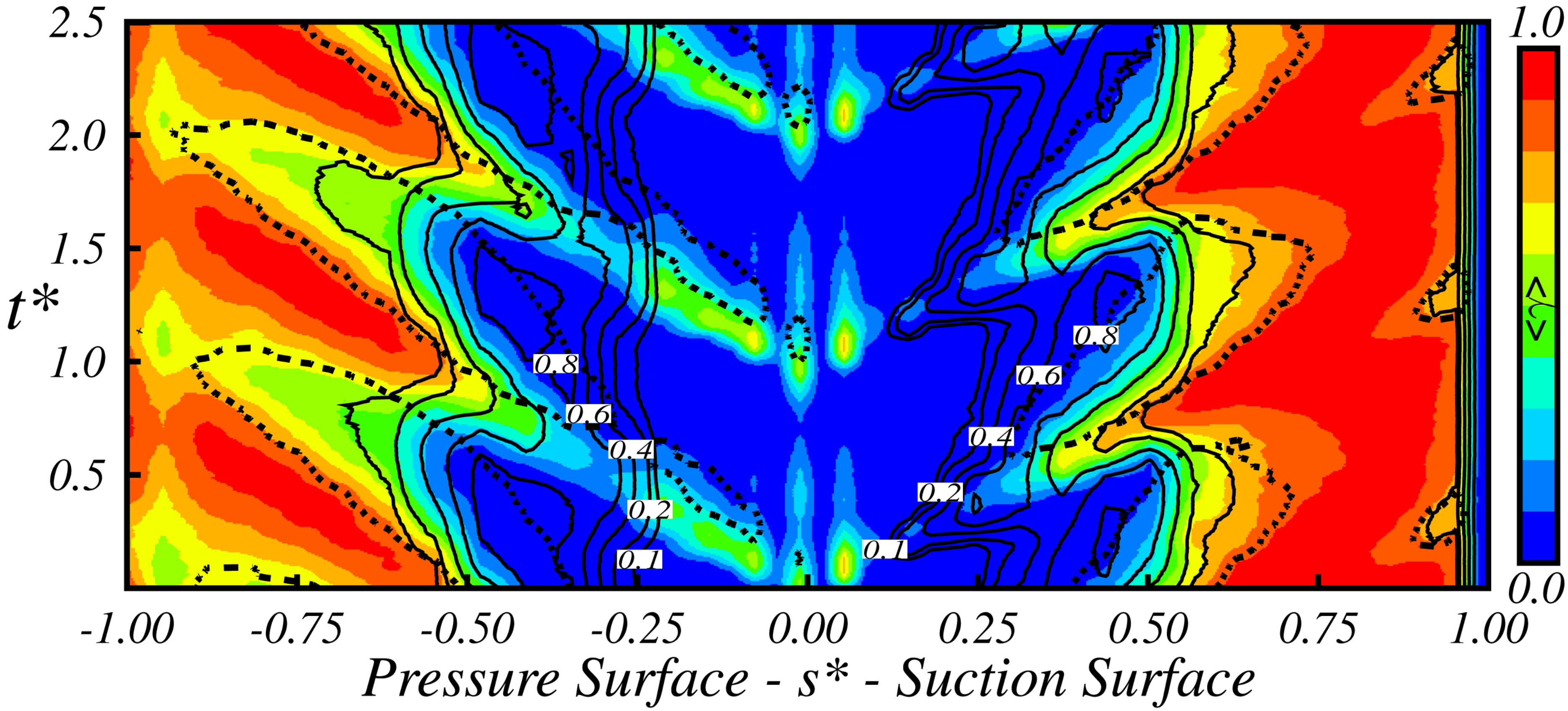
Comparison of Mexican hat and Morlet wavelets with typical data from the present study and Cohen et al. (1991). Note only the real part of the Morlet wavelet is plotted.



Top: Quasi-wall shear stress record from a hot-film gauge located at s* =0.3108 on the stator suction surface for the medium loading case. High-pass filtered signal amplified five times and superimposed. Darker shaded regions indicate turbulent flow: lighter shaded regions indicate instability wave occurrence. Bottom: Modulus of the Morlet wavelet transform for the above quasi-wall shear stress record. Hatching indicates frequency range under consideration by the detection algorithm.

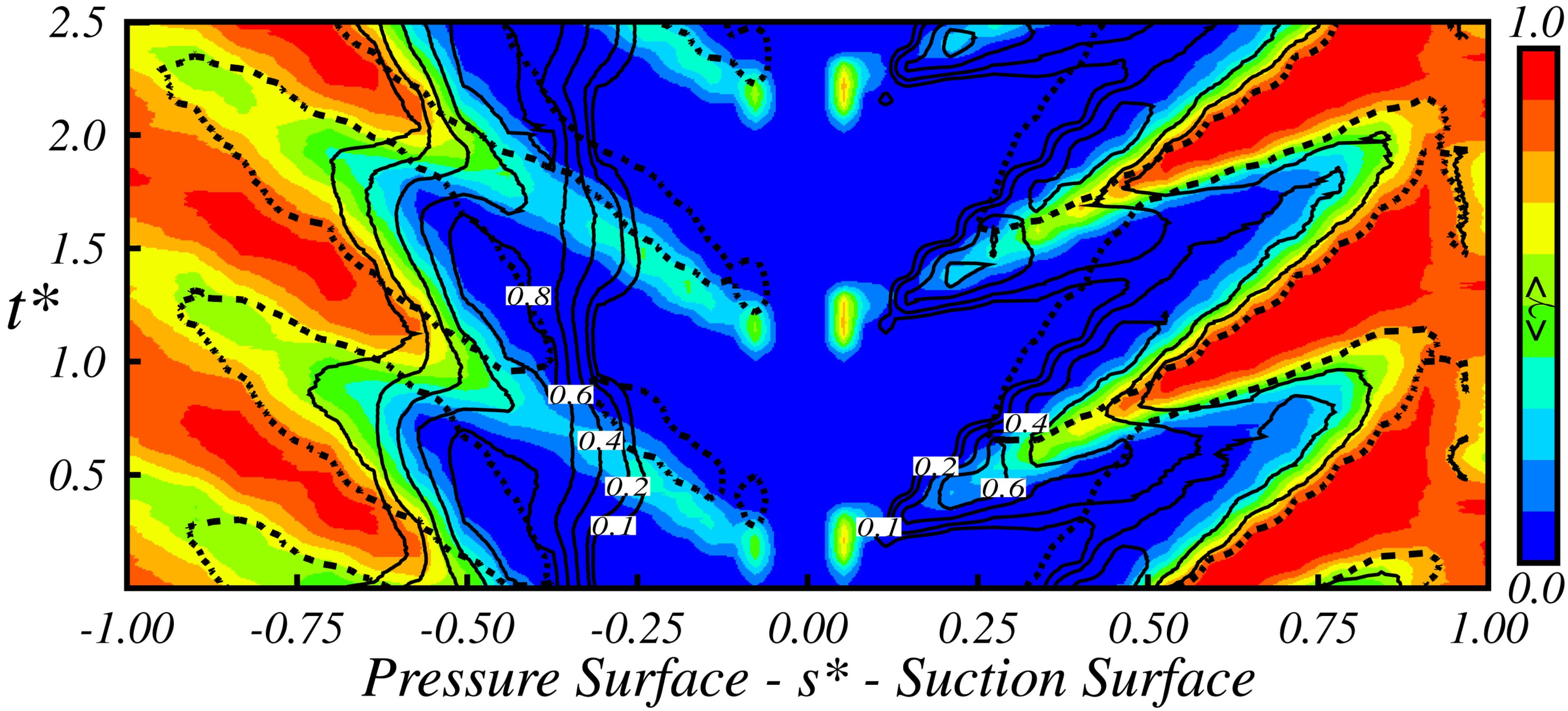


Simultaneous quasi wall shear stress records from five gauges spanning from s* = 0.1825 to 0.4390 on the stator suction surface. High-pass filtered traces amplified five times and overlaid on each raw signal. Darker shaded regions indicate turbulent flow: lighter shaded regions indicate instability wave occurrence. Individual events are highlighted by dashed lines.



IGV wake street on stator (a/S=0.00)

Ensemble average intermittency (colour shading) and probability of instability wave occurrence (line contours). Dashed line indicates 10% probability contour for relaxing non-turbulent flow. Medium Loading.



IGV wake street in passage (a/S=0.50)

Ensemble average intermittency (colour shading) and probability of instability wave occurrence (line contours). Dashed line indicates 10% probability contour for relaxing non-turbulent flow. Medium Loading.

CONCLUSIONS

Scant evidence of instability wave activity in previous investigations due to masking by laminar-turbulent switching

High-pass filtering and wavelet analysis allows identification of randomly appearing wave packets

Universal appearance of instability wave amplification prior to turbulent breakdown in decelerating flow regions on a compressor blade

No evidence for the direct production of turbulent spots even under high levels of freestream turbulence

Observations closely resemble wave packets and ultimate breakdown in basic experiments on artificially generated turbulent spots

CONCLUSIONS (cont.)

Identification of unstable laminar flow regions as long as 20% of chord in

- path of wake-induced transition
- regions between wake-induced path

Observed transitional flow lengths up to 20% chord

Total length of flow influenced by linear stability phenomena may be as much as 40% of chord, despite levels of freestream turbulence up to 8%

Wave activity may both occur in and originate from the calmed region following a wake-induced turbulent strip

Observations of instability wave activity relate entirely to regions of decelerating flow

DISCUSSION POINTS

Need for more precise definition of the term "bypass" in relation to transition on turbomachine blades

Need for greater consistency in definitions of bypass transition used by workers in the fields of turbomachinery and transition physics

Desirability of complementary transition studies in accelerating flow, where bypass phenomena should be relatively more important

Efficacy of zero pressure gradient transition studies, which lie on the boundary of two significantly different regimes

Remaining challenges for predicting turbulent breakdown on turbomachine blades

SEPARATION BUBBLE INTERACTIONS WITH TURBULENT SPOTS AND WAKES IN THE TURBOMACHINERY ENVIRONMENT AT REYNOLDS NUMBER OF AROUND 130,000

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Cambridge, U.K.

This paper describes the details of the interactions of individual turbulent spots, their calmed regions and separation bubbles.

Many hot wire and film measurements have shown that wakes cause turbulent spots to form in the boundary layer at the approximate position where flow separation would normally occur with steady inflow. Artificially generated individual turbulent spots were created just before flow separation on a flat plate with imposed turbine pressure distribution. This caused the (normally) separated boundary layer to reattach to the blade surface. A large number of detailed unsteady measurements were taken to show how the velocity profiles of a separation bubble were affected by the passage of turbulent spots and their calmed regions. Other experiments also included the effects of wakes.

These measurements showed that initially, the inner part of the separation bubble was reattached by the presence of a turbulent spot, while the outer half of the velocity profile remained unaffected. Only when 50% of the length of the spot had reached the separation location, did any changes occur in the outer half of the separation bubble. The spot seems to act like a wedge travelling under the separation bubble at first and as the rest of the spot reaches the separation location, the higher regions of what was the separation bubble are then affected. During this process there is a reduction in shape factor from 3.4 to 1.6. As the calmed region passed by, the flow gradually relaxed back to a separated boundary layer. At the trailing edge of the flat plate, the effects of the calmed region were present for up to three times the duration of the turbulent part of the spot.

Separation Bubble Interactions with Turbulent Spots and Wakes in the Turbomachinery Environment at a Reynolds of around 130,000.

RJ Howell and HP Hodson.

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CB3 0DY.

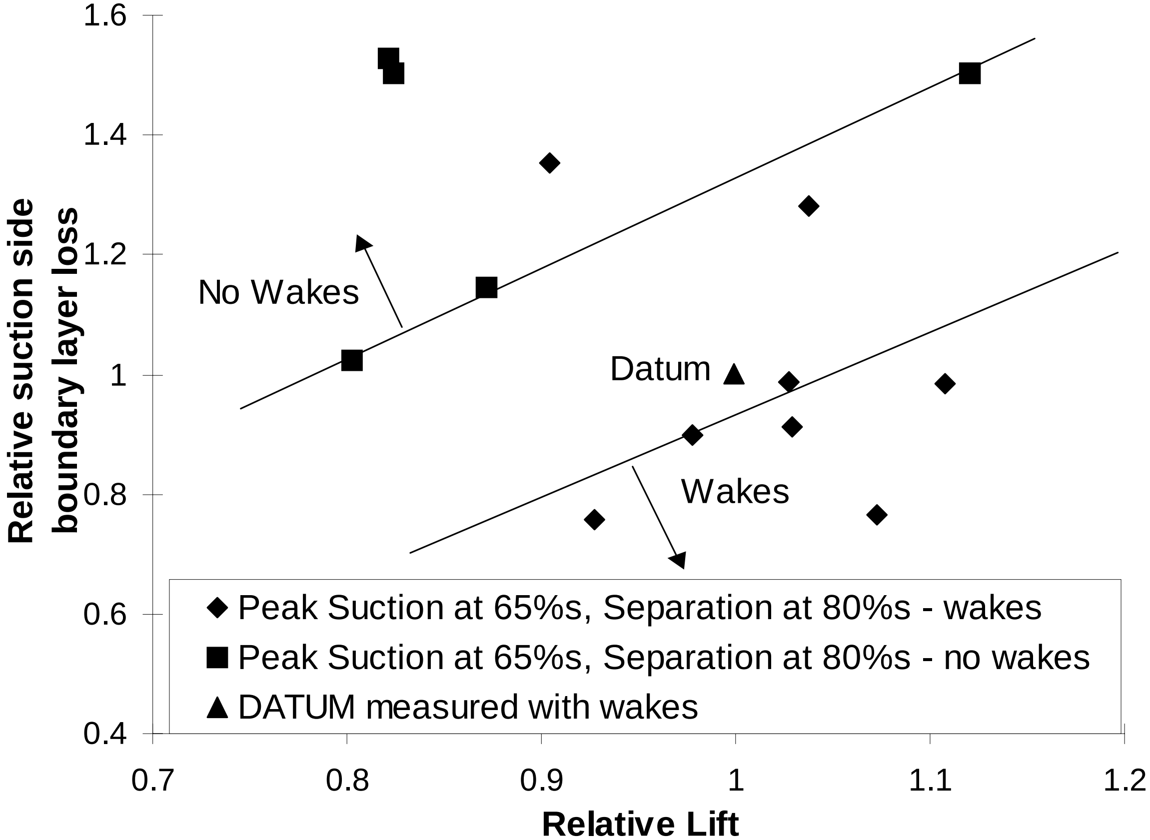
Introduction

Aero-engine manufacturers are continually striving to reduce the weight of their engines. This can be achieved in many ways, one of which is to reduce the number of blades in the LP turbine. When this is done, the blades that are left must be, for a particular duty, more highly loaded. When this happens it is usually, because of incidence tolerances considerations, necessary to increase the deceleration on the rear of the turbine blade profiles. This leads to larger separation bubbles on these profiles, which results in increased losses. This is unacceptable for the aero-engine manufacturer. Howell (1999) showed that as the diffusion on an LP turbine profile was increased the length of the separation bubble *decreased*. This seems to be because the increased diffusion causes the separation bubble to undergo transition more rapidly. When this happens, the boundary layer reattaches to the blade surface earlier, reducing the laminar length of the separation bubble. This earlier reattachment of the separation bubble results in a larger amount of turbulent boundary layer on the blade surface, which tends to cause increased losses. A way to reduce the losses is to remove that turbulent boundary layer. To achieve this, the position of boundary layer separation, separated flow transition, and reattachment can be moved aft along the blade and so reduce the amount of turbulent flow before the blade trailing edge. This is the key to aft loading LP turbine profiles as explained by Howell (2000).

However, as Howell (2000) showed, aft-loaded profiles only operate with reasonable losses if the flow is unsteady, i.e. wakes from an upstream blade row are used to control the (streamwise and stream normal) growth of the separation bubbles. The details of the wake boundary layer interaction has been investigated by many authors over the years, including Fotner …add more refs... However, the details of the interaction of turbulent spots with separation bubbles have not been well documented. It is however, these interactions that are the most important factors in determining the losses that a profile will generate. This research was aimed at understanding these interactions.

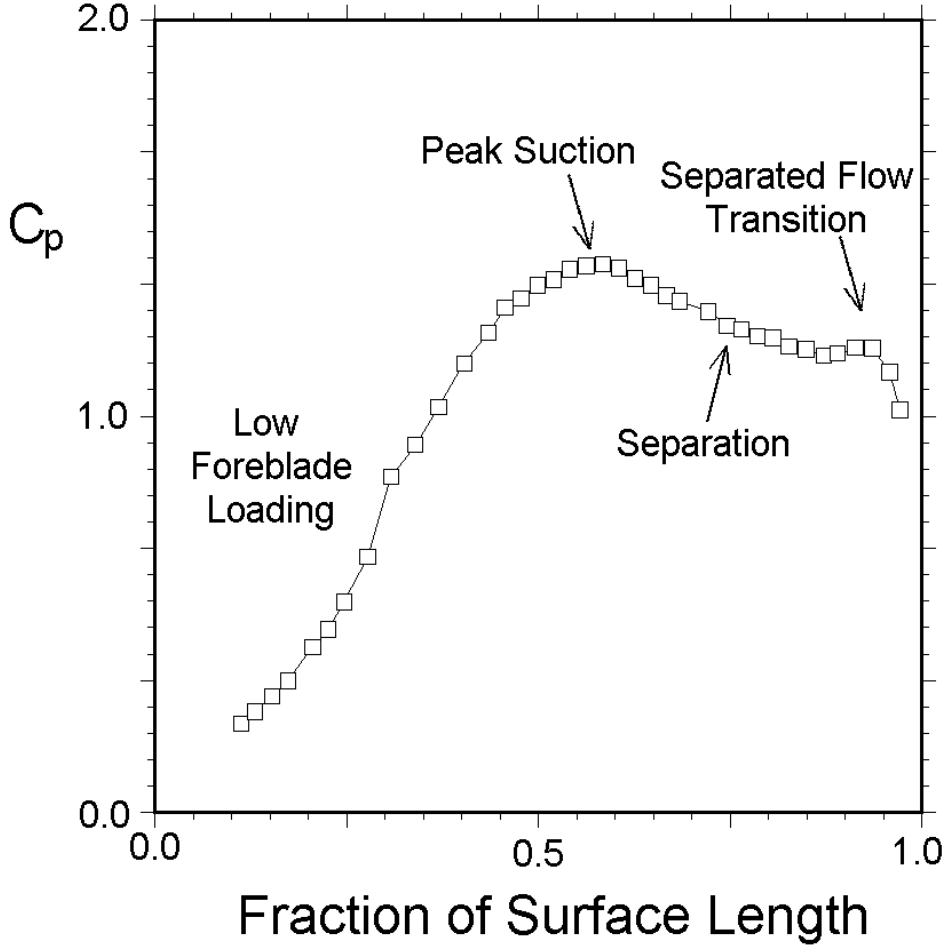
A turbulent spot generator was used to produce artificial turbulent spots in the decelerating part of a low-pressure turbine pressure distribution simulated on a flat plate experimental rig. The turbulent spot generator consists of a loudspeaker placed underneath a plate. When the loudspeaker was fed a stream of pulses (from a pulse generator via an audio amplifier) the diaphragm moves towards the plate forcing air to issue from a hole in the plate surface. This jet of air causes a disturbance in the boundary layer on the top surface of the plate.

Aft Loaded LP Turbine Profiles Reduce Losses



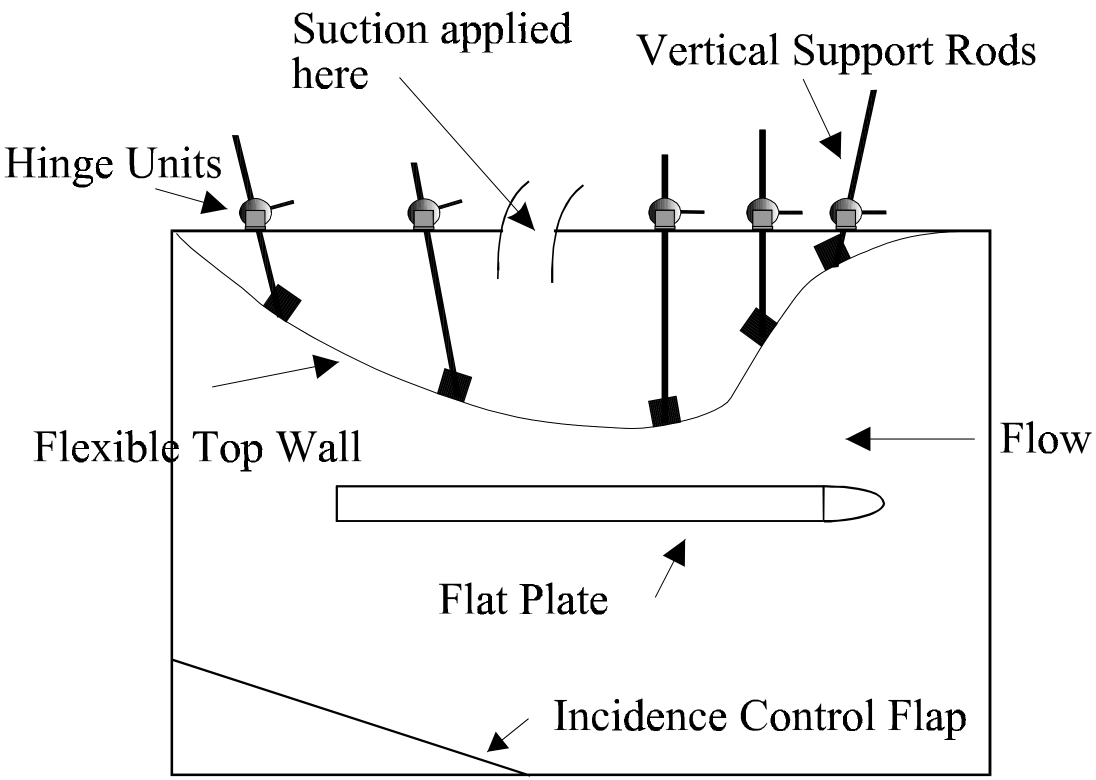
Separation Bubble Losses

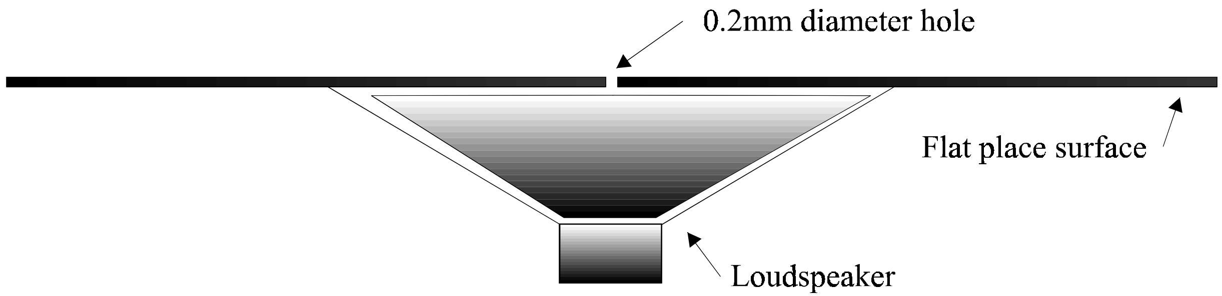
θ - Steady	θ - Spots Only	θ - Wakes
1.75	1.35	1.30



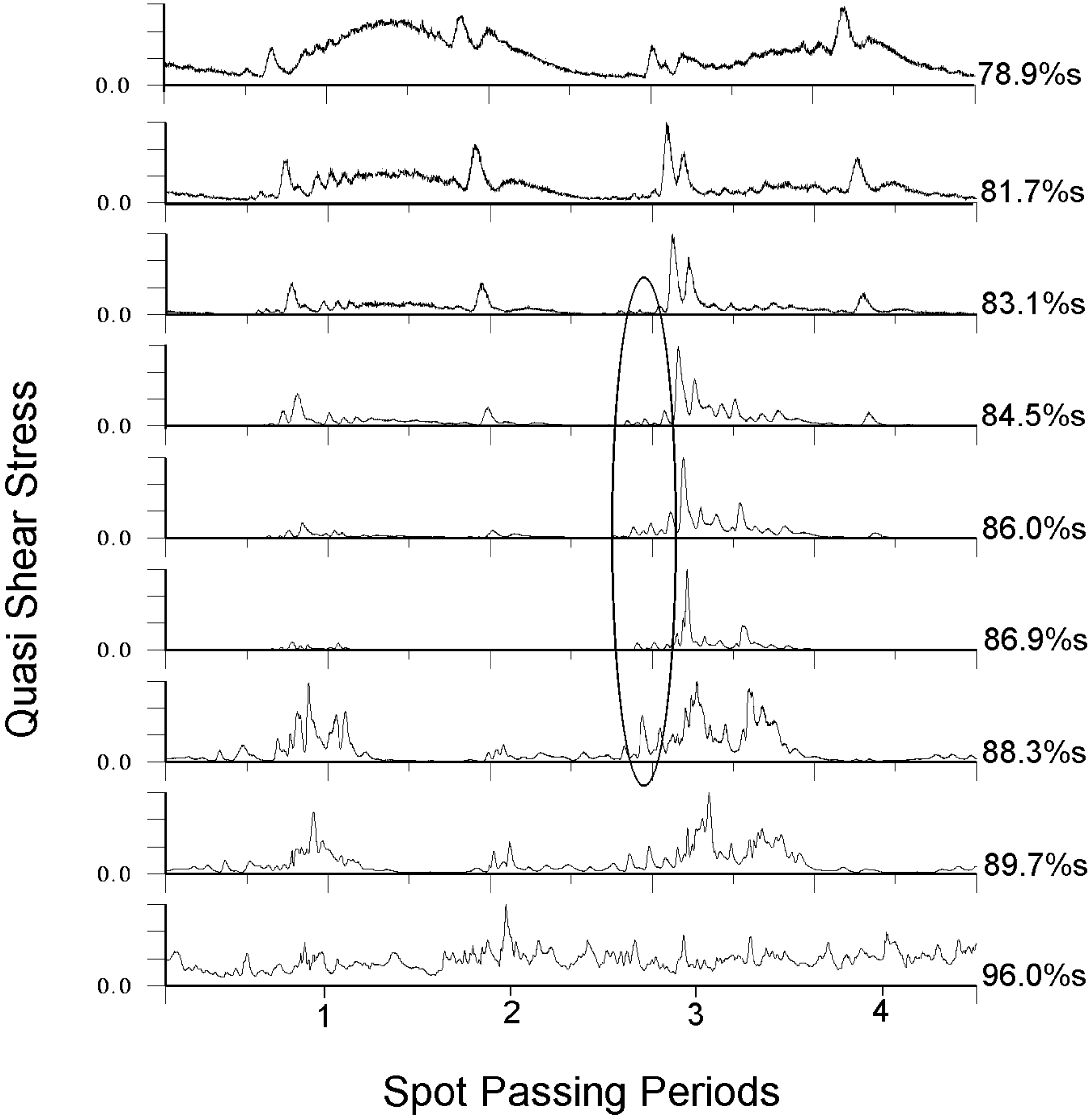
The LP turbine pressure distribution with high rear surface deceleration.

Experimental Setup – the Flat Plate Rig

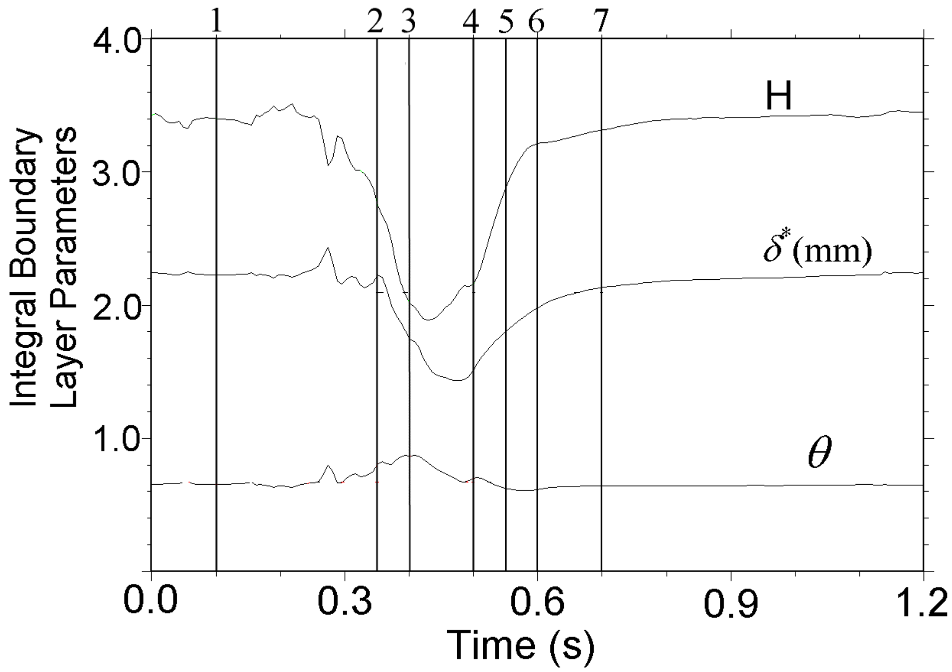




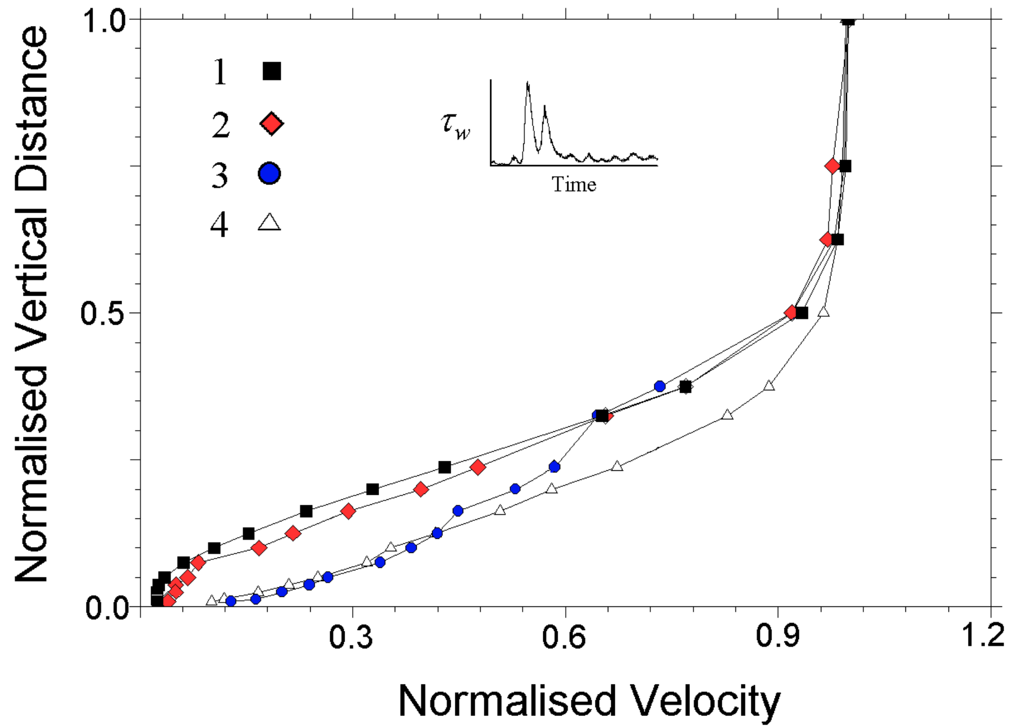
Hot film measurements through separation bubble.



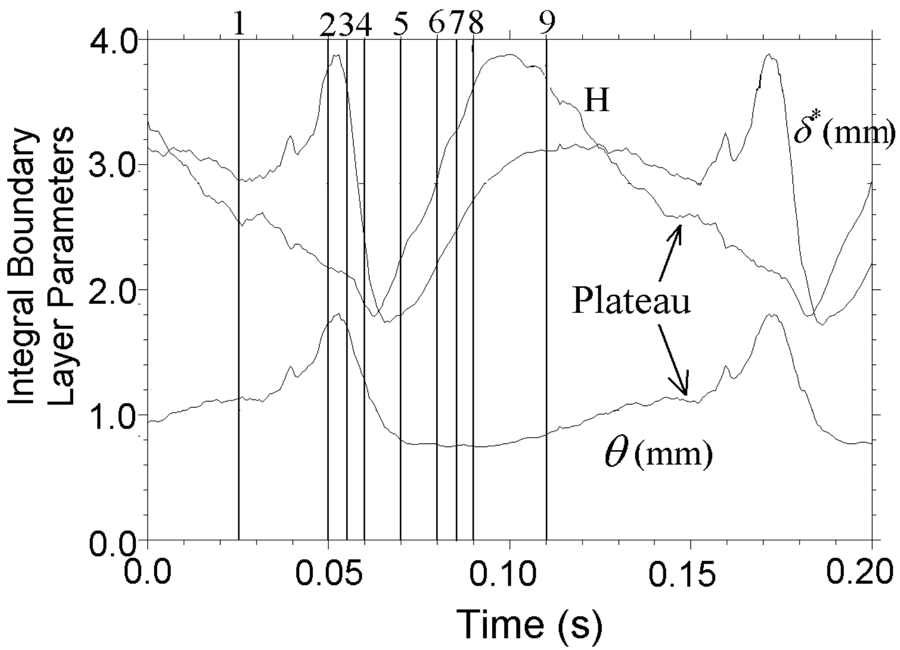
Integral properties at 78%s



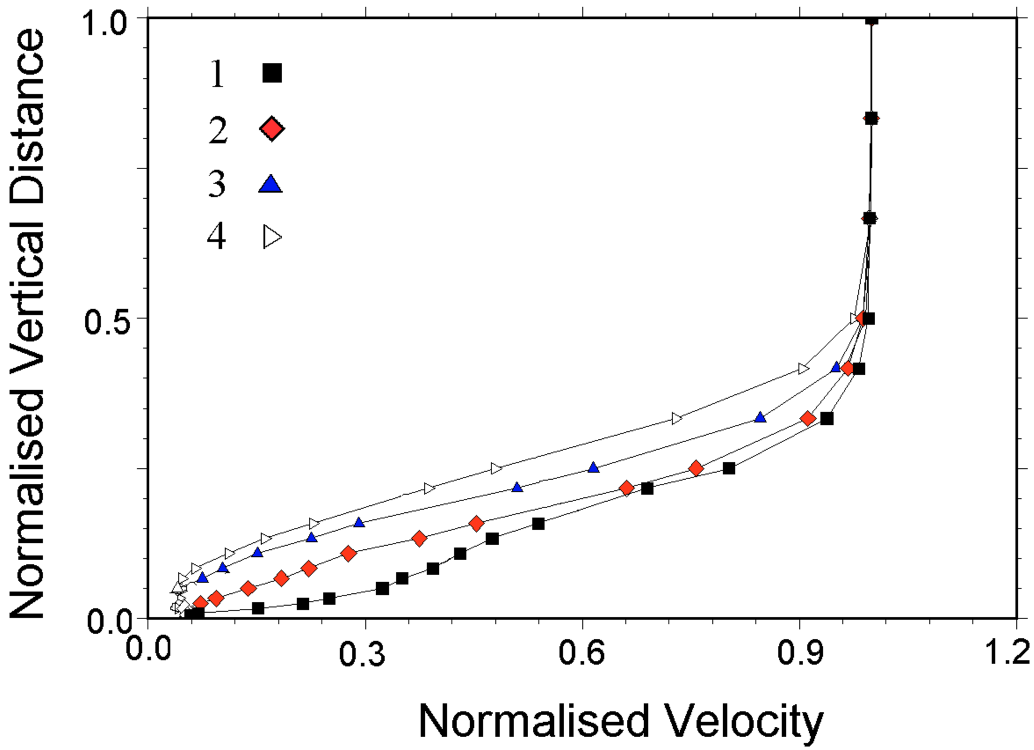
Velocity profiles 78%s



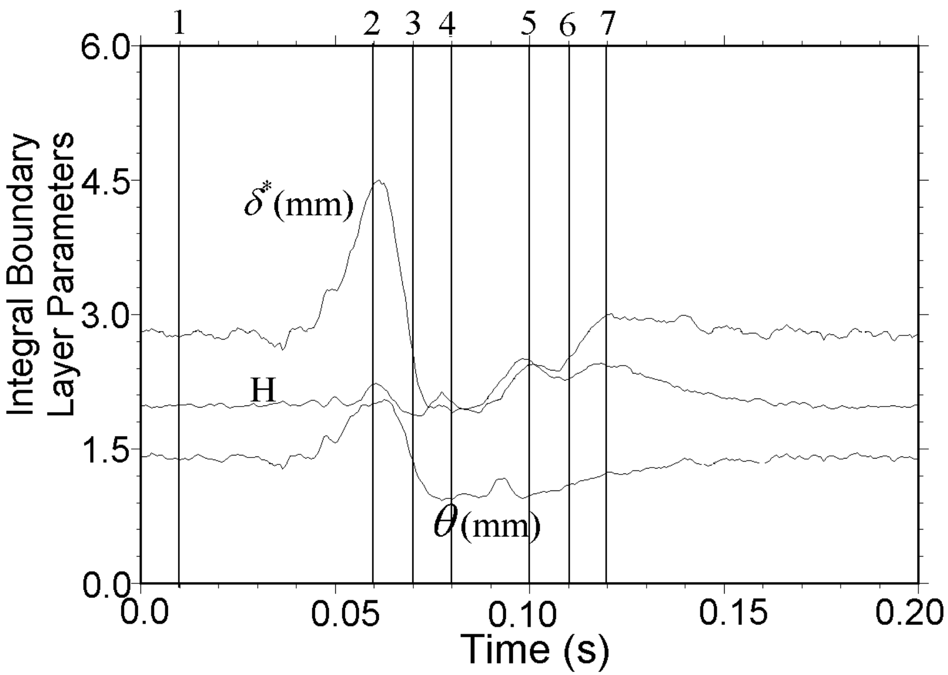
Integral properties at 89%s



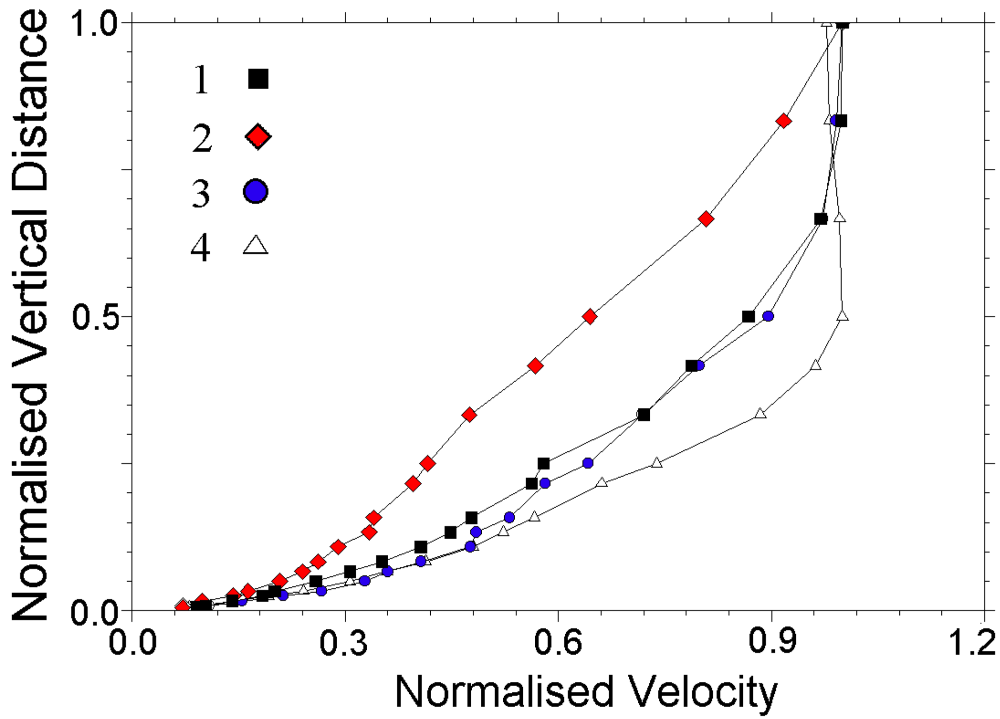
Velocity profiles at 89%s.



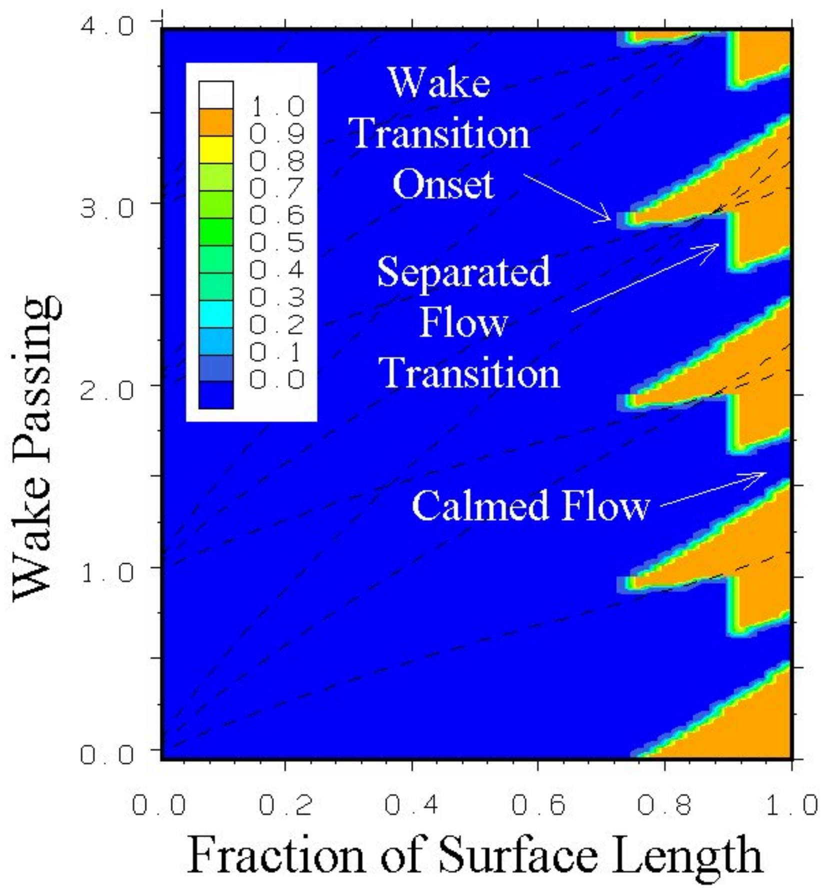
Integral properties at 96%s



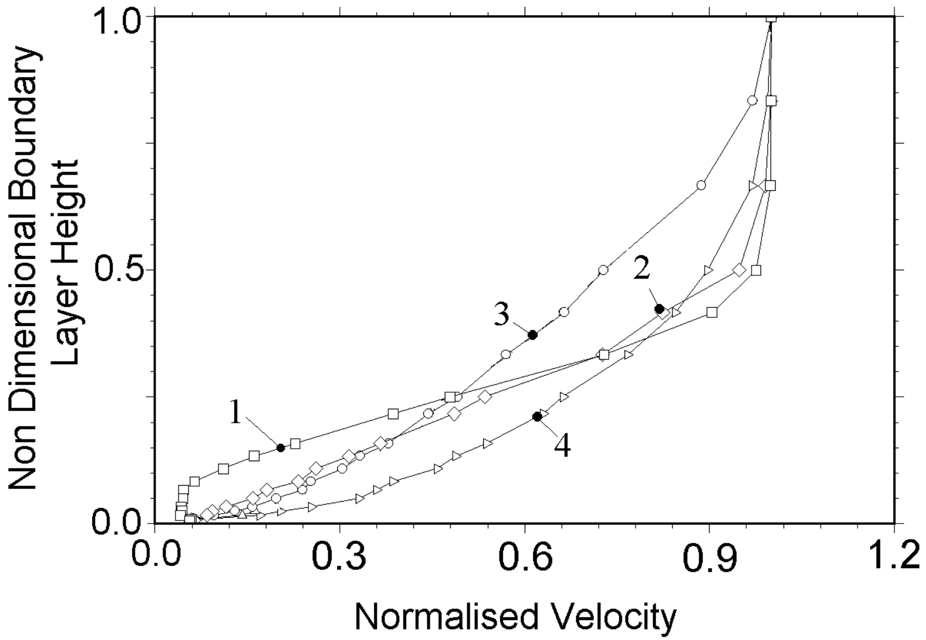
Velocity profiles at 96%s.



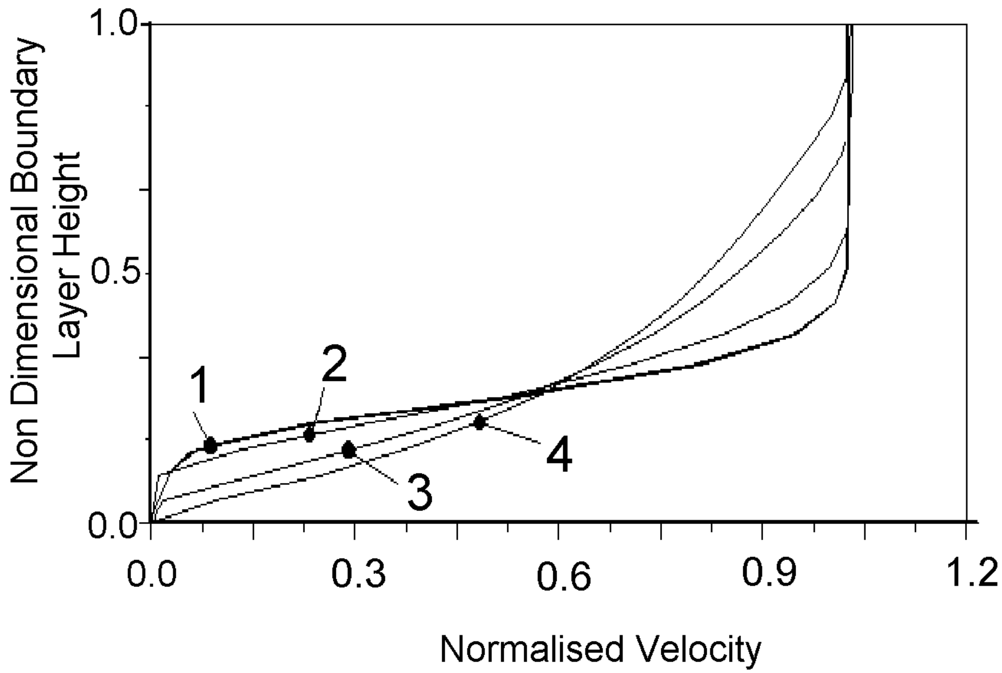
Predictions of Unsteady Multi-Mode Transition – PUIM



Velocity profiles of turbulent spot-separation bubble interaction
- at 89%s turbulent region

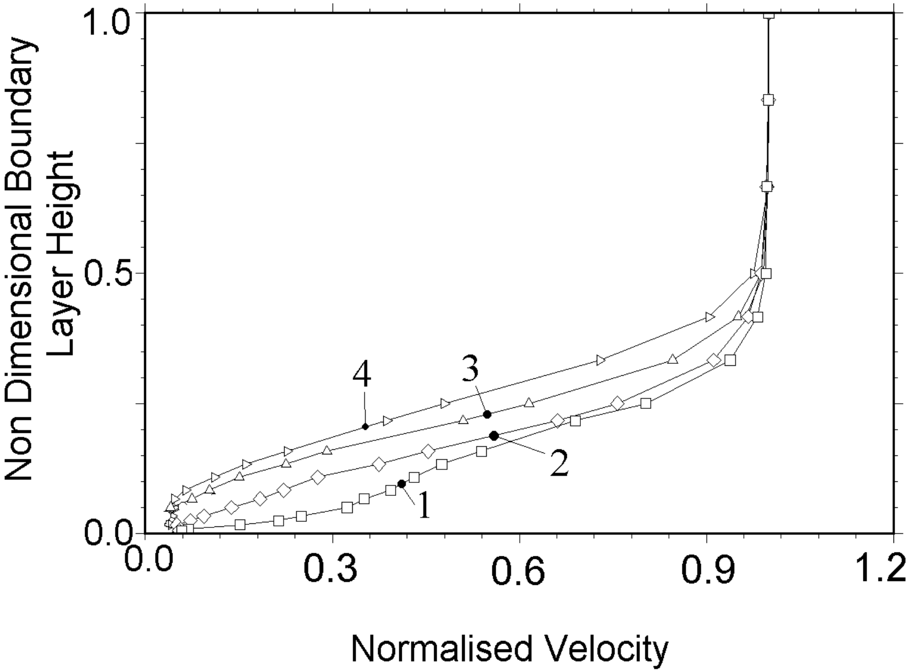


Measured

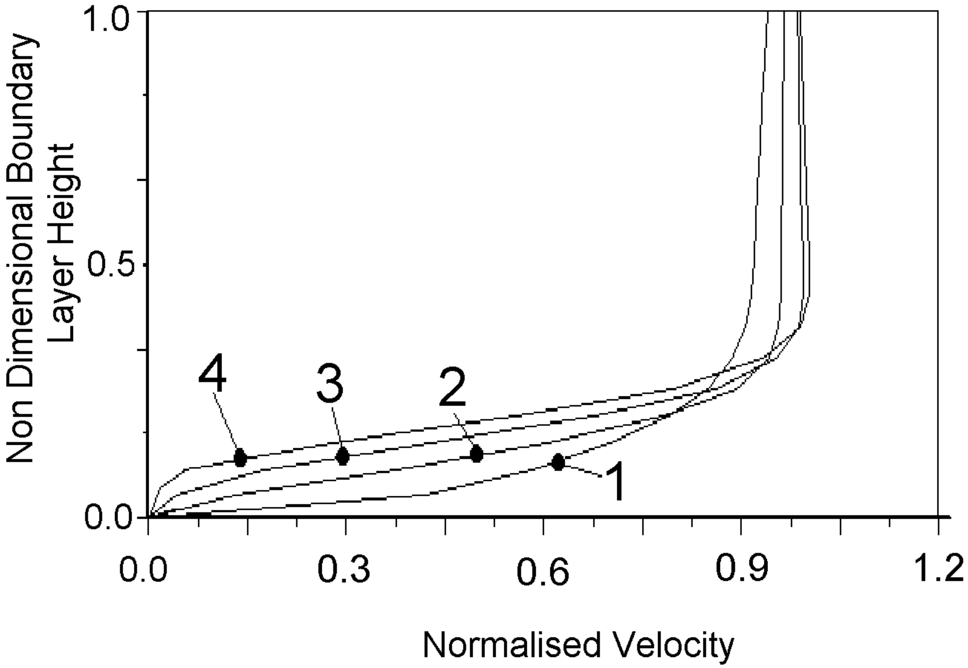


Predicted

Velocity profiles of turbulent spot separation bubble interactions
- at 89%s calmed region

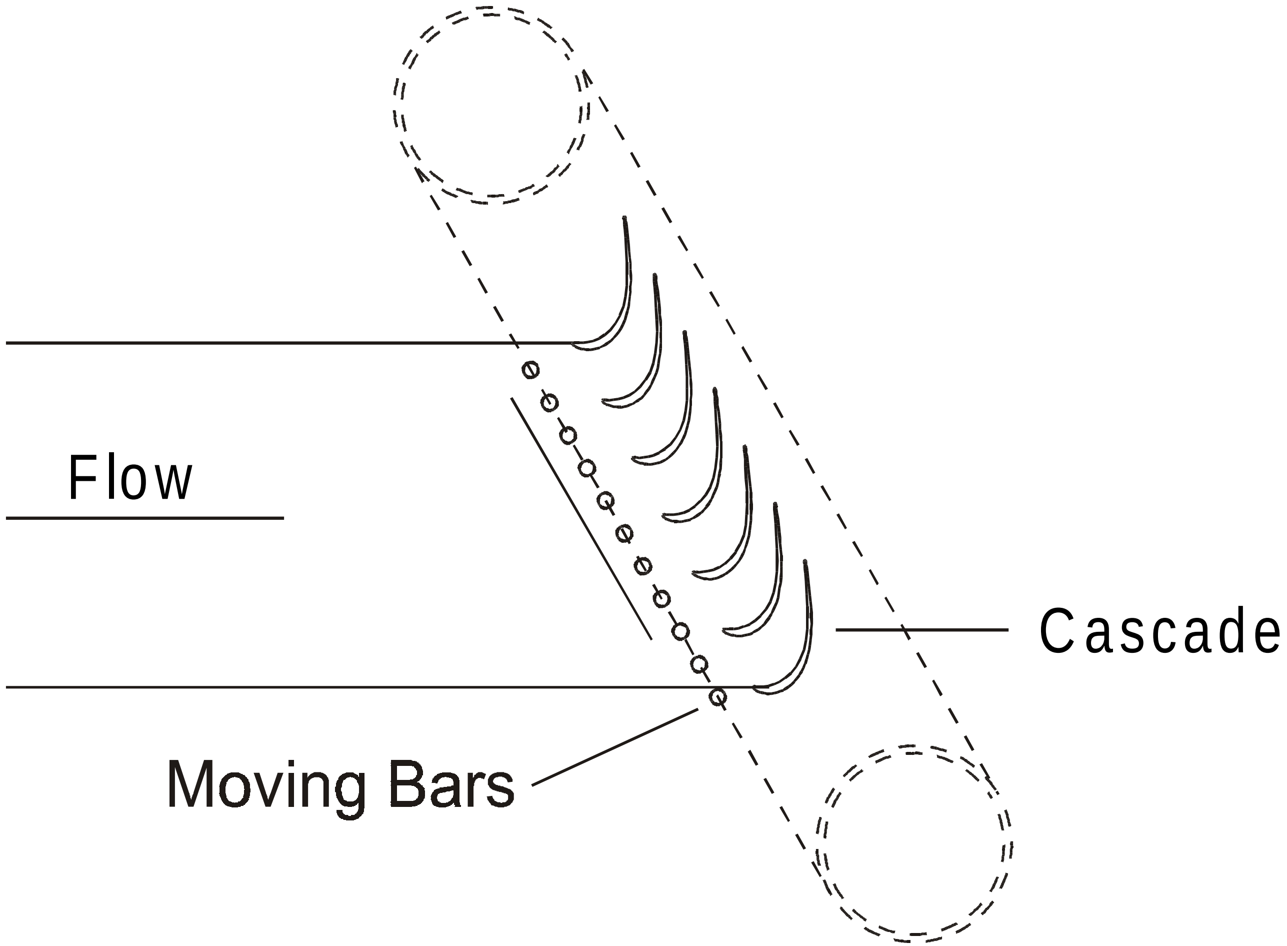


Measured

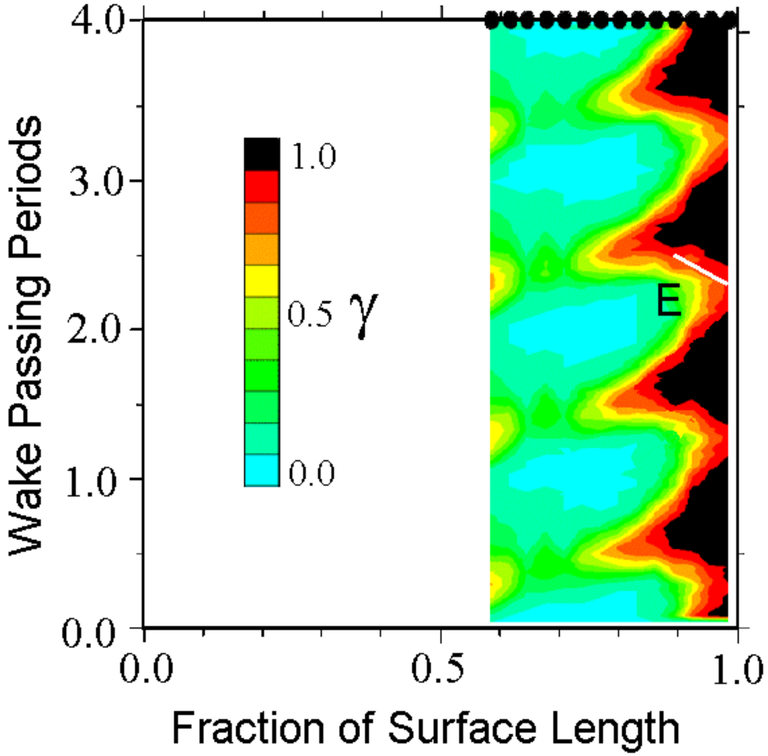


Predicted

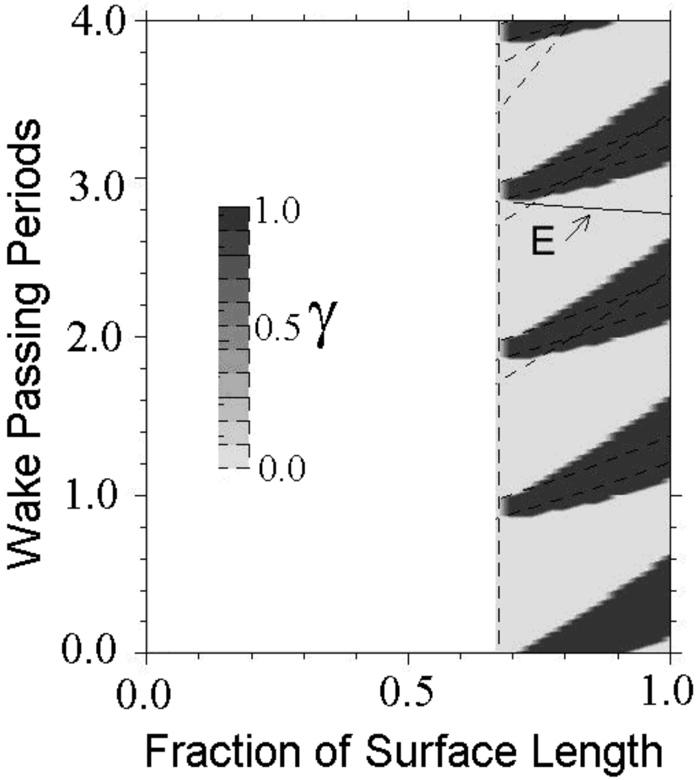
Moving Bar Rig and Cascade.



Effect of wakes and turbulent spots on losses .



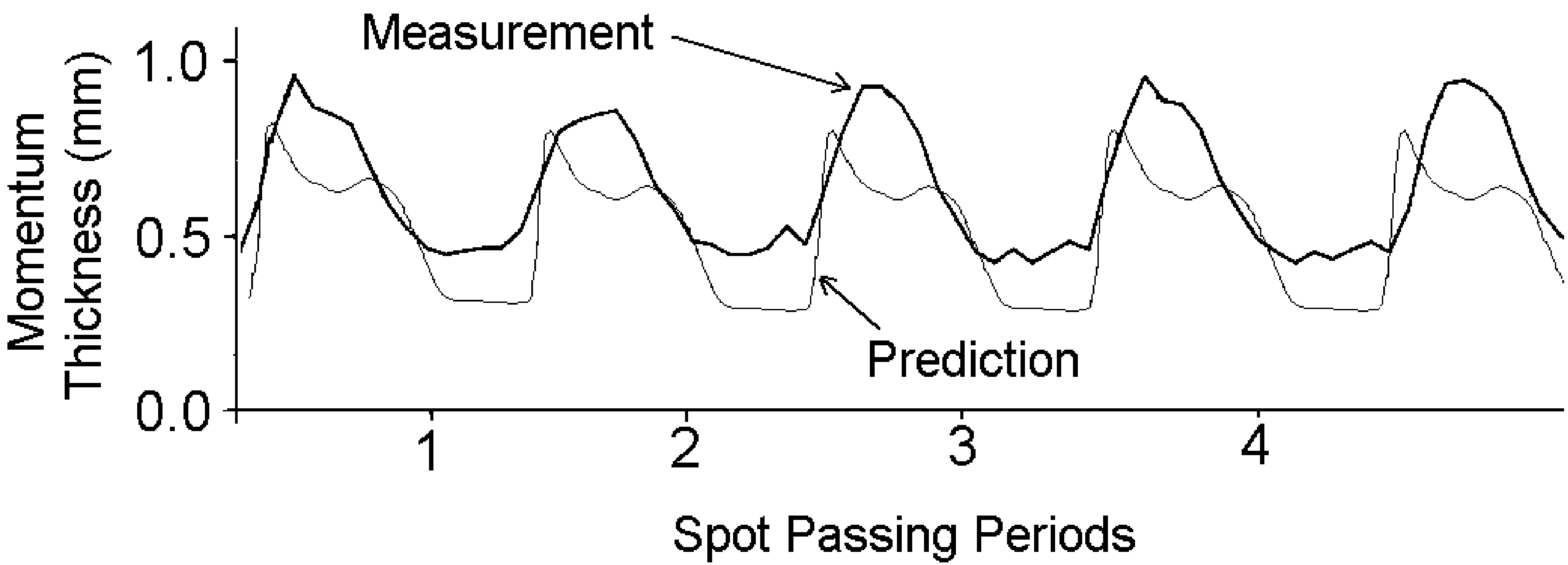
Measured



Predicted

Intermittency from Howell (1999)

Momentum Thickness Variation at 96%s for High Lift Cascade.



Conclusions I

78%s

- Spots not fully formed in early part of separation bubble.
- Inner part of separated profile attached first
- Outer half unaffected by spot/perturbation.

89%s

- Spots fully formed
- Inner region of separation is affected first by spot, (little effect in the outer half of the boundary layer).
- Profile almost linear out to free stream.
- Profile becomes fuller as calmed region passes this location
- Flow eventually relaxes back to separated profile.

96%s

- Large changes in profiles as turbulent part of spot passes
- Calmed region persists (as seen from momentum thickness data) for 3 times as long as turbulent part of total spot.

Conclusions II

- Predictions showed that most of the interactions of the turbulent spots and separation bubbles have been correctly captured.

- Good quality predictions of the performance of an LP turbine cascade were also obtained for a real LP turbine geometry.

VISUALIZATION OF TRANSITIONAL HEAT FLUX IN THE PRESENCE OF FREESTREAM TURBULENCE AND PRESSURE GRADIENT

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Optimum design of gas turbine blades depends on accurate prediction of boundary layer transition. The purpose of this research is to obtain more information on the generation, propagation, and coalescence of turbulent spots in a transitional boundary layer, including the effects of freestream turbulence, favourable and adverse pressure gradients, and spanwise acceleration.

Turbulent spot heat flux images are obtained using high-density thin film heat transfer gauge arrays developed especially for this study. The non-intrusive sensor arrays allow high frequency (up to 200 kHz), high spatial resolution (0.2 mm) surface heat flux measurements to be made. Figure 1 illustrates their use on a flat plate wind tunnel model. Experiments are run in a subsonic wind tunnel at Oxford over a range of Reynolds number and Mach number (0.1-0.4). Surface heat flux is driven by a temperature difference between the model and freestream airflow.

Experimental results clearly show increasing freestream turbulence intensity *Tu* significantly increases turbulent spot generation rate. At higher levels of freestream turbulence, most of the heat transfer fluctuations are caused by freestream eddies entering deep into the boundary layer. Favorable pressure gradient lengthens the transition region, while adverse pressure gradient hastens instability and can easily lead to abrupt separated flow transition. There also appear to be fundamental differences between the dynamics of bypass 'spots' or streaks, and natural spots. For example, individual bypass 'spots' do not appear to grow as much as natural spots in accelerating flow.

High frequency measurements with spanwise detail enable direct measurement of turbulent spot generation rate, spot size, and spot/streak shapes. The imaging capability presented may allow us to "see" a few more pieces of the transition "puzzle" that we have not been able to see clearly before. New data such as this may lead to a better understanding of boundary layer transition in complex flows.

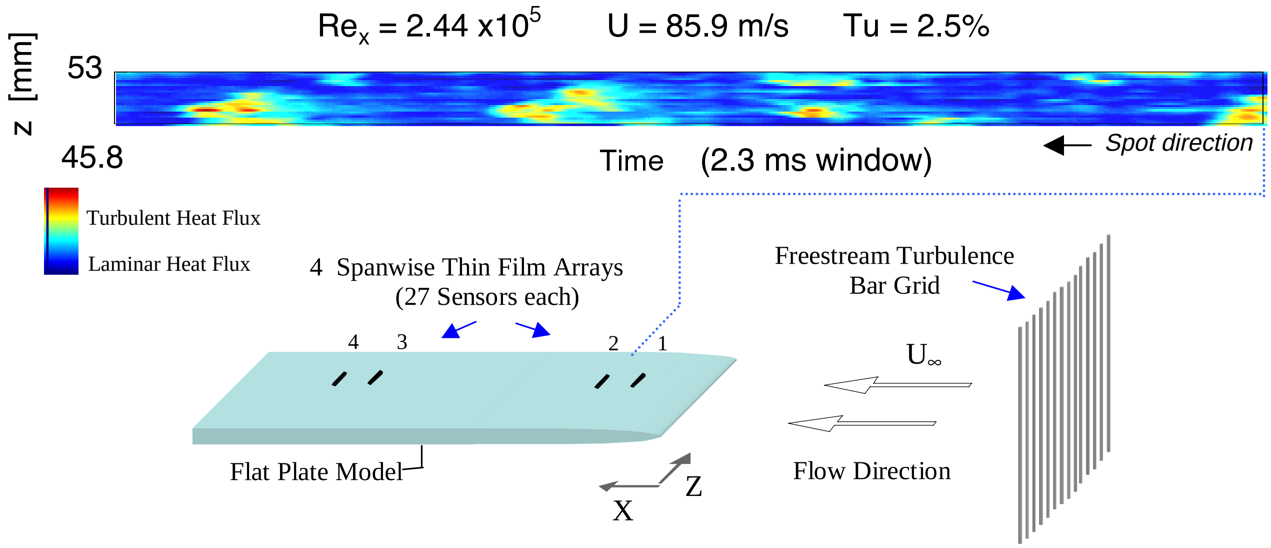

Figure 1 Experimental setup showing the flat plate wind tunnel model instrumented with high-density thin film arrays. The spanwise arrays shown are perpendicular to the flow direction. The top image is a view of transitional heat flux in the *z-t* plane from array #2 which shows the heat flux events crossing a 7.2 mm span in less than 2.3 ms. The high frequency, high spatial resolution measurements can capture turbulent spot detail in a high speed transitional boundary layer.

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VISUALIZATION OF TRANSITIONAL HEAT FLUX IN THE PRESENCE OF FREESTREAM TURBULENCE AND PRESSURE GRADIENT

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Research Objectives:

- Obtain a better understanding of transitional heat flux based on experimental studies of actual turbulent spot characteristics.

- Provide data for an improved boundary layer transition model that will allow more accurate prediction of heat transfer in turbines.

Approach:

- Develop advanced, non-intrusive, surface instrumentation capable of detailed turbulent spot heat flux “imaging”
- Perform fundamental experiments to quantify the effects of freestream turbulence, adverse and favorable pressure gradients, and spanwise acceleration.

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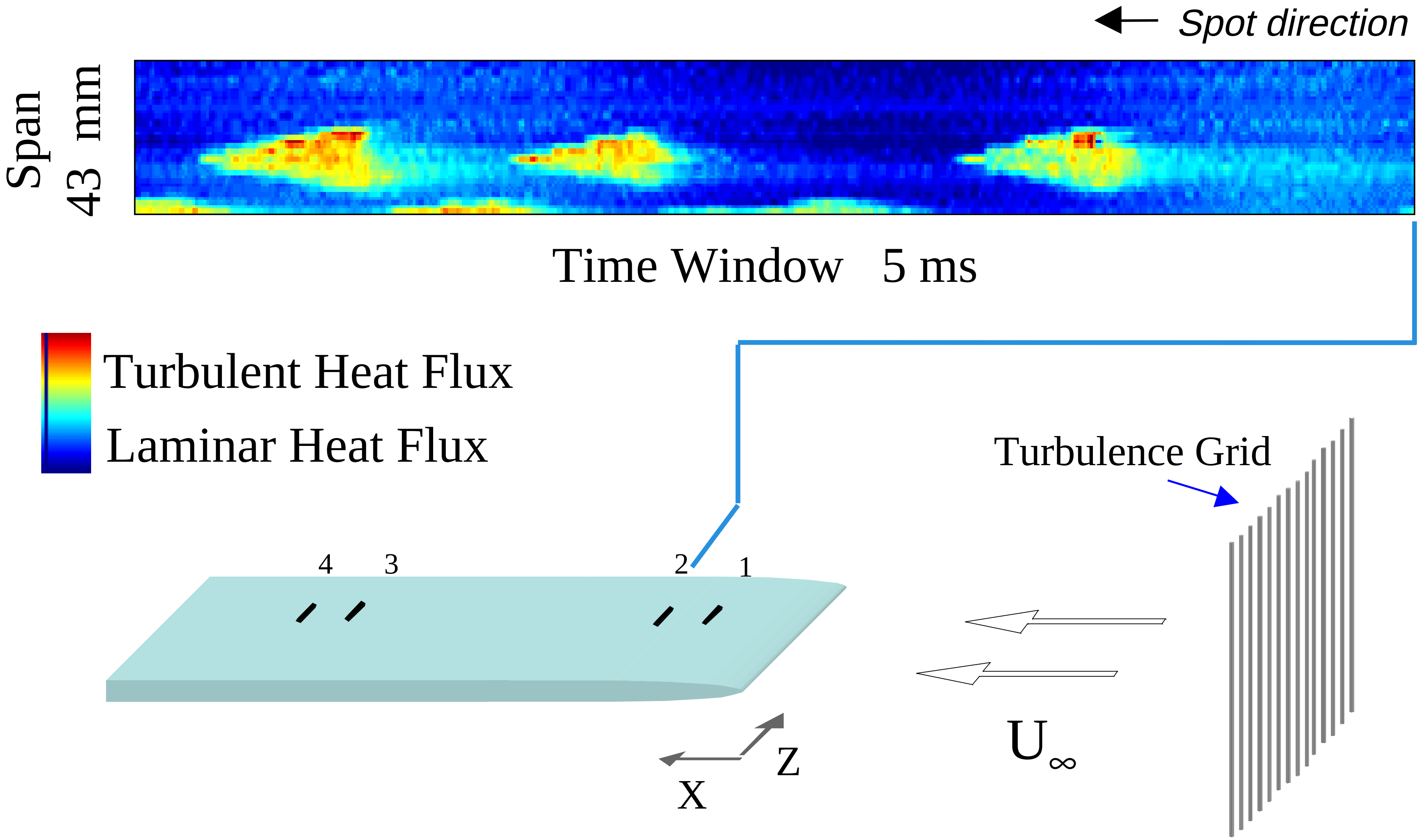
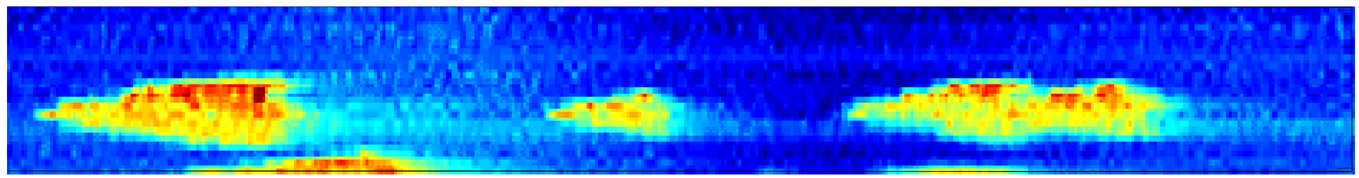
Visualizing Turbulent Spot Heat Flux



Heat Flux Images in the *z-t* and *x-t* planes

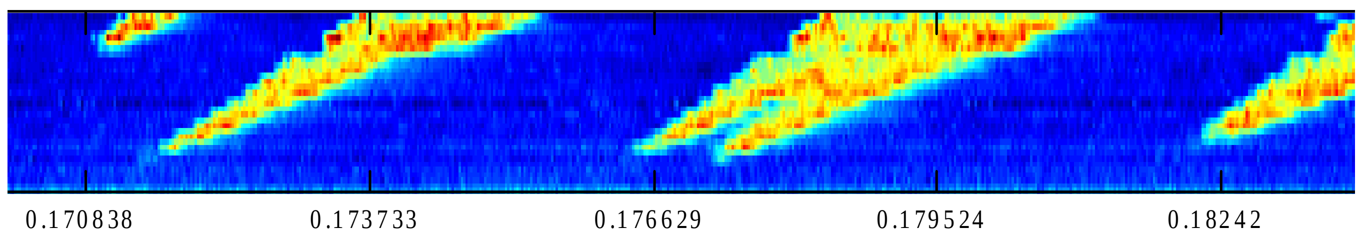
Span Z
(43 mm)



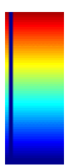
Time (5 ms)

← *Spot direction*

Streamwise
Distance X
(200 mm)



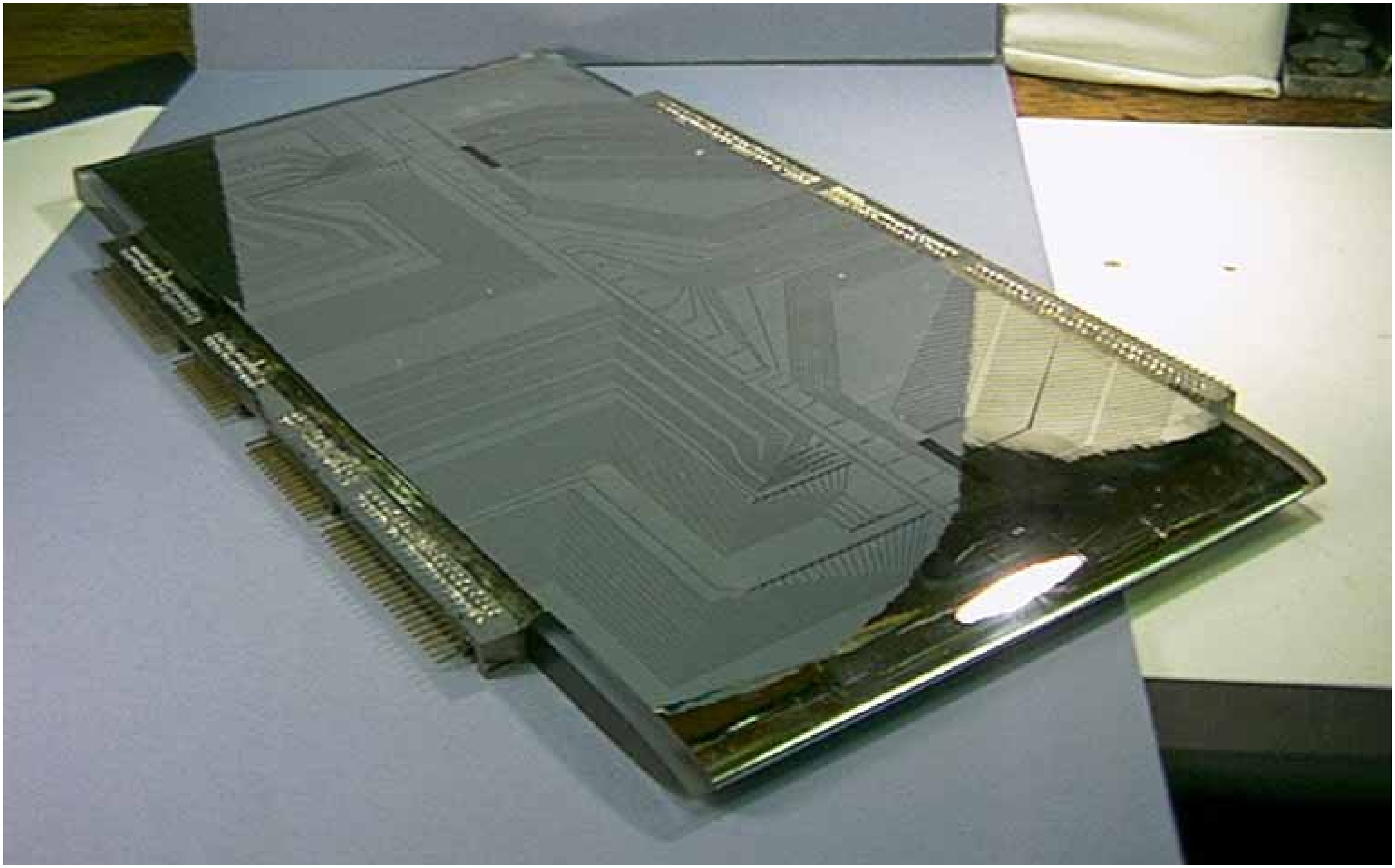
Time (14 ms)



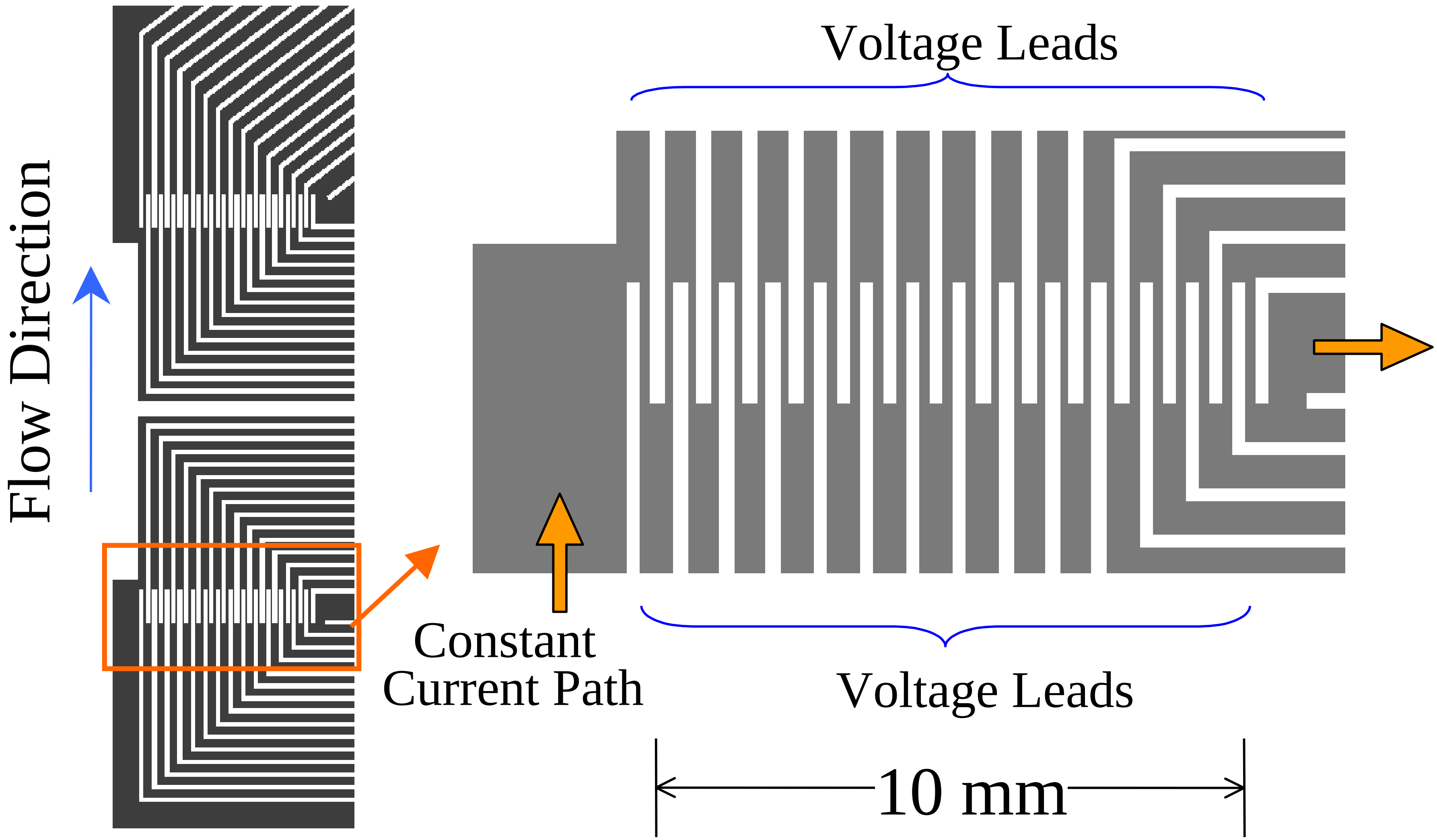
Turbulent Heat Flux

Laminar Heat Flux

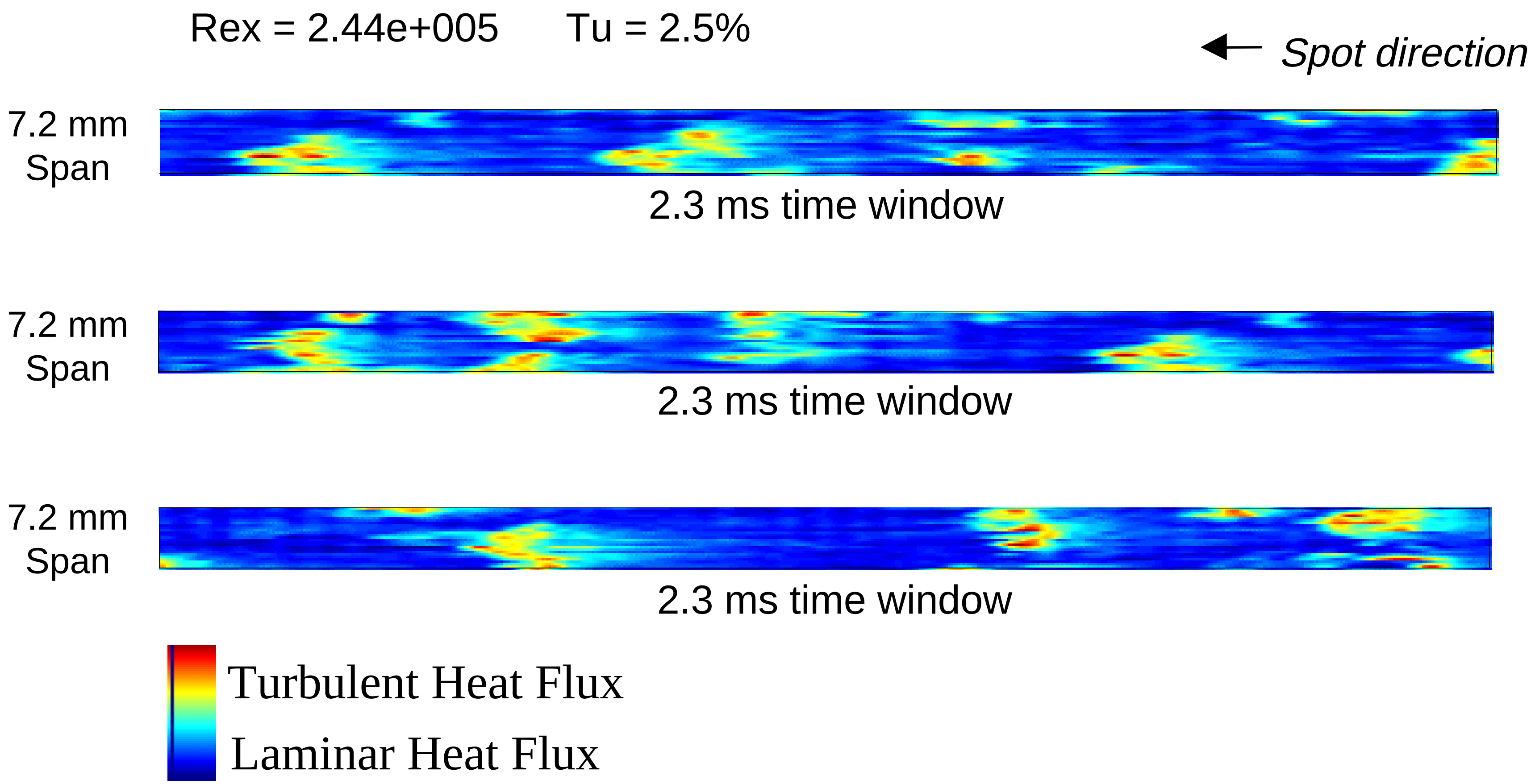
Model covered with 'sheet' of thin film gauge arrays



High Density Thin Film Gauge Arrays



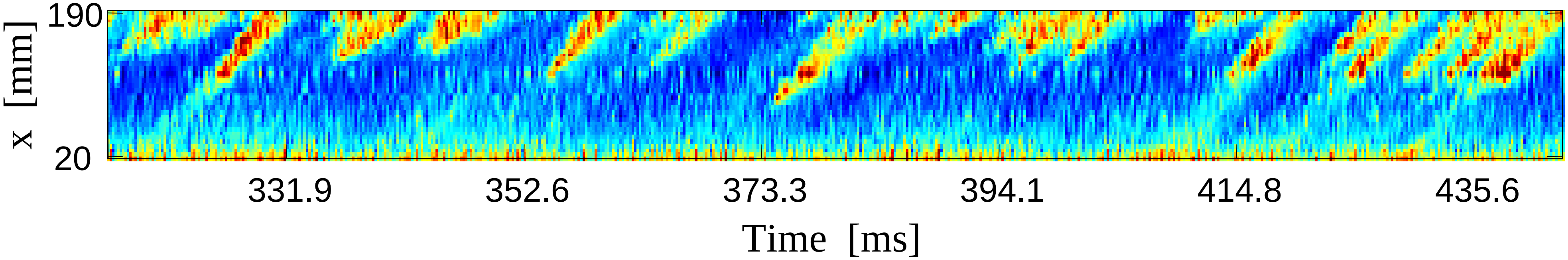
Imaging Turbulent Spot Generation & Development



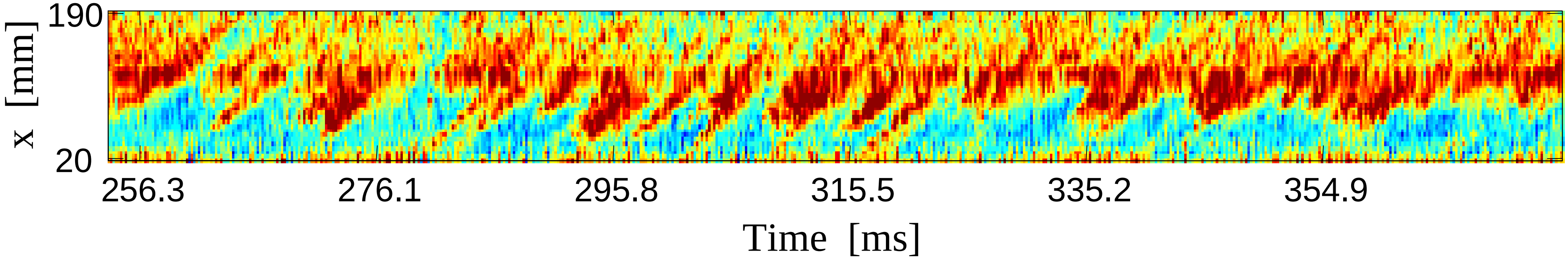
Increasing Freestream Turbulence Intensity *x-t*

$Re_L = 4.58 \times 10^5$ U = 20.6 m/s

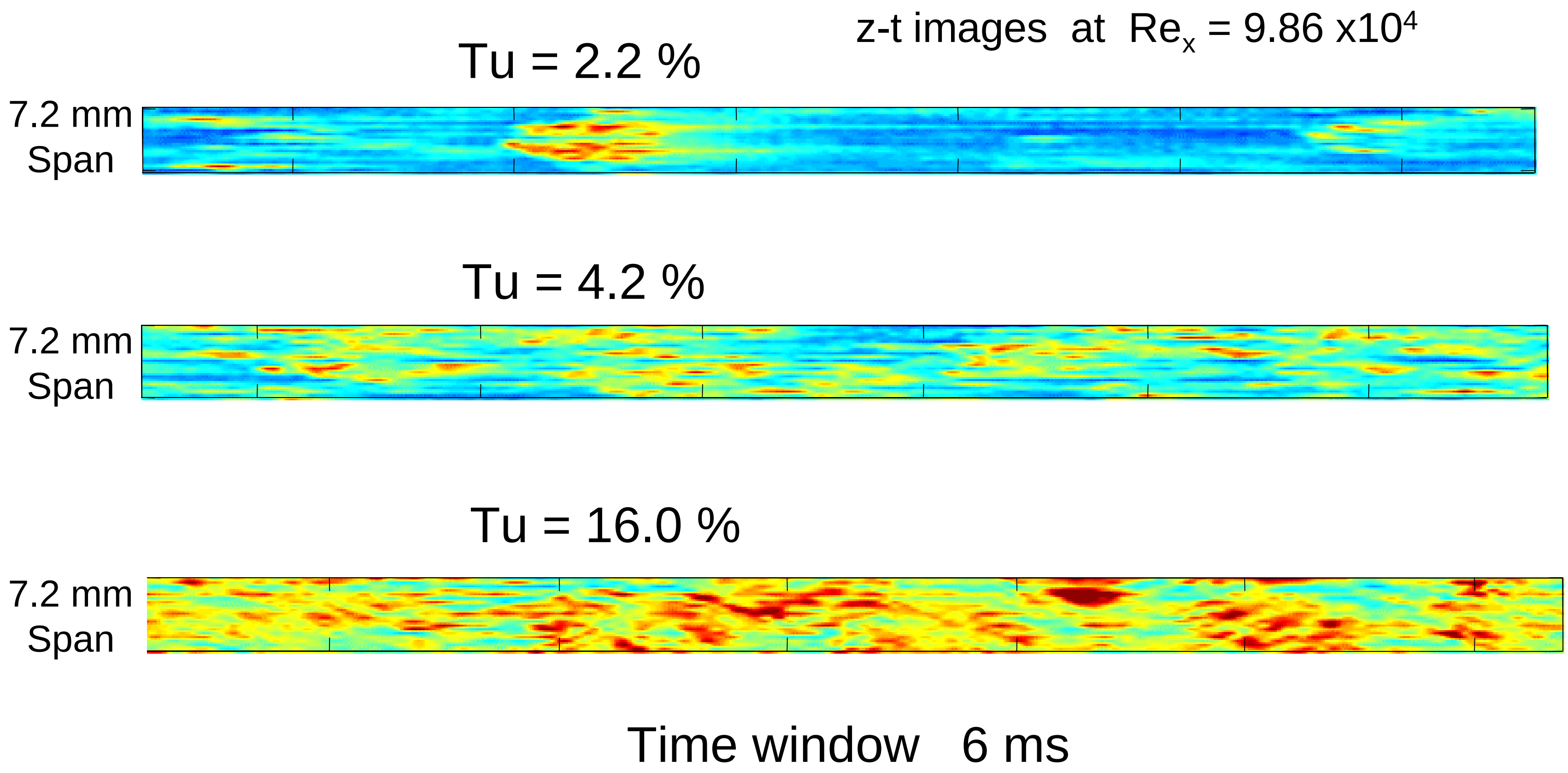
Tu = 2.5%



Tu = 4.6%



Increasing Freestream Turbulence Intensity *z-t*



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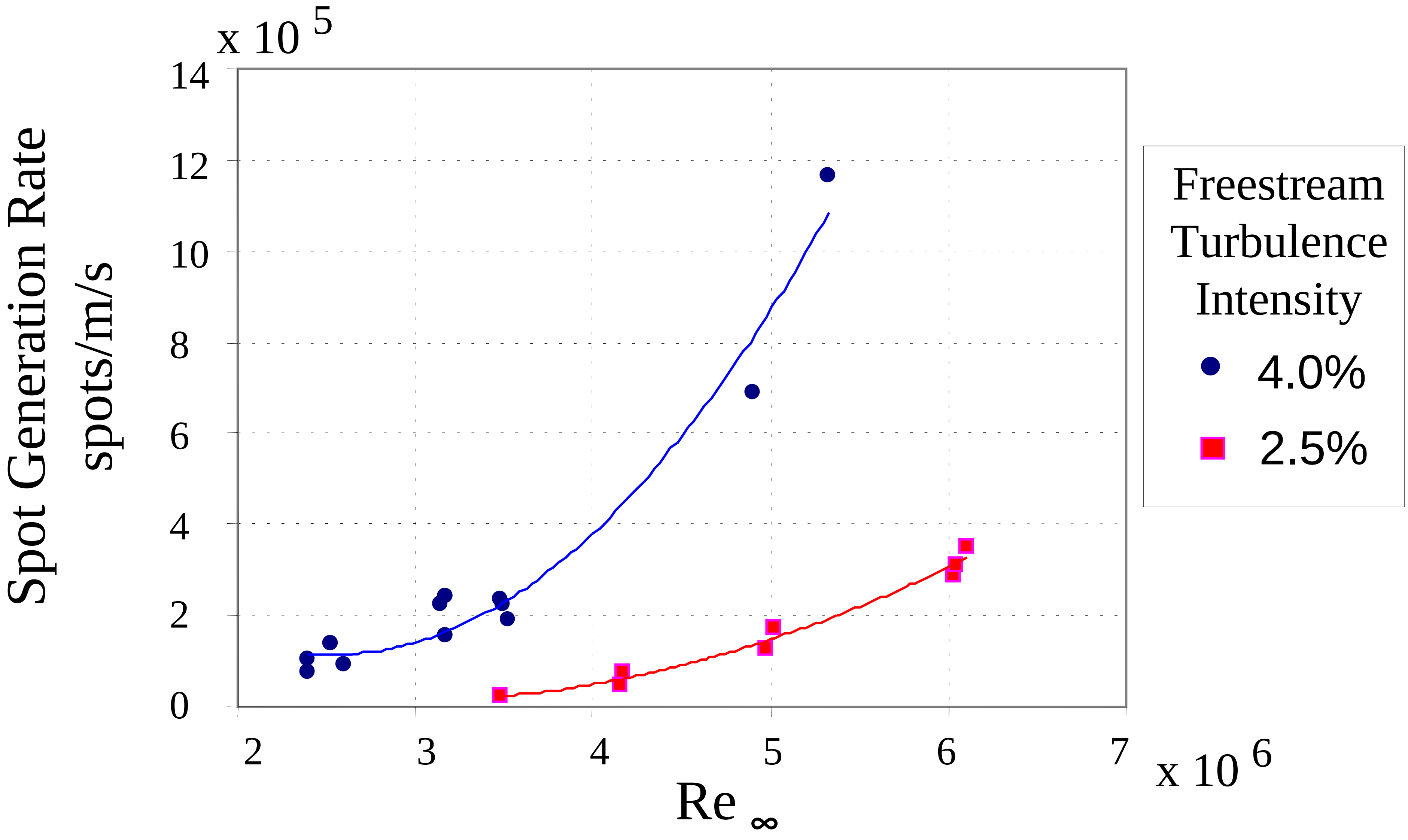
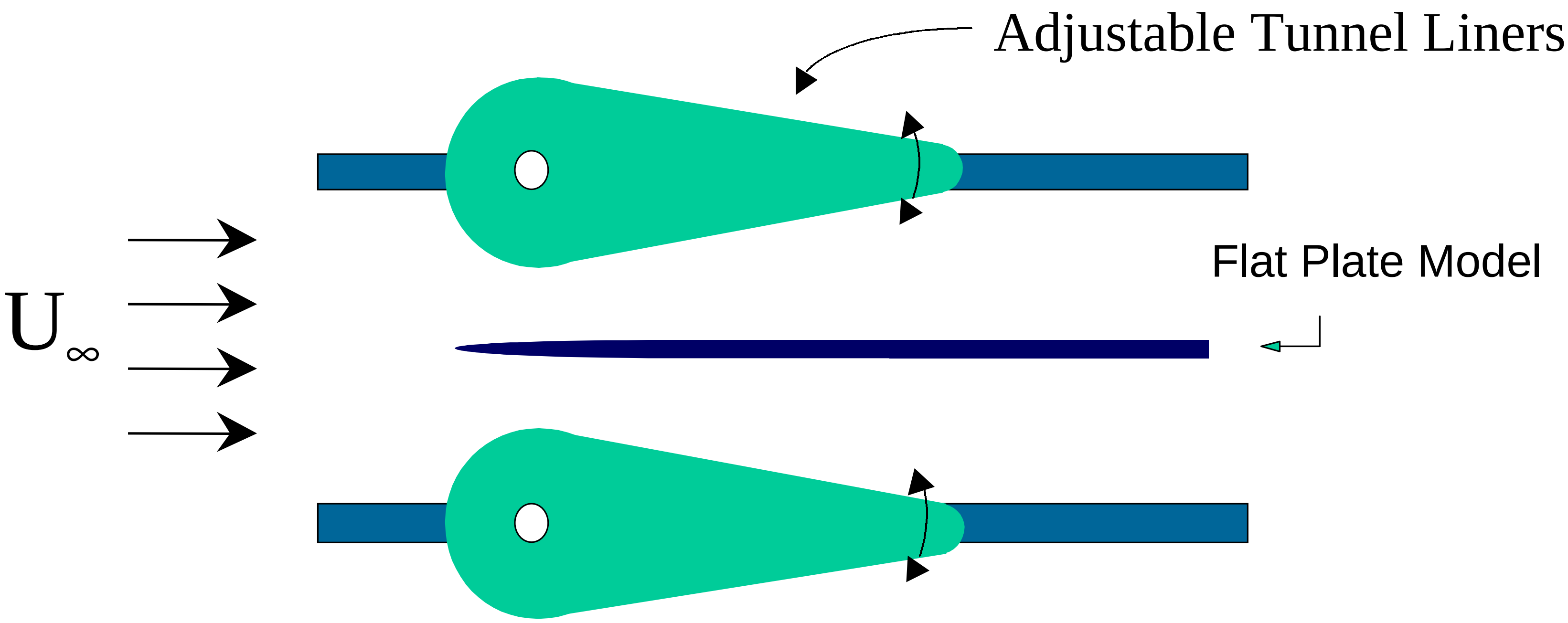
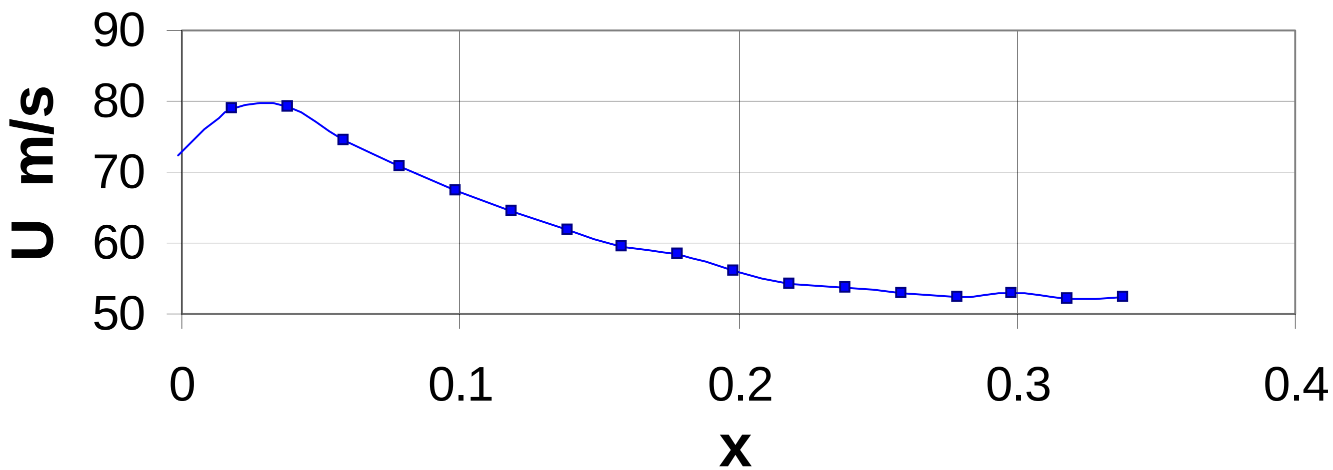
Turbulent Spot Generation Rate -Direct Measurement



Adverse Pressure Gradient Tests

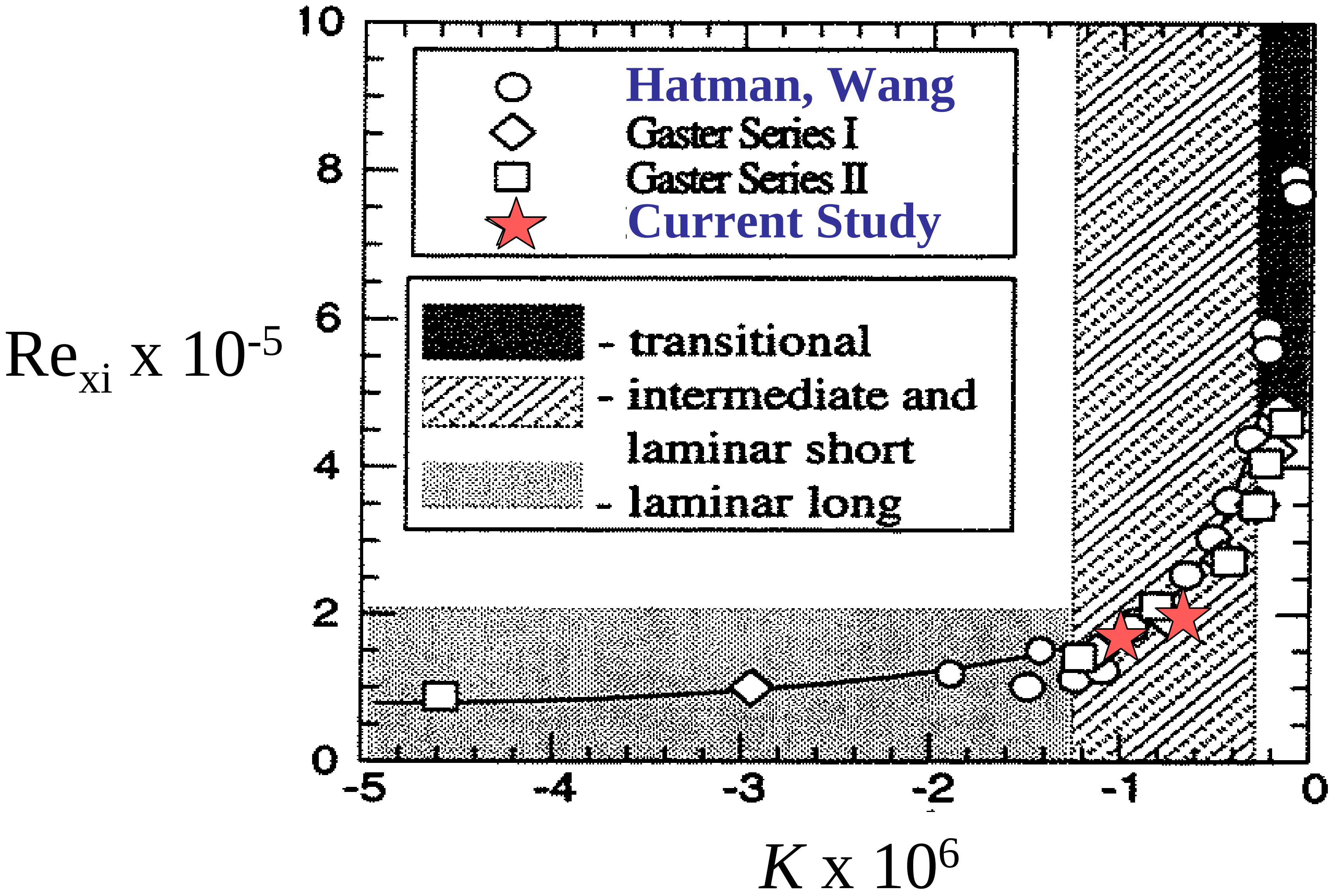




Transition under adverse pressure gradient

Adverse Pressure Gradient	Freestream Turbulence Intensity	Transition Mode
Strong	< 1 %	Laminar separation / short bubble transition
Strong	4 %	Bypass before separation
Weak	< 1 %	Natural before separation

Separation Bubble Transition in Adverse P.G.



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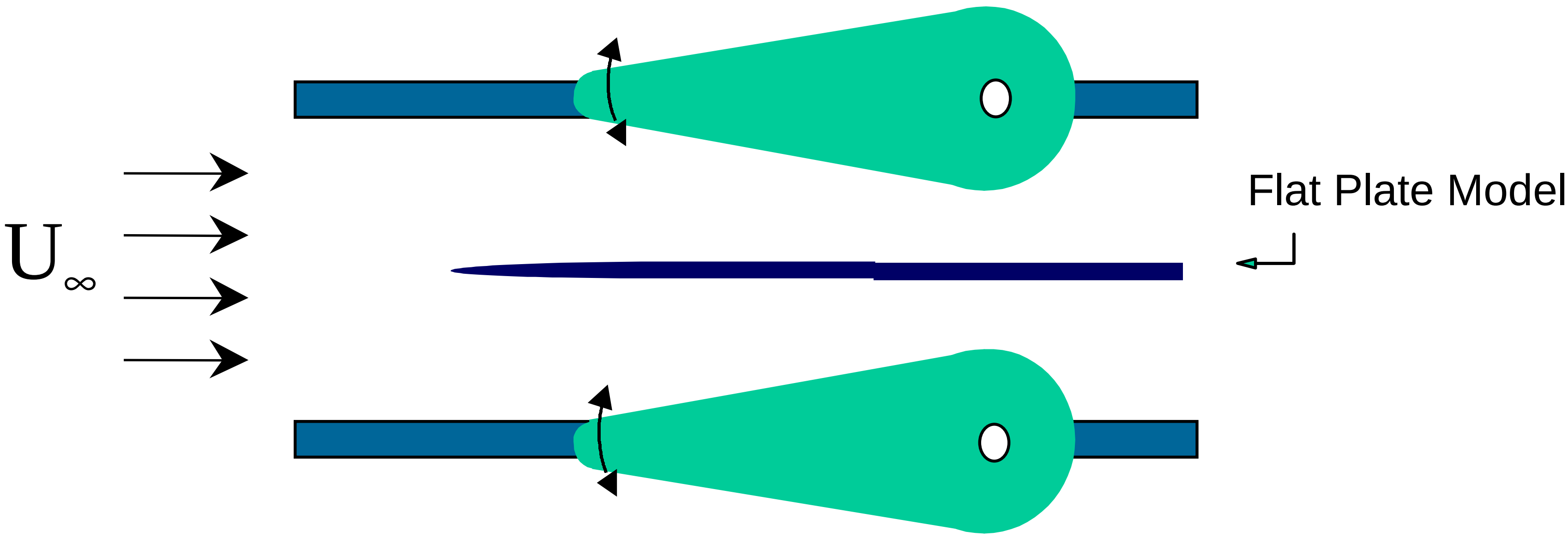
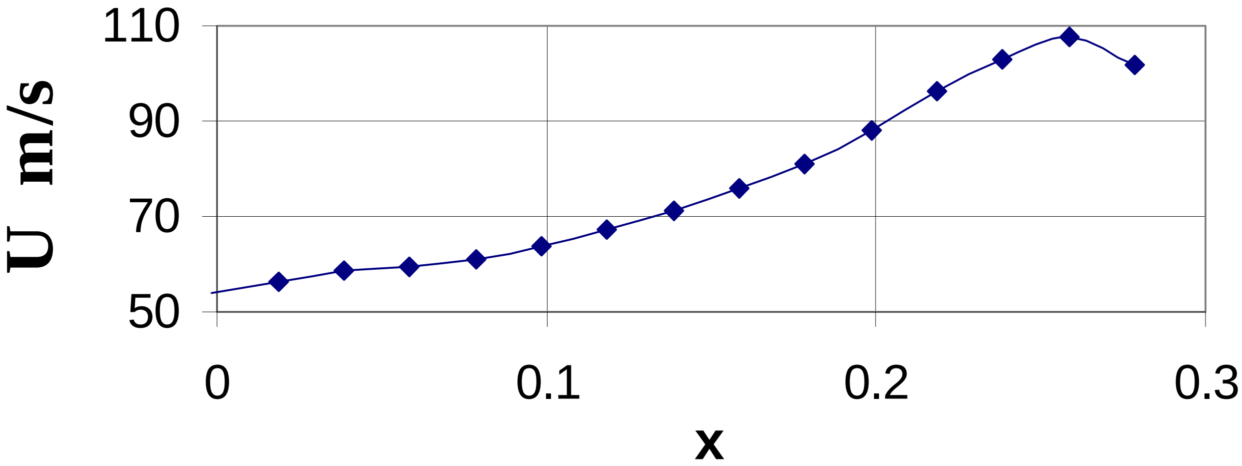
Favorable Pressure Gradient





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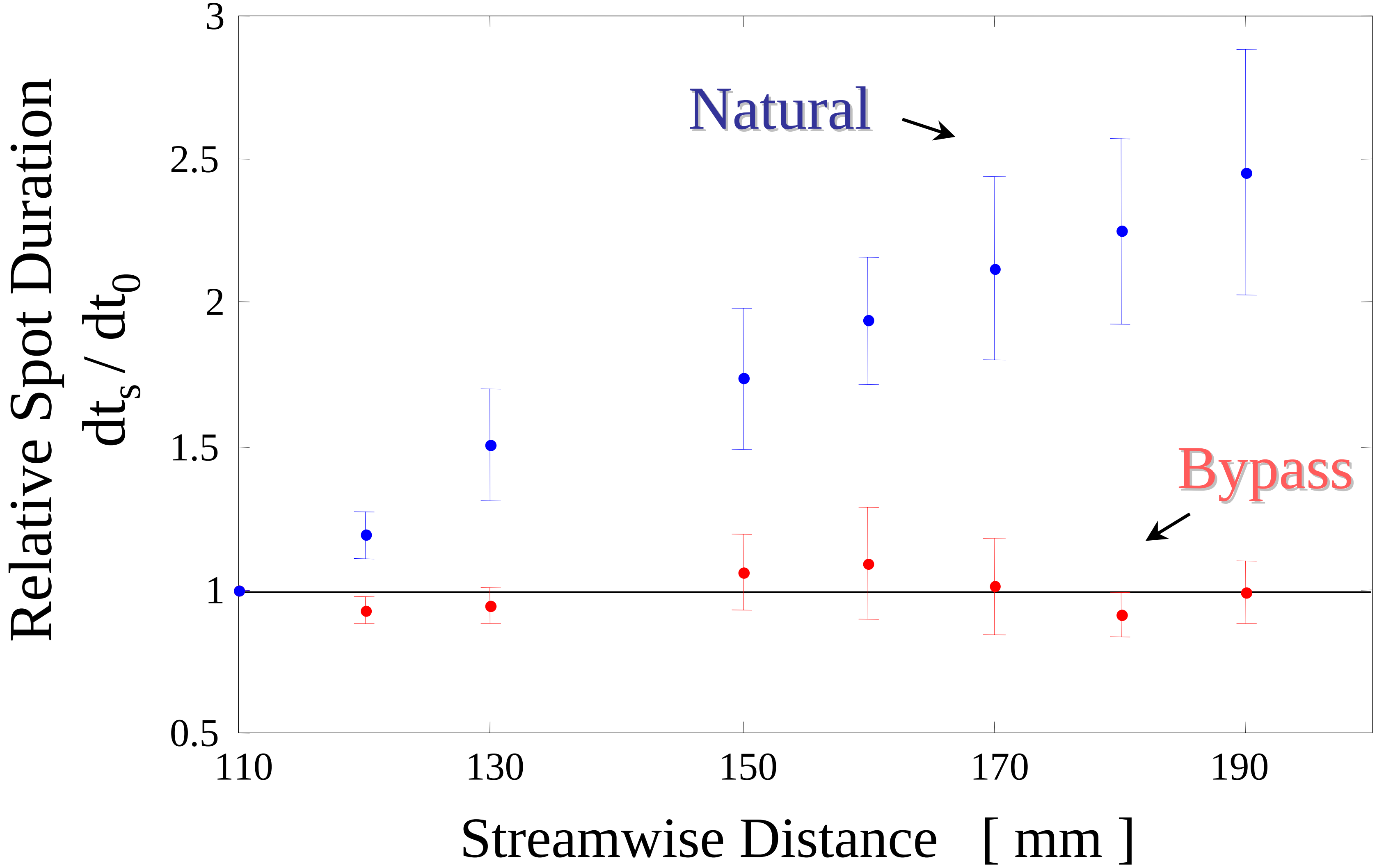
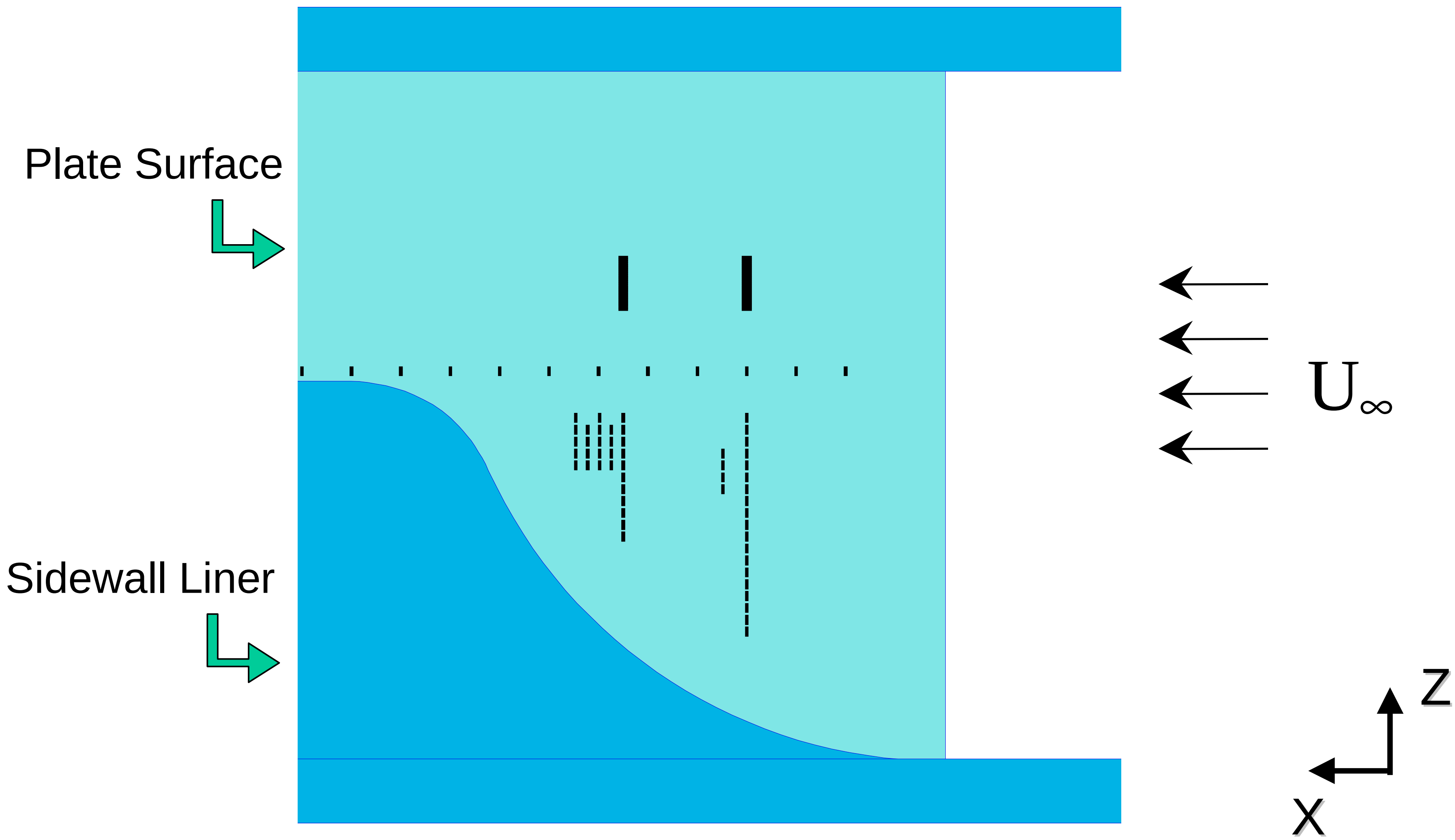
Bypass v. Natural Spot Growth in Accelerated Flow



Spanwise Acceleration Experiment



Summary

- Detailed turbulent spot information acquired with high-frequency, high resolution, surface thin film arrays
  - Spot Generation rate under freestream turbulence
  - Dynamics and growth in favorable, adverse, and spanwise pressure gradients

- New data obtained to improve models of boundary layer transition

Future Work

- Continue analysis of acquired experimental data
- Document all results and report
- Provide new information to transition modelers to improve prediction of heat transfer in turbines

THE INITIATION AND DEVELOPMENT OF TURBULENT SPOTS

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The turbulent spot can be considered as the 'building block' of a transitional boundary layer flow. The appearance of the first turbulent spots defines the start of transition location and the rate at which the spots grow and merge determines the transition length. A better understanding of how spots are initiated and develop can therefore lead to more accurate prediction in the transition process.

Work over the past few years (Johnson and Ercan [1999], Mayle and Schultz [1997] and Roache and Brierley [2000]), has shown that freestream turbulence leads to the development of low frequency fluctuations within the laminar boundary layer, which grow in amplitude as the boundary layer develops. For bypass transition this growth is approximately linear with streamwise distance, but in the case of natural transition the growth is supplemented through the exponential growth in Tollmien-Schlichting frequencies once the stability limit is reached. The laminar fluctuations eventually reach a critical amplitude which is sufficient to initiate turbulent spots. The author has previously developed a simple model which suggests that a turbulent spot is initiated each time the near wall local velocity drops below 50% of its mean value and that this criterion leads to a transient separation of the flow due to the onset of a local instability. In the present work, new statistical data derived from hot wire signals measured in the near wall region of pre-transitional boundary layers is shown to support this model. The rate at which threshold events are observed in the experiment also correlates with the observed spot production rate.

The structure of turbulent spots has been studied numerically using a linear perturbation procedure. The results show that, once a transient separation point is formed, it moves downstream below the trailing edge of the developing turbulent spot and hence moves with the spot trailing edge velocity of approximately 50% of that of the freestream. The fluid motion within the spot can be usefully interpreted from the point of view of an observer travelling with this velocity. In a laminar flow, this observer will see two streams of fluid. The first stream, consists of fluid close to the wall ($u/U < 0.5$) which will approach the observer from downstream. The second stream is formed from fluid further from the wall which will approach him from upstream. Once the spot is formed the first stream is lifted from the surface around the hairpin vortex, which exists at the tail of the spot, and is accelerated forwards into the spot to move downstream away from the observer. The second stream drops towards the surface, to fill the space vacated by the first stream, before bifurcating behind the spot. The lower bifurcation branch approaches the wall behind the separation point such that the resulting increase in skin friction decelerates the flow so that it moves, relative to the observer, back upstream to form the calmed region. The upper bifurcation branch moves over the top of the hairpin vortex to mix out with the first stream within the spot. A number of flow visualisation movies created from the calculation results have been used to interpret the details of the flow structure. Numerical information on the extent and shape of the spot and calmed region have also been used to create correlation equations for spot propagation parameters as functions of streamwise pressure gradient and boundary layer Reynolds number.

REFERENCES

Johnson, M.W. and Ercan, A.H., [1999], 'A Physical Model for Bypass Transition', Intl. Jnl. of Heat and Fluid Flow, Vol. 20, pp 95-104.

Mayle, R.E. and Schultz, A., [1997], 'The path to predicting bypass transition', ASME Jnl. of Turbomachinery, Vol 119, pp 405-411.

Roach, P.E. and Brierley, D.H. [2000], 'Bypass Transition Modelling: A new method which accounts for free-stream turbulence intensity and length scale', ASME paper 2000-GT-278.

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MINNOWBROOK III

The Initiation and Development of Turbulent Spots

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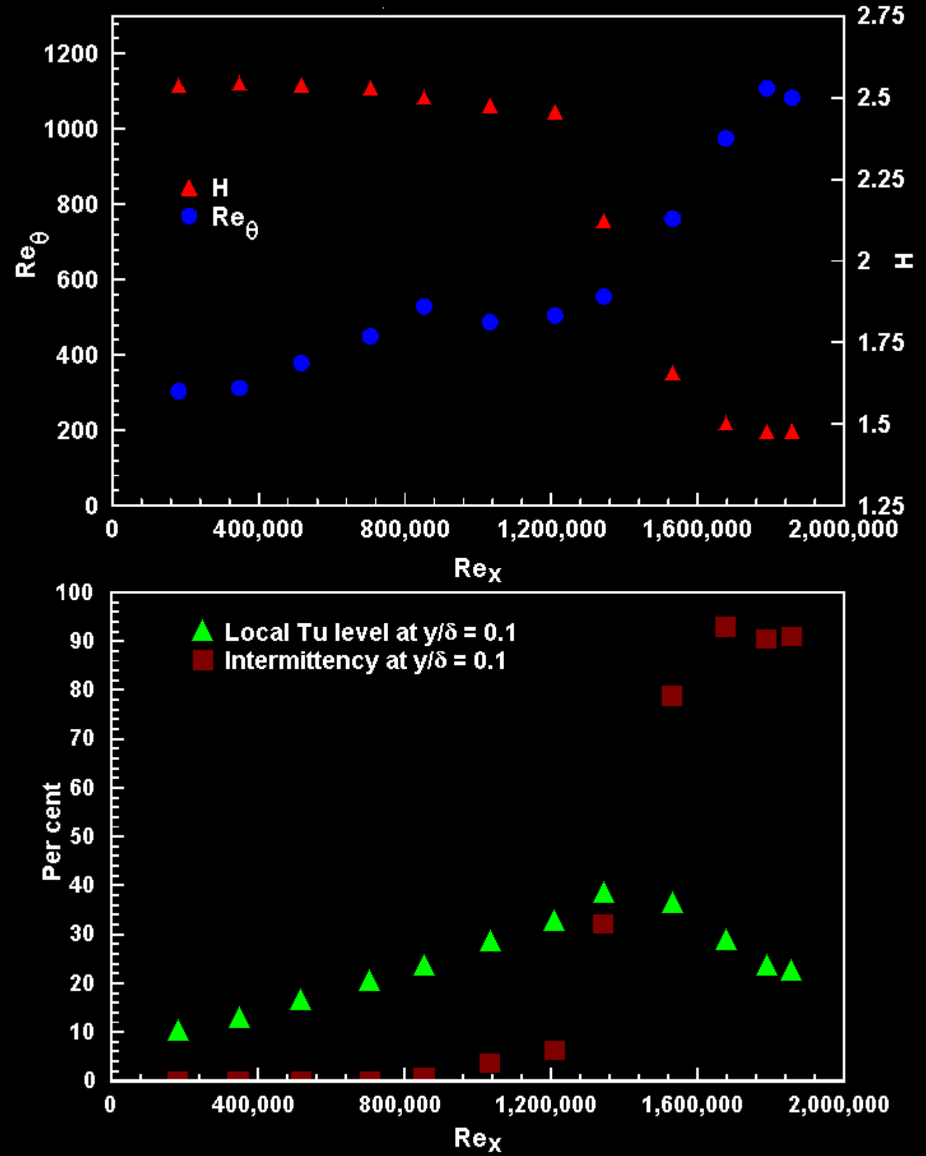
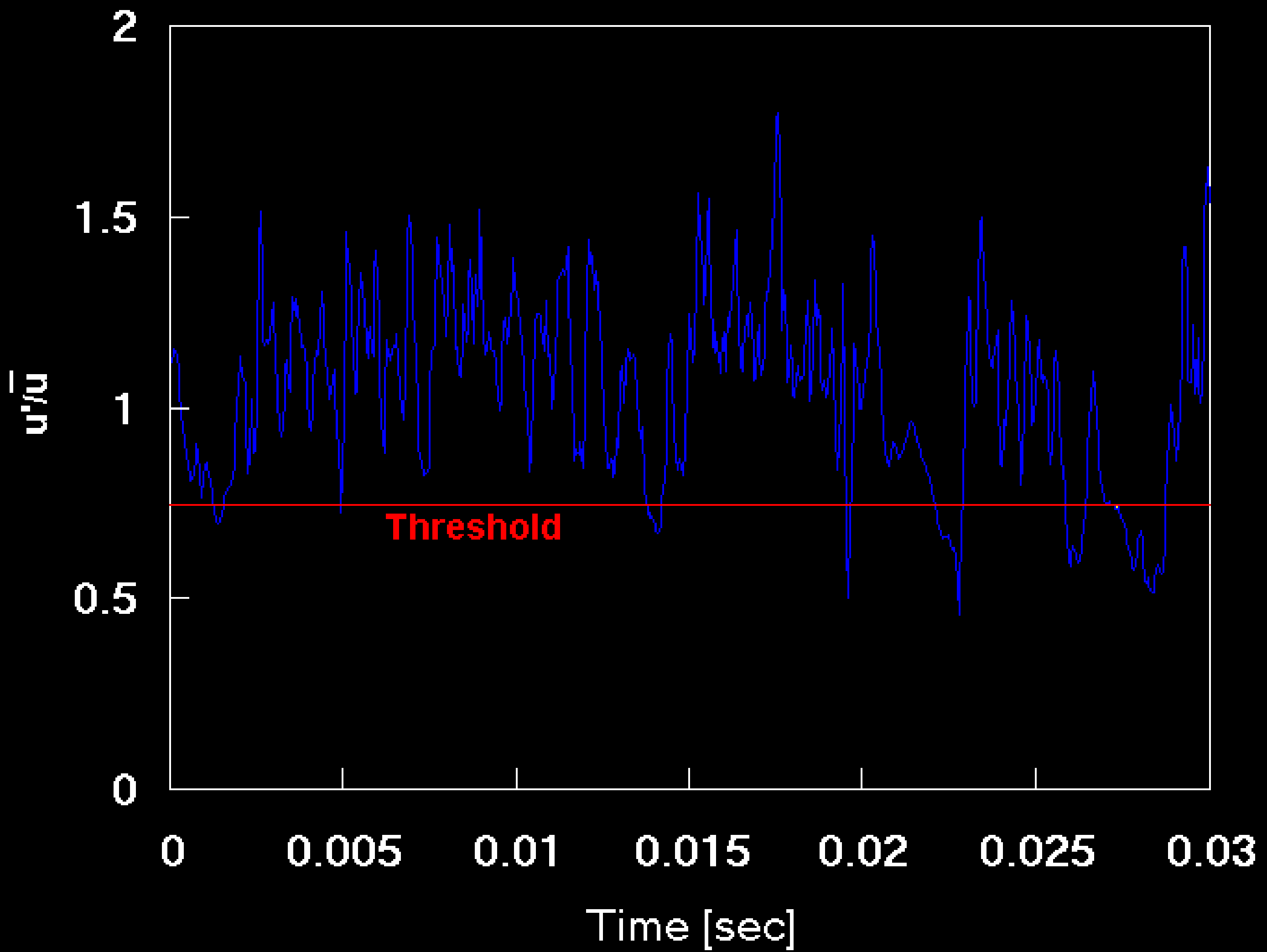
Spot Initiation

Hot wire measurements in a zero pressure gradient boundary layer
Freestream velocity = 30 m/s
Plate Reynolds number = 2,400,000
Freestream turbulence level = 1%

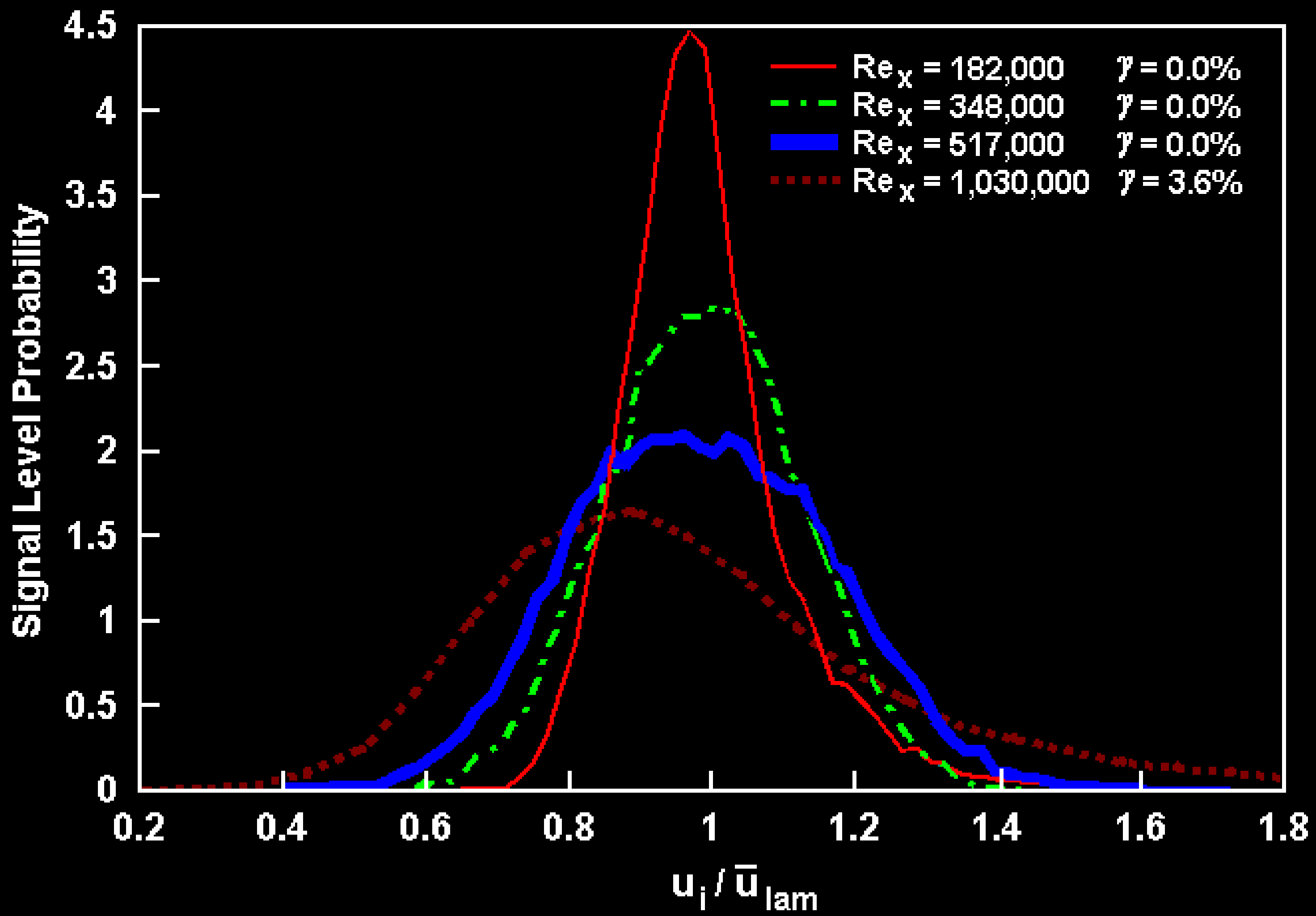
Hot wire signals obtained at $y/\delta = 0.1$for analysis



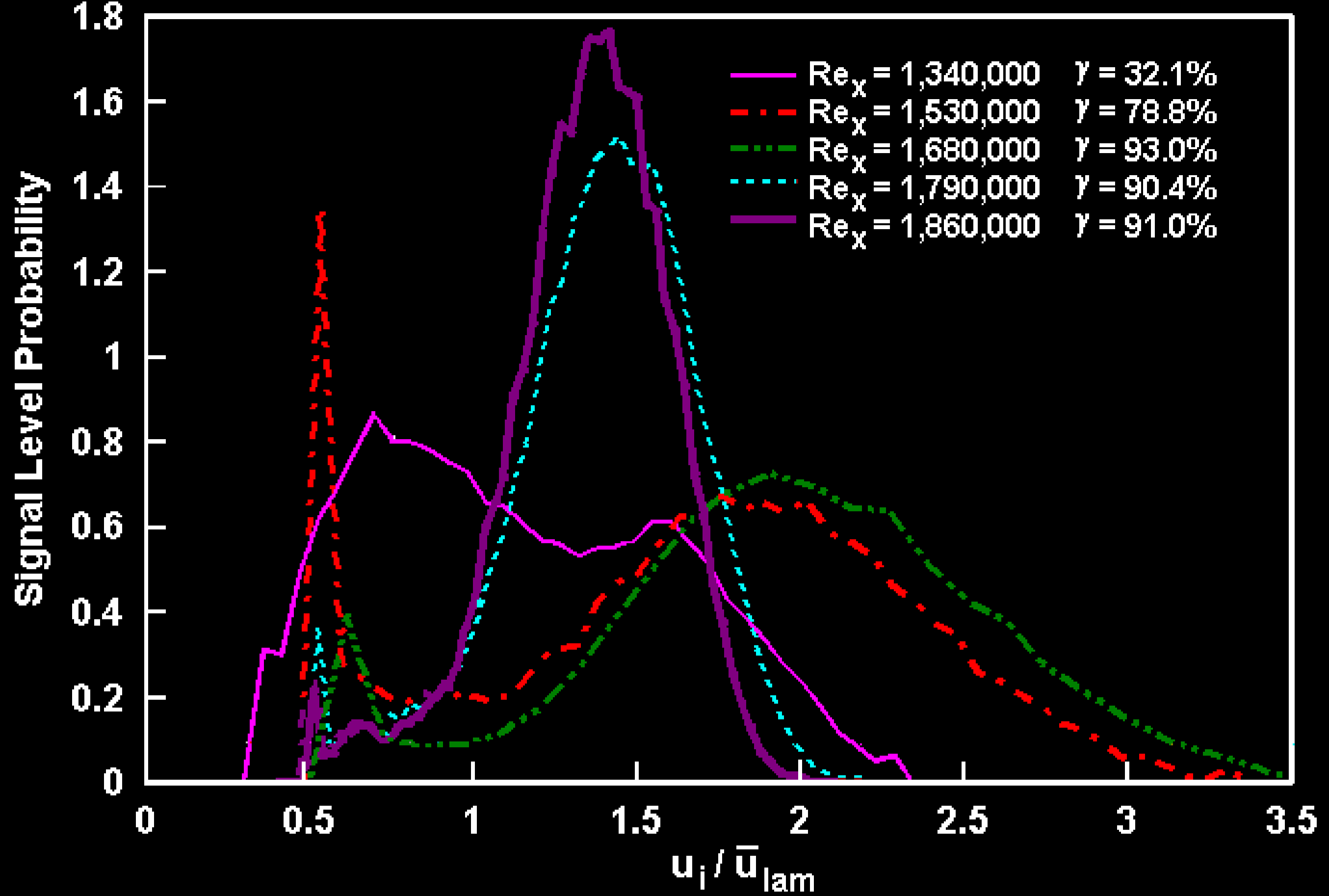
Measurements within a zero pressure gradient boundary layer developing on a flat plate with a f.s. turbulence level of 1%.



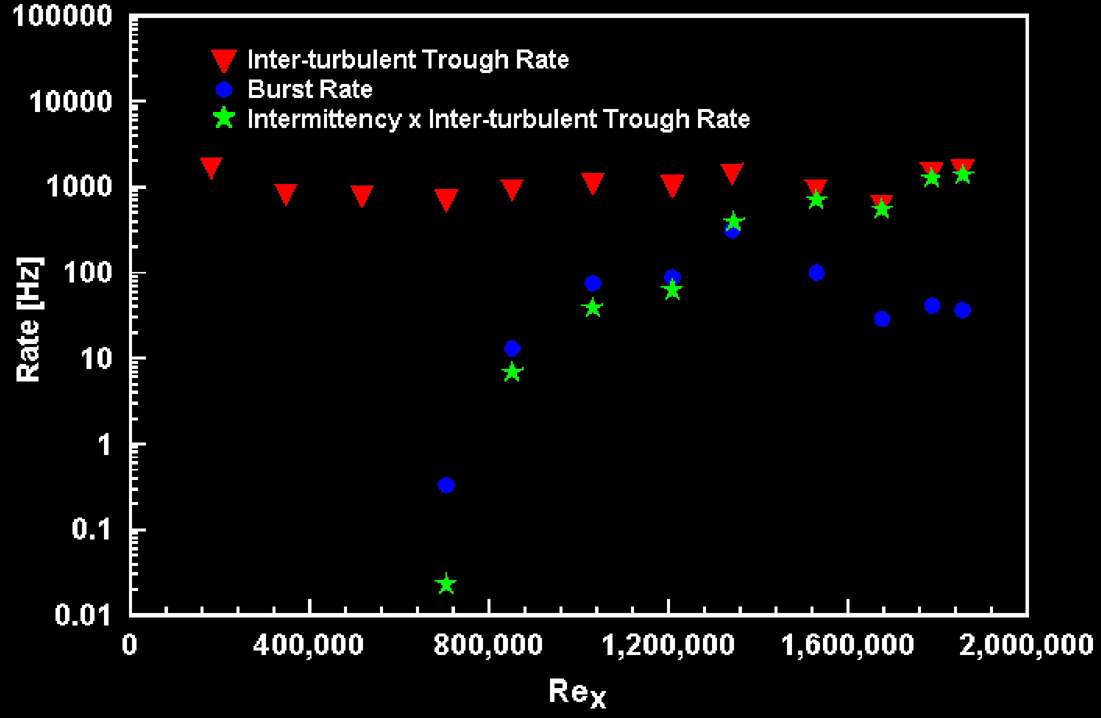
Hot wire signals are analysed within the laminar periods at $y/\delta = 0.1$ to determine the frequency at which the local velocity drops below varying threshold levels.



As Re_x increases the local Tu level increases and hence there is also an increase in the range of the signal level. The distribution remains symmetric prior to transition.



Transition appears to commence when the deepest signal trough velocities drop below 50% of the local mean velocity. The distribution appears to be truncated at this level through transition. The turbulent periods result in a second peak which increases in magnitude with increased intermittency.



The signal analysis shows that the overall trough rate for all depths is approximately constant within the inter-turbulent period. When this rate is multiplied by the intermittency, the rate at which troughs disappear into the turbulent period is determined. The results show that in the early part of transition, before significant merging of adjacent bursts takes place, the rate at which these troughs disappear is equal to the burst rate. This suggests that each trough disappearance, which occurs when its depth is 50% of the local velocity, is associated with the generation of a new turbulent burst.

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Spot Development

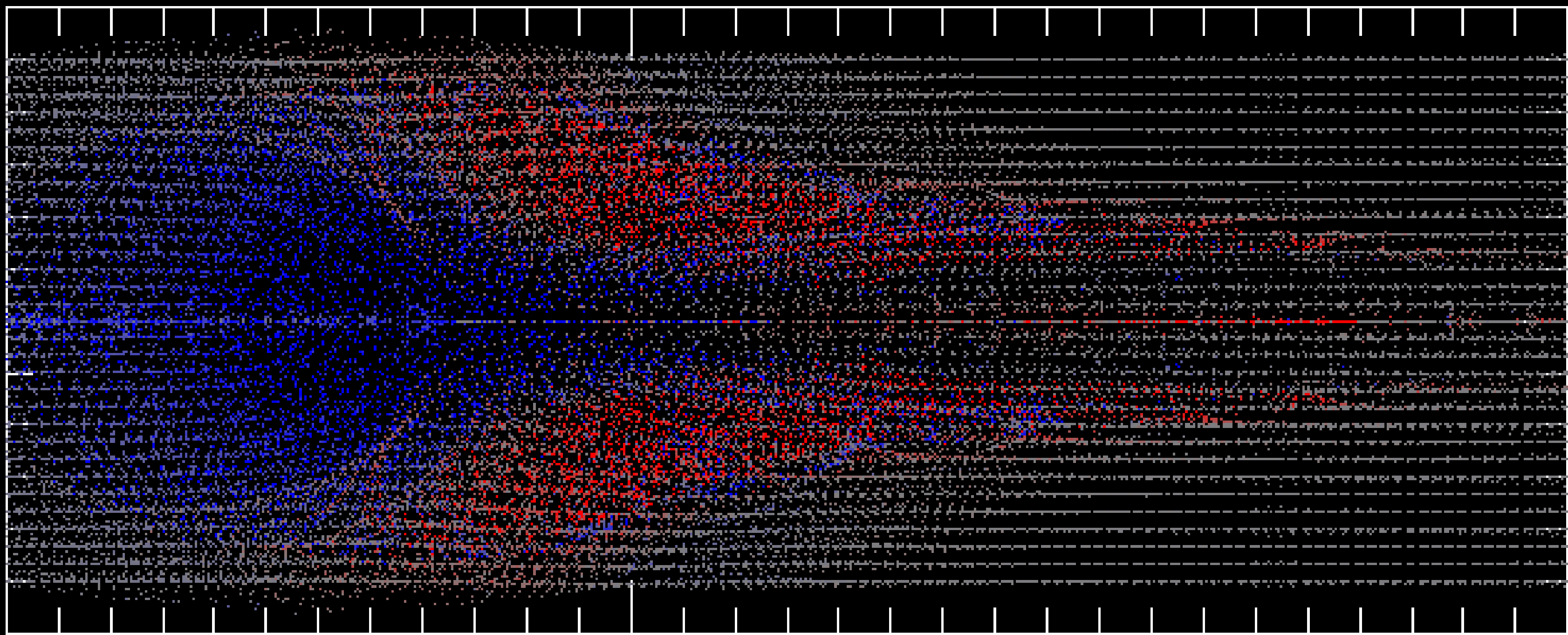
The spot is assumed to be a linear perturbation to a non-developing (inviscid) Pohlhausen boundary layer profile.

The perturbation is fully 3-dimensional and viscid.

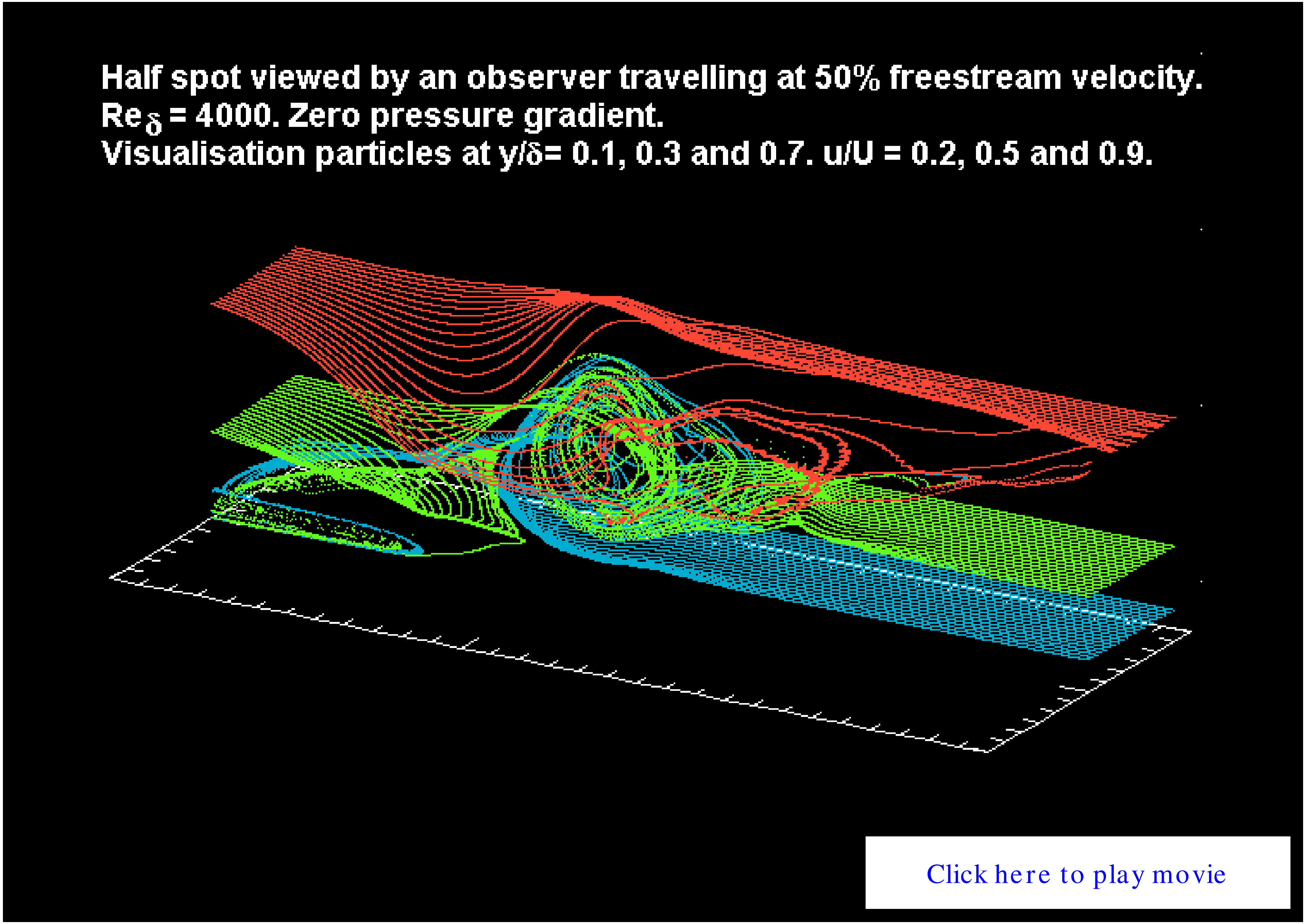
Current results are presented as flow visualisation animations.

The animations are for an observer who is moving with the spot at 50% freestream velocity (approx. the spot trailing edge velocity). For the unperturbed flow this observer will therefore see the fluid close to the wall, which has a velocity less than his own, approach him from downstream, whereas fluid further from the wall will approach from upstream.

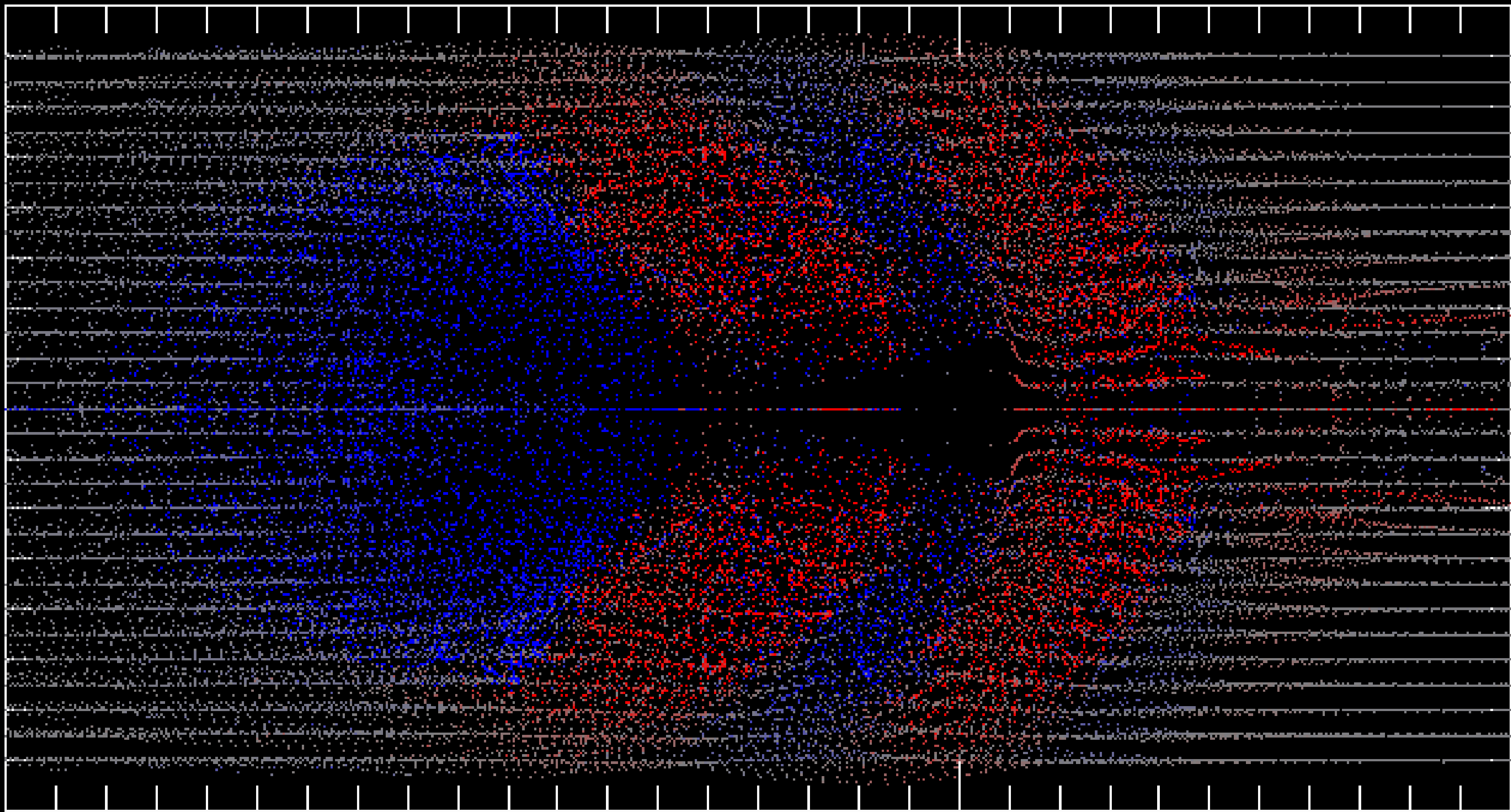
Spot viewed by an observer travelling at 50% freestream velocity.
Re_δ = 4000. Zero pressure gradient.
Blue particles have moved towards the surface.
Red particles have moved away from the surface.



Click here to play movie


Half spot viewed by an observer travelling at 50% freestream velocity.
Reδ = 4000. Zero pressure gradient.
Visualisation particles at y/δ= 0.1, 0.3 and 0.7. u/U = 0.2, 0.5 and 0.9.
Click here to play movie

Spot viewed by an observer travelling at 50% freestream velocity.
Re_δ = 4000. Strong adverse pressure gradient.
Blue particles have moved towards the surface.
Red particles have moved away from the surface.



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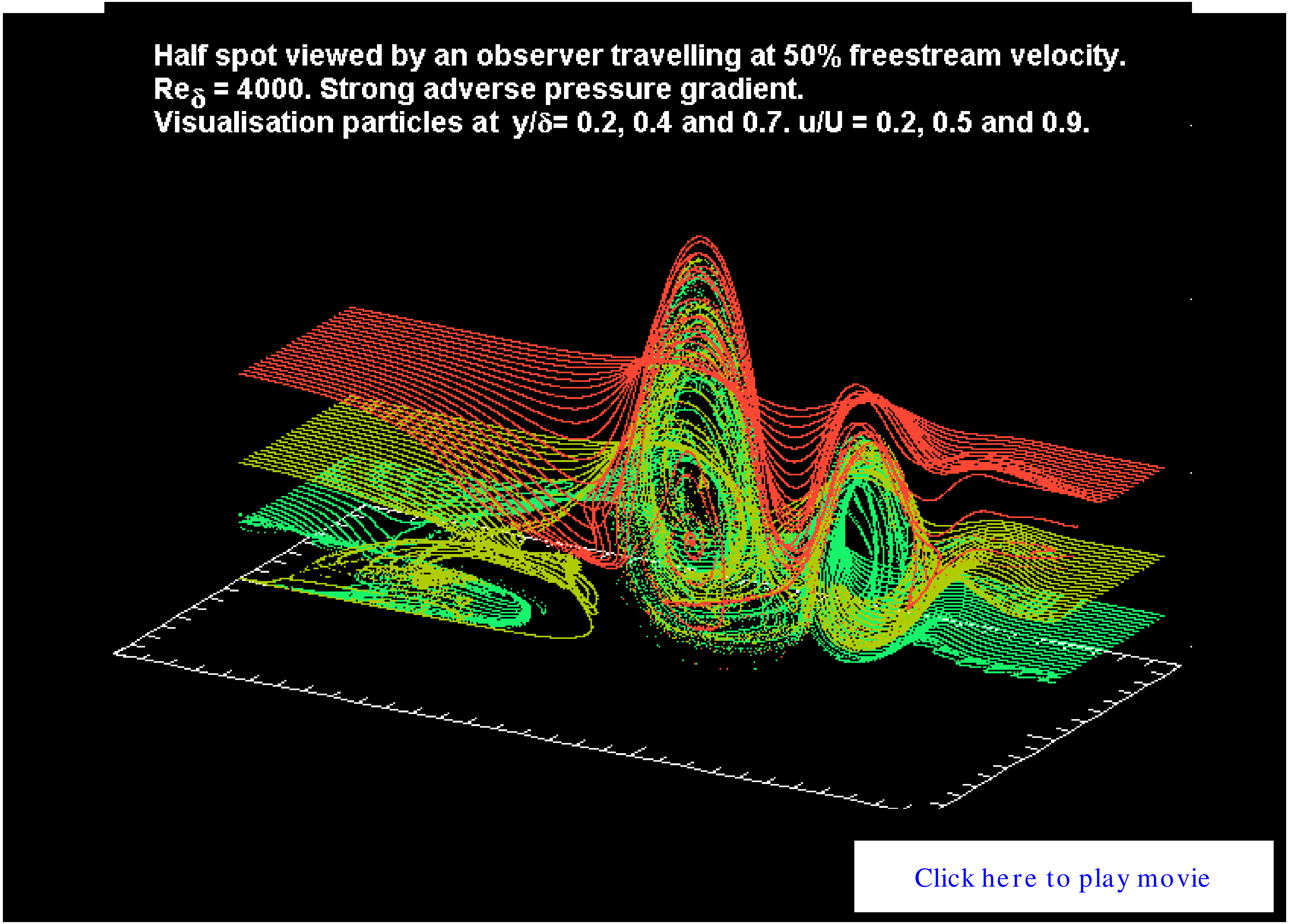
Half spot viewed by an observer travelling at 50% freestream velocity.
Re_δ = 4000. Strong adverse pressure gradient.
Visualisation particles at y/δ= 0.2, 0.4 and 0.7. u/U = 0.2, 0.5 and 0.9.
Click here to play movie

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Conclusions

1) Experimental results suggest that a turbulent spot is initiated each time the local velocity drops below 50% of the mean.

2) The current model for spot initiation suggests that the spot initiation sites are distributed rather than concentrated in the streamwise direction.

3) A separation line exists between the spot and calmed region. This line travels downstream at the spot trailing edge velocity.

4) Turbulence is generated within the spot through the high local shear which results when a low momentum stream from downstream combines with a high momentum stream from upstream.

5) The calmed region forms when the low momentum stream from downstream is diverted into the spot.

ON THE DYNAMICS OF THE CALMED REGION BEHIND A TURBULENT SPOT

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The calmed region behind a spot is the focus of this study. Here, a simple two-dimensional analysis is done in order to study the dynamics of the calmed region. By considering the near wall dynamics of the calmed region in an Eulerian sense, by neglecting advection and turbulent stress terms in the streamwise momentum equation, an expression for the time variation of the skin friction is obtained. This expression bears out the intuitive expectation that the skin friction at a location decays exponentially to the laminar value after the passage of a turbulent spot. This seems to be the case irrespective of the mean pressure gradient as long as the flow remains attached. Furthermore, it also suggests a way of plotting the skin friction variation with time for different pressure gradients so that all of them could be collapsed onto a single curve.

For calmed regions in a constant pressure flow, the variation of integral parameters and the duration of the calmed zone can be estimated by solving the unsteady momentum integral equation. The expression obtained for the duration is roughly in accord with the form suggested by a crude order of magnitude analysis of the momentum equation.

More importantly, it is shown that the benign aspects of the calmed region such as stability to infinitesimal disturbances could be explained heuristically. By considering the equation for near-wall dynamics for a constant pressure flow, it could be seen that the vorticity profile in the calmed region is qualitatively similar to that of a steady favourable pressure gradient flow and hence stable; the role of pressure gradient in the steady flow being similar to that of the unsteady term in the calmed zone. If there is a mean pressure gradient in the flow, it will add to the unsteady term thereby modifying the vorticity profile and hence the stability characteristics of the calmed zone.

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On the dynamics of the calmed region behind a turbulent spot

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Presented at the workshop on "Boundary layer transition and unsteady aspects in turbomachinery", Minnowbrook,21st August 2000.

Overview

- Introduction to the calming effect
- Why calming?
- A simple model of the calming effect
- Comparison with measurements (Hofeldt et al. 1997)
- Conclusions

Features of calmed zone

- A benign feature with a constant celerity trailing behind a turbulent spot or a wave packet (Gostelow et al. 1997)

- A fuller velocity profile than laminar flow

- Less dissipative than turbulent flow

- Stable to infinitesimal disturbances

- Robust against separation

- Longer duration in adverse pressure gradient flows compared to favourable pressure gradient flows(Gostelow et al. 1997)

Explanations for calming effect in the literature

• *Relaminarisation of an already turbulent fluid?*

There is hardly any fluid leaving the spot. That means hardly any of the fluid inside the spot getting out and becoming non-turbulent.Check the Lagrangian picture of Cantwell, Coles and Dimotakis (CCD), JFM,1978

• *Because of Reynolds stress generation due to the longitudinal streaks behind the spot, does the velocity profile in the calmed region become fuller and hence stabler?*

The relation between Reynolds stress and vorticity is (Tennekes & Lumley , 1972)

$$\frac{\partial}{\partial y}\left[-\overline{uv}\right] = \overline{v w_z} - \overline{w w_y}$$

It can be seen from this that the streamwise vorticity fluctuation cannot have any role in the creation of Reynolds stress gradient in the x-y plane. Hence the streamwise streaks are unlikely to have a dynamic role in deciding the fullness of calmed zone velocity profile.

Explanations for calming effect … continued

•*Is it a blockage effect due to the spot behind it?*

Blockage due to the turbulent spot is proportional to the displacement thickness, which is likely to be very small.

• *Regrowth of a disturbed laminar boundary layer?*

Lagrangian picture of CCD shows a stagnation point near the trailing edge of the spot. Hence this is view is plausible.

In this work, we suggest a different mechanism for the benign aspects of the calmed region.

We consider the calmed zone dynamics to be essentially two-dimensional in nature. Hence only midspan considered.

A simple model for calming effect

Consider the flow at a streamwise location. When a spot crosses by, in an Eulerian sense, we can write for the calmed region(CR) dynamics very close to the wall, for the mean flow

$$\frac{\partial u}{\partial t} = n \frac{\partial^2 u}{\partial y^2}$$

In arriving at this equation, we have neglected advection (since we are intereted only in near-wall dynamics) and the turbulent stress terms (as we can imagine the turbulent stresses to be switched off as the turbulent spot has crossed by). This equation is written in an ensemble averaged sense so that very small fluctuations don't figure in the dynamics.

Vorticity is given by

$$w_z = -\frac{\partial u}{\partial y}$$

Hence the first equation becomes

$$\frac{\partial u}{\partial t} = n \frac{\partial}{\partial y}\left(-w_z\right)$$

Therefore, when $\partial u/\partial t < 0$ in the near-wall zone, the wall acts 'like' a sink of vorticity $-\omega_z$.

Compare this with ….

a steady flow with a favourable pressure gradient.

$$n\frac{\partial^2 u}{\partial y^2} = n\frac{\partial}{\partial z}\left(-w_z\right) = \frac{1}{r}\frac{\partial p}{\partial x} < 0$$

By comparing this steady flow (with a favourable pressure gradient(FPG)) with the unsteady flow due to profile switching which we are considering in the present study, it is tempting to suggest that "unsteadiness" after the passage of a spot acts like a favourable pressure gradient factor, wherein there is a sink of spanwise vorticity at the wall.

However, what actually happens in a constant pressure flow after the passage of the spot is that the integrated vorticity across the boundary layer at any streamwise location is a constant. There is however a redistribution of vorticity between the near wall and far wall regions. As the flow switches from a turbulent to a laminar state (through an intermediate calmed state) the average velocity close to the wall decreases with time. This is in effect like a FPG flow with a stable velocity profile.

Does this mean that only near-wall dynamics primarily decide the stability of the profile?

Yes!

Because

1. Near-wall dynamics primarily determines the fullness and shape of the velocity profile.

2. Viscous instability mechanism is by production of Reynolds stress. This reaches a maximum value close to the wall.

Time Variation of skin friction/wall-vorticity in the Calmed Region

If we observe a spot (in a non-zero pressure gradient flow) passing a given streamwise location, in an Eulerian sense the vorticity equation at the wall can be written down as

$$\frac{\partial w}{\partial t} = n \frac{\partial^2 w}{\partial y^2}$$

with

$\omega = \omega_T$ at $t = 0$,

$\omega = \omega_L$ at $t = \tau$.

Here τ is the duration of the calmed region. Try separation of variables

$$w(y,t) = T(t)Y(y)$$

This leads to

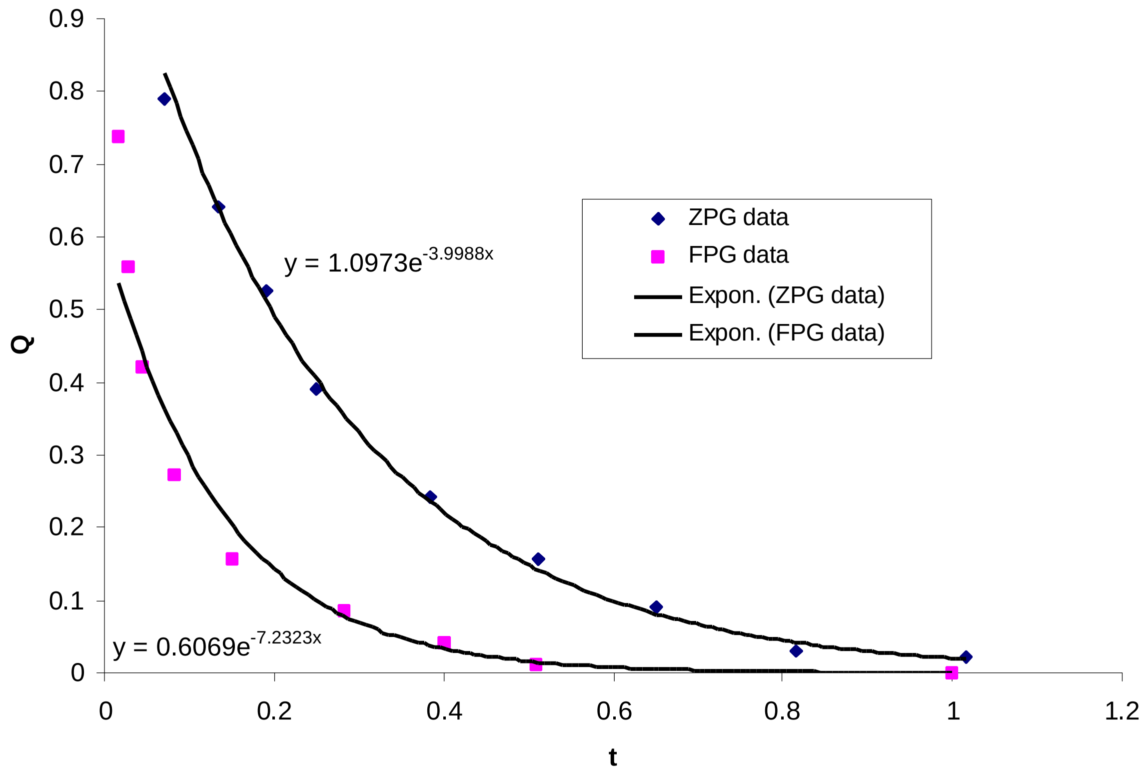
$$w(y,t) = w_T(y)e^{-lt}$$

or

$$C_f(y,t) = C_{f,T}(y)e^{-lt} \tag{1}$$

An exponential decay with time!

Heat Transfer Coefficient in calmed region-ZPG and FPG



Again,

$$C_{f,L} = C_{f,T}(y)e^{-lt}$$

for $t = \tau$ (2)

By (1) and (2),

$$\frac{C_f(t)}{C_{f,T}} = \left[\frac{C_{f,L}}{C_{f,T}}\right]^{t/t}$$

This can be re-arranged to give

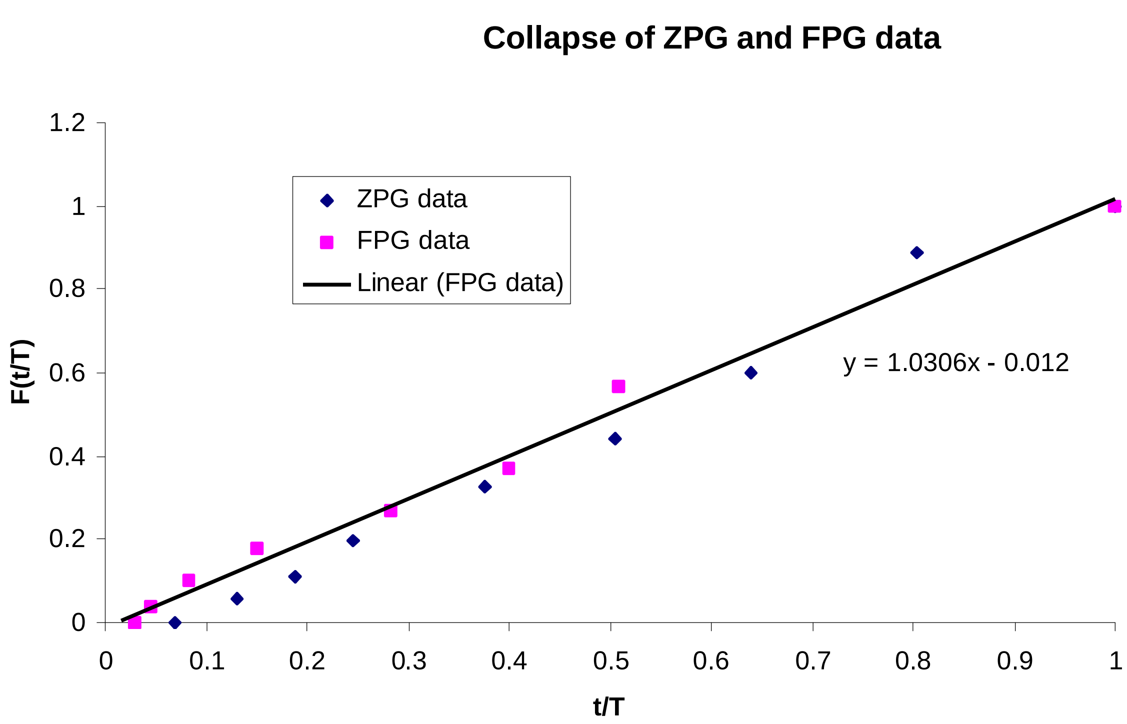
$$F(t) = \frac{\ln\left[C_f(t)/C_{f,T}\right]}{\ln\left[C_{f,L}/C_{f,T}\right]} = \frac{t}{t}$$

i.e., F(t) plotted against t/τ for different pressure gradients should collapse onto a single curve – a straight line of the form *y* = *x*.

It can also be seen from (2) that

$$t = \frac{1}{l}\log\left(\frac{C_{f,T}}{C_{f,L}}\right)$$

Larger the ratio of the skin friction of the turbulent spot to that of the eventual laminar state, the longer the calmed region. This is intuitively obvious.



An estimate for t for constant pressure flow

Consider the unsteady momentum integral equation:

$$\frac{1}{U}\frac{\partial d^{*}}{\partial t} + \frac{\partial q}{\partial x} = \frac{C_f}{2}$$

(I) (II)

For unsteadiness to matter in the dynamics terms (I) and (II) should be of comparable order.

$$\frac{d^{*}}{Ut} \approx \frac{q}{x}$$

$$\Rightarrow x \approx \frac{U}{H} t$$

i.e., structures travel with a celerity of

$$\tilde{U} = \frac{U}{H}$$

By this

Celerity of a turbulent spot	= U/1.4	= 0.7U
Celerity of an inviscid profile	= U/1	= U
Celerity of the trailing edge of the calmed region	= U/2.5	= 0.4U

Reasonably good agreement!

Conclusions

- Near-wall unsteady effect is identified to be the key factor responsible for the benign features of the calmed region like its stability to infinitesimal disturbances

- An expression for the skin friction variation with time in the calmed region has been derived based on this idea. The agreement with (heat transfer) measurements of Hofeldt et al. is good.

- A way of collapsing the skin friction variation for different pressure gradients onto a straight line is suggested.

- The agreement between the 2D model and measurements at the symmetry plane suggests that the flow in the calmed region is two-dimensional.

- An approximate expression for τ (duration of the calmed region) has been obtained for constant pressure flows.

THE VISUALISATION AND MEASUREMENT OF THE ONSET, TURBULENT SPOT PRODUCTION RATE, INTERMITTENCY AND HEAT TRANSFER DURING WAKE-INDUCED TRANSITION USING THERMOCHROMIC LIQUID CRYSTALS

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Department of Engineering
Cambridge, U.K.

A detailed experimental investigation was carried out to study the process of boundary layer transition induced by a bar generated wake travelling over a laminar boundary layer on a flat plate. Wake-induced transition is believed to take place via discrete turbulent spots and an encapsulated cholesteric liquid crystals coating has been employed on a heated flat plate to reveal detailed information over the full surface. The information includes the thermal characteristics, the spot onset locations in time and space and the spot formation rate. The results are also compared to intermittency plots and time-distance diagrams obtained by using surface-mounted thin film gauges. The data are also compared to well established correlations and other published data from the literature for existing wake-induced transition models. It is found that the onset is distributed beneath the trajectory of the wake.

NASA/CP—2001-210888

The Visualisation And Measurement of the Onset, Turbulent Spot Production Rate, Intermittency and Heat Transfer During Wake-Induced Transition using Thermochromic Liquid Crystals

C. Kittichaikarn and P.T. Ireland
University of Oxford

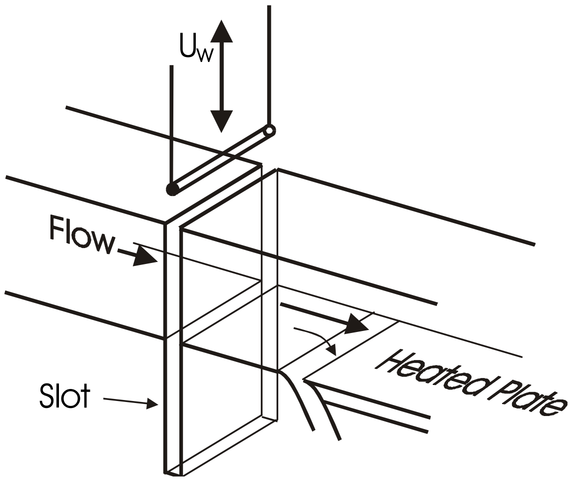
S. Zhong
University of Manchester

H.P. Hodson
University of Cambridge

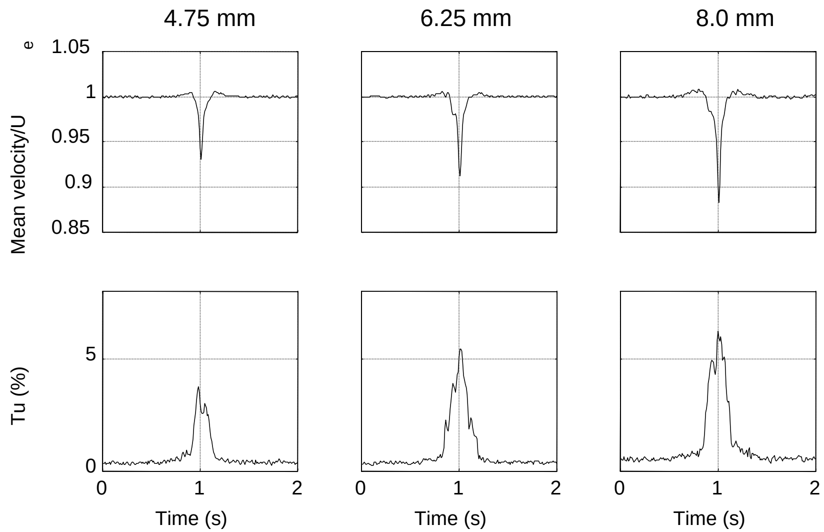
Outline

- Experimental Details
- s-t diagrams of onset due to wakes
- Examination of correlations and models
- Predictions of intermittency/heat transfer
- Conclusions

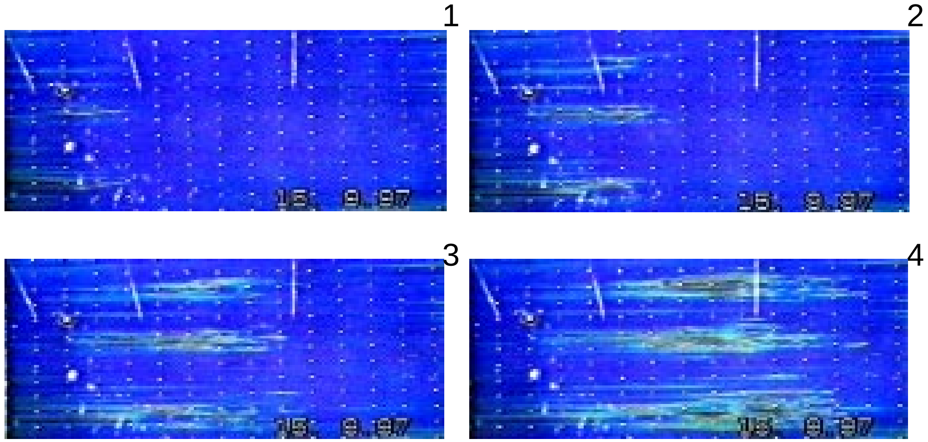
Experiment



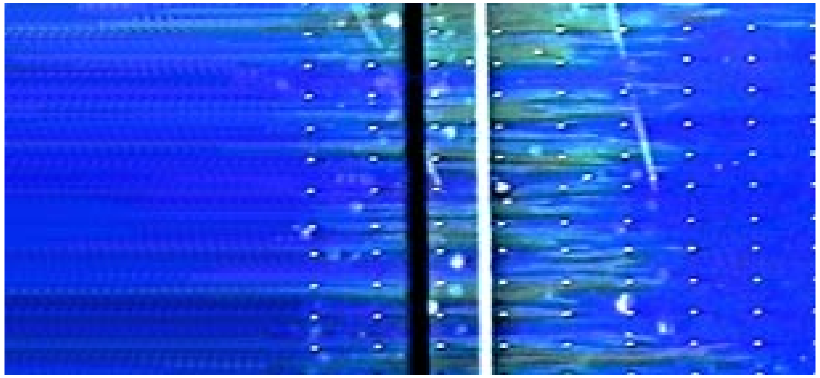
Wakes for bars moving down



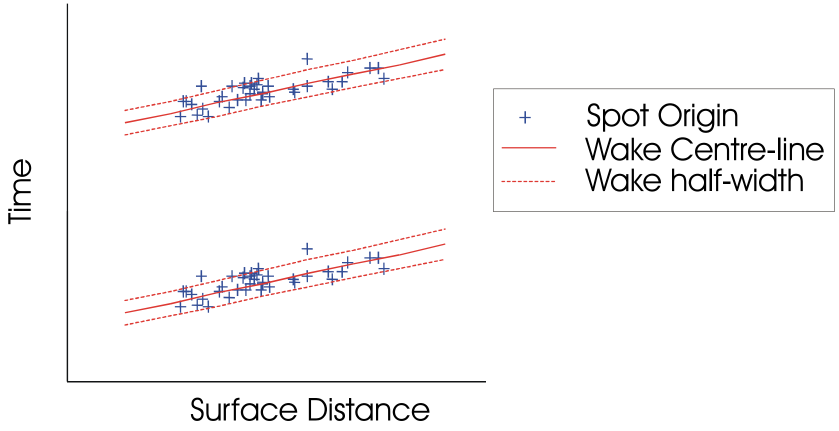
Surface temperature during wake-induced transition (4.75 mm bar down)



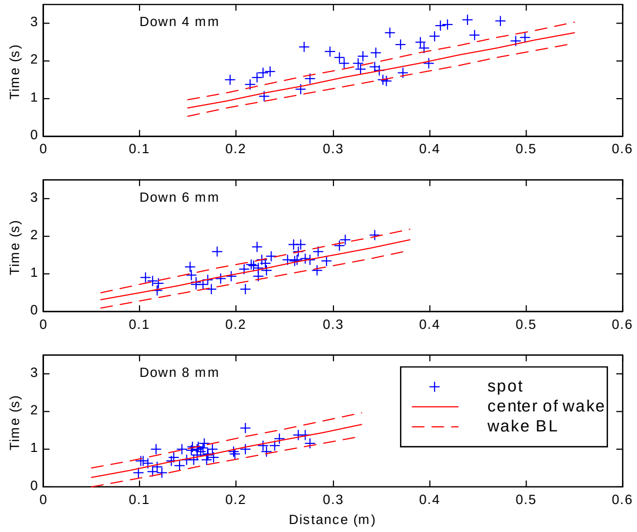
Wake-induced transition (8 mm bar down)



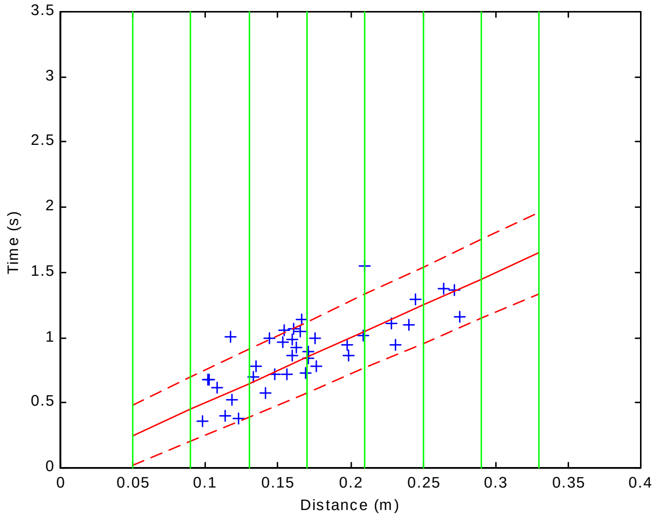
Distance-Time diagram of onset: 8 mm bars down



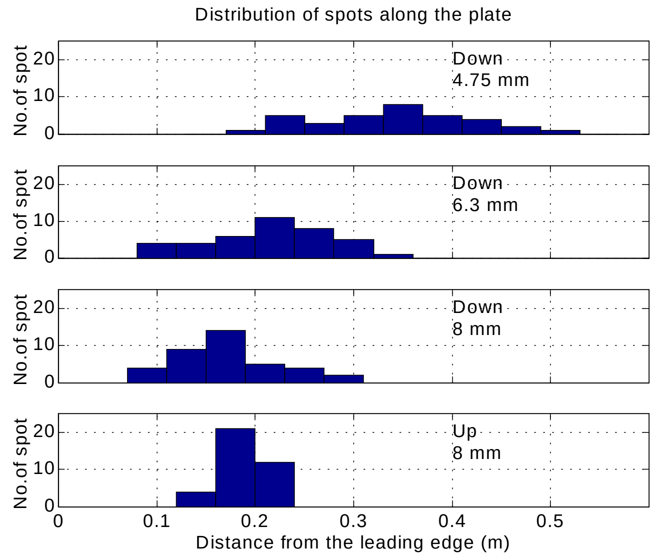
Distance-Time diagram of the onset: 4.75,6.25 & 8.0 mm bars



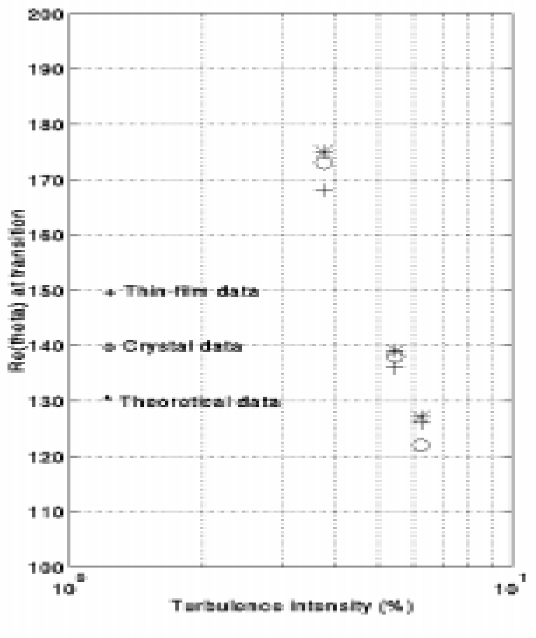
Method to obtain spot formation rate



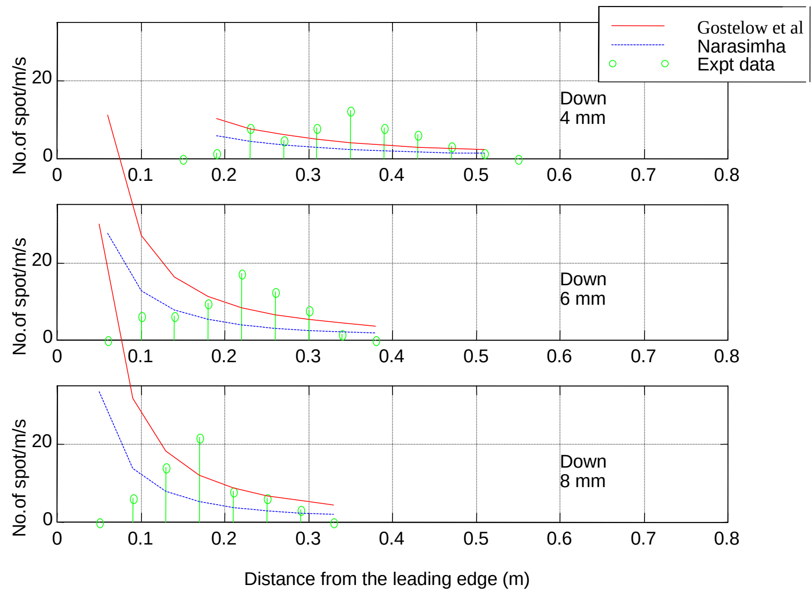
Distribution of spot formation



Onset based on centroid of spot formation (bars down)



Spot formation rate vs. Narasimha/Gostelow



Simple Models

Hodson:

$$\gamma(x) \approx \left(\frac{U_\infty}{U_{te}} - \frac{U_\infty}{U_{le}} \right) \frac{x - x_t}{U_\infty T} \qquad (1)$$

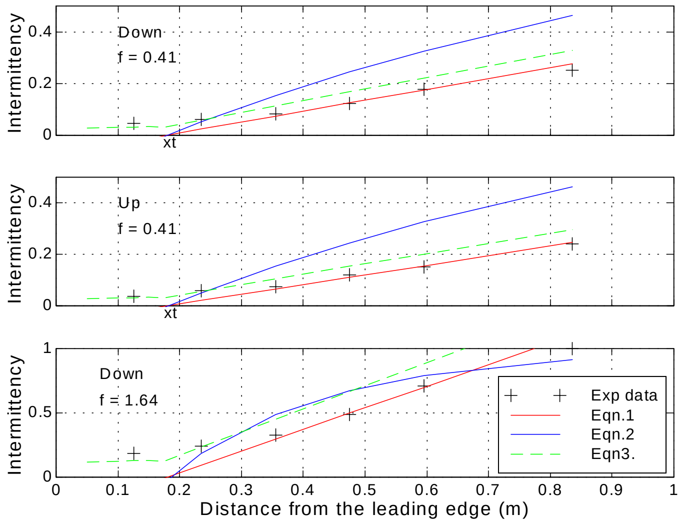
Mayle:

$$\gamma(x) = 1 - \exp\left[-1.9 \left(\frac{x - x_t}{U_\infty T} \right) \right] \qquad (2)$$

Hodson/Funazaki:

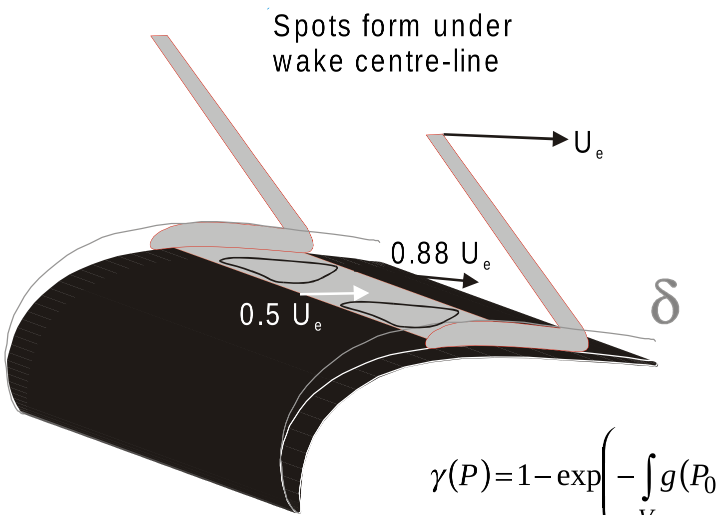
$$\gamma(x) \approx \left(\frac{U_\infty}{U_{te}} - \frac{U_\infty}{U_{le}} \right) \frac{x - x_t}{U_\infty T} + \frac{t_{wake}}{T} \qquad (3)$$

Intermittency - 4.75mm bar down



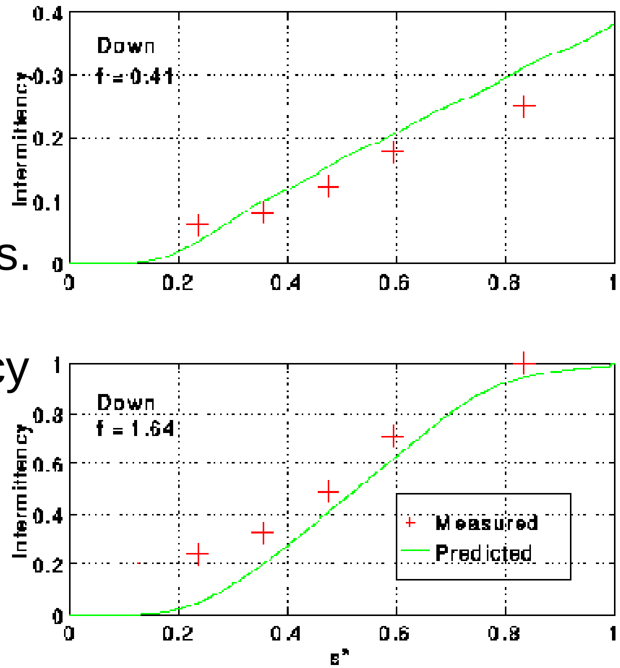
$$f = \left(\frac{L - x_t}{U_\infty T} \right)$$

Narrow Wake/Moving Source Model

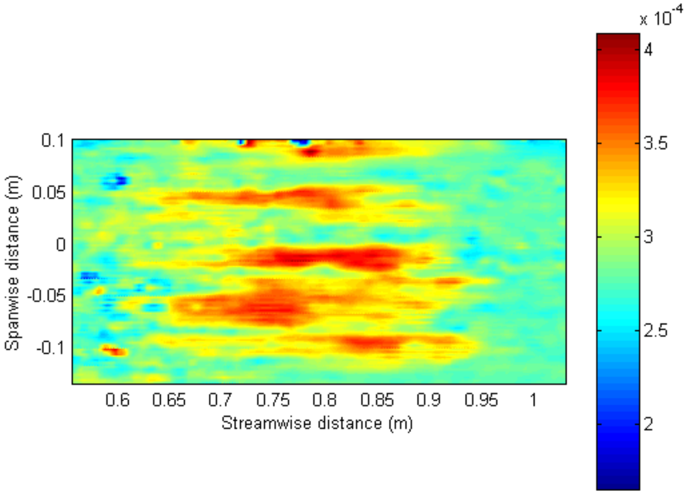


$$\gamma(P) = 1 - \exp\left(-\int_V g(P_0)\, dV_0 \right)$$

Predicted vs. Measured intermittency



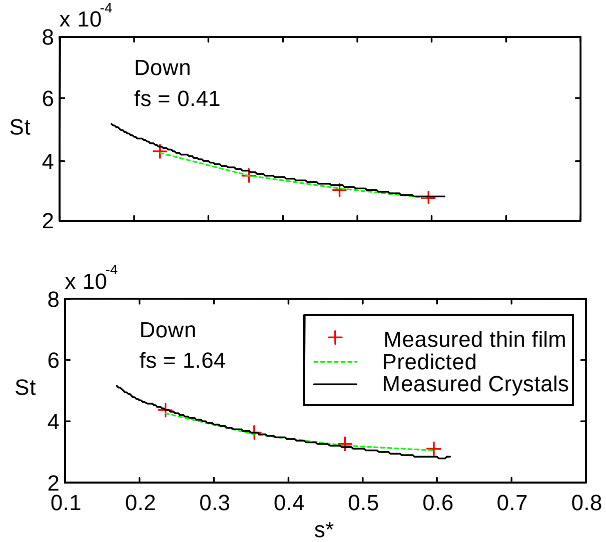
Instantaneous Stanton Number



CONCLUSIONS

- Leading and trailing edge celerities agree with expectations
- Spot formation is distributed along surface
- Centroid corresponds to Mayle prediction for onset
- Simple model (Hodson) predicts measured intermittency if Mayle onset used
- Narrow wake/moving source model predicts measured intermittency using measured spot formation rate

Predicted vs. Measured Heat Transfer



$$\overline{St}(x) = \gamma(x) St_{Tur}(x) + (\gamma(x) - 1) St_{Lam}(x)$$

THE NASA LOW-PRESSURE TURBINE FLOW PHYSICS PROGRAM—A REVIEW

David E. Ashpis
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, OH

An overview of the NASA Glenn Low-Pressure Turbine (LPT) Flow Physics Program will be presented. The flow in the LPT is unique for the gas turbine. It is characterized by low Reynolds number and high freestream turbulence intensity and is dominated by interplay of three basic mechanisms: transition, separation and wake interaction. The flow of most interest is on the suction surface, where large losses are generated due to separation.

The LPT is a large, multistage, heavy, jet engine component that suffers efficiency degradation between takeoff and cruise conditions due to decrease in Reynolds number with altitude. The performance penalty is around 2 points for large commercial bypass engines and as much as 7 points for small, high cruise altitude, military engines. The gas-turbine industry is very interested in improving the performance of the LPT and in reducing its weight, part count and cost. Many improvements can be accomplished by improved airfoil design, mainly by increasing the airfoil loading that can yield reduction of airfoils and improved performance. In addition, there is a strong interest in reducing the design cycle time and cost. Key enablers of the needed improvements are computational tools that can accurately predict LPT flows. Current CFD tools in use cannot yet satisfactorily predict the unsteady, transitional and separated flow in the LPT. The main reasons are inadequate transition & turbulence models and incomplete understanding of the LPT flow physics.

NASA Glenn has established its LPT program to answer these needs. The main goal of the program is to develop and assess models for unsteady CFD of LPT flows. An approach that consists of complementing and augmenting experimental and computational work elements has been adopted. The work is performed in-house and by several academic institutions, in cooperation and interaction with industry. The program was reviewed at the Minnowbrook II meeting in 1997. This review will summarize the progress that was made since and will introduce newly started projects.

The LPT program is focused on three areas: acquisition of experimental and numerical databases and on modeling and computation. Priority was initially given to experiments. There are three classes of experiments: simulated LPT passages, linear cascade, both with and without wakes, and low-speed rotating rig. They are being conducted as follows: At NASA GRC on a flat surface with blade pressure distribution, at the US Naval Academy on a curved surface. The addition of wakes is studied at the University of Minnesota in a curved passage with a retractable wake generator, and at Texas A&M University in a linear cascade with continuously running wake generator. The pressure distribution of the Pratt & Whitney blade "Pak B" is used in all these experiments. Experiments have been performed also in the GEAE Low-Speed Rotating Turbine (LSRT) rig with GE-designed airfoils. Work on numerically generated database is in progress at the University of Kentucky, using the DNS/LES code LESTool developed there. Turbulence/transition model assessment and development is performed also at the University of Kentucky, where a new intermittency transport model was developed and many experimental test cases have been numerically computed. Assessments of models using simulations of multistage LPT experiments were performed at Virginia Commonwealth University using the Corsair code. Work on suction surface separation delay, using passive and active flow-control, has also been initiated. Following the overview, Principal Investigators attending the workshop will present in detail several of the projects supported by NASA.

NASA/CP—2001-210888

NASA GLENN RESEARCH CENTER

THE NASA LOW PRESSURE TURBINE FLOW PHYSICS PROGRAM

A REVIEW

DAVID E. ASHPIS

TURBINE BRANCH
TURBOMACHINERY & PROPUSLSION SYSTEMS DIVISION

Prepared for
MINNOWBROOK III
2000 WORKSHOP ON BOUNDARY LAYER TRANSITION
AND UNSTAEDY EFFECTS IN TURBOMACHINERY
SYRACUSE UNIVERSITY CONFERENCE CENTER, BLUE MOUNTAIN LAKE, NY
AUGUST 20-23, 2000

THE NASA LPT FLOW PHYSICS PROGRAM OVERVIEW

OUTLINE

- **PROGRAM MOTIVATION AND APPROACH**
- **REVIEW OF ACTIVE WORK ELEMENTS**

1. DATA BASES – EXPERIMENTAL:

- 1.1 NASA GRC: SIMULATED BLADE ON FLAT PLATE -- HULTGREN & VOLINO *
- 1.2 USNA: CURVED CHANNEL – R. VOLINO
- 1.3 U. MINNESOTA: CURVED CHANNEL WITH WAKES-- T. SIMON & R. KASZETA *
- 1.4 TEXAS A&M: CASCADE WITH WAKES -- T. SCHOBEIRI
- 1.5 GEAE/OAI: LOW SPEED ROTATING RIG -- W. SOLOMON

2. DATA BASES – NUMERICAL

- 2.1 U. KENTUCKY: LES OF LPT FLOW -- G. HUANG & T. HAUSER

3. COMPUTATION & MODELING:

- 3.1 U. KENTUCKY: MODEL DEVELOPMENT -- G. HUANG & B. SUZEN *
- 3.2 VCU: ASSESSMENT OF MODELS IN MULTISTAGE LPT RANS -- D. DORNEY *

4. OTHER LPT-RELATED ACTIVITIES AT GRC: (Sponsored by other programs and not reviewed here)

- THEORETICAL ANALYSIS - RECEPTIVITY TO FST -- M. GOLDSTEIN, D. WONDROW, S. LEIB (GRC):
- FINE-GRID RANS OF LPT BLADE B -- S. ENOMOTO (NAL, JAPAN) & C. HAH (GRC)
- MODEL INTEGRATION IN MSU-TURBO CODE -- J. ADAMCZYK, A. SHABBIR, W-M TO (GRC), CHEN (MSU)
- JOINT PROJECTS WITH INDUSTRY-- HONEYWELL, P&W, UTRC
- ACTIVE & PASSIVE FLOW CONTROL -- D. ASHPIS, L. HULTGREN, R. VOLINO (USNA), T. CORKE (UND)

- **SOME COMMENTS AND ISSUES**

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* See presentation by the author here at Minnowbrook III

LOW PRESSURE TURBINE FLOW PHYSICS PROGRAM

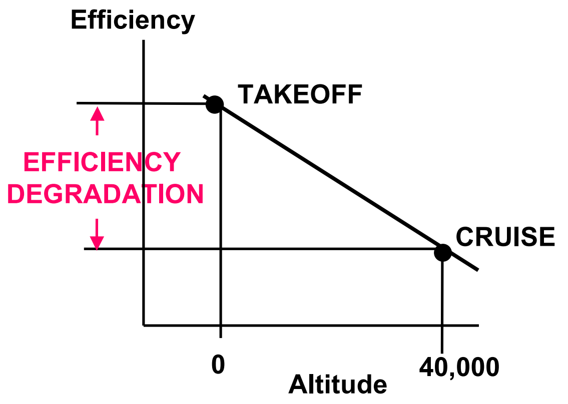
GOAL STATEMENT:
To Provide Accurate Models and Physical Understanding of of Transition/Separation/Wakes Which Lead to Improved Design and Performance of the LP Turbine.

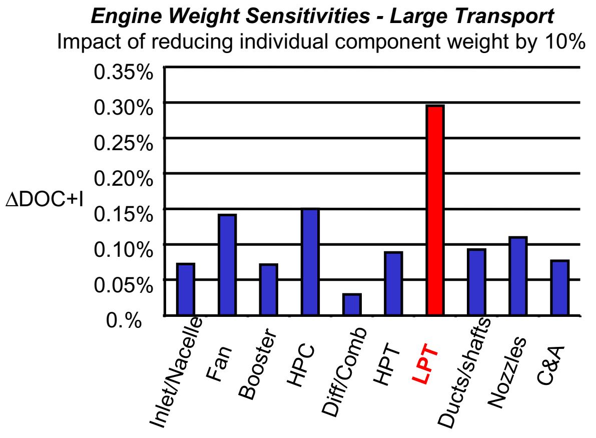
LPT IMPROVEMENTS NEEDS:

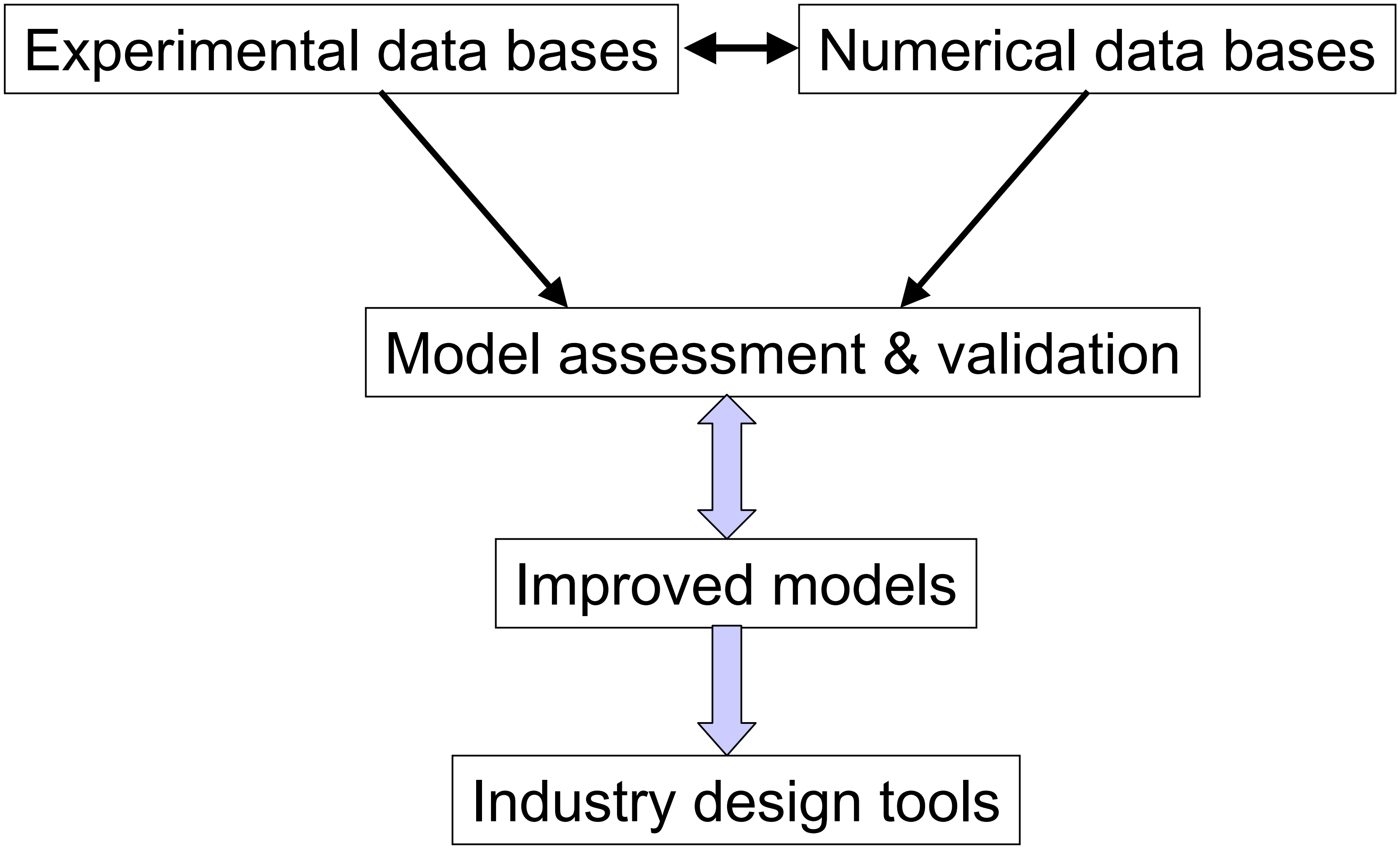
- Reduce: Part count, number of stages, weight, design cycle time and cost.
- Minimize performance degradation from takeoff to cruise:
  - 2 pts large commercial engines.
  - 7 pts small military engines high altitude.
- Needs expressed by aero-engine industry (GE, P&W, AlliedSignal), Air Force.

GRC Propulsion System Analysis Study ("MOASS" 1998):
Compared engine components - LPT improvements has the highest payoff in terms of DOC+I and SFC.

APPROACH:
Combined experimental and modeling/computational effort.

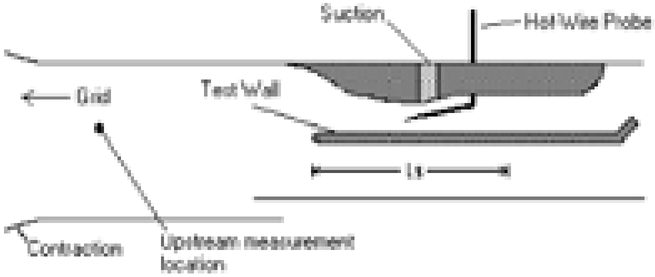





Experimental data bases
Numerical data bases
Model assessment & validation
Improved models
Industry design tools

1. Experimental Data Bases

1.1 L. Hultgren (NASA GRC) & R. Volino (USNA)



Objective:

- Acquire detailed test case for model development

Approach

- Experiment in CW-7 Tunnel on flat plate with blade-B pressure distribution
- Hot wire measurements

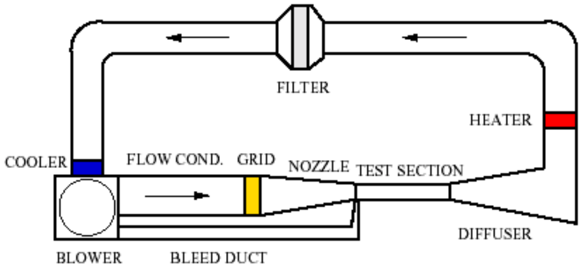
Status:

Project currently focused on separation flow-control

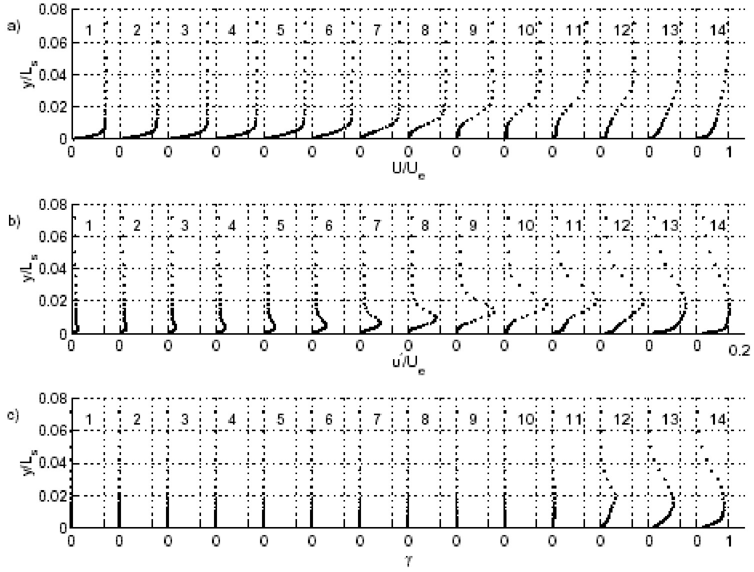
Accomplishments:

- Completed several cases for FSTI = 0.2%, 2.5% (in test section, 2.5%, 7% in inlet)

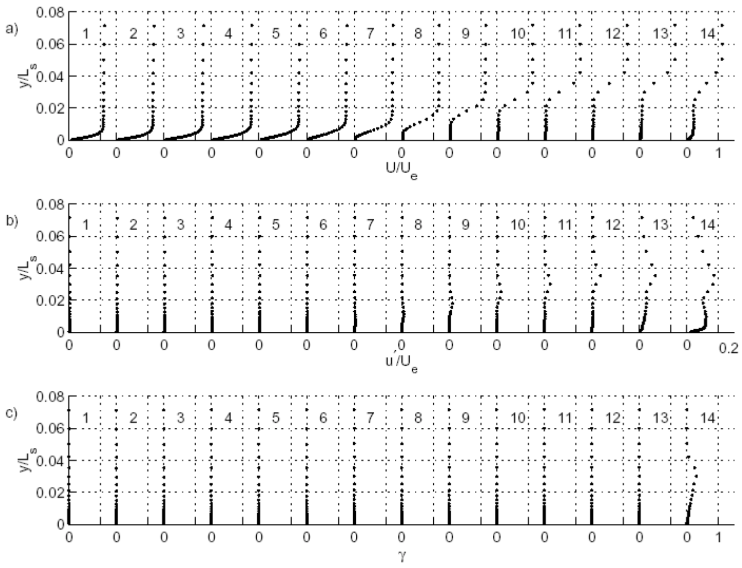
  Comprehensive data sets for Rey = 50,000, 300,000, preliminary sets for 100,000, 200,000
- Data transferred to U. Kentucky and used for CFD

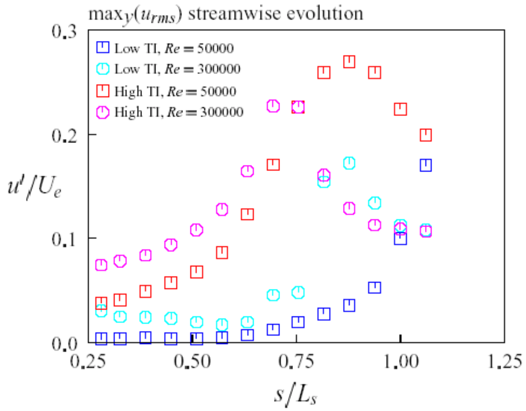


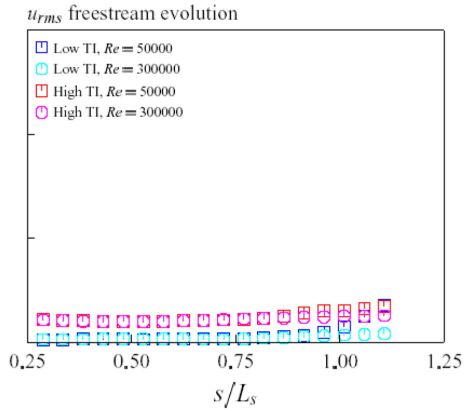
Re=50000—HIGH TI



Re=50000—LOW TI







U_RMS

- KLEBANOFF MODE GROWTH AND EFFECTS CLEARLY EVIDENT

1. Experimental Data Bases (Cont.)

1.2 US Naval Academy – Prof. R. Volino

Objective:

• Acquire detailed test case for CFD (baseline)

• Study feasibility of passive & active flow control

Approach

• Experiment in single blade-B passage

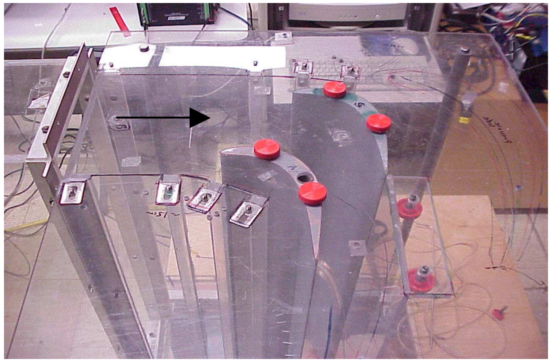
• Hot wire measurements, single and X wire

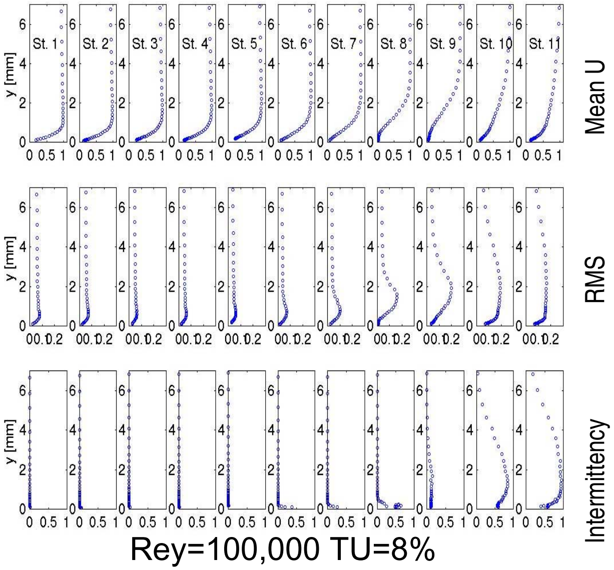
Status:

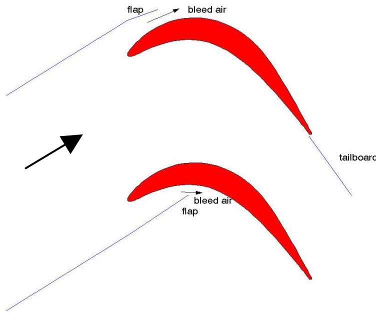
• Baseline (no flow control) in progress

(Rey 25,000 – 300,000, FSTI 0.5%, 8%)

• Preliminary passive flow control (Trip, dimpled tape, vortex generators) in progress.







1. Experimental Data Bases (Cont.)

1.3 University of Minnesota – Prof. T. Simon

Objective:

Acquire detailed datasets to serve as test cases for CFD with & without wakes

Understand flow physics

Approach

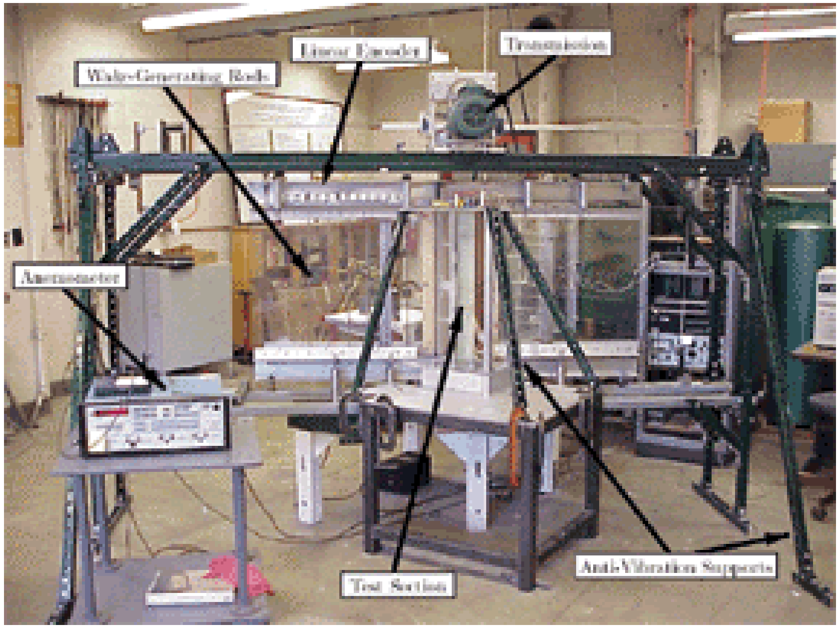
- Experiments in single blade-B passage, retractable wake generator
- Hot wire measurements, single wire, surface hot film diagnostics

Accomplishments

- Constructed test section with single blade B passage
- Completed baseline (no-wake) data set – Reynolds 50,000 to 300,000, FSTI 0.5, 2.5, 10 %
- Constructed and qualified cylinder bars wake generator
- Completed extensive dataset with wakes – retained time series signals
  - Strouhal No. = 0.8, Rey =50,000, FSTI=2.5%
- In progress/planned:
  - Strouhal No. = 0.4, Rey =50,000, FSTI=2.5%
  - Strouhal No. = 0.4, Rey =50,000, FSTI=10%
- In progress: Development of hot-film technique to identify separation
- Data (no-wake) used extensively for CFD by U. Kentucky & Penn State
- Data (unsteady wakes) in process of CFD by U. Kentucky

Future work

• Complete experiment with additional parameters combination (wake frequency, Rey numbers and FSTI)
• Perform measurements of unsteady surface pressures
• Perform comprehensive data analysis of completed experiments
• Revisit experiments for detailed measurements in flow regions of interest
• Add simultaneous multi-channel surface hot-film surface pressure
• Study effects of turbulent scales in wake by replacing bars with small airfoils



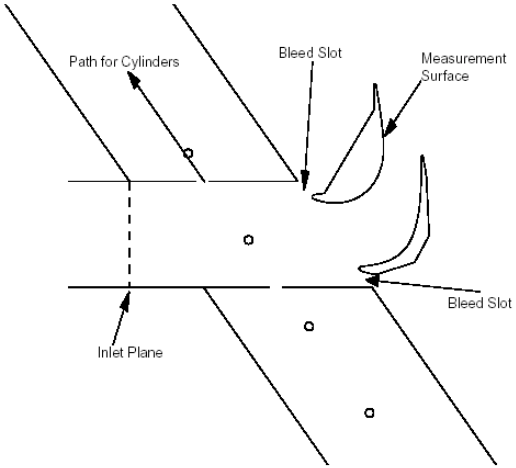
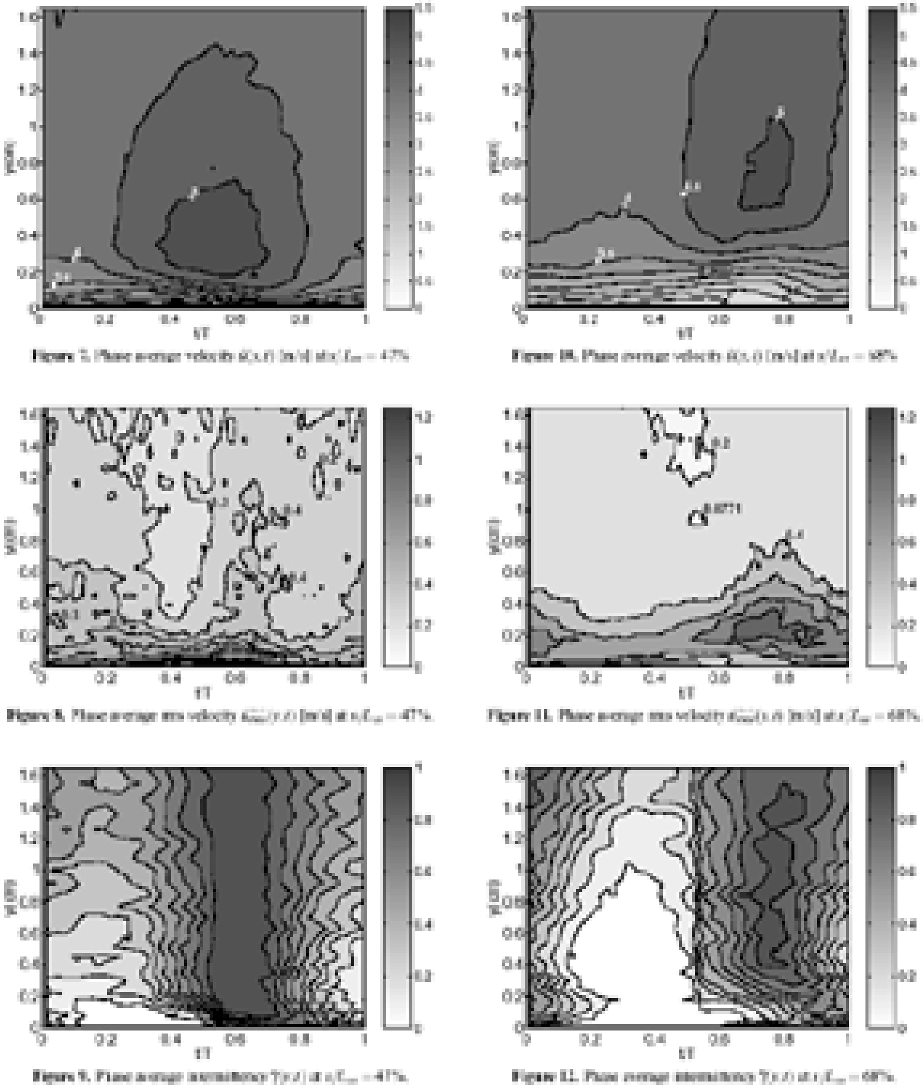


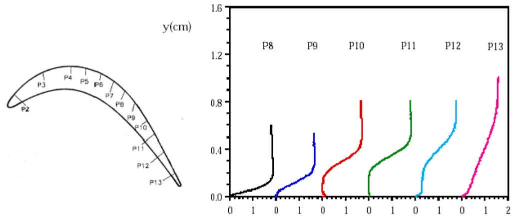
Figure 1. Cross-sectional view of the experimental facility.



41%S- upstream separation   68%S- downstream separation

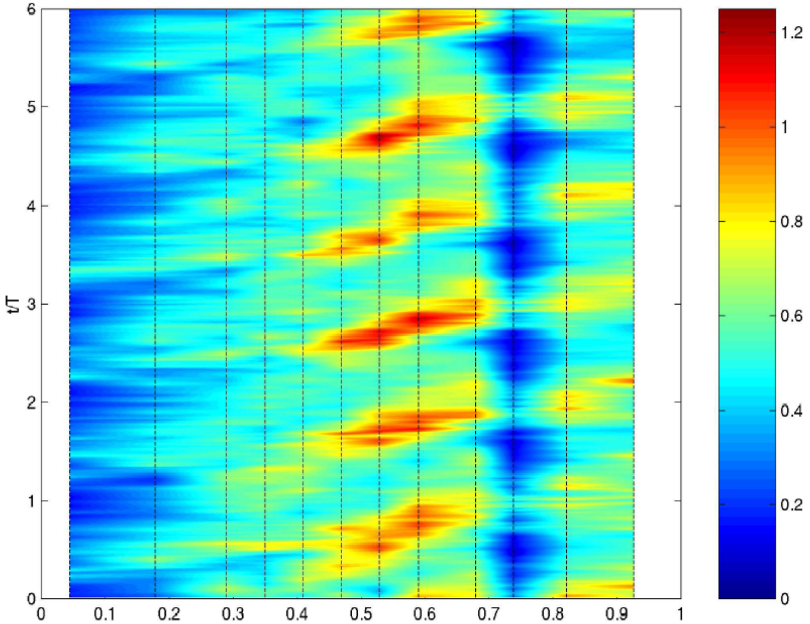
Wake case - Y-T plots of U, U_RMS, Intermittency

Example Data



Velocity Profiles Downstream
Re = 50,000, TI = 2.5%

No-wake case



Wake case- T-S plot –U

1. Experimental Data Bases (Cont.)

1.4 Texas A&M University – Prof. T. Schobeiri

Objective:

• Acquire detailed test case for CFD in cascade with wakes

Approach

• Experiment in blade-B cascade with wake

• Hot wire and surface hot-film measurements

Status: On-going, project started recently

Accomplishments:

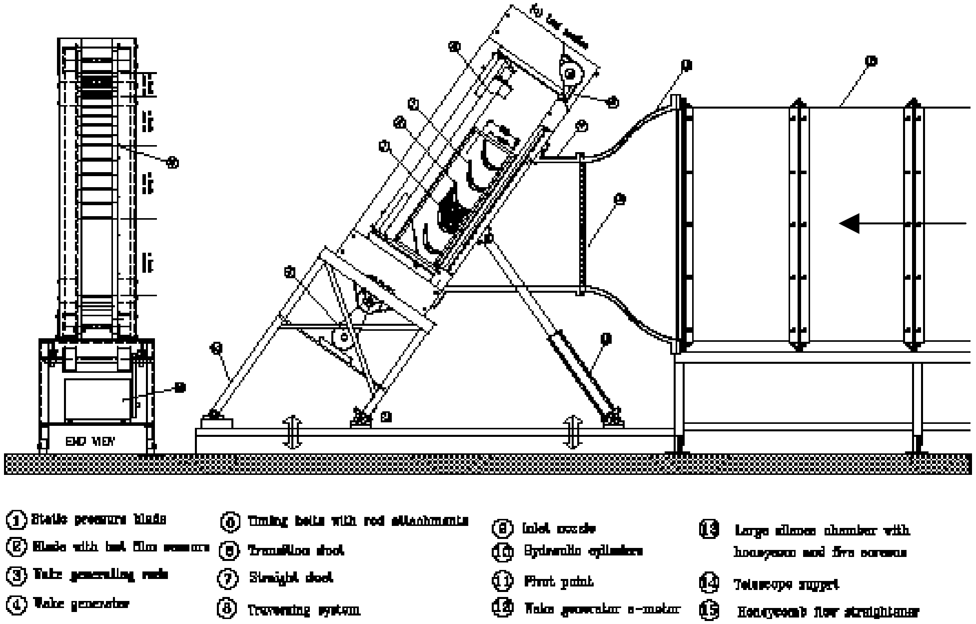
• Relocated and modified facility to accommodate adjustable non-zero inlet angle

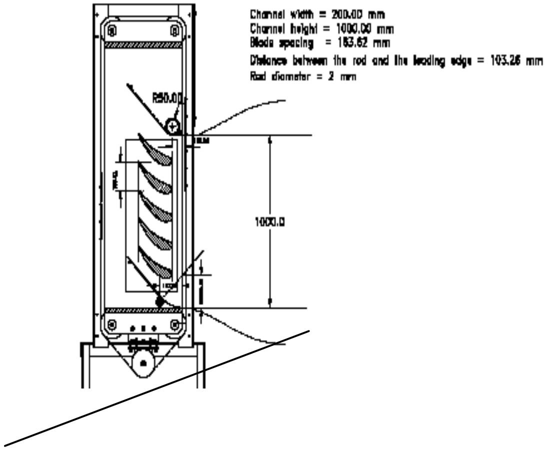
• Designed and fabricated blade B cascade

• In progress: Instrumented blade with 190 hot-film sensors, updated computerized data acquisition system

• Qualification of test section in progress

Unsteady Turbine Cascade Research Facility
Turbomachinery Performance and Flow research Laboratory
Texas A&M University
M.T.Schobeiri





Metal & composite resin resin blades

1.5 Experimental Data Bases - OAI /GE Low Speed Rotating Rig – Dr. B. Solomon

Objective: **Acquire data base for model development and validation for unsteady transitional flow with wakes in rotating rig.**

Build 1
- conventional blades design
- one instrumented blade

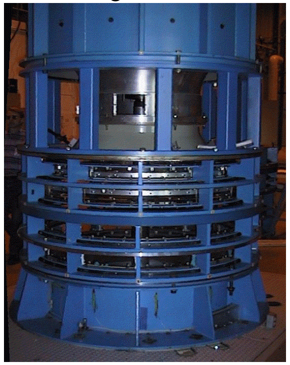
Build 2
- low solidity, hi-lift design
- 2 instrumented blades
-

Status:
- Data taking completed (Dr. Solomon's joined compressor group at GEAE)

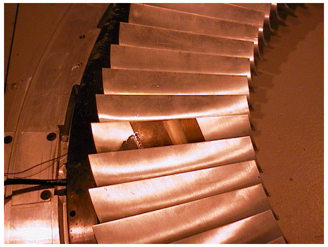
Accomplishments:
- Completed Build 1 testing
  - Surface film
  - hot-wire & pressure traverse
- Completed most of Build 2 testing
  - completed hot-wire & pressure traverse
  - completed surface hot-film hot film
- Extensive data set documented and delivered

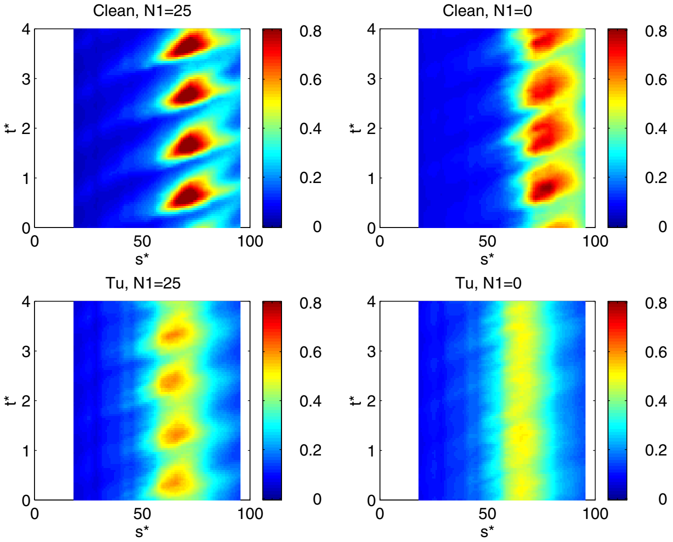
Future Work:
- Data processing, analysis & reports.
- Boundary Layer hot wire measurements if technically possible

LSRT Rig

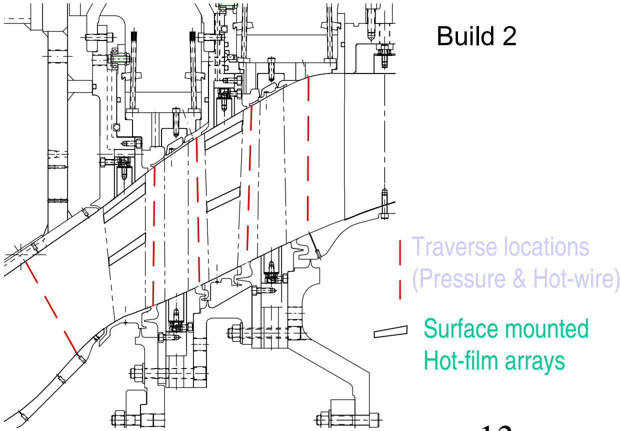


Build 1





Shear stress as function of time and surface length
Effect of turbulence grid and indexing



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2. Numerical Data Bases

2.1 University of Kentucky – Prof. George Huang & Dr. Thomas Hauser

Objective:

- Generate numerical data base for LPT flows with separation, transition and wakes
- Understand flow physics

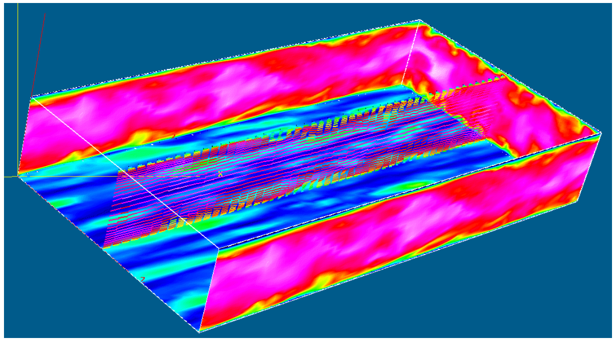
Approach

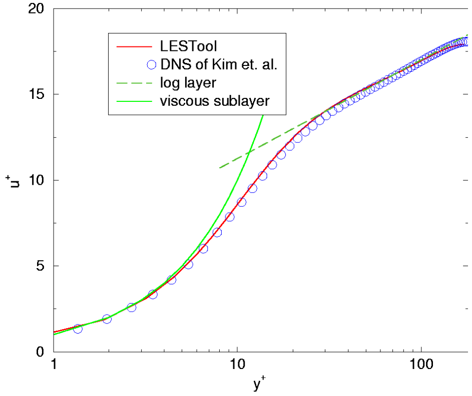
- DNS/LES/DES Simulation of blade passage with wakes

Status: On-going

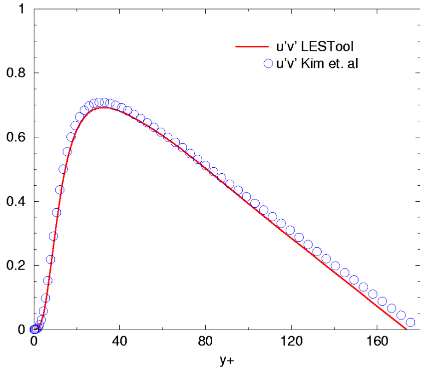
Accomplishments:

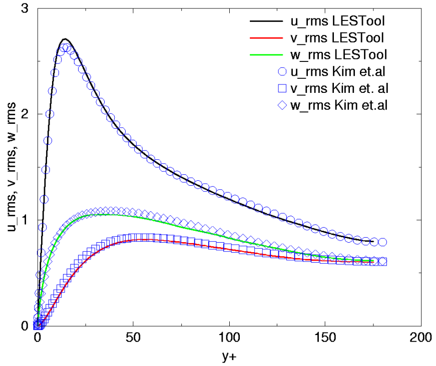
- Developed a new LES/DNS/DES code named LESTool
- Highly efficient code optimized to shared and distributed memory platforms
  - SGI Origin, Linux cluster
  - OpenMP + MPI
- Test cases :
  - Coarse grid completed – turbulence in a box, channel flow, blade B
  - Circular Cylinder – in progress
  - Fine grid cases in progress



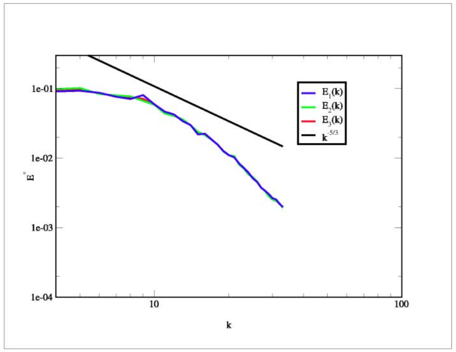


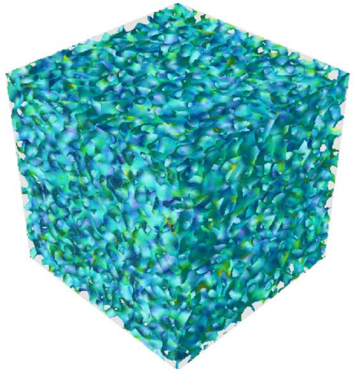
Channel flow

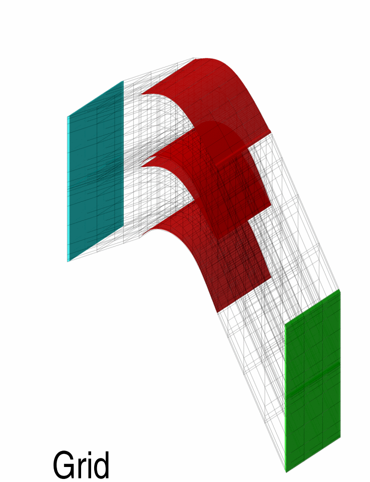


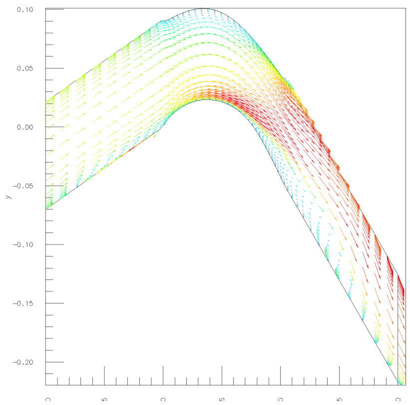


Isotropic Turbulence

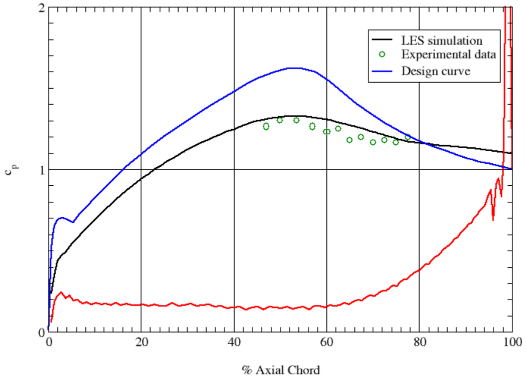






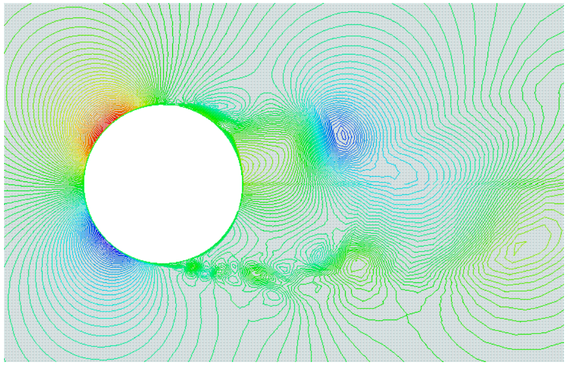


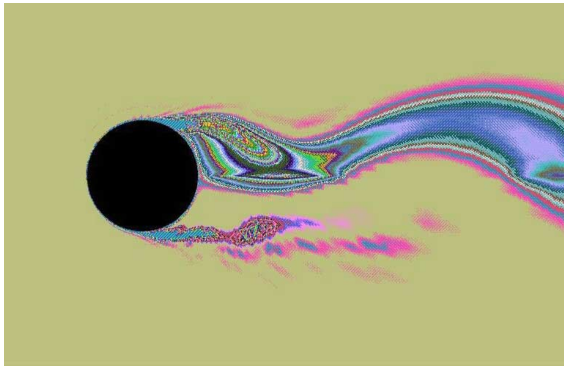
Velocity vectors



Cp - X

Blade B





Circular Cylinder

3. Computation & Modeling of LPT Flows

3.1 University of Kentucky – Prof. George Huang & Dr. Bora Suzen

Objectives:

- Assessment of existing models
- Development of new models

Approach:

RANS simulations of experimental test cases using steady/unsteady time-accurate RANS code (TURCOM)

Status: On-going

Summary of Accomplishments:

- Adapted TURCOM code for internal/turbomachinery flows with & without passage periodicity
- Incorporated models for transition on attached and separated boundary-layers
- Developed methodology for separation prediction
- Modified TURCOM code for multi-zone, unsteady, computations (in progress)
- Performed 2D simulations of a number of test cases
- Developed new model for transition represented by intermittency transport equation
- Modified empirical model of transition start prediction

Test cases computed

Completed:

- ERCOFTAC T3A, T3B, T3C1, T3C2
- U. Minnesota Blade B Experiment (no wakes)
- AFRL (Wright lab) Lake Blade B experiment
- NASA GRC CW-7 flat-plate Blade B Experiment

In progress:

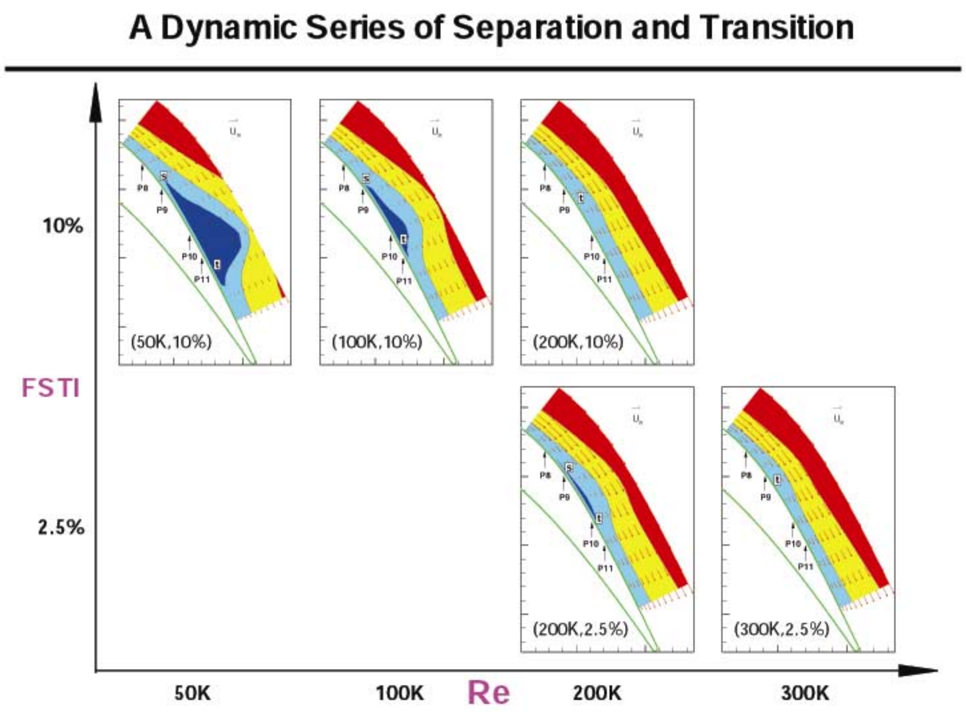
- U. Minnesota (T. Simon) Blade B Experiment (with wakes)

Some future test cases:

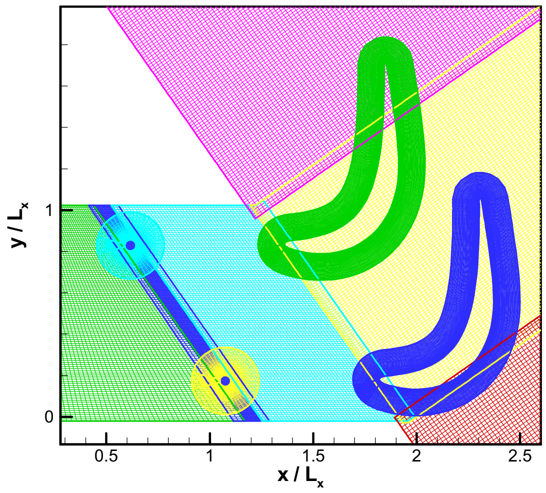
- US Naval Academy (Volino) Blade B passage
- AFRL Low Reynolds blade B (Sondergaard)
- Butler USAF Academy Langston cascade experiment
- USAF Academy Ultra Low Reynolds number Langston cascade
- UBM Munich (Stadtmuller) hi-lift wake subsonic cascade experiment
- Texas A&M (Schobeiri) wake rig experiment
- GEAE LSRT rig LPT experiments (Halstead, Solomon)
- Carleton University rig with and without wakes (Blade B + future high-lift blades)
- Industry LPT designs

Future work

- Complete development of unsteady multi-zone code capability
- Complete development of 3D code and 3D and compressible model versions
- Asses models for additional steady cases
- Assess models for unsteady wake cases
- Make arrangement for work on industry LPT designs
- Assess time-accurate computations results versus averaged approach
- Develop new models that will better capture separation, transition and wakes
- Develop and asses models for separation flow-control devices

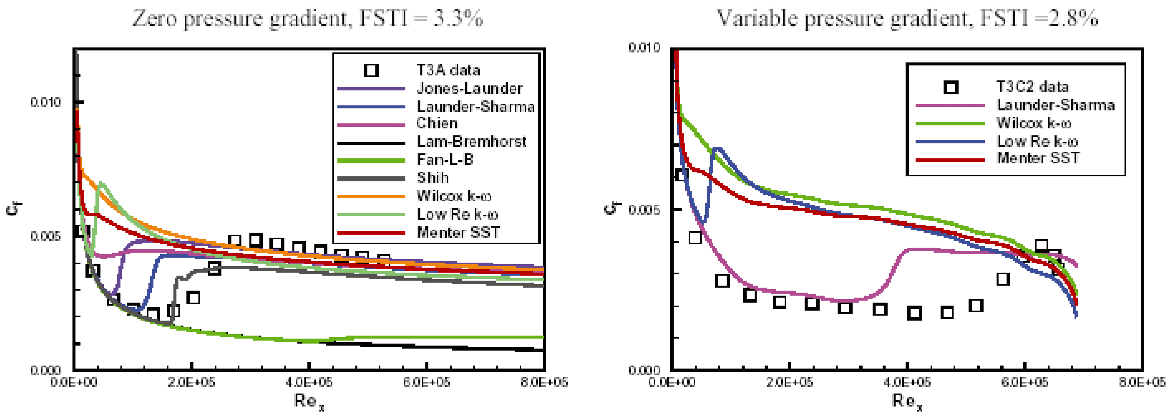


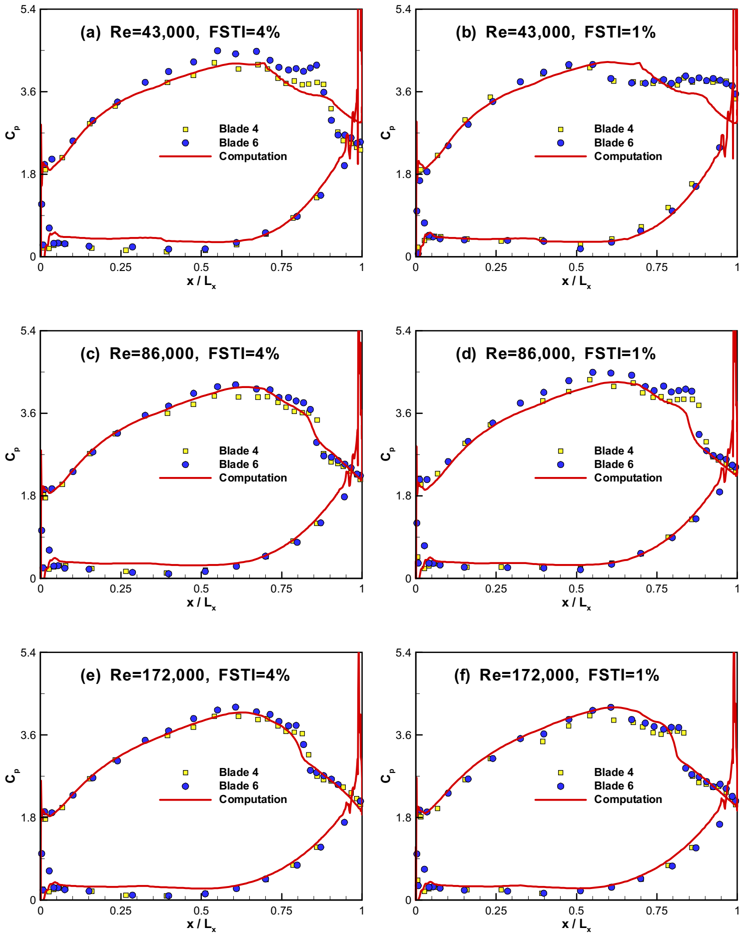
U. Minnesota blade B

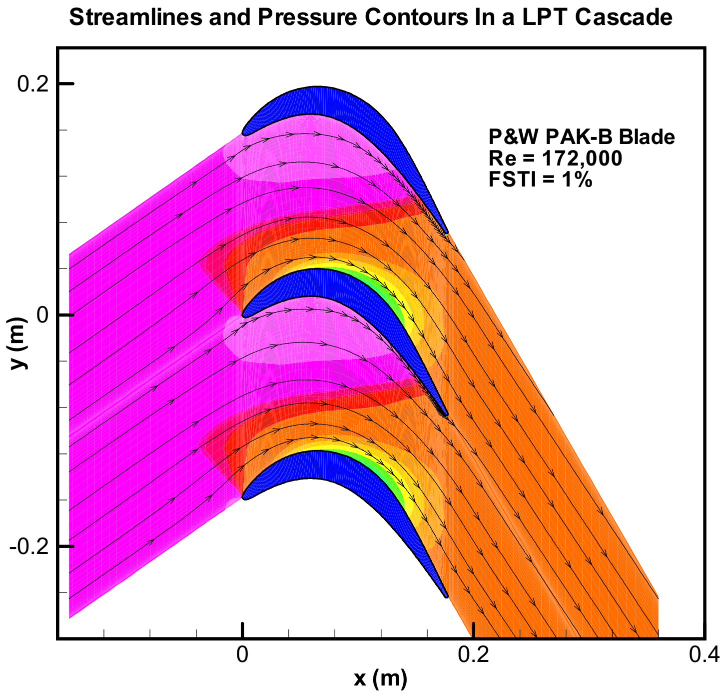


Grid for U. Minnesota w/ wakes

ERCOFTAC T3 cases







AFRL/WL Lake blade B cascade

3. Computation & Modeling (cont.)

3.2 Virginia Commonwealth University (VCU) – Prof. Dan Dorney

Objectives:

RANS validation and assessment of models in multistage LPT flows

Approach:

RANS simulations of experimental test cases using unsteady time-accurate RANS code Corsair

Status: On-going

Accomplishments:

- Adapted the Corsair/Wildcat codes to LPT computations
- Large number of complex cases simulated:
  - Pre-experiment prediction of flow over blade B – gave insight, guidance to experiments
  - Simulation of GE/LSRT 2-stage Halstead 1995 experiments (cylindrical casing)
  - Simulation of AFRF Wright Lab Cap. Lake blade B cascade experiment
  - Simulation of GE/LSRT hi-lift 2-stage LPT Solomon 2000 experiment (slanted end walls, proprietary)
  - Simulation of Honeywell LPT 4 stages + EGV (proprietary)

Future plans

- Work to be continued at GRC with collaboration with Dorney (transferring to NASA MSFC)
- 2D & 3D simulations of Industry LPT cases
- Post-processing of GE/LSRT data & comparisons to experiment

Time-dependent
Momentum thickness

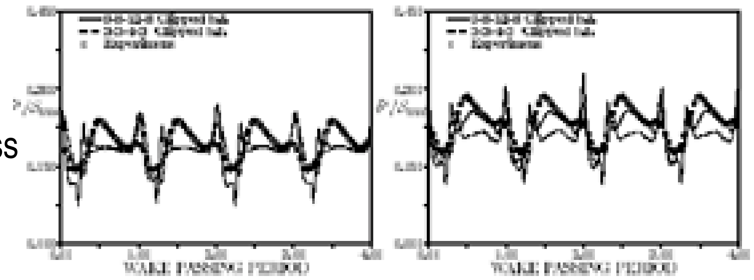
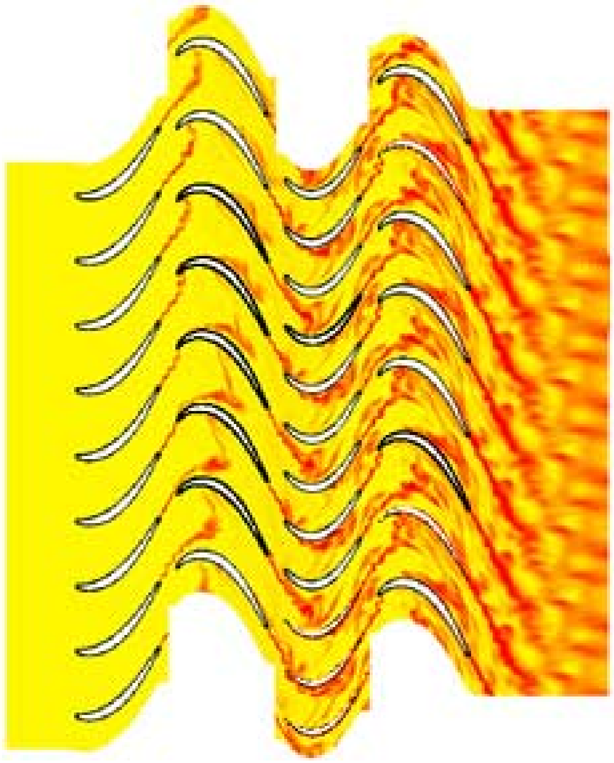


Figure 9: Displacement thickness history, [illegible] a.x., Point [illegible], nozzle=2.

Figure 11: Displacement thickness history, [illegible] a.x., Point [illegible], nozzle=2.



Halstead 1995 case

Some Comments, Issues and Challenges

Model assessment and development is impeded by some realities:

* Limitations of experimental data
    - Experiments are not perfect – more are needed
    - Limited data from rotating rigs (only GE LSRT)
    - Only one data set from subsonic cascade (UMB, in progress)
    - No 3D data, no data from subsonic rotating rig or dual spool rig
    - No data on inflow turbulence conditions in real engines
    - Limited boundary layer data – mostly single velocity component
    - Inaccurate separated boundary layer data
    - Single passage experiments do not have periodicity and there are some CFD difficulties in formulating boundary conditions
    - Hot film data cannot be calibrated to wall shear stress – impedes quantitative CFD comparisons
* Hard to come up with new ideas for models. Need to work on model assessment, validation, implementation, to get inspiration for new models
* Focus was only on suction surface (limited resources) need also pressure surface
* Transition start prediction is empirical
* No theory for bypass transition under freestream turbulence conditions – Transient Growth theories look promising

* **Recommendation**: Conduct improved experiments, develop LES/DNS data bases, more work on theory of bypass transition

PREDICTIONS OF TRANSITIONAL FLOWS IN A LOW PRESSURE TURBINE USING AN INTERMITTENCY TRANSPORT EQUATION

Y.B. Suzen, G. Xiong, and P.G. Huang
University of Kentucky
Department of Mechanical Engineering
Lexington, KY

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

The new model is applied to predictions of a modern low-pressure turbine experiment and detailed comparisons of the computational results with the experimental data are presented. The new model has been shown to be capable of predicting the low-pressure turbine flow transition under a variety of Reynolds number and freestream turbulence conditions.

NASA/CP—2001-210888

Predictions of Transitional Flows in a Low Pressure Turbine Using an Intermittency Transport Equation

Y. B. Suzen, G. Xiong, P. G. Huang

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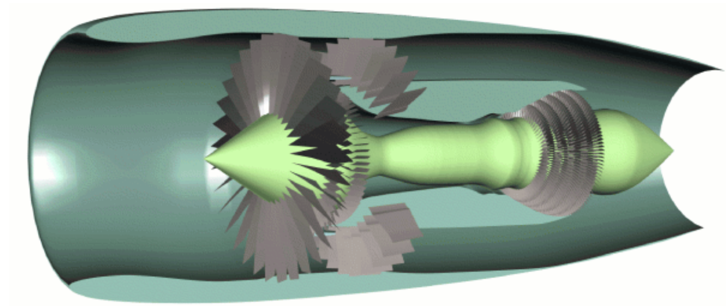
Department of Mechanical Engineering
University of Kentucky

Supported by NASA-Glenn Research Center

Presentation Outline

- Background
- Motivation
- Intermittency Concept + Turbulence Model
- New Intermittency Transport Model
- ERCOFTAC Test Cases
- Low-Pressure Turbine Experiments
- Conclusions

Background



<u>Flow Field of Interest</u>:

- Low Pressure Turbine Applications
  - Transitional Flows Under Effects of
    - Reynolds Number Variations
    - Free Stream Turbulence Level
    - Pressure Gradients
    - Flow Separation

⇒ *Methods for Modeling Transitional Flows*

Motivation

Predicting Transitional Flows:

Desired Features of Method:

- Accurate and versatile
- Efficient and inexpensive
- Compatible with current CFD methods

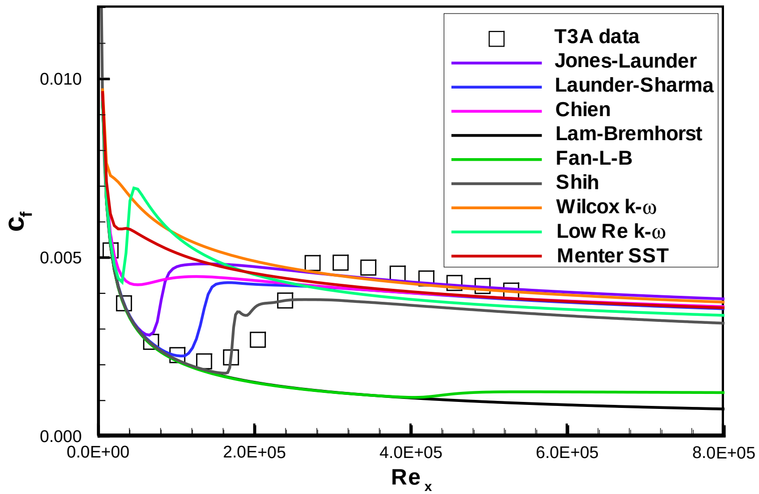
Existing Methods:

- Stability Theory
- Empirical Correlations
- Low-Reynolds Number Turbulence Models
- Intermittency Concept + Turbulence Model

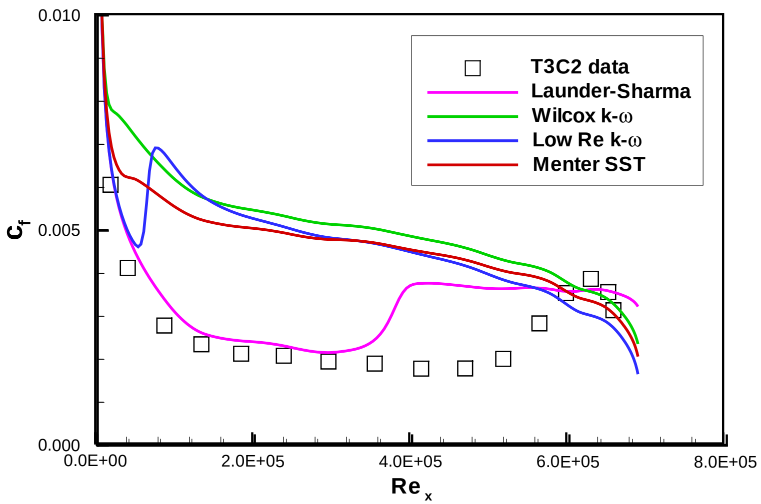
Motivation

Low-Reynolds Number Turbulence Models

Zero pressure gradient, FSTI = 3.3%



Variable pressure gradient, FSTI =2.8%



$\Rightarrow$ *Existing models are inadequate to predict flow transition under diverse conditions.*

Modeling Flow Transition

Intermittency Concept + Turbulence Model:

- Easy to implement into RANS solvers
- Intermittency factor, $\gamma = T_{Turbulent}/T_{Total}$
- In the mean flow equations

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

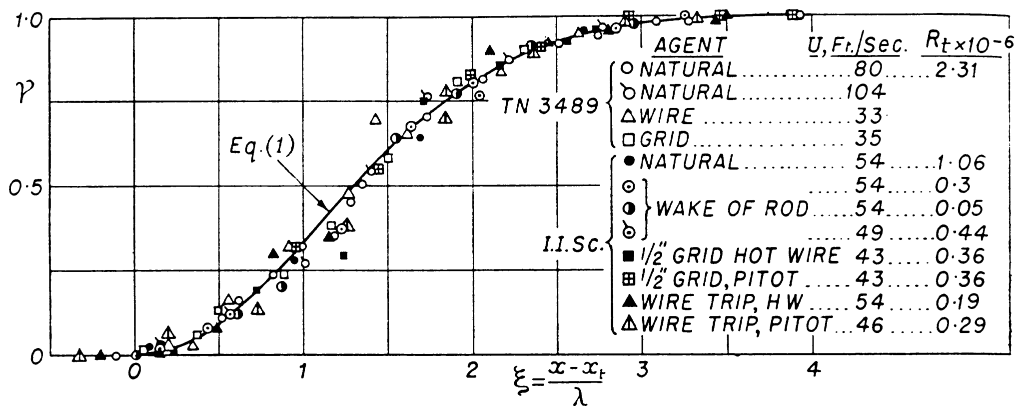
  - μ_t – from a turbulence model
  - Intermittency factor, γ :
    - Empirical correlations
    - Modeling of γ with a transport equation

Intermittency Factor, γ

Universal Streamwise Distribution:

- Correlation of Dhawan and Narasimha (1958):

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



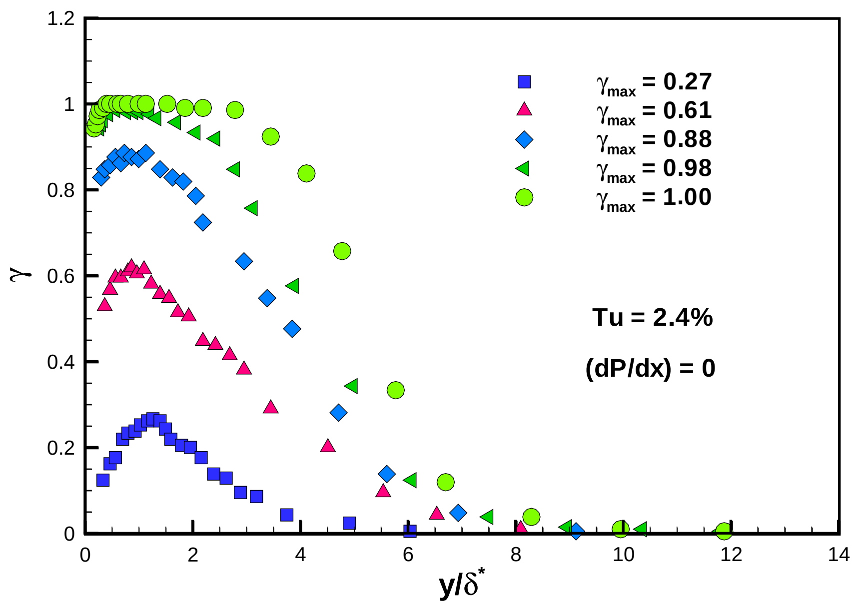
- Effects of pressure gradient and free stream turbulence

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

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 $y/\delta^* = 8$

New 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

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

New Transport Model for Intermittency

$$\frac{\partial \rho \gamma}{\partial t} + \frac{\partial \rho u_j \gamma}{\partial x_j} = (1 - \gamma)\Bigg[(1-F)C_0 \rho \sqrt{u_k u_k}\beta(s)$$

$$+F\left(\frac{C_1 \gamma}{k}\tau_{ij}\frac{\partial u_i}{\partial x_j} - C_2 \gamma \rho \frac{k^{3/2}}{\epsilon}\frac{u_i}{\sqrt{u_k u_k}}\frac{\partial u_i}{\partial x_j}\frac{\partial \gamma}{\partial x_j}\right)\Bigg]$$

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

$$+ \frac{\partial}{\partial x_j}(((1-\gamma)\gamma \sigma_{\gamma_l}\mu + (1-\gamma)\sigma_{\gamma_t}\mu_t)\frac{\partial \gamma}{\partial x_j})$$

$$\sigma_{\gamma_l} = \sigma_{\gamma_t} = 1.0, \qquad C_0 = 1.0, \qquad C_1 = 1.6$$

$$C_2 = 0.16, \qquad C_3 = 0.15$$

Implementation

- Easy implementation into RANS solvers
- In the mean flow equations,

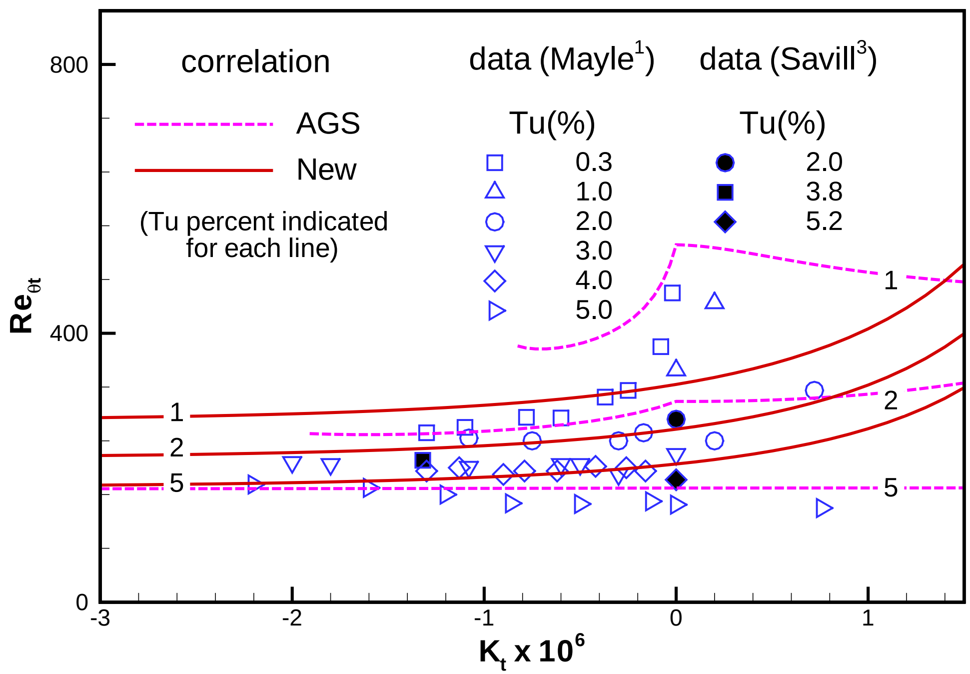
$$\mu_t^* = \gamma\, \mu_t$$

  - μ_t – from SST model of Menter
  - γ – from new model
- Onset point of transition from correlations

Implementation

Onset of attached flow transition

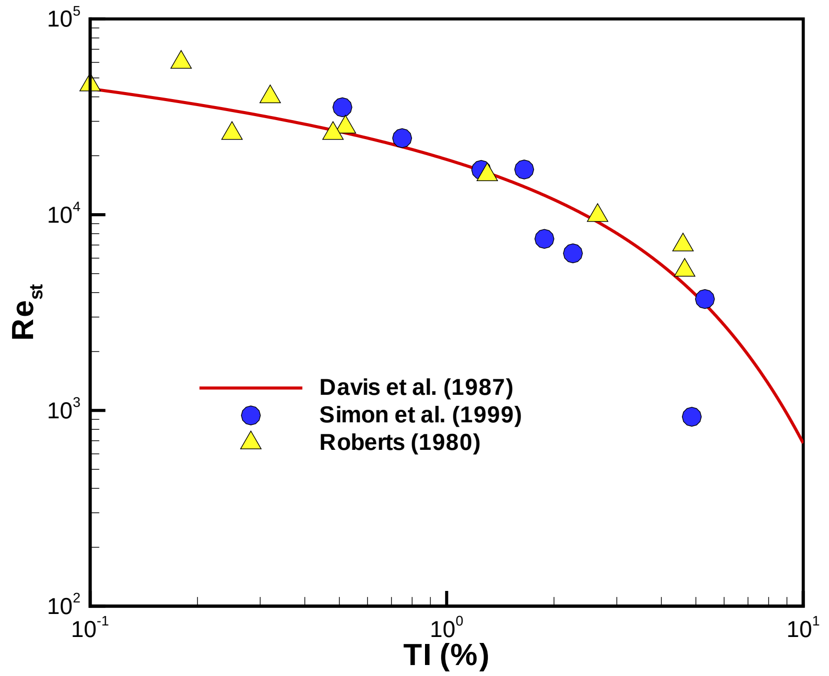
$$Re_{\theta_t} = (120 + 150\,Tu^{-2/3})\coth[4(0.3 - K_t \times 10^5)]$$



Implementation

Onset of separated flow transition (Davis *et al*., 1987)

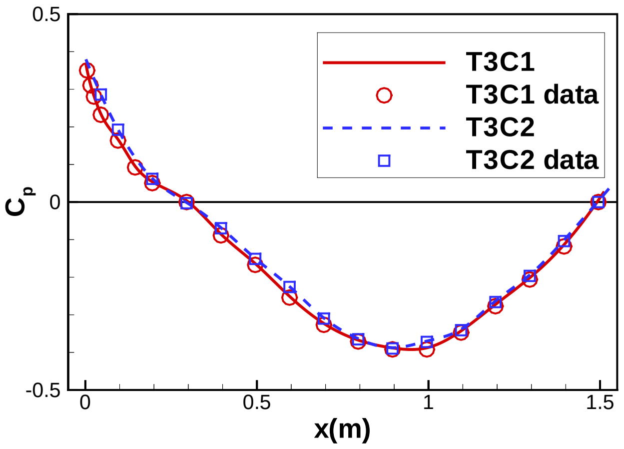
$$Re_{\mathrm{st}} = 2.5 \times 10^4 \log_{10} \coth(0.1732 Tu)$$



ERCOFTAC Test Cases

Benchmark Cases for Transitional Flows:

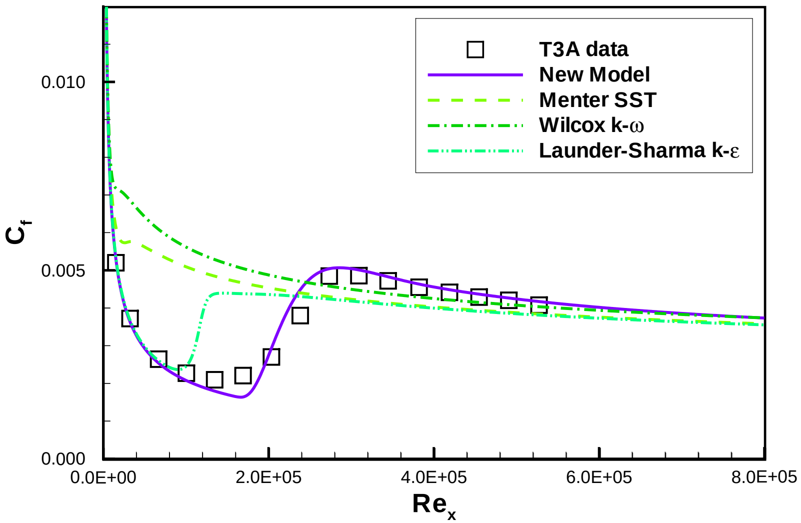
- Zero pressure gradient
  - T3A case, FSTI = 3.3%
  - T3B case, FSTI = 6.2%
- Favorable-to-adverse pressure gradient (Aft-loaded turbine blade)
  - T3C1 case, FSTI = 7.8%
  - T3C2 case, FSTI = 2.8%



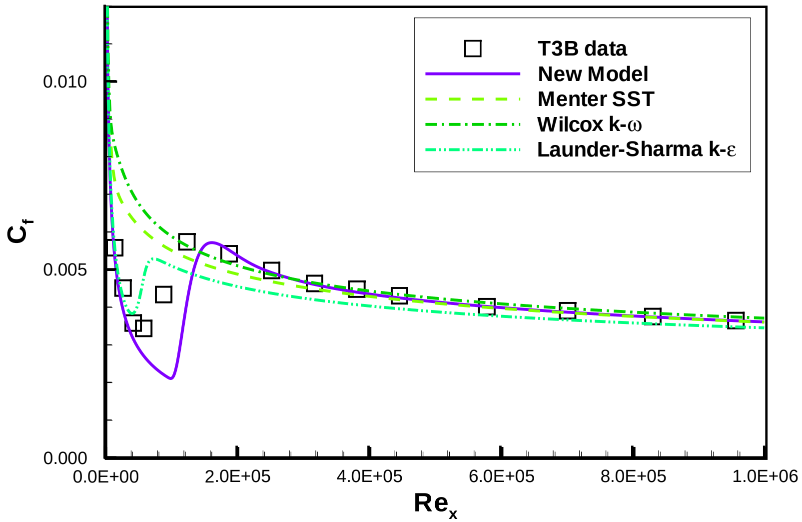
ERCOFTAC Test Cases

Zero pressure gradient:

FSTI=3.3%



FSTI=6.2%

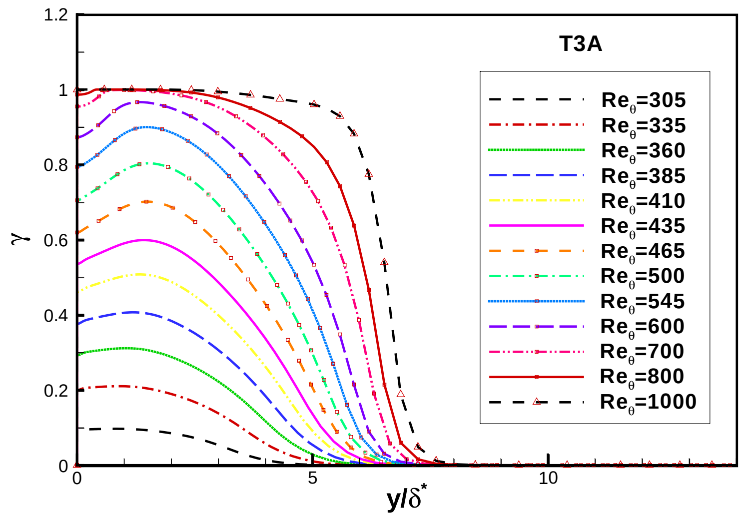


Skin friction coefficient distributions

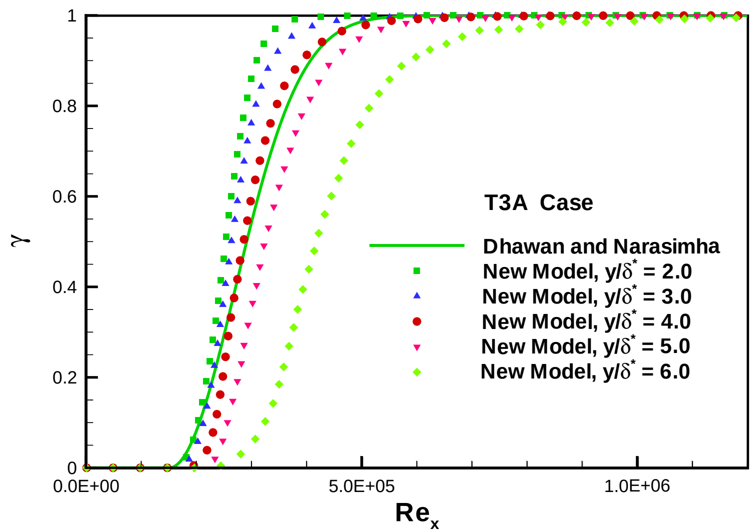
ERCOFTAC Test Cases

Variation of γ through transition region

Zero pressure gradient, FSTI=3.3%



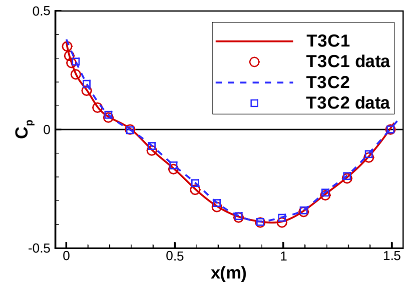
γ profiles



Streamwise γ variation

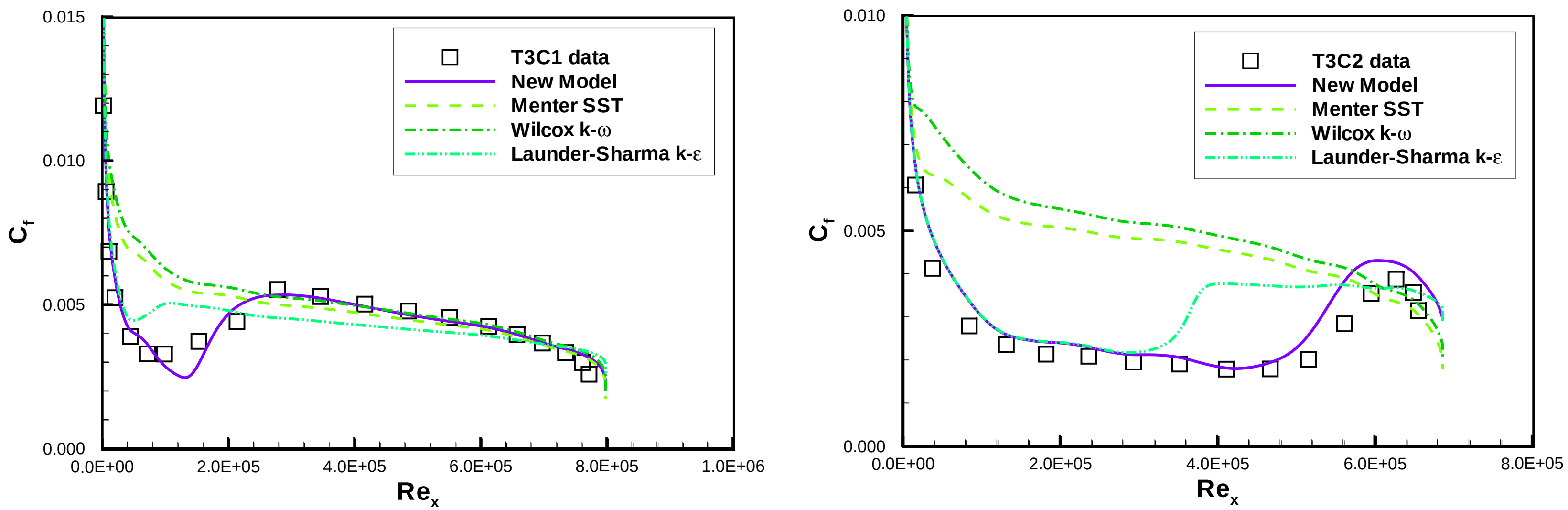
ERCOFTAC Test Cases

<u>**Variable pressure gradient:**</u>



FSTI=7.8%

FSTI=2.8%

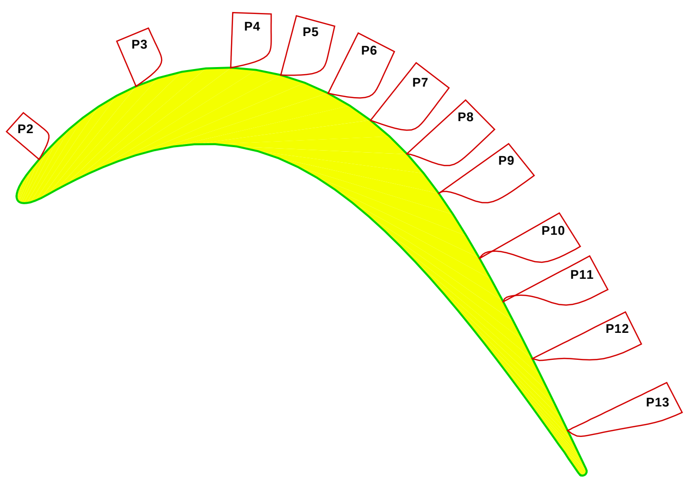


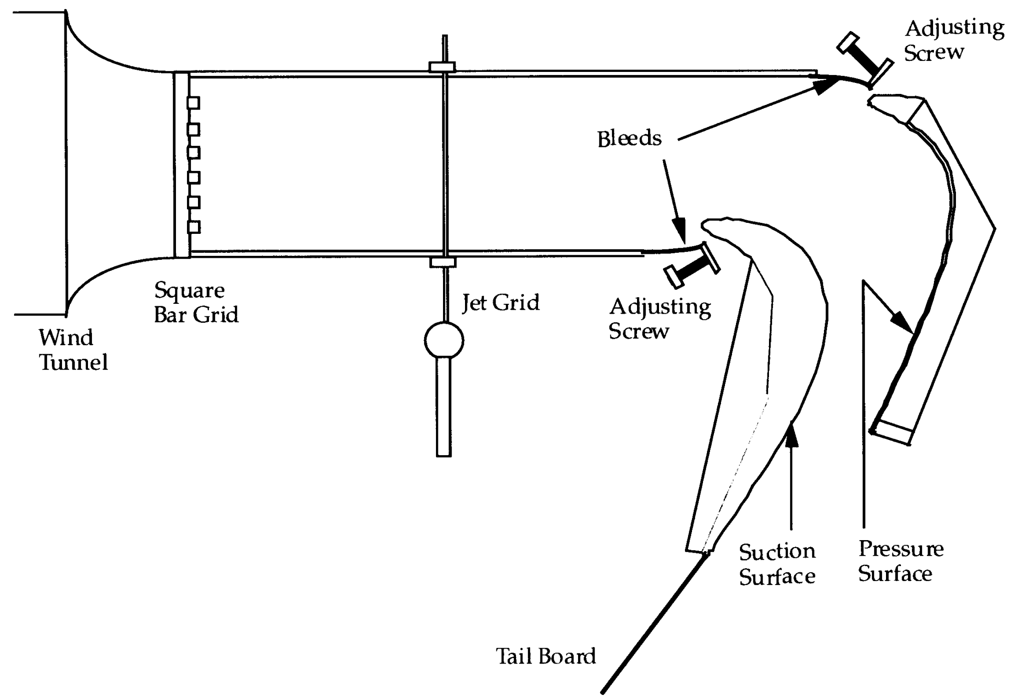
Skin friction coefficient distributions

Low-Pressure Turbine Flows

<u>Experiments of Simon *et al*. (1999):</u>

- 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



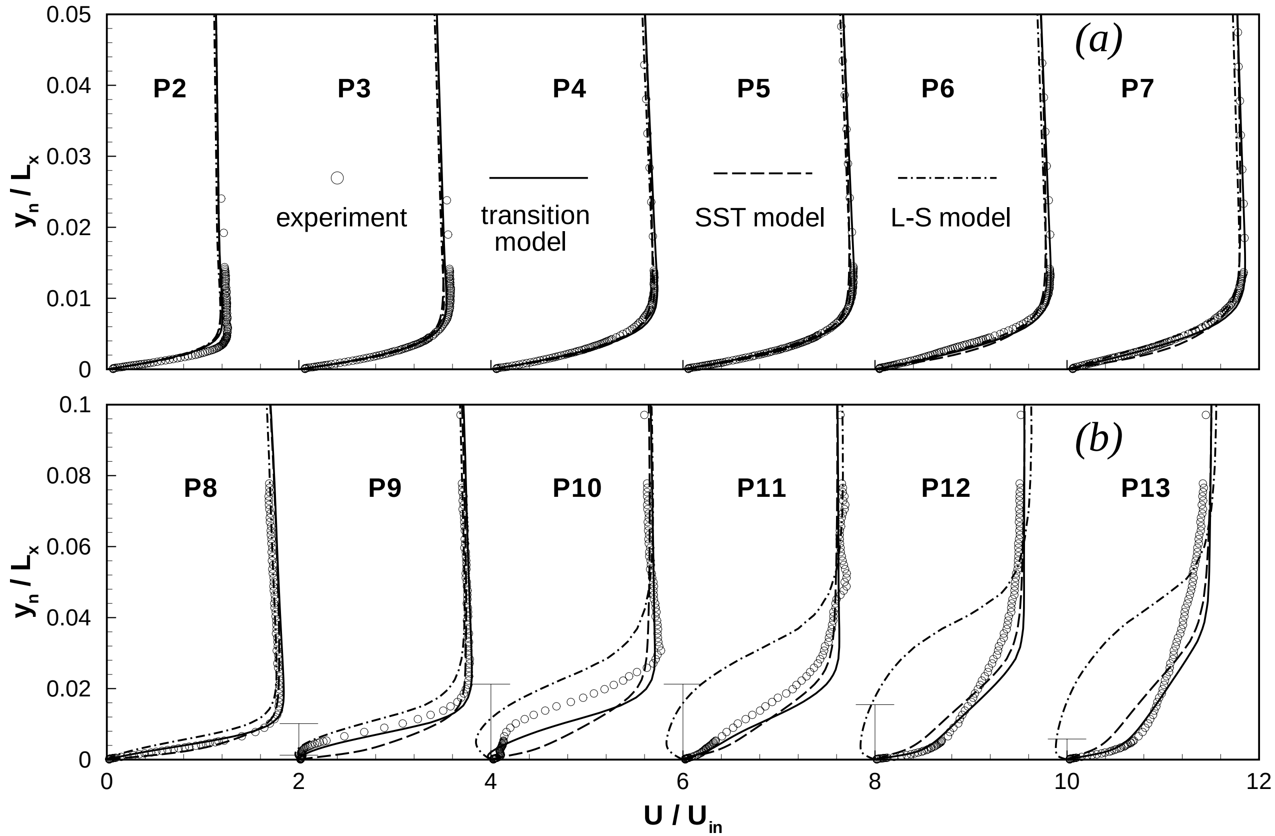


Low-Pressure Turbine Flows

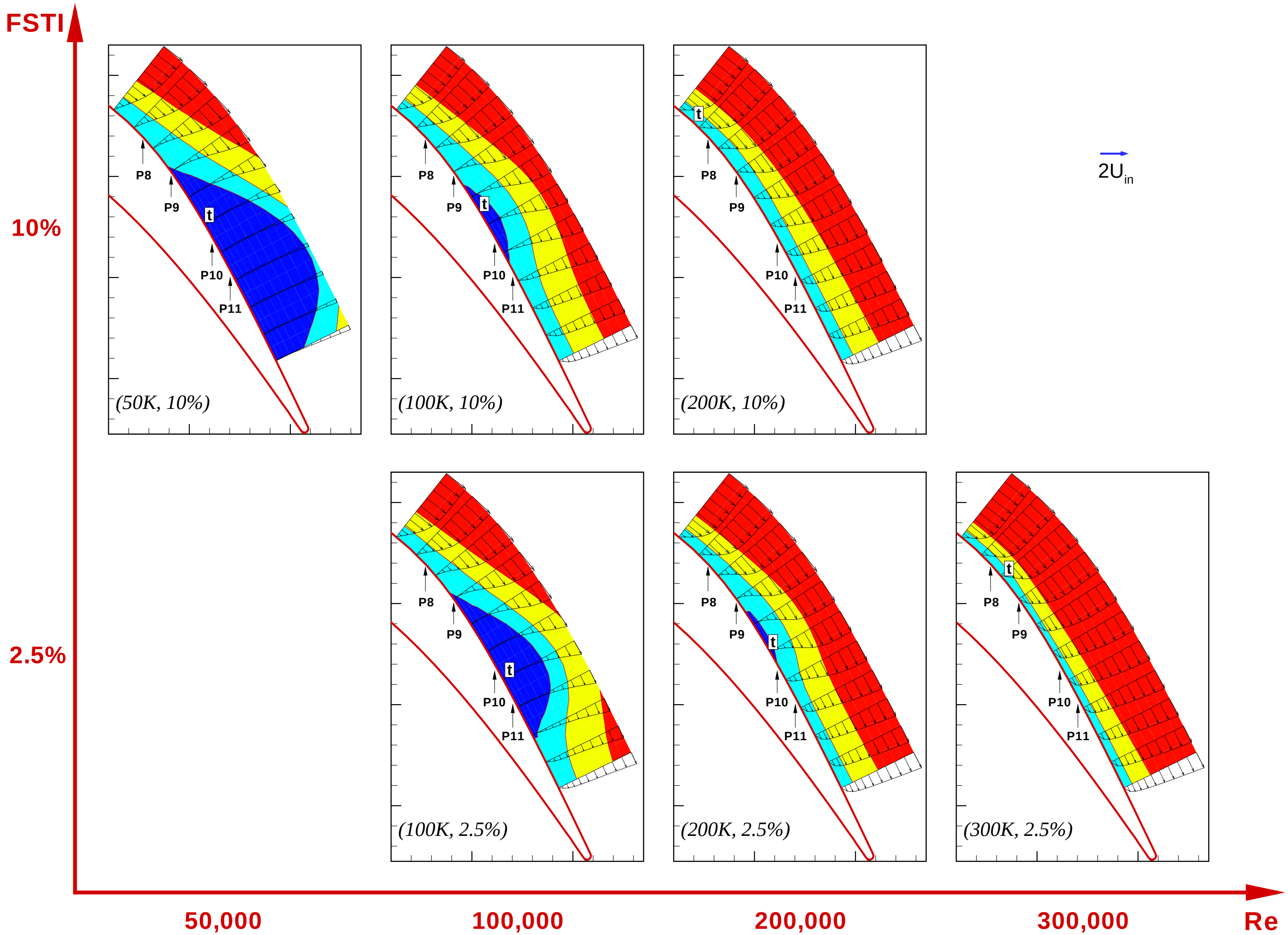
NASA/CP—2001-210888

Transition model vs. "pure" turbulence models

Re = 100,000   FSTI=10%

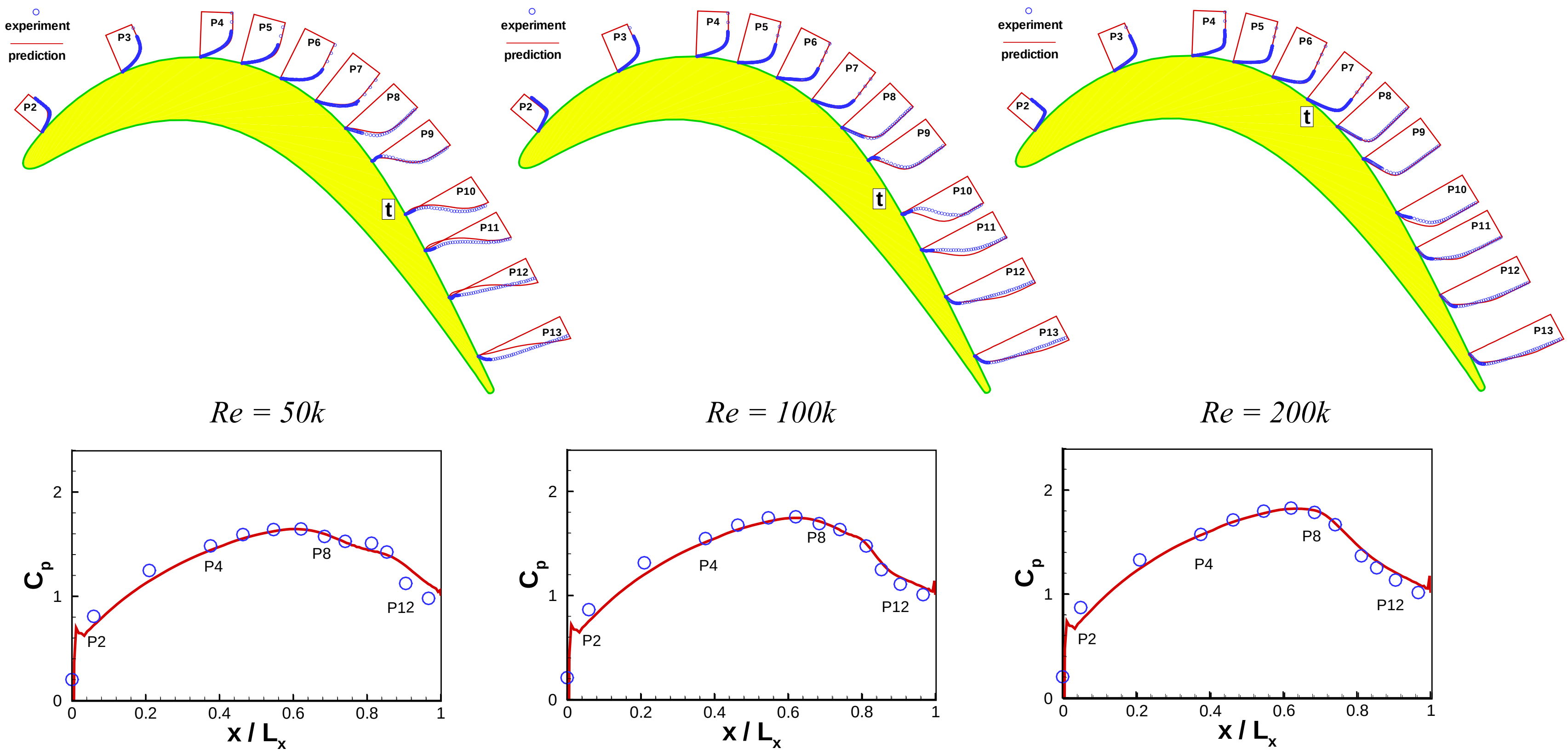


Low-Pressure Turbine Flows



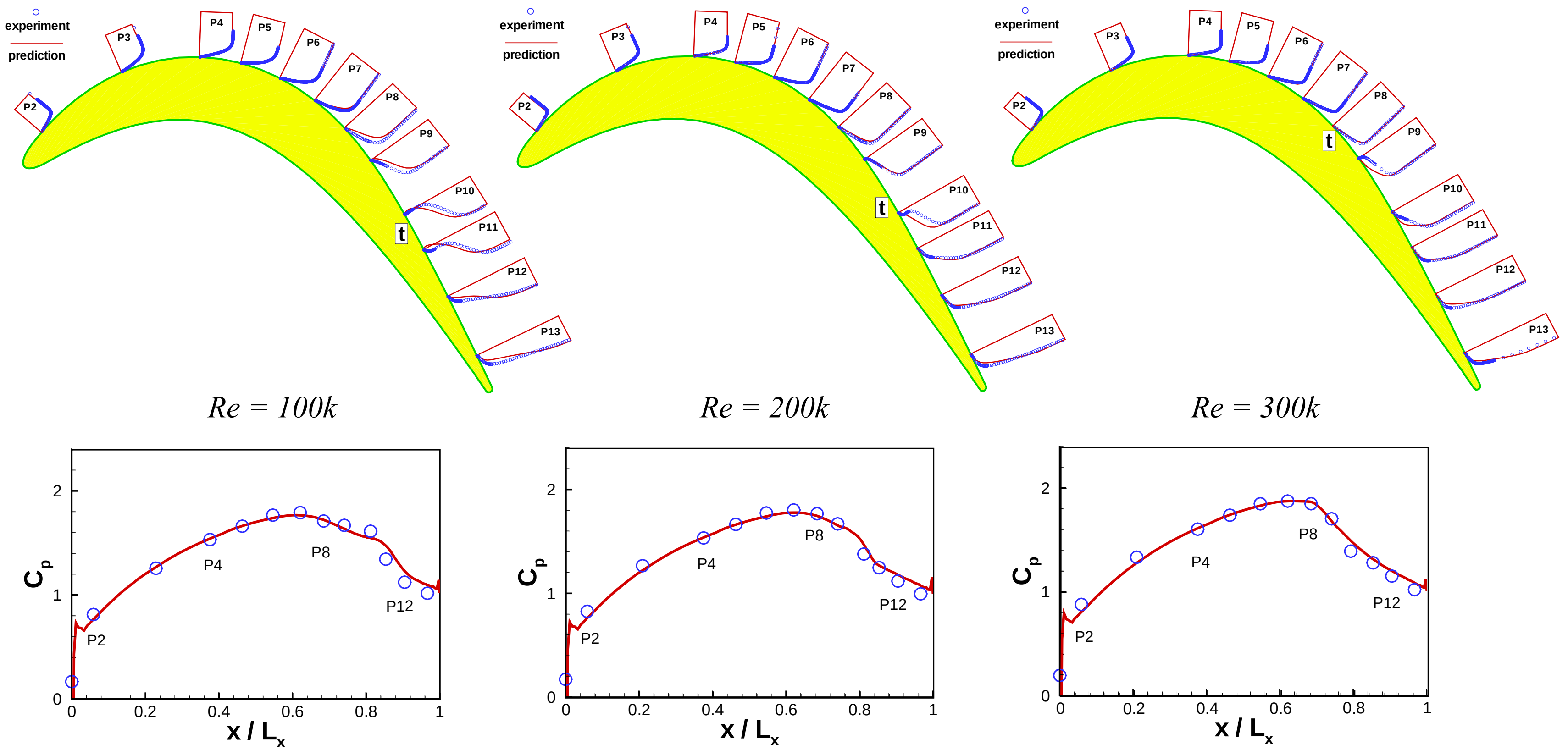
Low-Pressure Turbine Flows

FSTI = 10%



Low-Pressure Turbine Flows

FSTI = 2.5%



Conclusions

- A new transport equation for intermittency is developed for modeling transitional flows.
    - Streamwise γ distribution of Dhawan and Narasimha
    - Realistic γ distribution in cross-stream direction
- New model is used to compute
    - ERCOFTAC benchmark cases
        - Zero pressure gradient: FSTI = 3.3%, 6.2%
        - Variable pressure gradient: FSTI = 7.8%, 2.8%
    - Low-Pressure Turbine experiments of Simon *et al*.(1999)
        - FSTI=2.5%, Re = 100k, 200k, 300k
        - FSTI=10%, Re = 50k, 100k, 200k
- Good comparisons with the experimental data are obtained for all cases.

ERCOFTAC TRANSITION MODELLING SPECIAL INTEREST GROUP

THEMATIC NETWORK TRANSPRETURB: TRANSITION PREDICTION METHODS FOR TURBOMACHINERY AND OTHER AERODYNAMIC FLOWS

Erik Dick
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Department of Flow, Heat, and Combustion Mechanics
Gent, Belgium

The interest group and thematic network have 25 participating research groups from universities, research institutes and industry. There are 5 subgroups: “Intermittency and Simple Model Approaches” studies intermittency concept based methods and integral methods; “Eddy Viscosity Models” studies two-equation approaches, including non-linear extensions like NLEVM and EARSM; “Reynolds Stress Transport Models”; “Transition Simulation” mainly uses LES as analysis tool and as means to create numerical data bases; “Experimental Data”, aims at near-reality test cases, both steady and unsteady. The thematic network receives EC funding for the period September 1998 to August 2001. The thematic network has as objective to come to models for bypass transition which can be used in everyday industrial practice. The industrial partners insist on methods with sufficient generality but without much complexity. This implies that integral methods are considered as not general enough and that approaches based on conditionally averaged equations and approaches using RSM are seen as too complex. The technique preferred by the industrial partners is two-equation turbulence models (k-ε and k-ω types, two-layer types), with or without non-linear extensions, complemented with an intermittency transport equation. As a consequence of this industrial preference, in practice there is no strict distinction between the activities of the subgroups 1,2 and 3. Subgroups 2 and 3 have formally merged and some partners are active in different subgroups.

For the development of models, it was agreed to use a sequence of test cases with increasing complexity: T3L, semi-circular leading edge (Rolls-Royce data), to be used by all partners working on modelling, especially T3L1 (0.2 % fst) and T3L3 (3% fst); further, to be used by as many partners as appropriate: T3H, flat plate with heat transfer, 5% fst (Kiev data); T3K, linear turbine cascade (Ercoftac Turbomachinery Sig data): T3K (Durham), T3K+(Lyon); T106, unsteady turbine cascade (Cambridge data); IGV-rotor-stator (Tasmania data). Additionally, Subgroup 1 uses VKI linear turbine cascade data. Subgroups 2 and 3 use DNS data for laminar separation bubble induced transition, DNS data for oscillating flat plate boundary layer, DNS data for wake passing transition, all three data from Stanford. Subgroup 4 works at LES simulations of the cases T3L and T106 with and without wake passage (Surrey). Fundamental DNS simulations have been done (Stockholm). Subgroup 5 works at experiments on a steam turbine IGV/rotor (Genua), a steam turbine rotor/stator (Czestochowa), a multi-stage compressor (Cranfield). Experimental work on T3L with and without wake passage (Thessaloniki and Brussels) is finished at this moment.

Some industrial partners (Rolls-Royce, Alstom) have up to now been concentrating on validating their existing codes for T3L and T3K, often with a rough transition model, typically based on Abu-Ghannam and Shaw correlations with turbulence shut off upstream of transition. Other industrial partners (BMW-RR,KEMA) implement a specific model (Dresden and Delft). TU.Delft, Umist and U.Thessaloniki work on RSM and k-ε models without use of an intermittency equation. Some successful results were obtained. AEA, U.Roma3, U. Gent, Institute of Thermomechanics Prague and U. Cambridge work at k-ε and k-ω types linked with an intermittency transport equation. The most encouraging results up to now have been obtained by U. Cambridge with a two equation k-ε model and the intermittency equation coming from the SLY-RSM or a prescribed intermittency method. U. Leicester and U. Liverpool work at fundamental experiments and simulations of the behaviour of turbulent spots with the aim to improve intermittency correlations or intermittency equations. The Institute of Thermomechanics Prague works with the same aim on fundamental experiments on the effect of the turbulence length scale on transition.

Ref: Ercoftac Bulletin No 45,June 2000, p7-10.

ERCOFTAC TRANSITION MODELLING SPECIAL INTEREST GROUP

THEMATIC NETWORK TRANSPRETURB: TRANSITION PREDICTION METHODS FOR TURBOMACHINERY AND OTHER AERODYNAMIC FLOWS

Erik Dick
Ghent University, Department of Flow, Heat and Combustion Mechanics
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The interest group and thematic network have 25 participating research groups from universities, research institutes and industry.

There are 5 subgroups:

"Intermittency and Simple Model Approaches" studies intermittency concept based methods and integral methods;

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"Reynolds Stress Transport Models";

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"Experimental Data", aims at near-reality test cases, both steady and unsteady.

The thematic network receives EC funding for the period September 1998 to August 2001.

Workshops:

London, September 23, 1998 (kick-off)

Cambridge, March 25-27, 1999 (workshop 1)

Genoa, March 9-10, 2000 (workshop 2)

Ghent, March 7-9, 2001 (workshop 3)

The thematic network has as objective to come to models for bypass transition which can be used in everyday industrial practice.

The industrial partners insist on methods with sufficient generality but without much complexity.

This implies that integral methods are considered as not general enough and that approaches based on conditionally averaged equations and approaches using RSM are seen as too complex.

The technique preferred by the industrial partners is
two-equation turbulence models (k-ε and k-ω types, two-layer types),
with or without non-linear extensions,
complemented with an intermittency transport equation.

Test Cases used by the modelling groups

sequence of test cases with increasing complexity:

T3L, semi-circular leading edge (Rolls-Royce data),
to be used by all partners working on modelling,
especially T3L1 (0.2 % fst) and T3L3 (3% fst);

further, to be used by as many partners as appropriate:
T3H, flat plate with heat transfer, 5% fst (Kiev data) ;
T3K, linear turbine cascade (Ercoftac Turbomachinery Sig data):
T3K(Durham), T3K+(Lyon);
T106, unsteady turbine cascade (Cambridge data);
IGV-rotor-stator (Tasmania data).

Additionally,
Subgroup 1 uses VKI linear turbine cascade data.
Subgroups 2 and 3 use
DNS data for laminar separation bubble induced transition,
DNS data for oscillating flat plate boundary layer,
DNS data for wake passing transition,
all three data from Stanford.

Further development of test cases

Subgroup 4

LES simulations of the cases T3L and T106
with and without wake passage (Surrey).
Fundamental DNS simulations have been done (Stockholm).

Subgroup 5

Experiments on
a steam turbine IGV/rotor (Genoa),
a steam turbine rotor/stator (Czestochowa),
a multi-stage compressor (Cranfield).

Experimental work on T3L with and without wake passage (Thessaloniki and Brussels) is finished at this moment.

Industrial Participants

Rolls-Royce, Alstom

validating their existing codes for T3L and T3K,
often with a rough transition model,
typically based on Abu-Ghannam and Shaw correlations with turbulence shut off upstream of transition.

BMW-RR, KEMA
implement a specific model (Dresden and Delft).

EVM and RSM without intermittency equation

TU. Delft
UMIST
U. Thessaloniki

Example: RSM TU. Delft

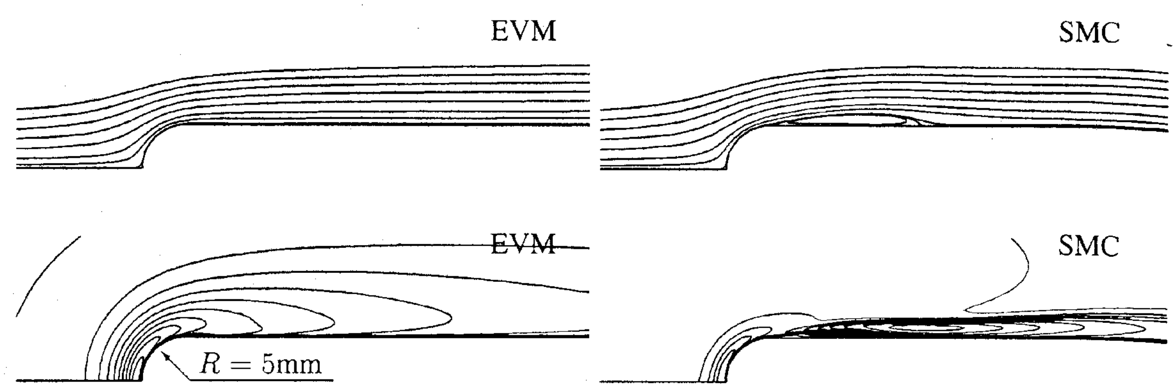

Figure 1: Computed stream lines and contours of turbulence kinetic energy k for T3L4 case obtained with EVM and SMC, $Re = U_o 2R/\nu = 3333$. For the value of k see Fig. 3.

Hadzic, Hanjalic
Flow, Turbulence and Combustion, Vol 63, 2000, p153-173.
Separation-induced transition to turbulence: second-moment closure modelling

EVM with intermittency equation

AEA
U. Roma3
U. Gent
I. Thermomechanics Prague
U. Cambridge

Example: U. Cambridge: k-ε Yang-Shih+Durbin limiter
eddy viscosity multiplied with γ
γ from SLY (Cho&Chung) or PUIM
T3L3

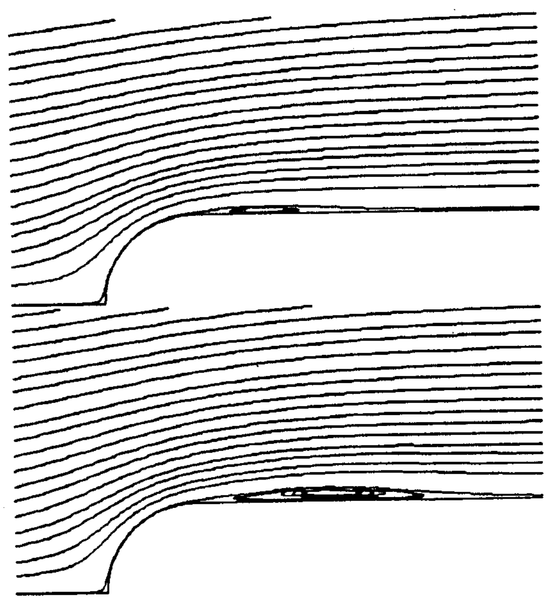

Figure 2: Streamlines of the flow around the plate: $k - \varepsilon$ model (top); $k - \varepsilon$-PUIM (bottom).

Vicedo, Vilmon, Dawes, Hodson, Savill
Proc. 8th European Turbulence Conference, Barcelona, July 2000
The extension of CFD-friendly turbulence modelling to include transition

Fundamental experiments and simulations

U.Leicester
U.Liverpool
I.Thermomechanics Prague

Example: IT.Prague; influence of length scale

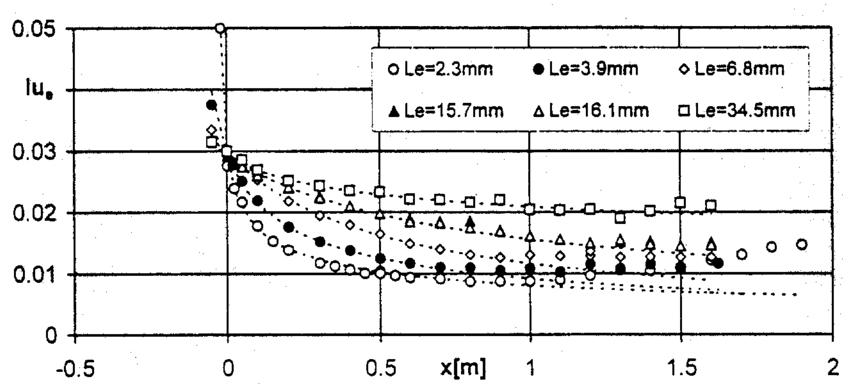

Fig. 2 Free stream turbulence intensity distributions

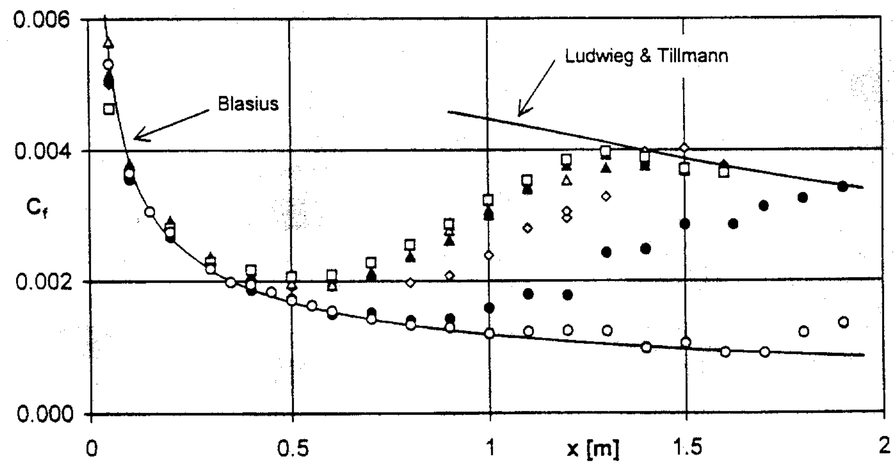

Fig. 5 Skin friction coefficient distributions along the plate; key as in Fig.4

Jonas,Mazur,Uruba
Proc. 3rd European Conf. Turbomachinery Fluid Dynamics and Thermodynamics,London,March 1999
Experiments on bypass boundary layer transition with several turbulence length scales

Realism of the industrial target

EVM or RSM without γ? No

EVM with γ? Yes

Examples from other groups:

Y.B Suzen and P.G. Huang
Modelling of flow transition using an intermittency transport equation
Journal of Fluids Engineering, June 2000

Intermittency: mixture equations SD and CC
T3A, T3B,T3C

J. Hu and T. Fransson
Numerical performance of transition models in different flow conditions: a comparative study
ASME Turboexpo, Munich, May 2000

Baldwin-Lomax+prescribed intermittency
VKI linear cascade

MODELLING OF BY-PASS TRANSITION BY MEANS OF A TURBULENCE WEIGHTING FACTOR

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Noordwijk, The Netherlands

E. Dick
Ghent University
Department of Flow, Heat, and Combustion Mechanics
Gent, Belgium

In contrast to natural transition which emanates from the breakdown of amplified disturbances within the boundary layer, by-pass transition is caused by the free-stream turbulence affecting the pre-transitional (pseudo-laminar) layer directly by diffusion and indirectly by pressure fluctuations. If the free-stream turbulence is high enough, i.e. $Tu \geq 1\%$, the transition happens far further upstream than what would be expected for natural transition. Also the transition length is shorter and is directly related to the turbulence level.

The diffusion of turbulent eddies into the boundary layer prior to the transition onset has an intermittent character and is first localized in the outer part of the laminar boundary layer. Intermittent behaviour is also seen during the transition where the flow in the boundary layer is characterized by distinct turbulent and laminar phases alternating in function of time. The intermittent behaviour during transition has been quantified by the intermittency factor γ. This factor is the relative fraction of time during which the flow is turbulent at a certain position. It evolves from 0% at the transition point up to 100% at the end of transition.

The same relative fraction of time can be taken to quantify the intermittent behaviour of the diffusing turbulent eddies in the pseudo-laminar boundary layer. This parameter, named here as freestream factor ω, is 0% near the wall and tends to 100% in the freestream.

In intermittently changing flows, global time averages commonly used in classical turbulence modelling are not valid anymore. To describe the transitional zone and the outer layer zone, it is necessary to use conditional time averaging. These averages are taken during the fraction of time the flow is laminar or turbulent respectively. As we are only interested in the state of the flow, i.e. laminar or turbulent, at a certain position, it is sufficient to use a turbulence weighting factor $\tau(x,y)$, which is the sum of the intermittency factor $\gamma(x,y)$ and the freestream factor $\omega(x,y)$: $\tau(x,y) = \gamma(x,y) + \omega(x,y)$. As a consequence, this factor τ incorporates two effects: firstly the diffusion of freestream turbulent eddies into the boundary layer and secondly the transport and growth of the turbulent spots during transtion. Hence, this factor is 0% in the vicinity of the wall within the pretransitional boundary layer, and 100 % in the freestream and inside a fully turbulent boundary layer.

To evaluate the two-dimensional τ-value in the computational field, a transport equation is derived [1]:

$$\frac{\partial \bar{\rho}\,\tilde{u}\tau}{\partial x} + \frac{\partial \bar{\rho}\,\tilde{v}\tau}{\partial y} = \frac{\partial}{\partial x_i}\left[\mu_\tau \frac{\partial \tau}{\partial x_i}\right] + P_\tau - C_3 \mu_\tau \frac{\tilde{c}}{\tilde{c}_\infty^2}\frac{\partial \tilde{c}}{\partial n}\frac{\partial \tau}{\partial n},$$

which also accounts for the effects of turbulence intensity, pressure gradient and compressibility on the spot growth rate. The wall-value of τ is set to zero only at the wall prior to transition onset. The latter is described by a correlation [1]. This transport model in combination with the conditioned Navier-Stokes equations [2] has been validated with success on both flat plates and turbine cascades.

References

[1] Steelant J., and Dick E., 'Prediction of By-Pass Transition by Means of a Turbulence Weighting Factor -Part I: Theory and Validation, -Part II: Application on Turbine Cascades', ASME-GT-029 and ASME-GT-030, 1999.

[2] Steelant J., and Dick E., 'Modelling of Bypass Transition with Conditioned Navier-Stokes Equations Coupled to an Intermittency Transport Equation', *Int. J. of Numerical Methods in Fluids*, Vol. 23, 193-220, 1996.

Modelling of By-Pass Transition by Means of a Turbulence Weighting Factor.

J. Steelant

Section of Aerothermodyamics
ESTEC-ESA
The Netherlands

E. Dick

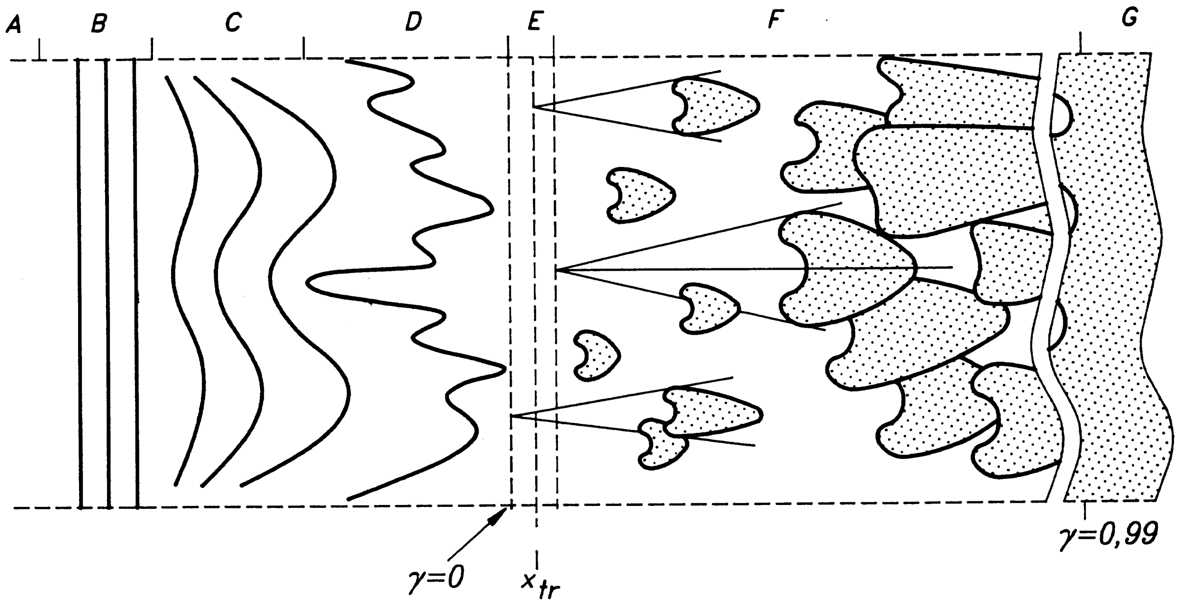
Department of Flow, Heat and Combustion Mechanics
Universiteit Gent
Belgium

Outline

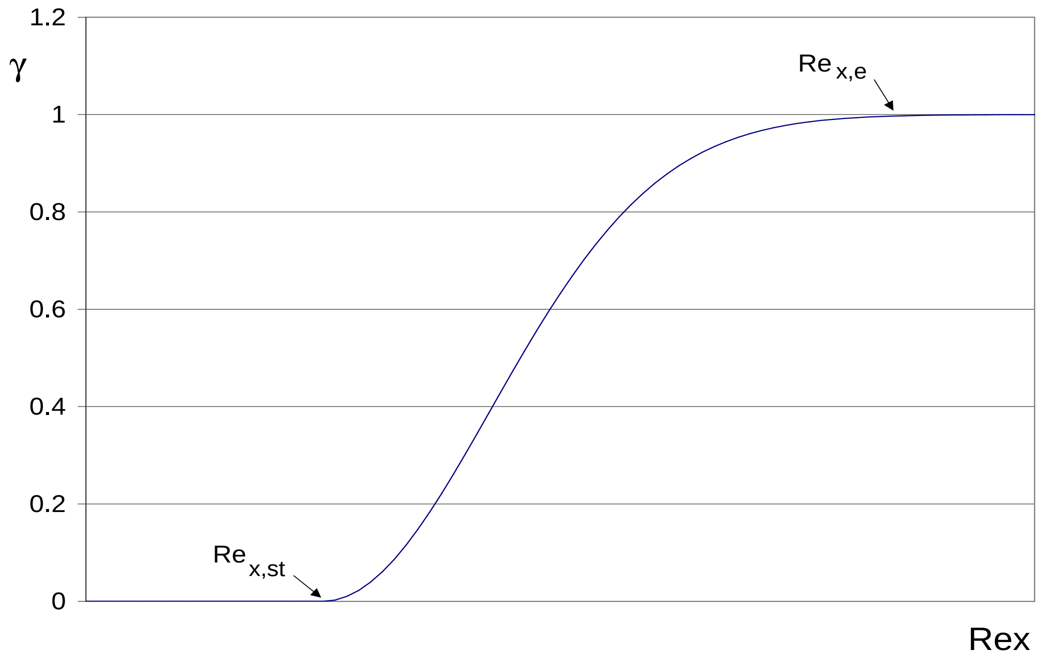
1. Transition: background
   - Natural: intermittency factor γ
   - By-pass: turbulence weighting factor τ
2. Transition Models
3. Transport equation for τ
4. Applications
   - Flat plate
   - Turbine guide vane
5. Conclusions

Natural transition

Plan view:



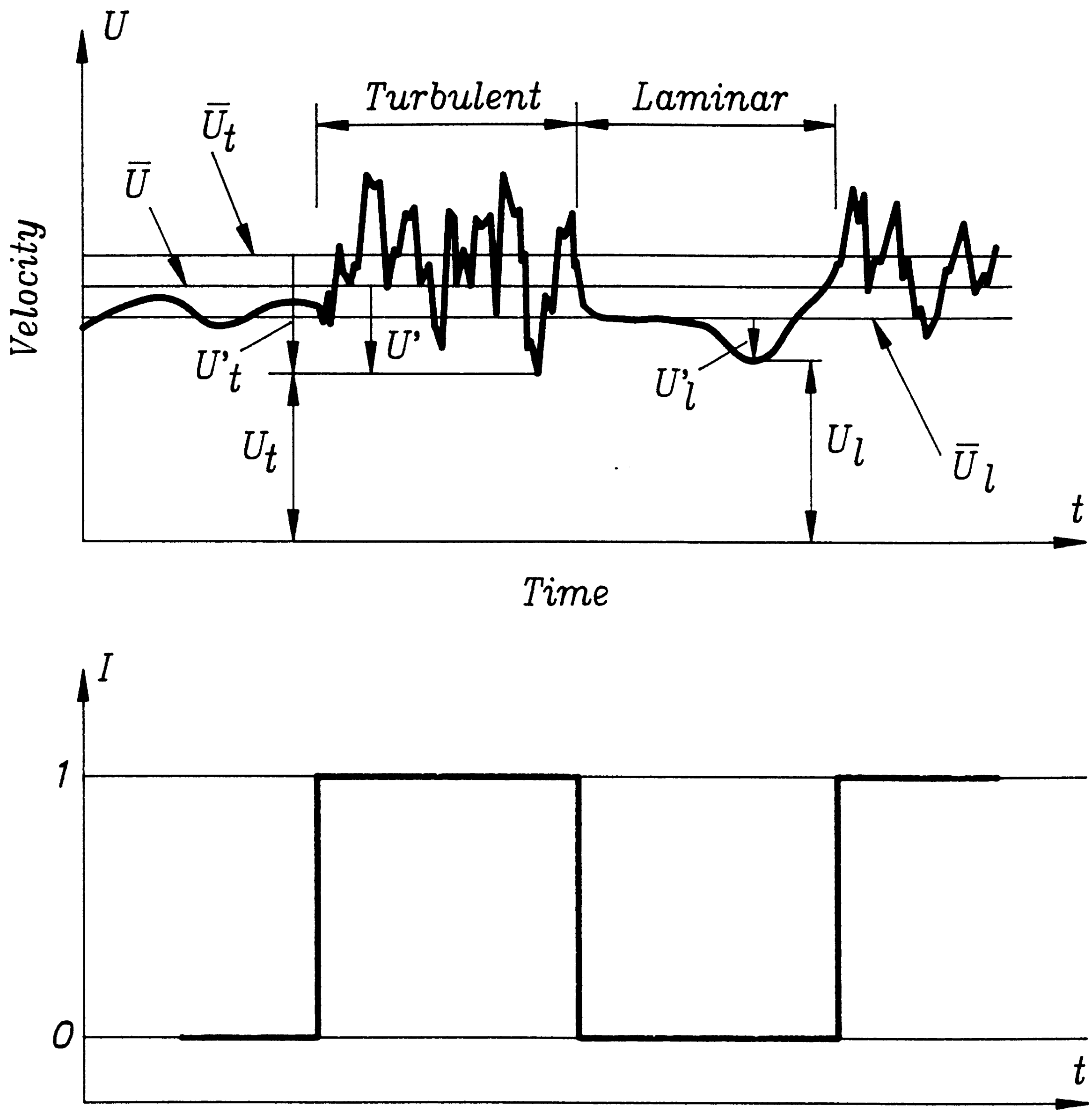
Intermittency factor: γ



$$\gamma = 1 - \exp\left[-\hat{n}\sigma\left(Re_x - Re_{x_{st}}\right)^2\right]$$

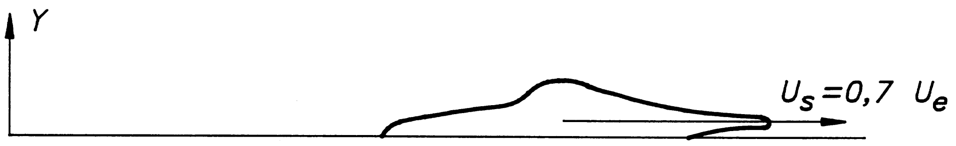
Natural transition

Probe signal:

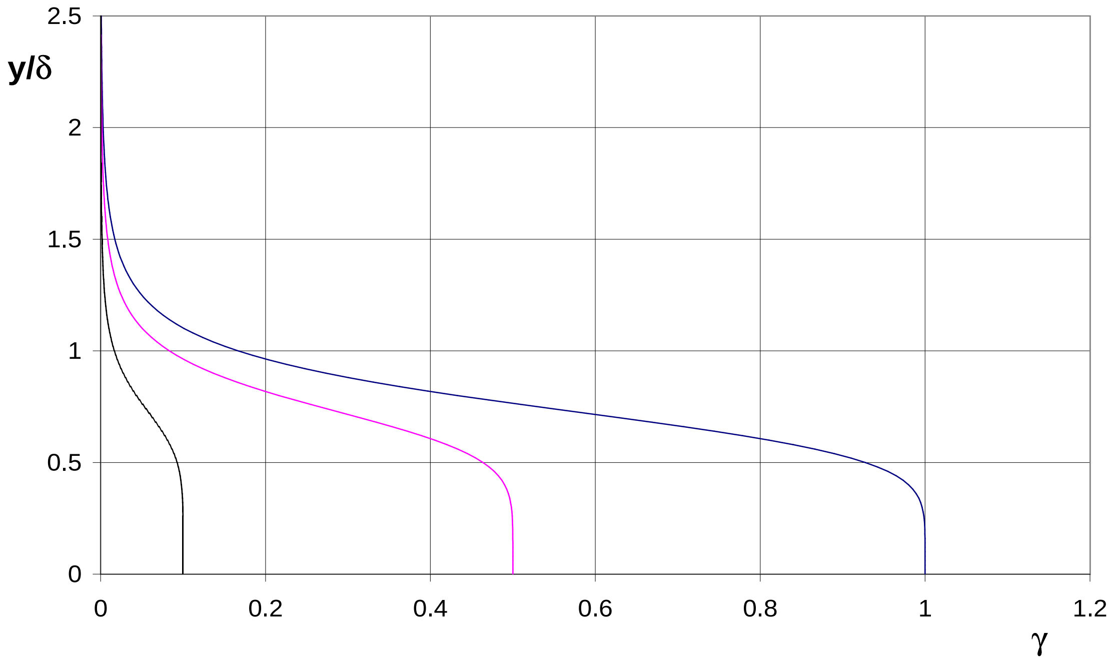


Natural Transition

Side view:



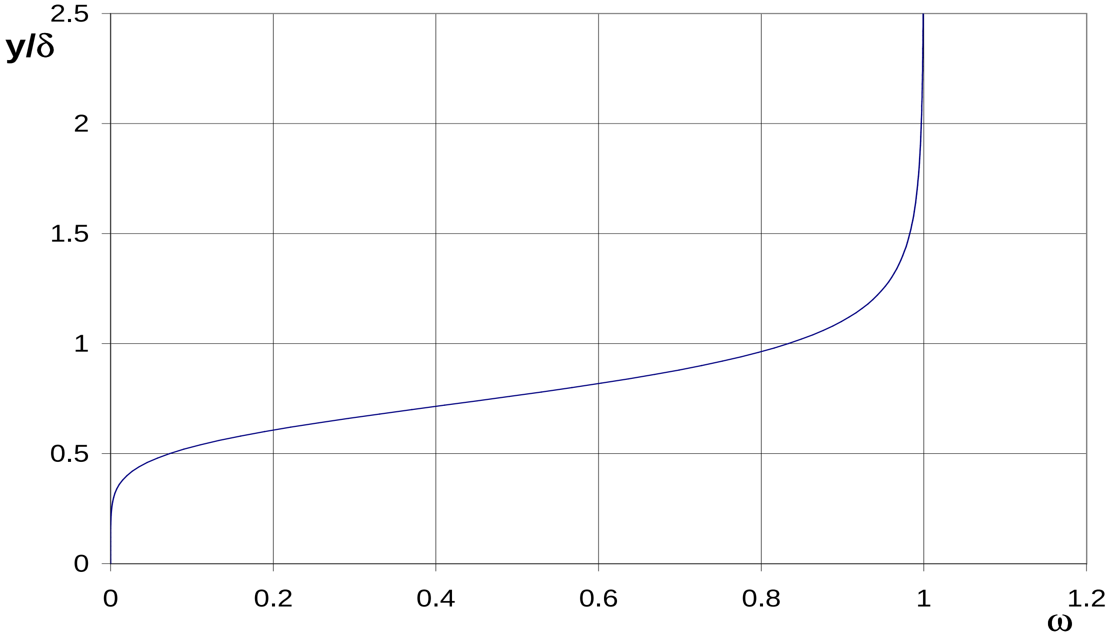
Edge intermittency factor: γ



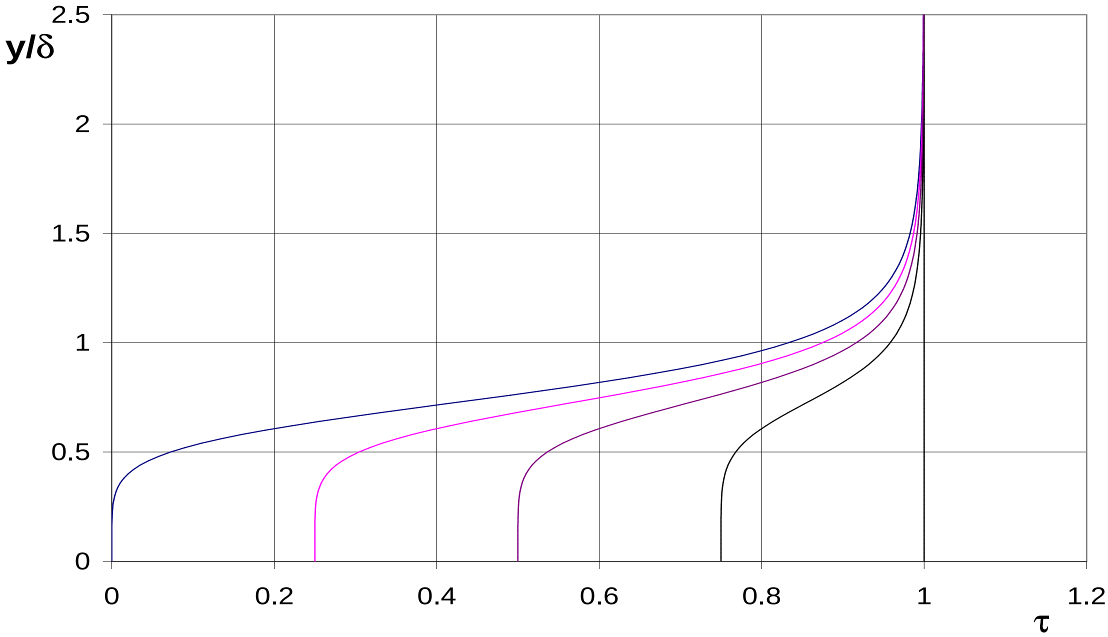
$$\gamma = \frac{\gamma_w}{1 + 5\left(\frac{y}{\delta}\right)^6}$$

By-Pass Transition

Freestream factor ω:



Turbulence weighting factor: $\tau = \gamma + \omega$



Transition models

1. *Linear Combination model:*

   Laminar N.S.: $F_l(\Phi_l) = 0 \quad \rightarrow \quad \Phi_l$

   Turbulent N.S.: $F_t(\Phi_t) = 0 \quad \rightarrow \quad \Phi_t$

   $\Phi = (1 - \tau)\Phi_l + \tau\Phi_t$

   $\rightarrow$ No Interaction between both phases

2. *Conditioned Navier-Stokes equations:*

   Laminar N.S.: $F_l(\Phi_l) = S_l(\Phi_l, \Phi_t, \tau) \quad \rightarrow \quad \Phi_l$

   Turbulent N.S.: $F_t(\Phi_t) = S_t(\Phi_l, \Phi_t, \tau) \quad \rightarrow \quad \Phi_t$

   $\Phi = (1 - \tau)\Phi_l + \tau\Phi_t$

   $\rightarrow$ Interaction between both phases

Turbulence Weighting Factor τ: Determination.

1. *Algebraic model:*
   Combination of Narasimha-law and Klebanoff-function
2. *Differential method:*

$$\frac{\partial \overline{\rho}\, \tilde{u} \tau}{\partial x} + \frac{\partial \overline{\rho}\, \tilde{v} \tau}{\partial y} = D_\tau + P_\tau - E_\tau$$

with
- D_τ: diffusion of freestream turbulence towards wall.

$$D_\tau = \frac{\partial}{\partial x_i}[\mu_\tau \frac{\partial \tau}{\partial x_i}]$$

- E_τ: dissipation of near wall fluctuations induced by freestream.

$$E_\tau = 2.5 \mu_\tau \frac{\tilde{c}}{\tilde{c}_\infty^2} \frac{\partial \tilde{c}}{\partial n} \frac{\partial \tau}{\partial n}.$$

- P_τ: growth of turbulent spots.

$$P_\tau = 2 f_\tau (1-\tau) \sqrt{-\ln(1-\tau)}\, \beta \overline{\rho}\, \tilde{c}$$

$$\beta \text{ dependent of } \begin{cases} \text{Start of transition} \\ \text{Distributed breakdown} \\ \text{Turbulence level} \\ \text{Turbulence length scale} \\ \text{Pressure gradient} \\ \text{Compressibility} \\ \text{Shock wave} \end{cases}$$

Test Cases

Flat plate with sharp leading edge:

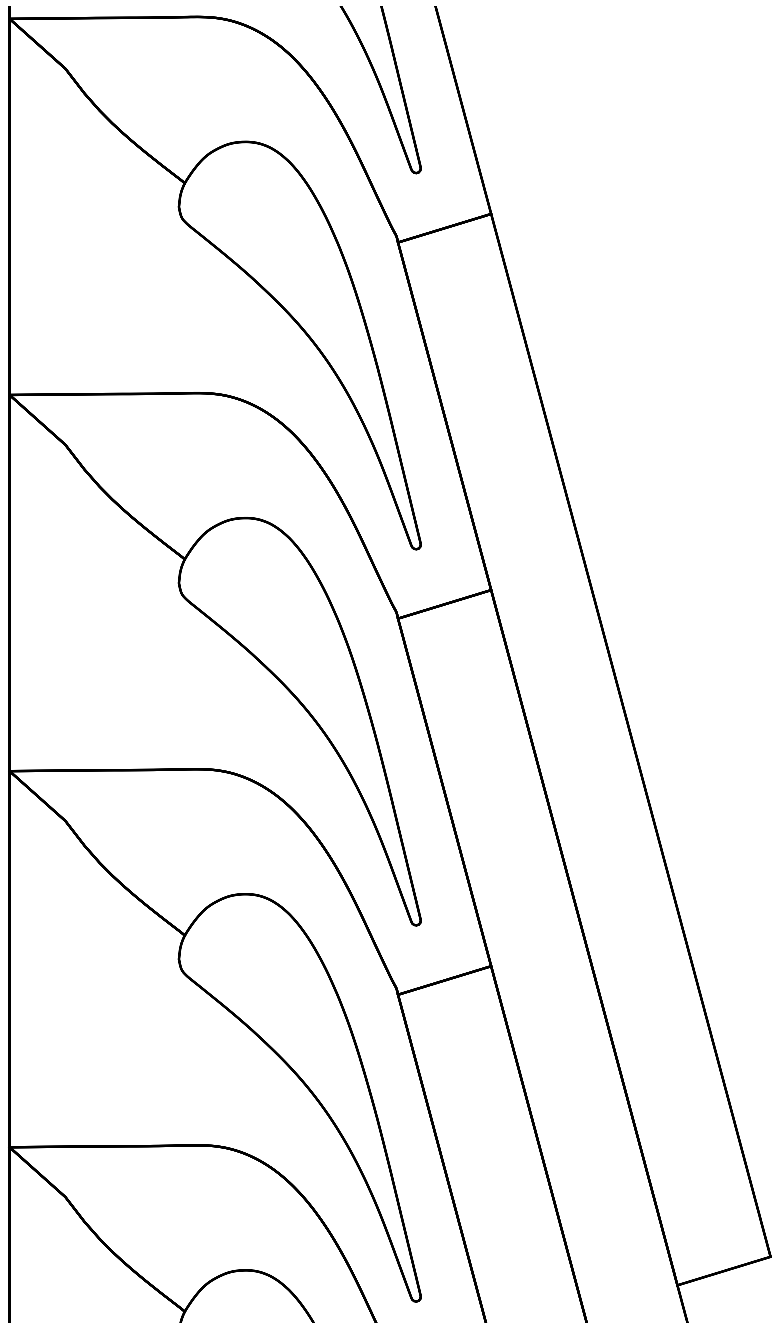
Case	$U_\infty (m/s)$	$Tu_{le}(\%)$
T3A	5.0	3.14

Turbine guide vane:

Case	$M_{2,is}$	$Tu_i(\%)$	Tu_{le} (%)	$Re_{c,2}$
MUR239	0.922	6	4.52	2.10^6
MUR245	0.924	4	3.34	2.10^6
MUR241	1.089	6	4.52	2.10^6

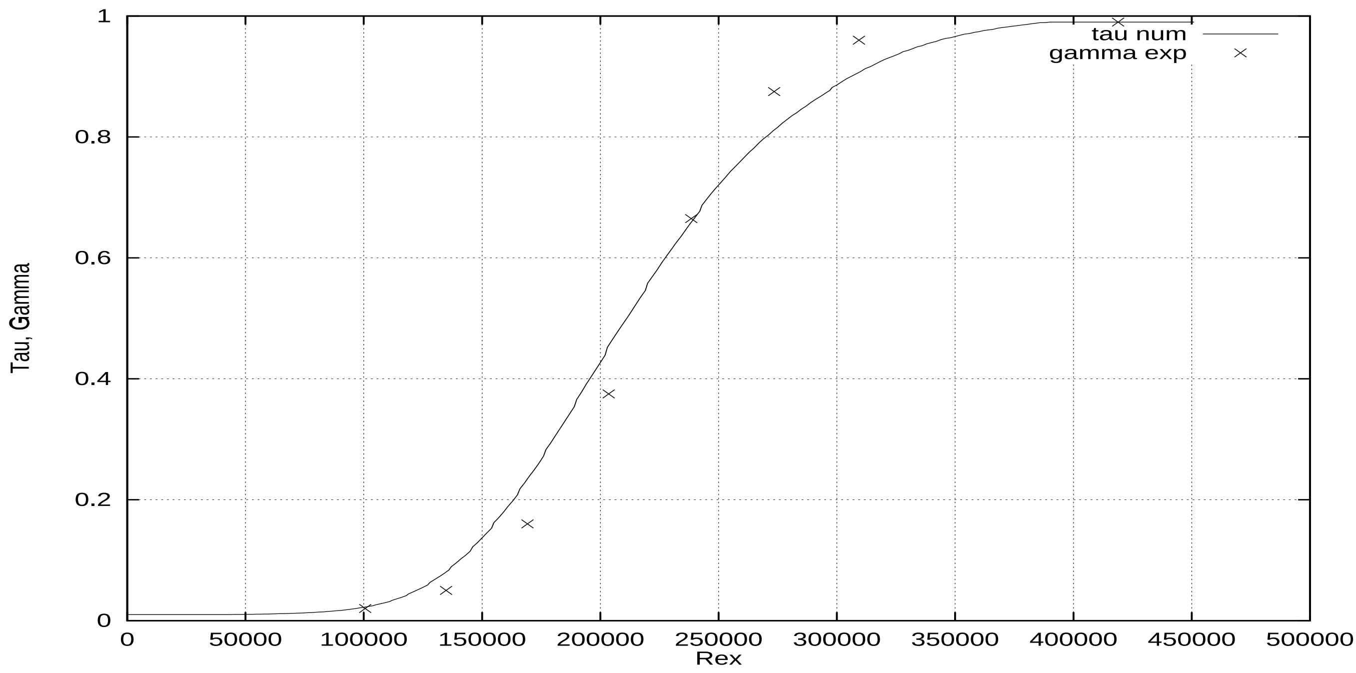
Turbine Guide Vane: mesh

2 blocks:
- O-mesh: 433×73
- H-mesh: 217×49

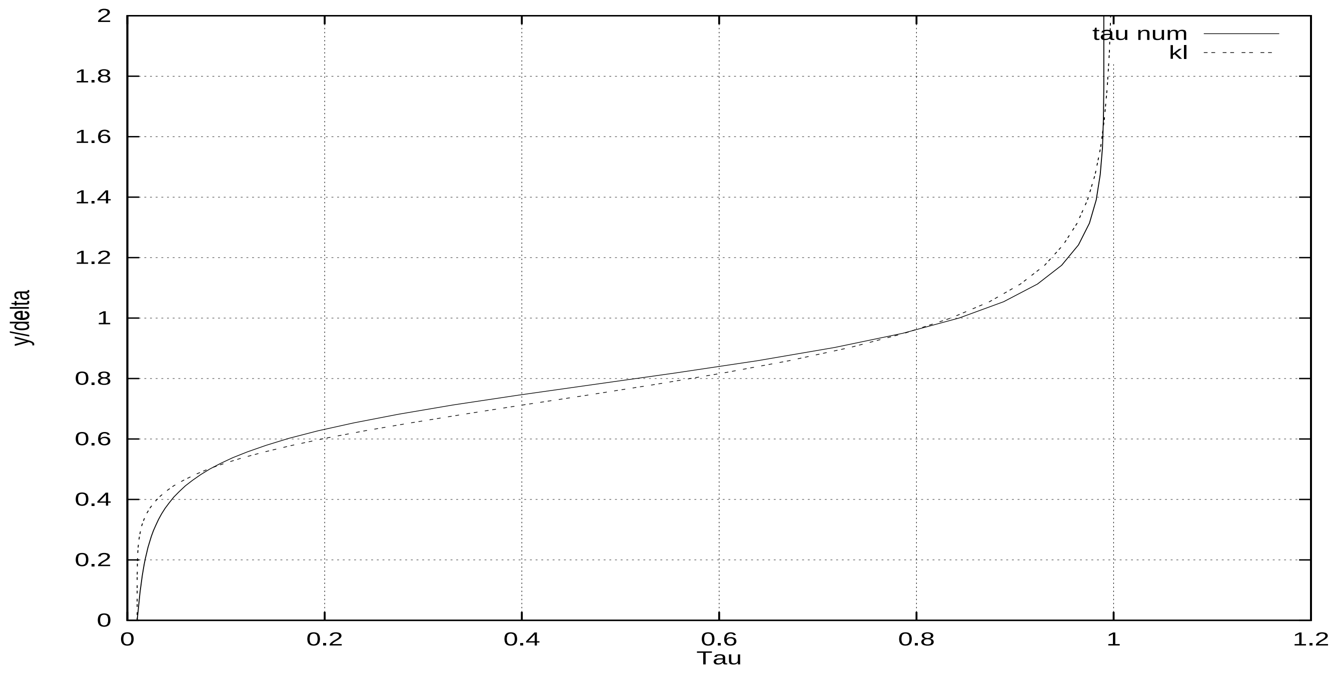


Geometry and block location of the 2D turbine cascade

Test Case T3A: flat plate

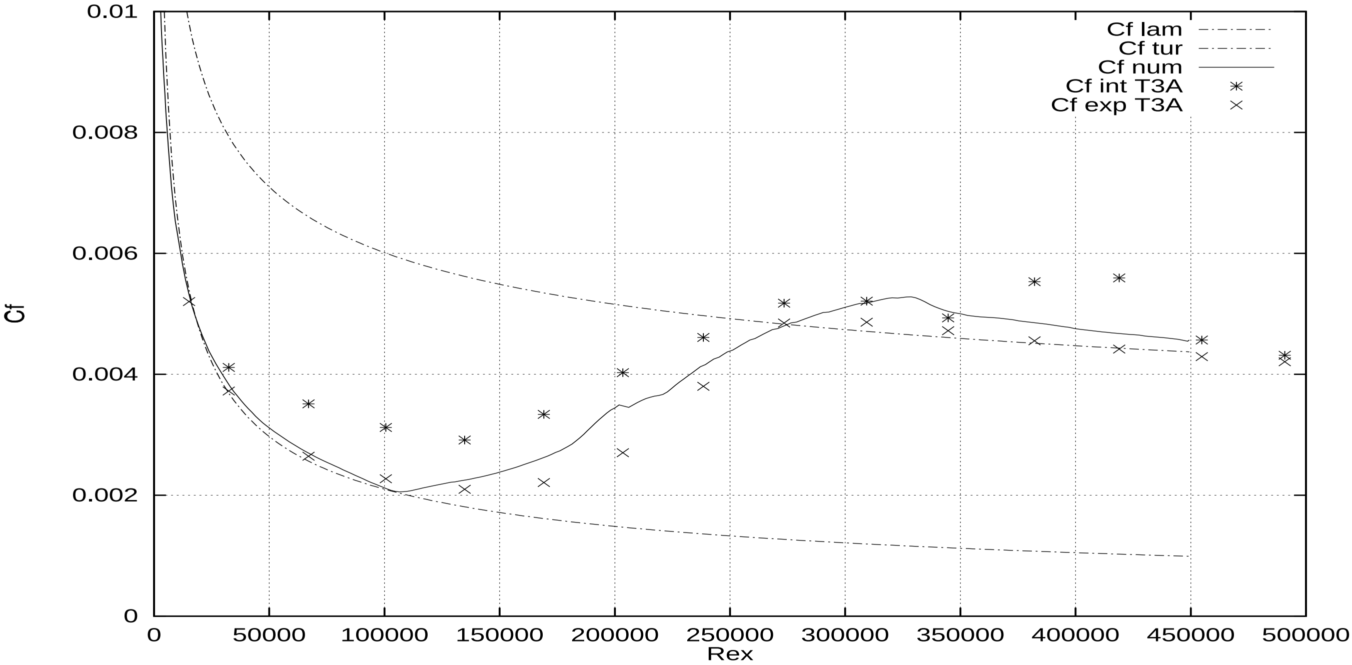


Evolution of τ along the wall compared with experimental γ values.

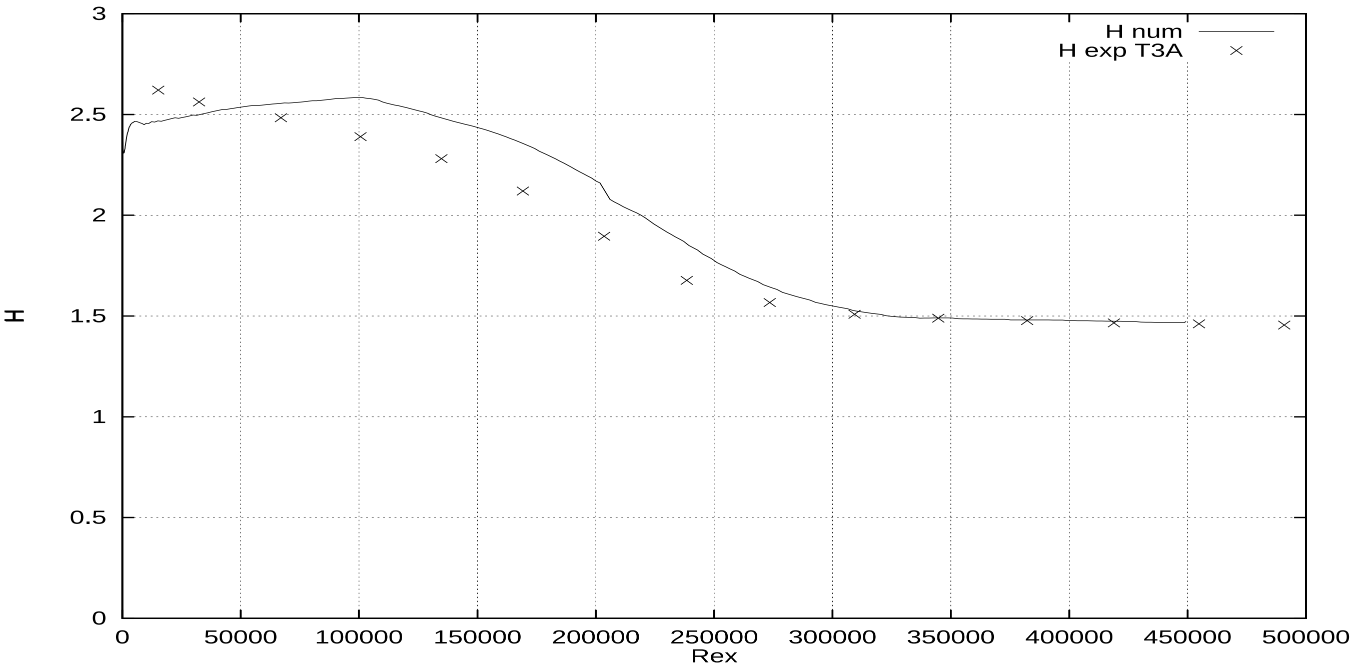


Normal variation of τ compared with the suggested free stream factor.

Test Case T3A: flat plate

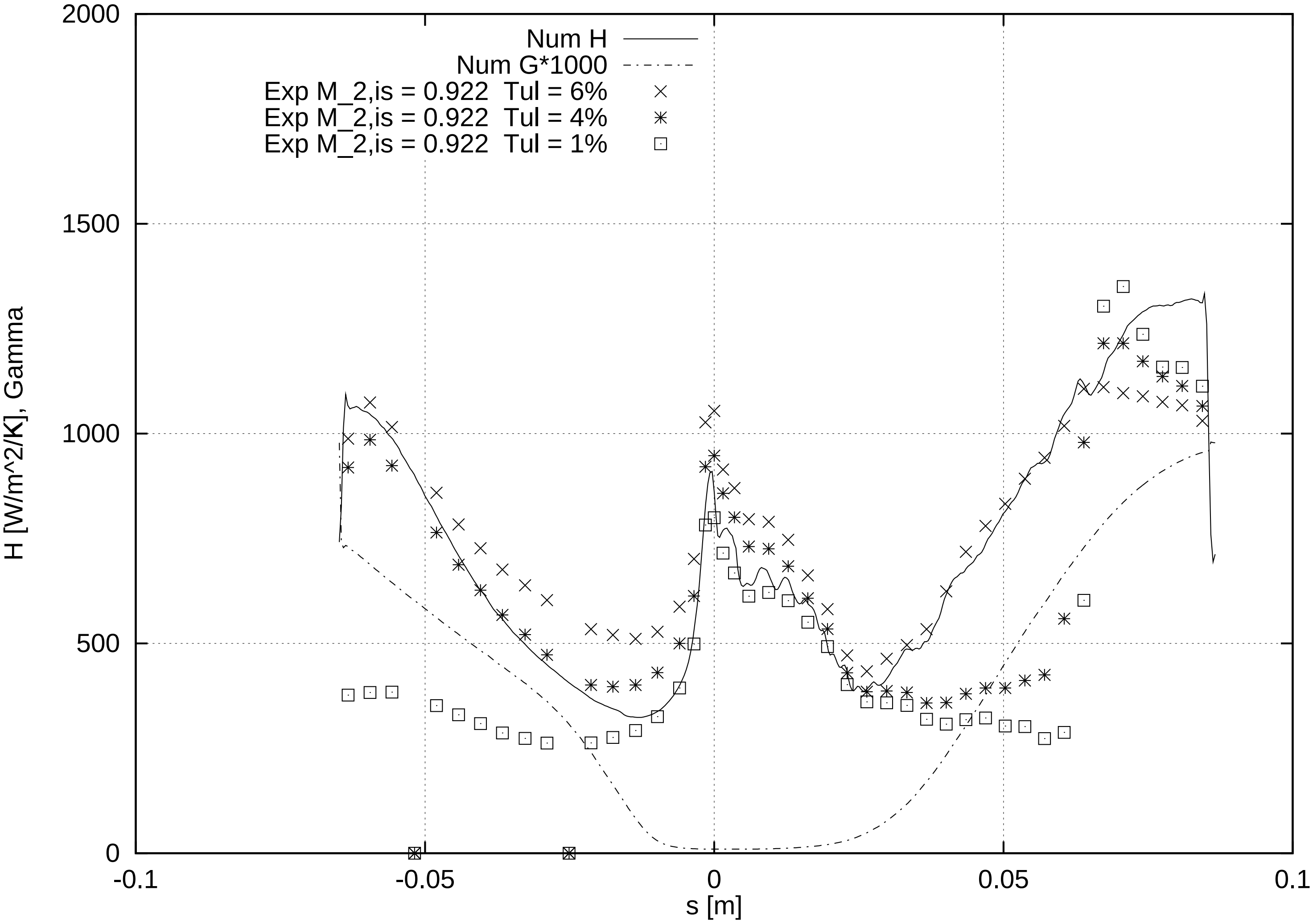


Skin friction in function of Re_x



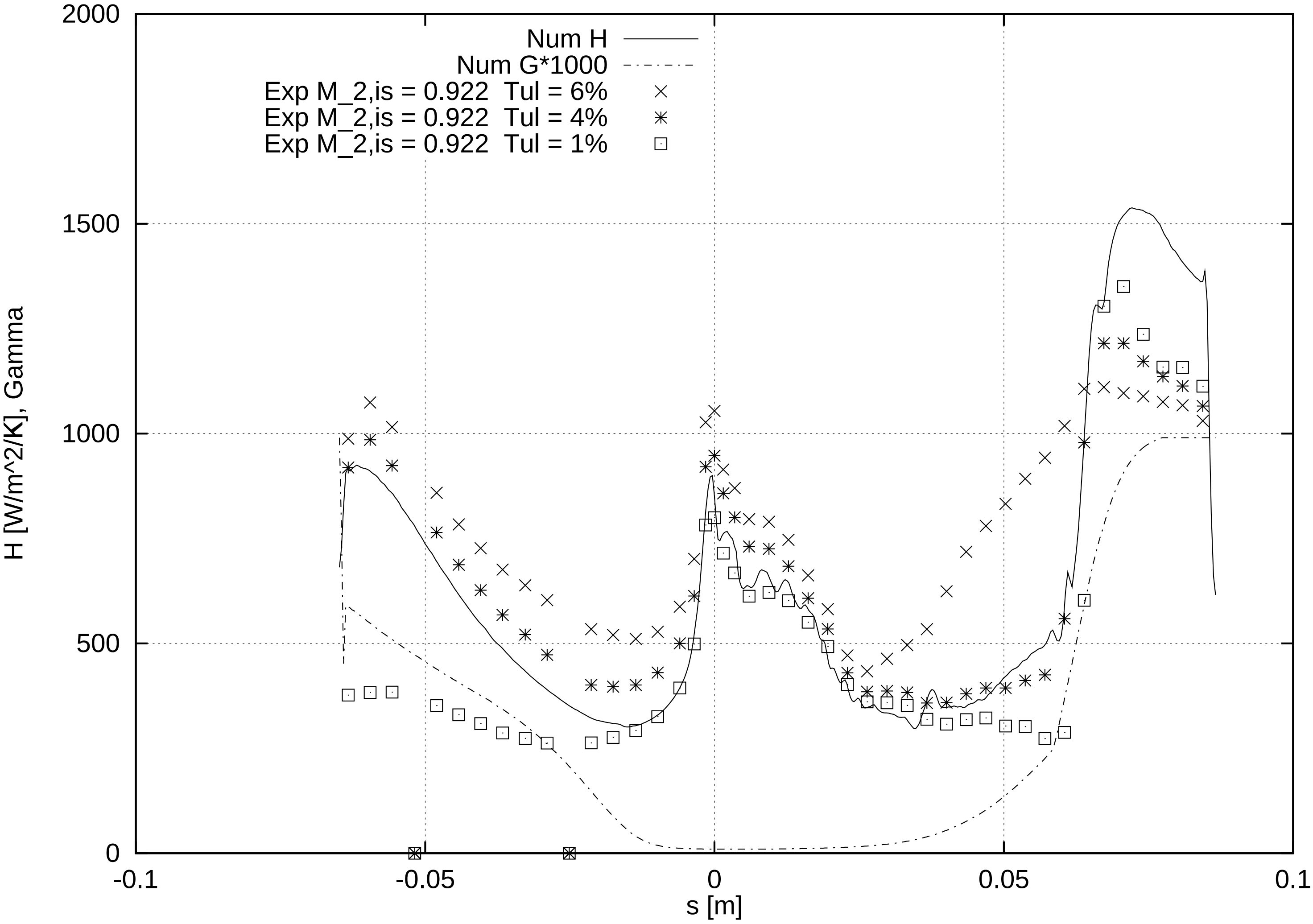
Shape factor in function of Re_x

Turbine Guide Vane: MUR239



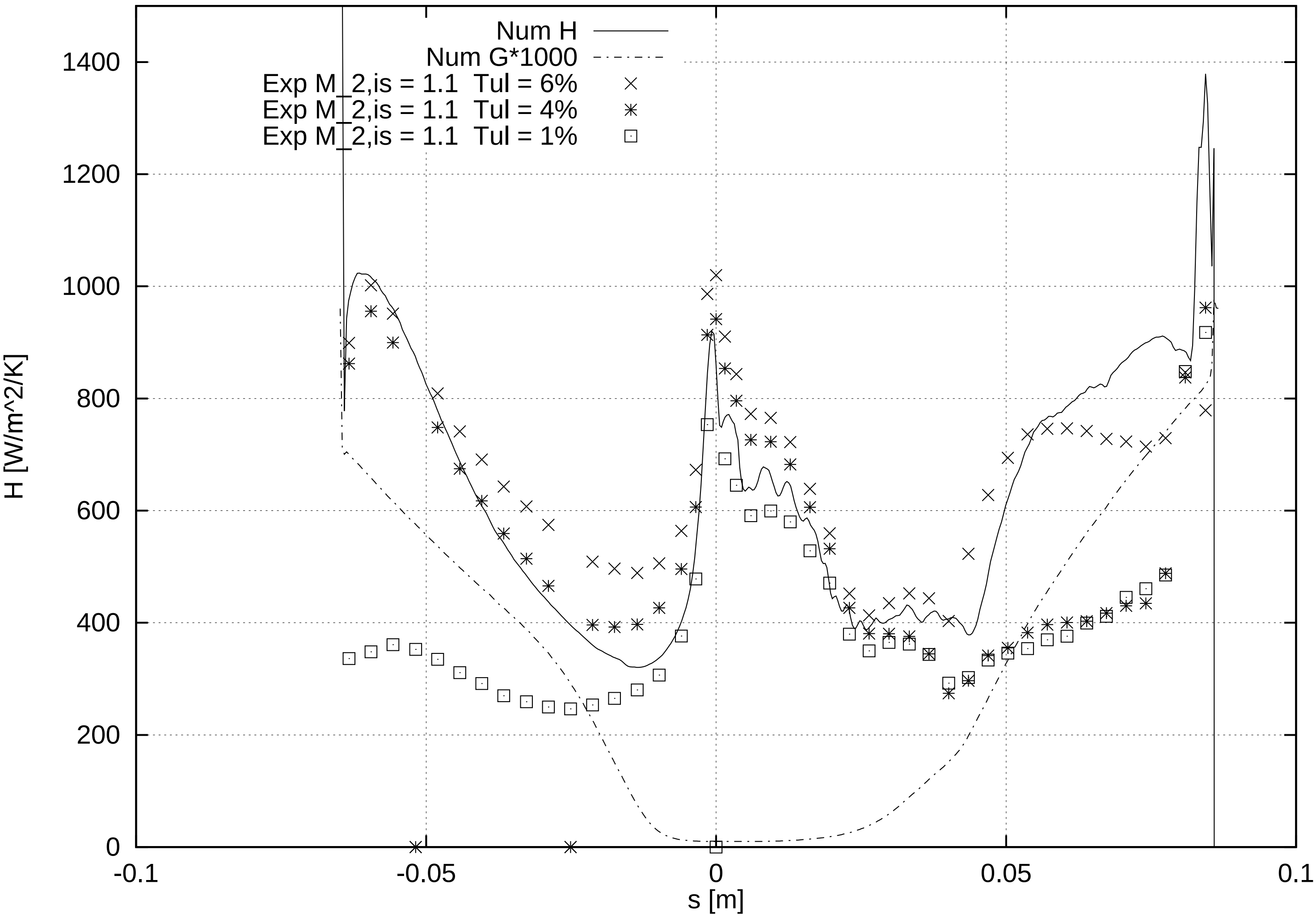
Heat transfer distribution for MUR239 (Tu_i =6 % $M_{2,is}$ = 0.922); red line: calculated heat transfer, green line: intermittency (× 1000), symbols: experiments (left: pressure side; right: suction side).

Turbine Guide Vane: MUR245



Heat transfer distribution for MUR245 (Tu_i =4 % and $M_{2,is} = 0.924$); red line: calculated heat transfer, green line: intermittency ($\times$ 1000), symbols: experiments (left: pressure side; right: suction side).

Turbine Guide Vane: MUR241



Heat transfer distribution for MUR241 (Tu_i=6% and $M_{2,is}$ = 1.089); red line: calculated heat transfer, green line: intermittency (× 1000), symbols: experiments (left: pressure side; right: suction side).

Conclusions

- Model
  - New parameter: turbulence weighting factor τ
    $\rightarrow$ separation between laminar and turbulent phase.
    -turbulent spots
    -boundary layer/freestream
  - Conditional averaging of N.S.-equation guarantees interaction between laminar and turbulent phases.
  - Transport equation for τ
- Application
  - Very good agreement with experiments:
    - ZPG
    - FPG & APG
    - Turbulence level
    - Compressibility effects
- Future work
  - Laminar Fluctuations
  - Turbulence length scale

TOWARD DIRECT NUMERICAL SIMULATIONS OF TURBINE FLOWS

Thorwald Herbert
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Department of Mechanical Engineering
Columbus, OH

In spite of partial success, we have halted our attempt to analyze transition in turbine boundary layers by studying the stability of an initially laminar flow because the rise of turbulence seems to be associated with unacceptable changes of the core flow. Instead, we have adopted the conclusion of the last meeting and worked toward the direct simulation of realistic flows in turbines to obtain insight into the structure of turbulence and heat transfer. Estimates show that, in spite of a patchy turbulent core flow, the buffeted boundary layer may go through transition, but the time of travel through the passage may be insufficient, the change in local conditions too rapid, and periodic unsteadiness too severe to establish the mature "textbook turbulence" underlying common turbulence models.

The large scale of the computational task requires distributing the work load over a group of computers. Different basic equations (e.g. for fluid flow and heat conduction) may need to be solved in adjacent domains. Moreover, the results of the unsteady computation cannot be saved and analysis of the data must be performed simultaneously with the computation. To address these and other requirements, we have designed and developed major components of DICE – a Distributed Interactive Computing Environment. On the highest level, DICE consists of a framework void of any physical problems or numerics. This framework executes any number of addressable modules on prescribed or internally chosen hosts on a heterogeneous computer network, typically a network of workstations under Unix, Linux, or Windows NT. These modules can be computational solvers for a given set of equations in one block of the physical domain, modules for visualization or plotting, graphical user interfaces for controlling the code or the visualization, analysis modules, print module, file manager, or an archive for collecting selected data. Integration of data production and analysis is key to the task at hand. Modules communicate by a command language that is compact, easy to read, use, and extend. Every module includes a minimum set of objects to interpret certain parts of the command language, communication routines, and the capability to start the whole system (which enables developing and debugging new modules locally).

The code receives input commands from a file stack, standard input, graphical user interface, an interactive viewing window, or from a module that imports data from CAD/CAM systems or Plot3D files. Graphical interface and viewing window can be used to draft or edit the geometry, to assign materials, equations, or parameters, to decompose the physical domain into blocks, to assign grid sizes, or to change the point distributions along boundaries or within a block. Routines for different types of grid generation are an integral part of the viewing windows and the numerical solvers. All objects are embedded in a hierarchy and offer a standard set of operations. For example, every object is capable of sending its status across the network or to a file, enabling scripting and full restart capabilities for both computational solvers and other modules by performing one send operation on the highest level.

The code is written in C++ and is driven by events. The asynchronous operation of the code components under PVM is coordinated by a central hub. Every computational solver is able to initialize or restart grid generation or computation in some block of the physical domain, to perform a given number of time steps, to receive data from the network, and to send selected data to a given destination. The integration of grid generation and computation provides for adaptive grids, moving interfaces, and inspection/correction of the grid quality. The current version of the code is restricted to structured grids (transfinite, control-net, or elliptic). So far the code solves the heat conduction equation, incompressible Navier-Stokes equations, full potential equation, and provides for gas-liquid and liquid-solid interfaces. Second-order and higher-order methods with optional multigrid acceleration have been implemented. Within a special C++ framework and coding scheme, implementation and verification of new or modified equations is usually a matter of days.

There are still many loose ends to be tied up, and ongoing efforts aim at improving the numerical solvers and the quality of the data transferred between blocks with different grids and relative motion. The available basis, however, has proven versatile and capable of making many dreams of large-scale computation come true.

Toward Direct Numerical Simulations of Turbine Flows

Thorwald Herbert

The Ohio State University
Columbus, Ohio

Minnowbrook 8/20-23/00 B

00-M-01

Outline

Background

DNS Requirements

DICE - A Distributed Interactive
Computing Environment

Modules of the System

Communication Issues

Grid Generators & Solvers

Conclusions & Outlook

00-M-02

Problems

- There is no current capability to compute turbine flow with sufficient accuracy
- It is unlikely that turbulence models and RANS codes can be substantially improved without a reliable data base
- The structure of turbulence in gas turbines may prevent the development of reliable turbulence models

Solution

Accurate direct numerical simulations (DNS) of turbine flows appear possible with today's or tomorrow's computational capabilities (if certain requirements can be met)

00-M-03

Sample Turbine (Abhari)

Two-stage HPT with 38, 56, 52, and 58 blades
Hub dia 0.15 m, chord 20 mm, span 40 - 60 mm
Inlet 1650 K, blade cooled to 1250 K
Rotation at 21,000 rpm

At $Re = 3 \cdot 10^6$, the accelerated boundary layers are stable up to 60% chord

At an average axial velocity of 400 m/s ($Ma = 0.5$), the flow traverses a blade in $50 \mu s$

A rotor blade cuts through the stator wakes every $51 \mu s$

The turnover time of the largest turbulent eddies (the time to establish a turbulent cascade) is about $5 \mu s$

Considered the strong spatial and temporal changes, "classical turbulence" will not develop in this turbine

00-M-04

DNS Requirements

DNS cannot be accomplished with a traditional reasearch code on a supercomputer.

- The physical domain must be decomposed into numerous blocks and the computation distributed over a network of computers
- Different equations (e.g. for fluid flow and heat conduction) may need to be solved in different blocks
- The results of the unsteady simulation cannot be saved. Data analysis must be carried out simultaneously with data production
- Quality of grids and numerical data must be monitored and interactively refined during the computation
- The integrity of the computation must be maintained through hardware failures, check-points, and restarts on the same or a modified network configuration

●●●

00-M-05

The System DICE

(Distributed Interactive Computing Environment)

DICE consists of modules and serves to distribute a set of modules over a network of computers

The system is written in C++ and is driven by events. Modules consist of a hierarchy of objects (partly in shared libraries)

Inter-module communication uses a standard asynchronous message passing system (PVM), a readable language, internal data types, and dedicated communication routines

Every module contains objects to “understand” a subset of the language and to start the whole system, enabling local debugging

Every object can parse itself and send itself to a file (scripting) or to other modules (updates)

The system has four groups of modules: administrative, computational, utility, and control modules

Administrative modules (Main, Hub) control the system, monitor integrity of input and operation, synchronize the computational modules, and perform checkpoints/restarts

Computational modules register their data with a SendQueue. Steps are initiated by the Hub. Computational modules are replicated for every block

00-M-06

DICE (Continued)

Utility modules can request computational data from the SendQueue and serve for visualization, plotting, video recording, data reduction or import of geometry and data (IGES, STEP, PLOT3D). Utility modules can be replicated, suspended, and reactivated

Control modules can be replicated once per graphics workstation and control the function of utility modules

Computational data can be reduced (e.g. converted to spectra, correlations) by a Filter module

Using Main to combine Import, View, and ViewControl produces a standard visualization system (with additional capabilities)

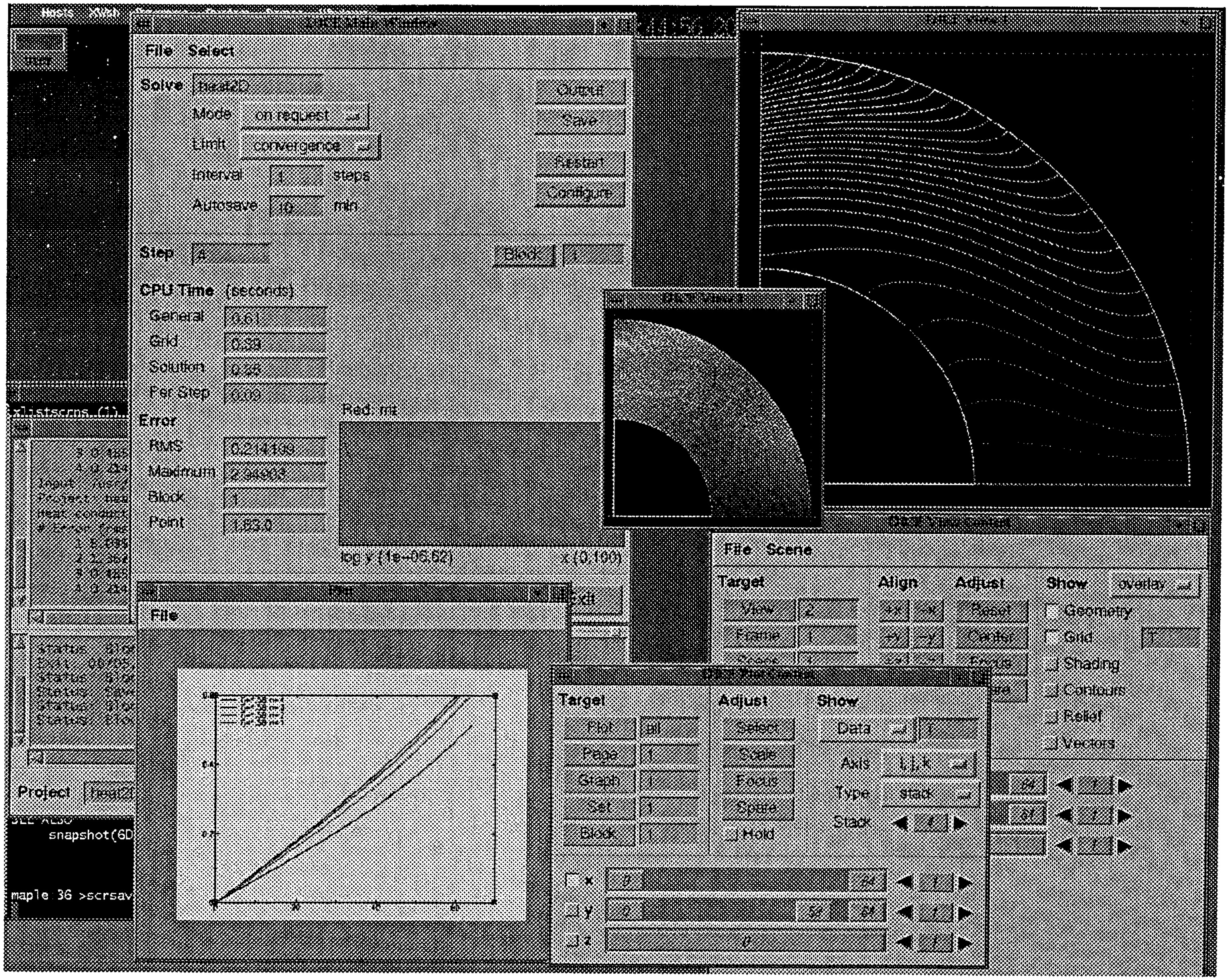
Main provides guidance and functions to set up a complete computation

View permits input and editing of geometry, domain decomposition into blocks, interactive change of grids (with simultaneous display of metric information)

Parameters and grids can be changed during the computation

View and Plot allow multiple Scenes and Graphs, and enable dynamic and static (frozen) data display

00-M-07


File Select
Solve heat2D
Mode on request
Limit convergence
Interval 1 steps
Autosave 10 min
Output
Save
Restart
Configure
Step 4
Block 1
CPU Time (seconds)
General 0.61
Grid 0.39
Solution 0.45
Per Step 0.09
Error
RMS 0.214109
Maximum 2.94903
Block 1
Point 1,63,0
log y (1e-06,62)
x (0,190)
Exit
Plot
File
File Scene
Target
View 2
Frame 1
Align
Adjust
Reset
Center
Focus
Show overlay
Geometry
Grid
Shading
Contours
Relief
Vectors
Target
Plot all
Page 1
Graph 1
Set 1
Block 1
Adjust
Select
Scale
Focus
Spare
Hold
Show
Data
Axis i, j, k
Type stack
Stack
x
y
z
Project heat2D
snapshot(6D
maple 36 >scrsav

Communication

A readable text language is used for the compact description of simulations and the configuration and control of modules. The language distinguishes input (of objects) and commands

The input syntax is similar to VRML and permits building hierarchies of objects

```
Object[=name] ( [# comments]
                [field[s]]
                [Object[s]] )
```

where items in brackets are optional

Commands serve for short communications with modules:

```
[destination] [origin] [field[s]]
```

where "destination" can be a single module or a group of modules (e.g. all computational modules: Solve step=2)

All fields start with a keyword that determines format and meaning of subsequent information. The "vocabulary" of objects, commands, and fields is easily extendable.

Various formats are available to exchange binary data across blocks and with utility modules

00-M-08

```
Project (
 title=Heat conduction in a sector
 name=heat2D
 coordinates=Cartesian,2D
 time=steady
)

read ~/.Hosts

Codenet (
  Code( plot=1 host=maple )
  Code( view=1 host=maple )
  Code( view=2 host=maple )
)

Parameter (
  kappa = 1
  accuracy = 1e-6
)

Geometry (
  Segment=xlo (
    Shape=line ( start=1,0 end= 2,0 )
  )
  Segment=yhi (
    Shape=circular_arc ( origin=0,0 radius=2 angle=0,90 )
  )
  Segment=xhi (
    Shape=line ( start=0,2 end=0,1 )
  )
  Segment=ylo (
    Shape=circular_arc ( origin=0,0 radius=1 angle=90,0 )
  )
)

Domain (
  Block=first (
    Material ( solid )
    Equation ( heat_cond )
    Grid ( type=transfinite imax=64 jmax=64 )
    Surface=z (
      Segment=xlo (
        Bc ( value= 0 )
      )
      Segment=yhi (
        Bc ( normal_derivative=0 )
      )
      Segment=xhi (
        Bc ( normal_derivative= x^2+y^2 )
      )
      Segment=ylo (
        Bc ( normal_derivative=0 )
      )
    )
  )
)
start
end
```

Grid Generation and Solvers

Grid generators are part of the View (for adjustments) and integral part of the numerical modules (enabling grid updates and adaptive grids)

Only structured (transfinite, control-point, and elliptic) grids are implemented for accurate computations

High-order (Hermitian) methods are used to compute the metric data

High-order accurate interpolations are employed to transfer data between different grids (in different blocks)

Numerical modules can be used as a single task, in sequence, or in loops (design), including regeneration of grids if necessary

Numerical codes are integrated into a standard interface that offers a set of functions: initialize, step, save, restart, output, and special functions

Adapting a reasonably well written Fortran code to DICE requires a day or a week. Some C/C++ features (#define) are exploited to simplify this task. Input/output are completely separated from the computation

Performance data are relayed to the Hub and Main modules and can be used to identify bottlenecks and fine-tune the configuration

00-M-09

Solvers

Numerical modules are availiable to solve

- 2D/3D heat conduction
- 2D/3D panel code
- 2D steady Navier-Stokes w/wo buffer zone
- 3D unsteady Navier-Stokes (cartesian) w/wo buffer zone
- 3D full potential equation and adjoint
- 3D boundary-layer equations and adjoint
- 3D parabolized stability equations and adjoint

Multi-block applications await completion of high-order interpolation routines which enable different grids and relative motion across block boundaries

00-M-10

Conclusions and Outlook

- The design concepts of DICE are (almost) frozen
- The system has shown great potential and robustness, and has supported the efficient development of new codes
- Problems with the asynchronous communication and timing problems with visualizations are largely solved
- Inevitable overhead has been found to be negligible, especially in large-scale computations
- Many loose ends in utility modules need to be tied up (just a matter of time), (a lot of time)
- Control modules may need to be developed for the Linux and Windows environment
- Some funding may definitely benefit completion of the system
- We are confident DICE can be scaled up from single passages through stator or stator/rotor to computing one half of a complete turbine including heat conduction in the blades and, ultimately, cooling flows.

00-M-11

EXPERIMENTAL INVESTIGATION OF TRANSITION TO TURBULENCE UNDER LOW-PRESSURE TURBINE CONDITIONS: MEASUREMENTS WITH AND WITHOUT WAKES

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University of Minnesota
Heat Transfer Laboratory
Department of Mechanical Engineering
Minneapolis, MN

This research was designed to address a need for detailed experimental data which document transition in boundary layers and separated flows over highly-loaded airfoils, including the effects of passing wakes. The program objectives are accomplished with the following steps:

First, the effects of freestream turbulence and Reynolds number are documented without wakes in a facility which simulates the flow through a modern, highly-loaded, low-pressure turbine.

Next, this case is repeated, but with the influence of simple, rod-generated wakes added. By comparing, we can identify the effects of wakes on transition in the boundary layer.

We have completed the first part, Qiu and Simon (1997) and Simon et al. (2000). It shows cases with strong separation at low Reynolds numbers and low turbulence levels and cases with much smaller separation bubbles with higher Reynolds number or freestream turbulence. It shows also that a correlation for the streamwise distance from separation to the start of transition by Davis et al. (1985) is quite accurate and that a model for the intermittency path by Dhawan and Narasimha (1958) is remarkably good, in spite of its derivation from attached boundary layer flow transition data. A need for better prediction of the transition length is indicated, however.

Early results of the with-wake data were presented and comparisons were made to the no-wake study. Wakes are generated by sliding a rack of rods through the approach flow tunnel. A photogate was used to verify that the wake generator sled is moving at a uniform velocity when measurements of the flow are made. To characterize the wakes, 100 separate traverses of the sled were made and an ensemble average of 100 separate traverses of each rod was generated. We see that the minimum velocity at the center of the wake is approximately 85% of the average value, which matches the work of (Halstead et al, 1995) who used a rotating airfoil stage (simulating a rotating turbine stage) to create wake profiles, but the turbulence intensity peaks at 15%, more than twice that reported by Halstead. This may be consistent with Halstead's assertion that rods seem to produce more turbulence than airfoils of the same loss coefficient. It should be noted, however, that flow over the airfoils of the Halstead study was not strongly separated and a highly-loaded airfoil, such as that of the present study (Pak B), will be inclined to separate more strongly.

The unsteady boundary layer measurements include the ensemble-averaged, period-resolved profiles of velocity, rms velocity fluctuation and intermittency over the surface. Characterization of this flow will demonstrate the influence of the passing wake on the state of the boundary layer or separated flow zone, including the “calming” region (Halstead et al, 1995). Further, such data will allow testing of transition models which have been developed to incorporate the effects of passing wakes on transition.

References

Davis, R. L., Carter, J. E. and Reshotko, E., 1985, "Analysis of Transitional Separation Bubbles on Infinite Swept Wings," AIAA paper # AIAA-85-1685.

Dhawan, S. and Narasimha, R., 1958, "Some Properties of Boundary Layer Flow During the Transition from Laminar to Turbulent Motion," J. Fluid Mech., Vol. 3, pp. 418-436.

Halstead, D. E., Wisler, D. C., Okiishi, T. H., Walker, G. J., Hodson, H. P. and Shin, H., 1995, "Boundary Layer Development in Axial Compressors and Turbines," ASME 4-part paper, #'s 95-GT-461 thru 464.

Qiu, S. and Simon, T. W., 1997, "An Experimental Investigation of Transition as Applied to Low Pressure Turbine Suction Surface Flows," ASME Paper # 97-GT-455.

Simon, T. W., Qiu, S. and Yuan, K., 2000, "Measurements in a Transitional Boundary Layer under Low-Pressure turbine Airfoil Conditions," NASA-CR-2000-209957.

Experimental Investigation of Transition to Turbulence under Low-Pressure Turbine Conditions: Measurements with and without Wakes

Terry Simon
Richard Kaszeta
Kebiao Yuan
and
Federico Ottaviani
Heat Transfer Laboratory
University of Minnesota

for presentation at the Minnowbrook Workshop

NASA/CP—2001-210888

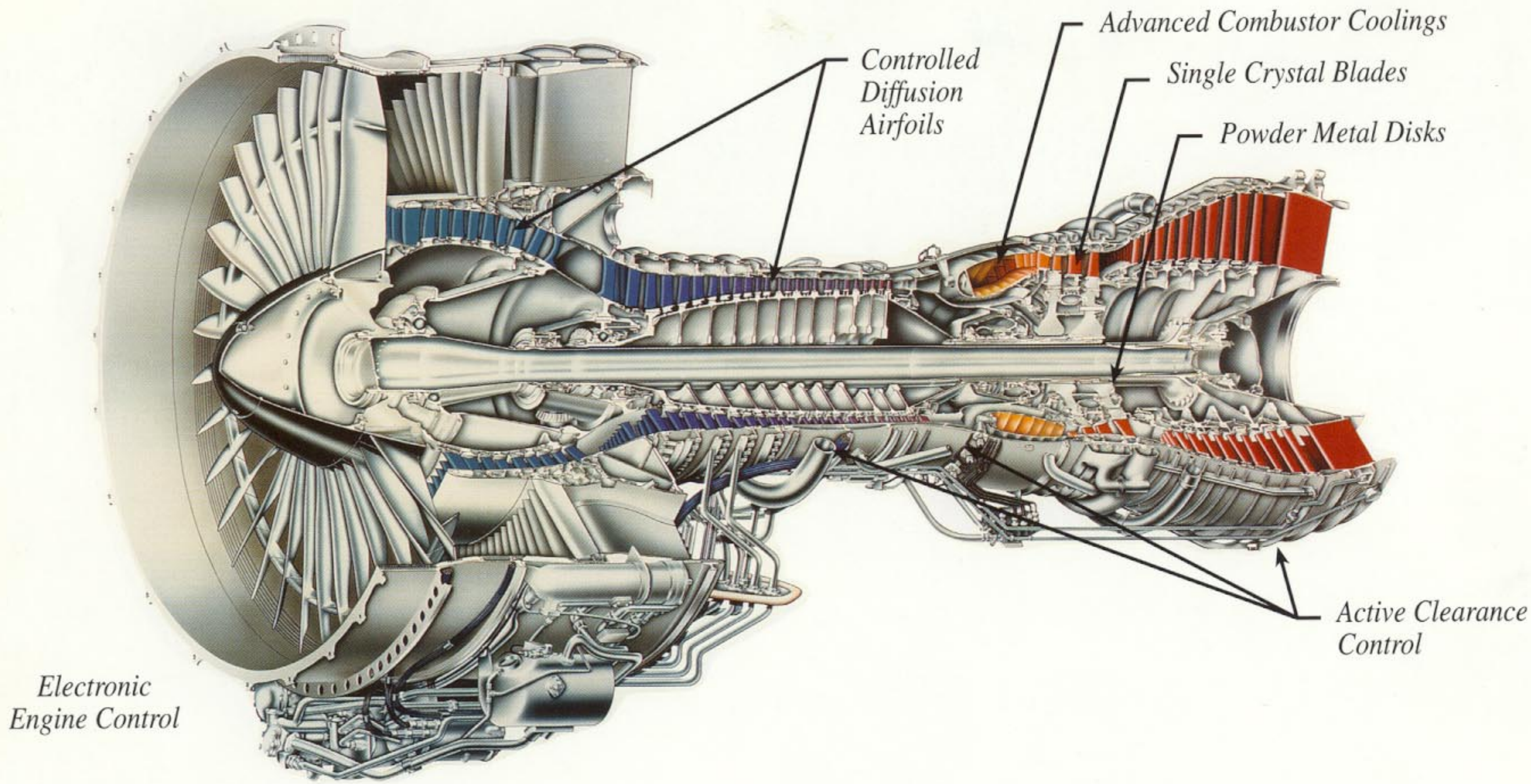
Main Contributors

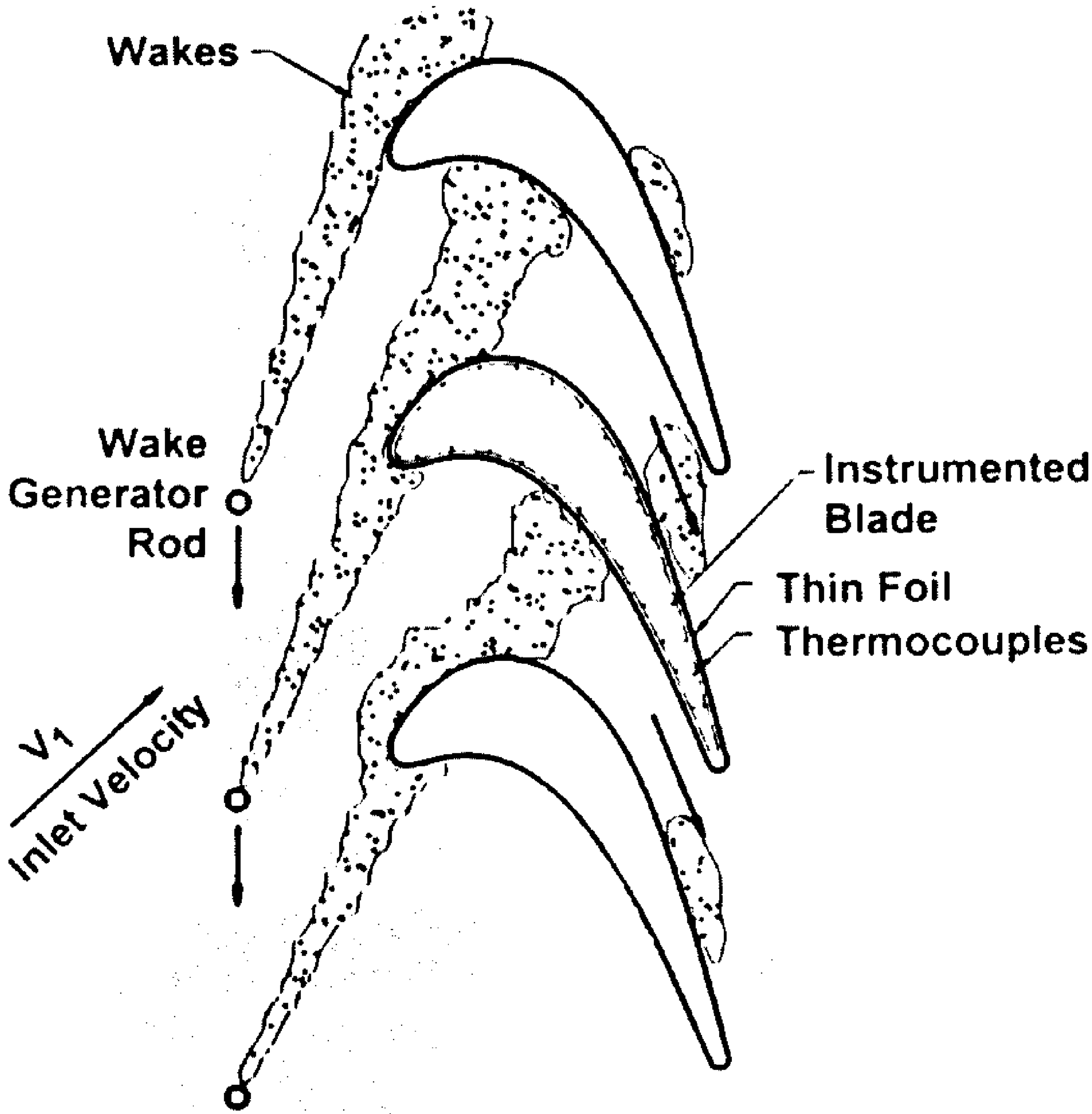
- Songgang Qiu (Presently at Stirling Technologies)
- Ralph Volino (Presently at the U. S. Naval Academy)
- Kebiao Yuan (Presently at Seagate)
- Richard Kaszeta (Completing his Ph. D.)
- Federico Otavianni (Completing his M. S.)

OUTLINE

- Introductions and background.
- Objectives of the program.
- Measurements without wakes.
- The wake generator.
- Measurements with wakes.
- Conclusions

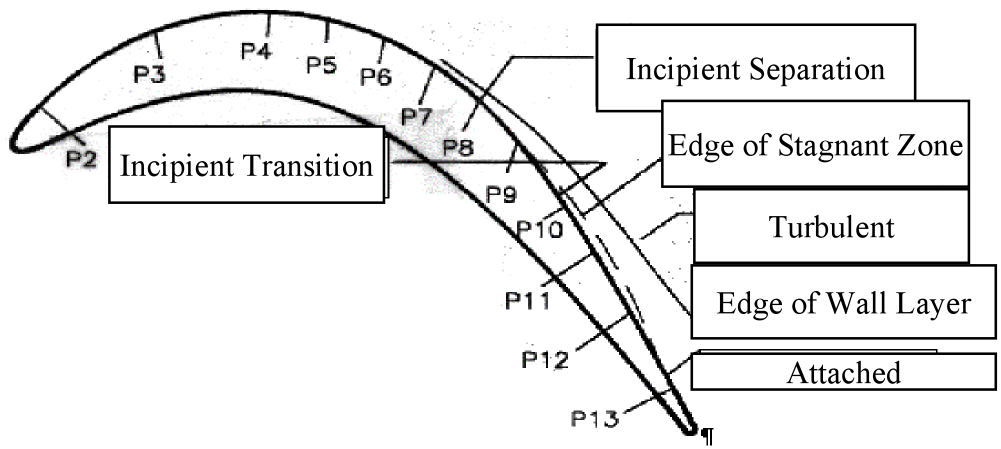
F117-PW-100 Turbofan Engine



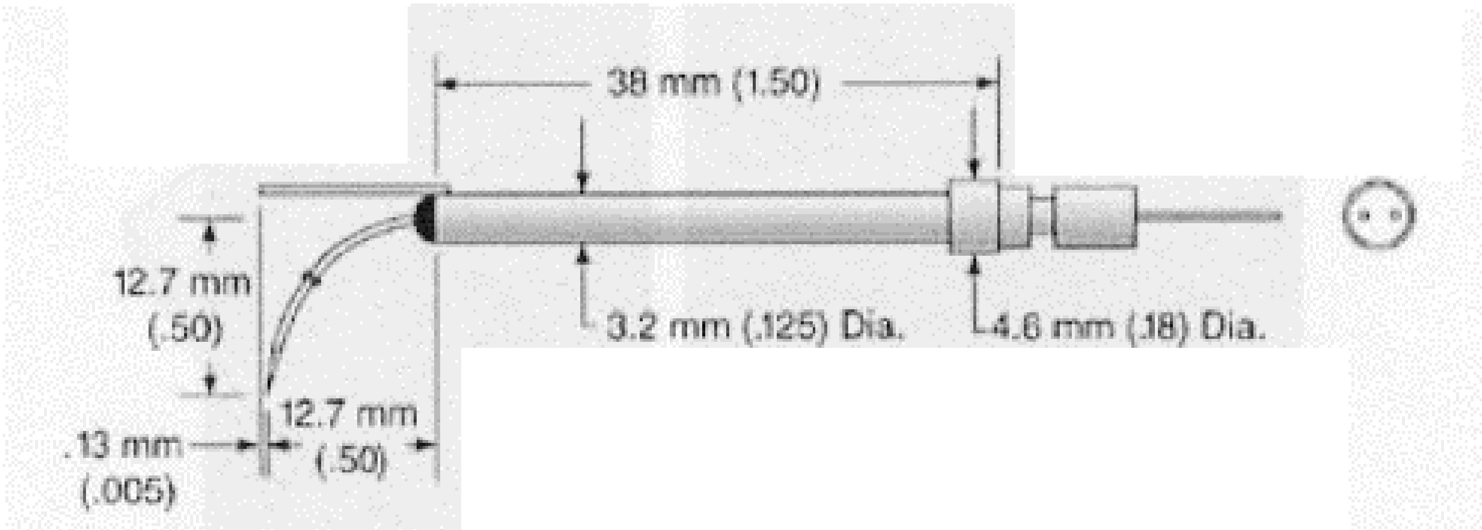

Wakes
Wake
Generator
Rod
V_1
Inlet Velocity
Instrumented
Blade
Thin Foil
Thermocouples

Measurements

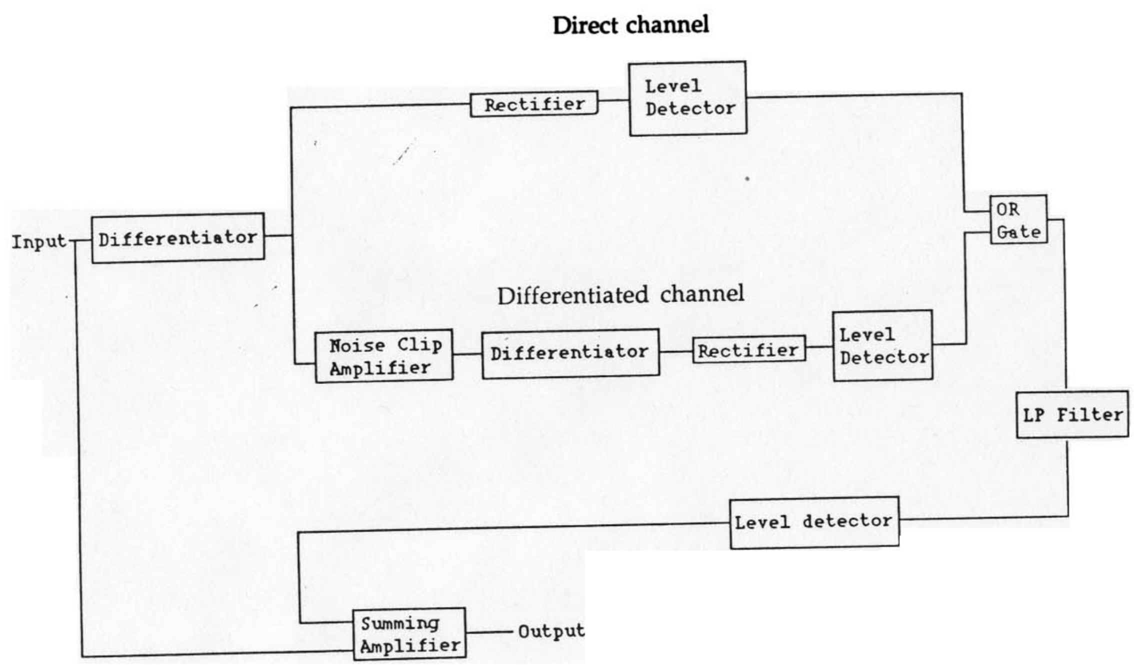
- Ensemble-Averaged Velocity
- rms of the Ensemble (turbulence)
- Intermittency
- Separation/Reattachment



Hot-Wire Anemometer

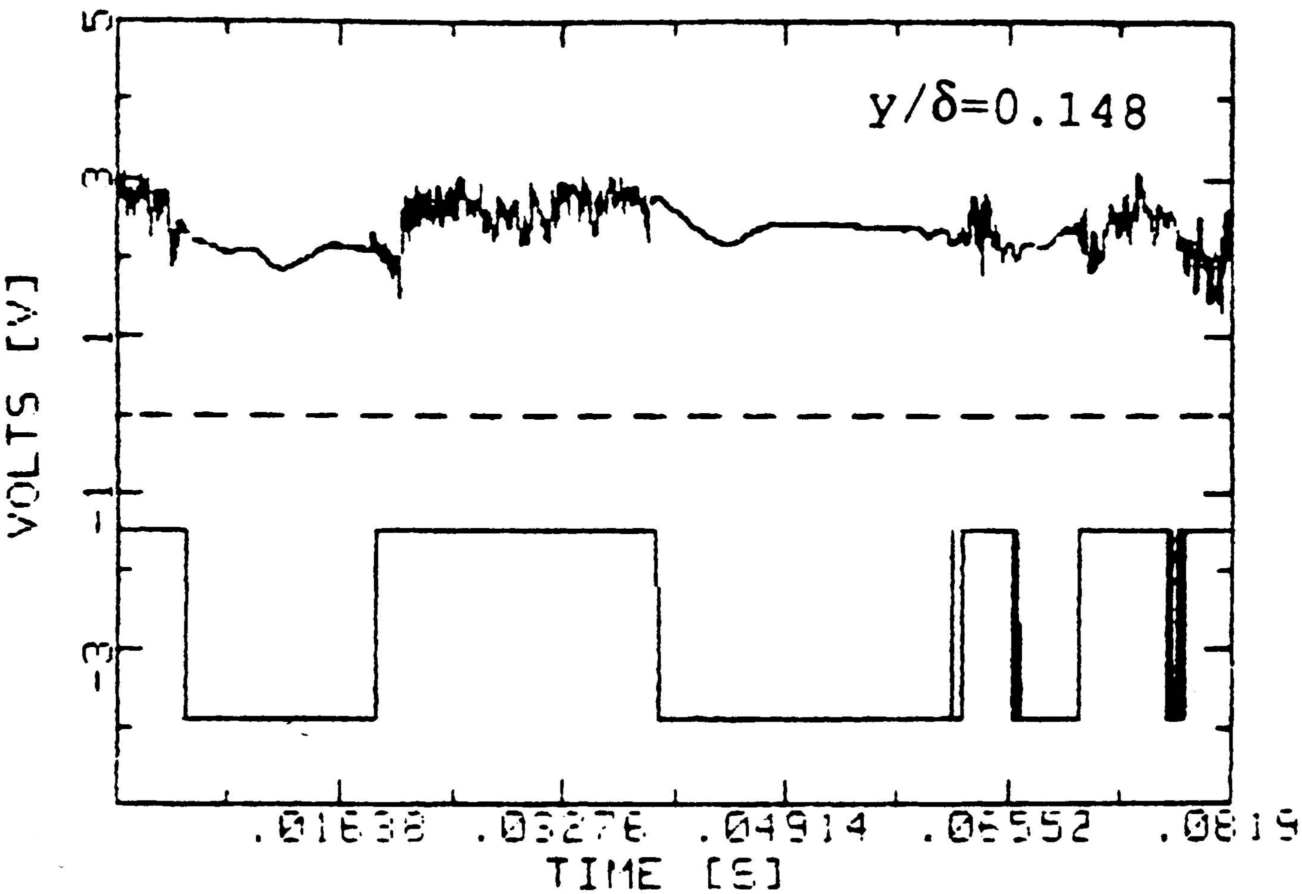


Intermittency Circuit

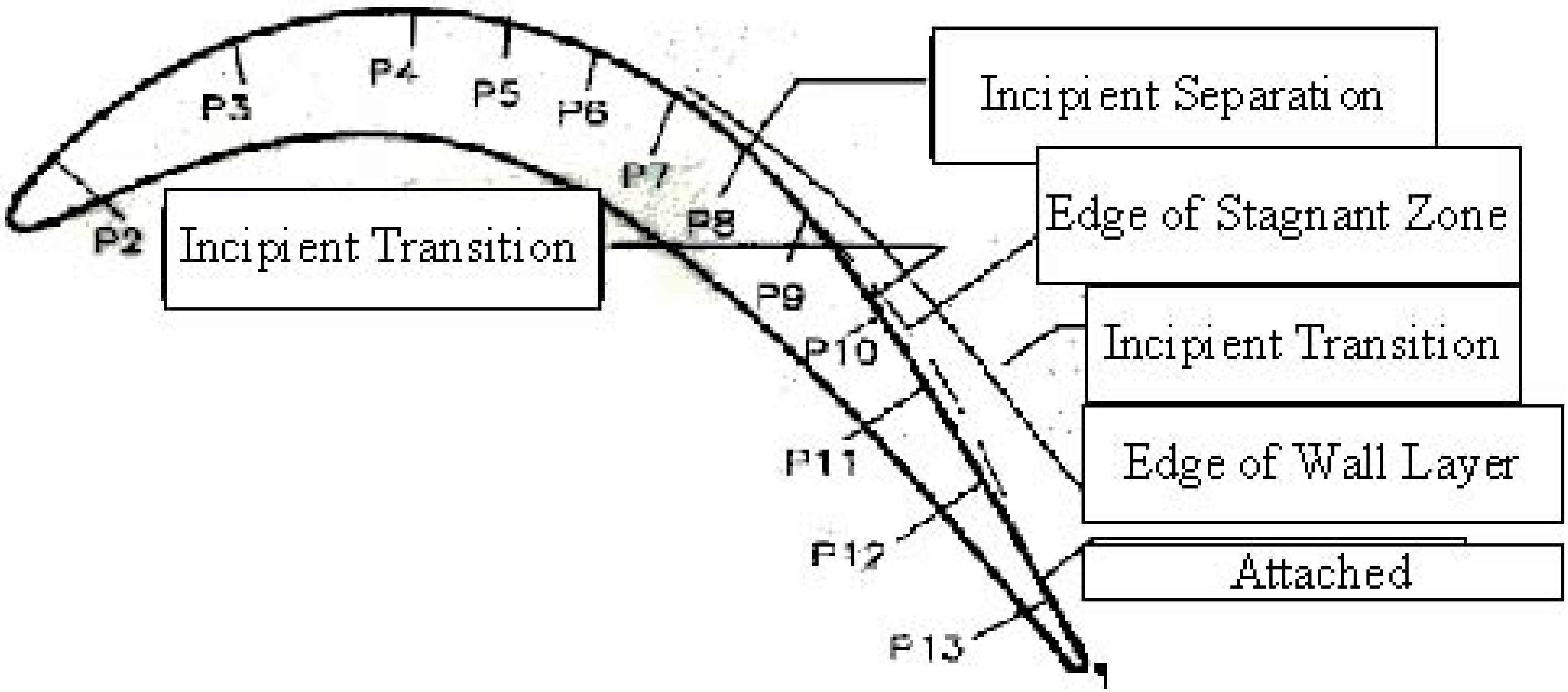


NASA/CP—2001-210888

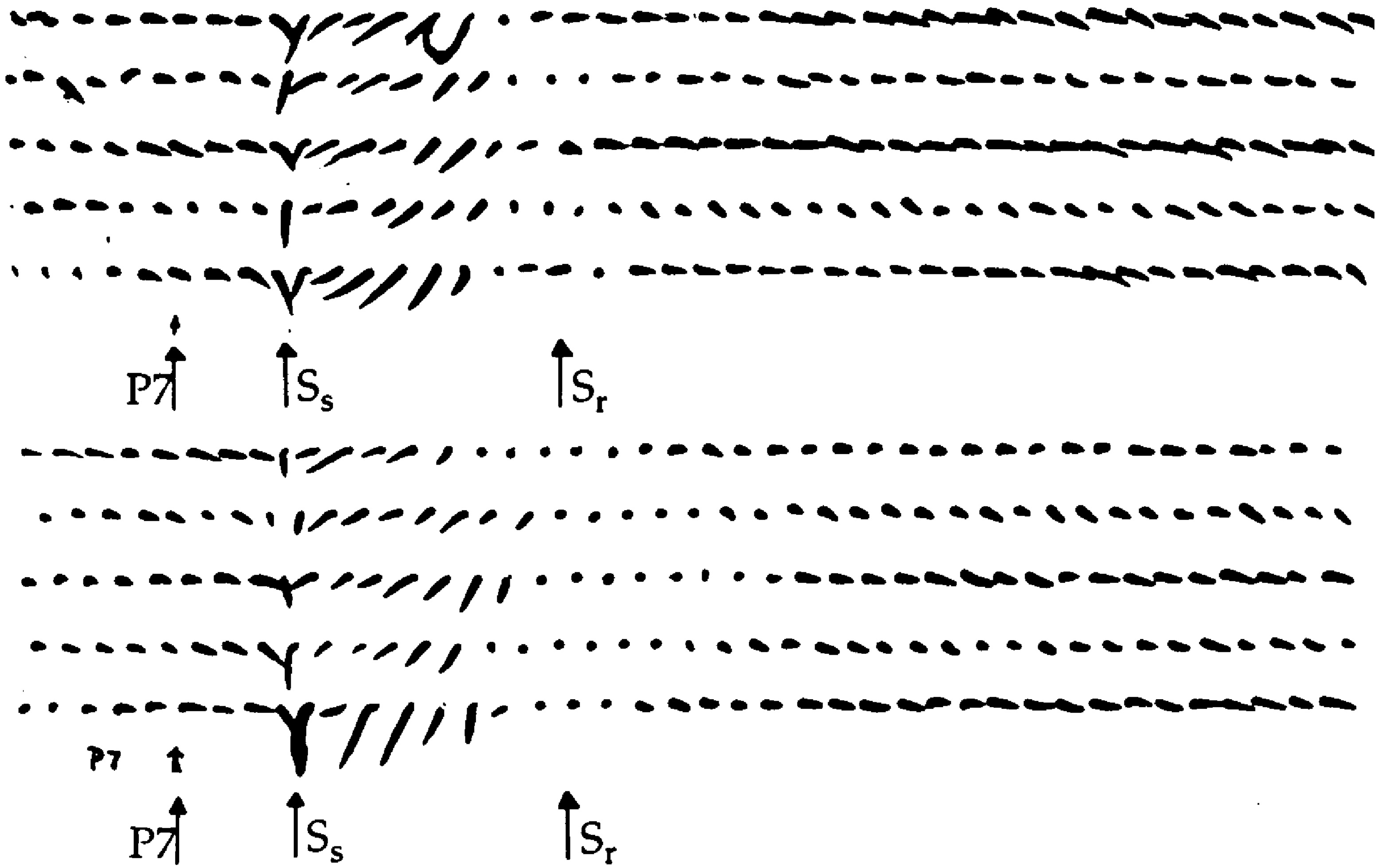
Intermittency



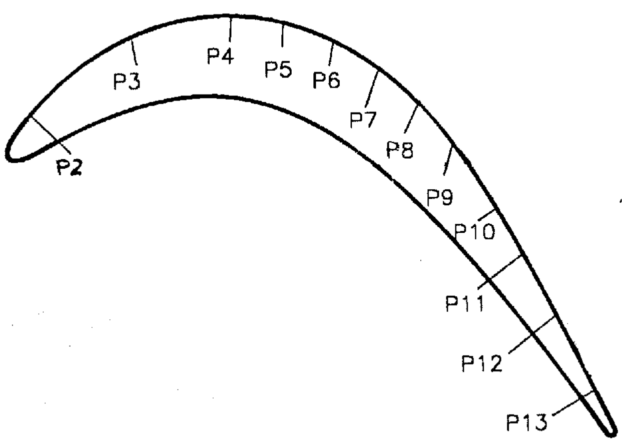
Separation of the Flow

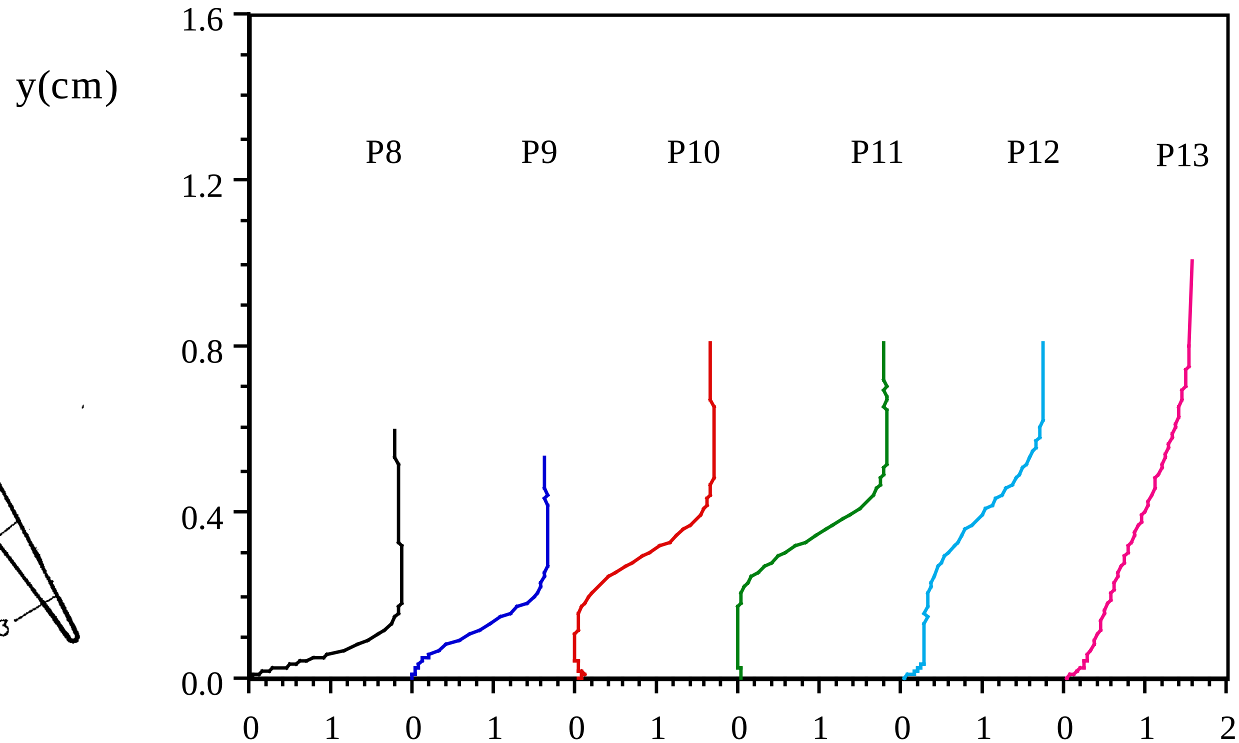


Ink Dot Technique



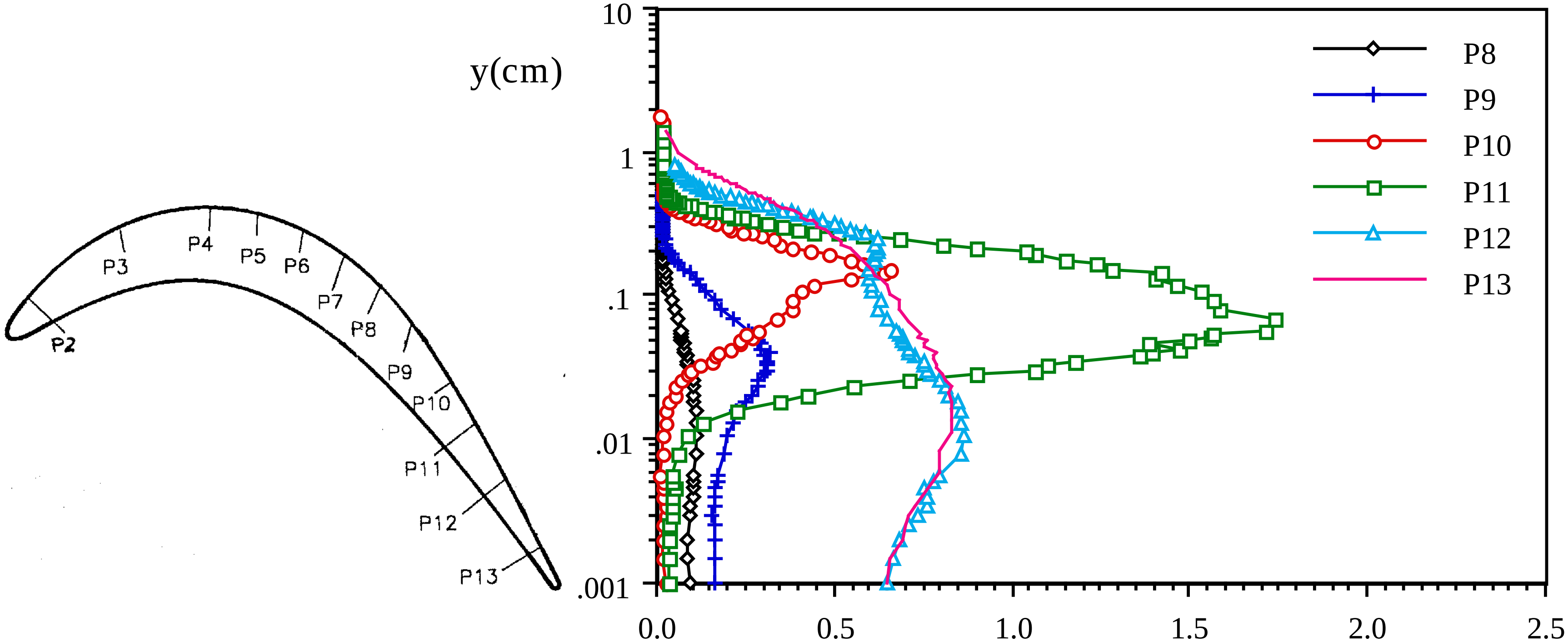
Example Data





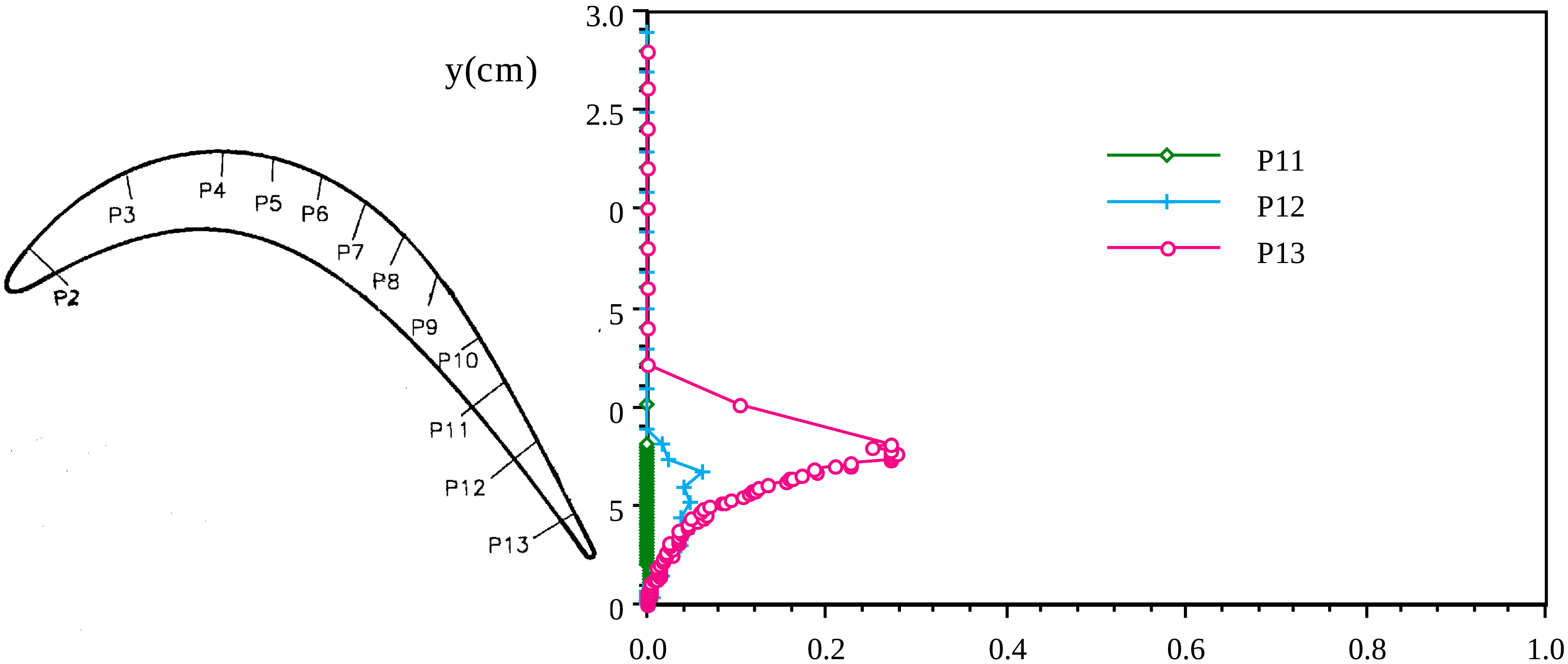
Velocity Profiles Downstream
Re = 50,000, TI = 2.5%

Turbulence Intensities

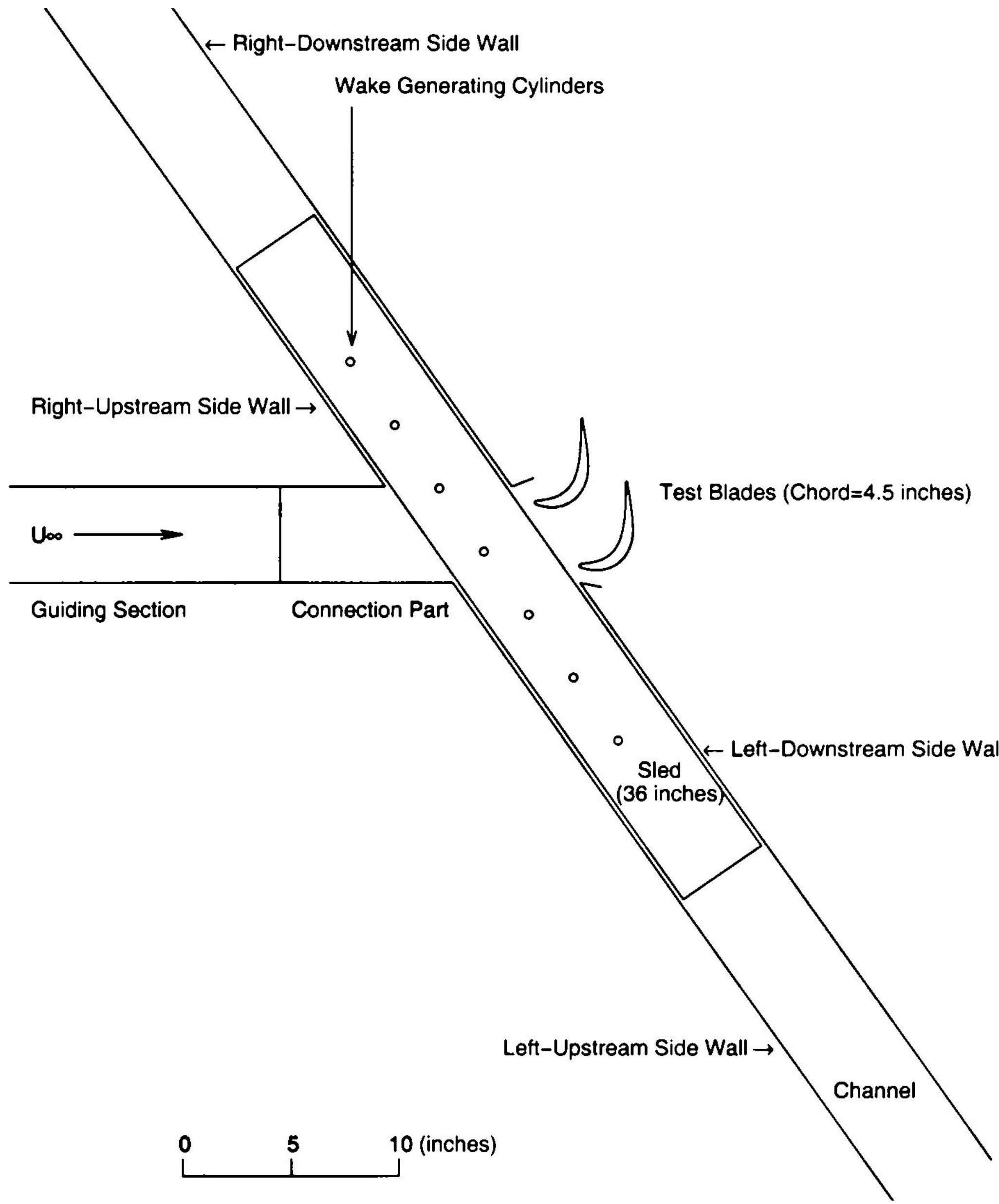


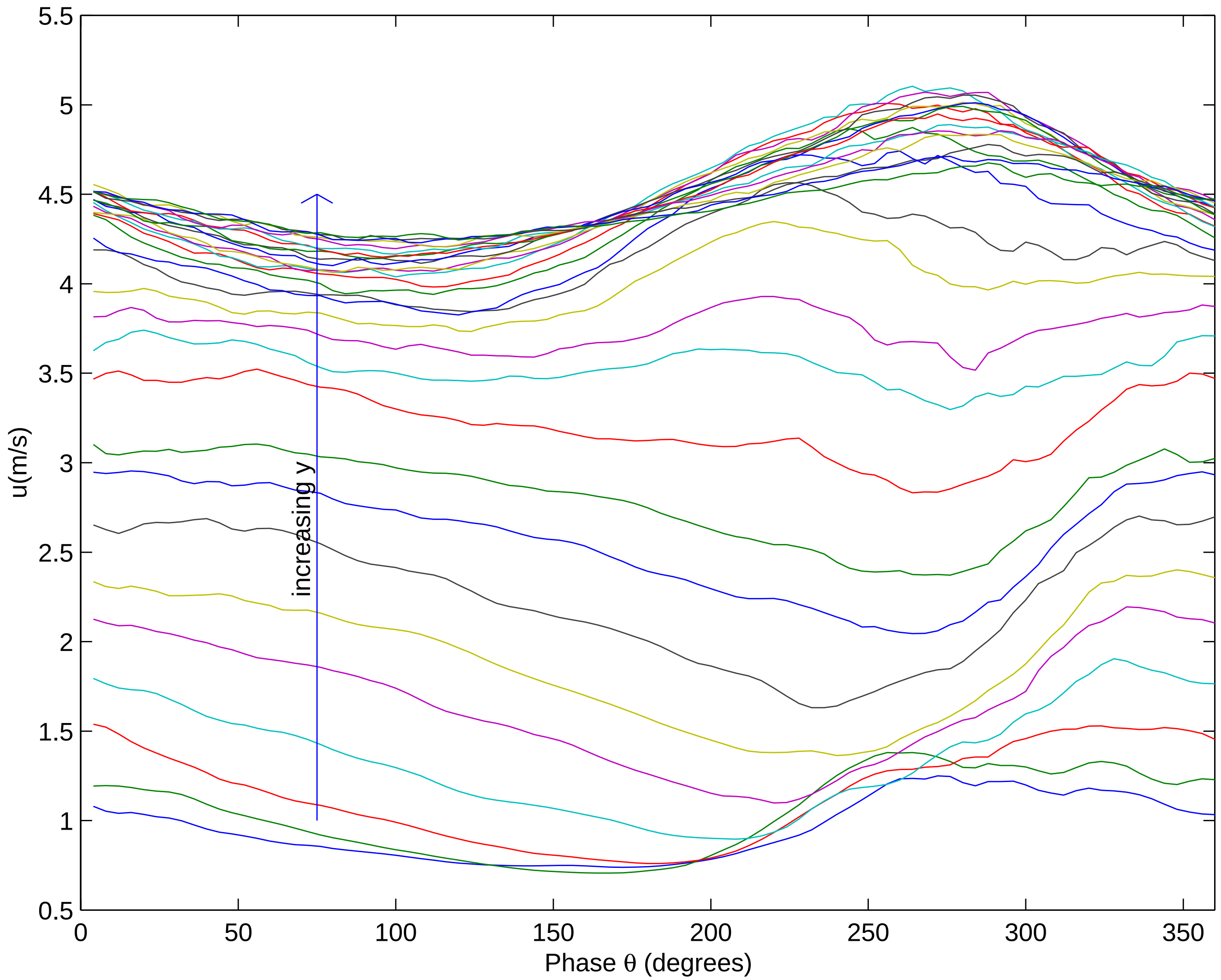
Turbulence Intensities Downstream
Re = 50,000, TI = 2.5%

Intermittency

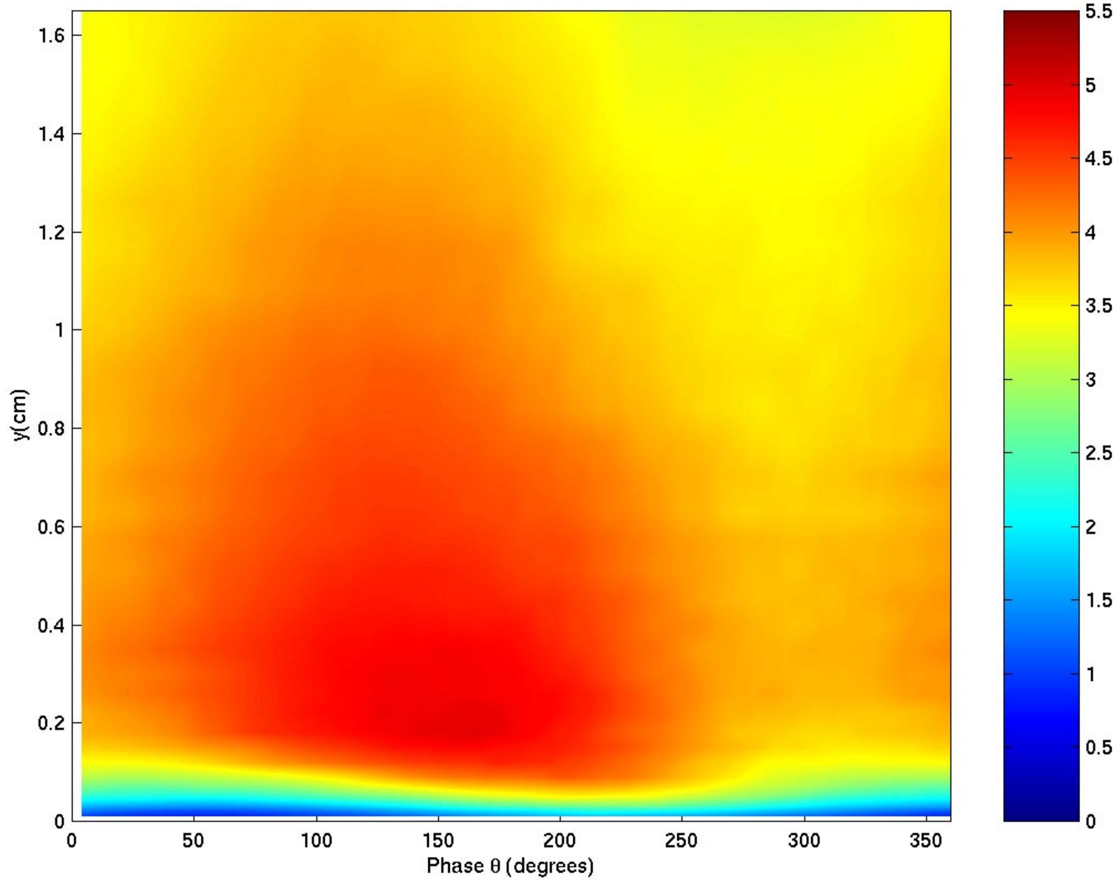


Intermittency
Re = 50,000, TI = 2.5%

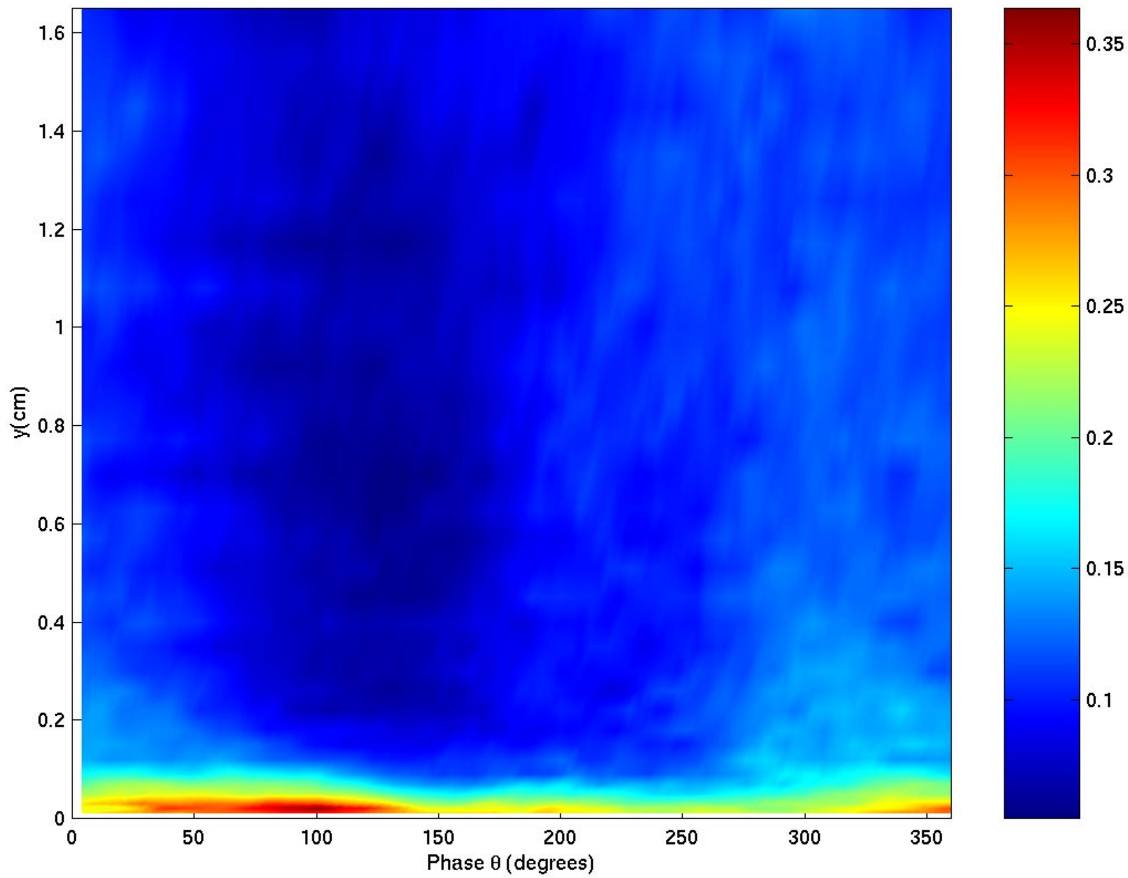

← Right-Downstream Side Wall
Wake Generating Cylinders
Right-Upstream Side Wall →
Test Blades (Chord=4.5 inches)
U∞
Guiding Section
Connection Part
← Left-Downstream Side Wall
Sled
(36 inches)
Left-Upstream Side Wall →
Channel
0
5
10 (inches)



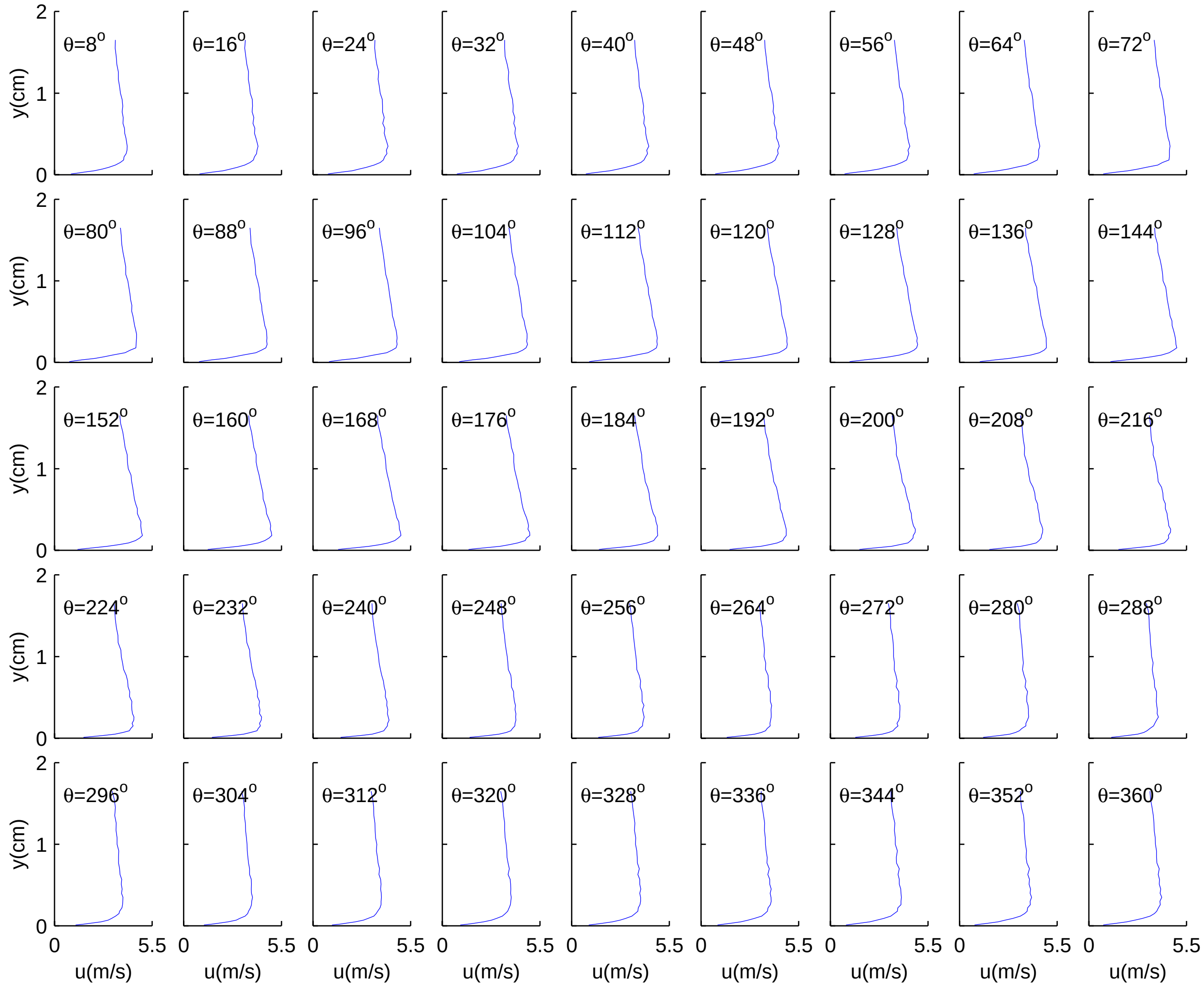
Ensemble Average Velocity $\tilde{u}(y,t)$ at 67.93% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$



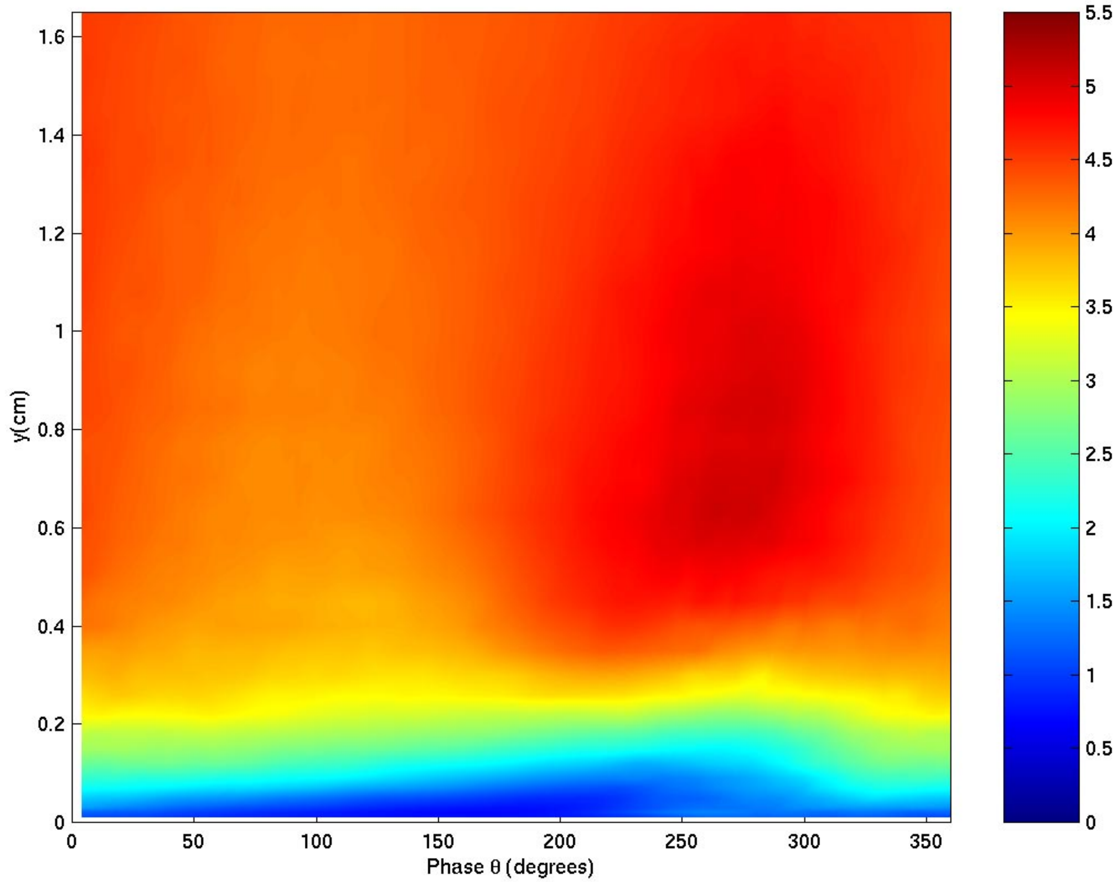
Ensemble Average Velocity $\tilde{u}(y,t)$ at 46.67% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$



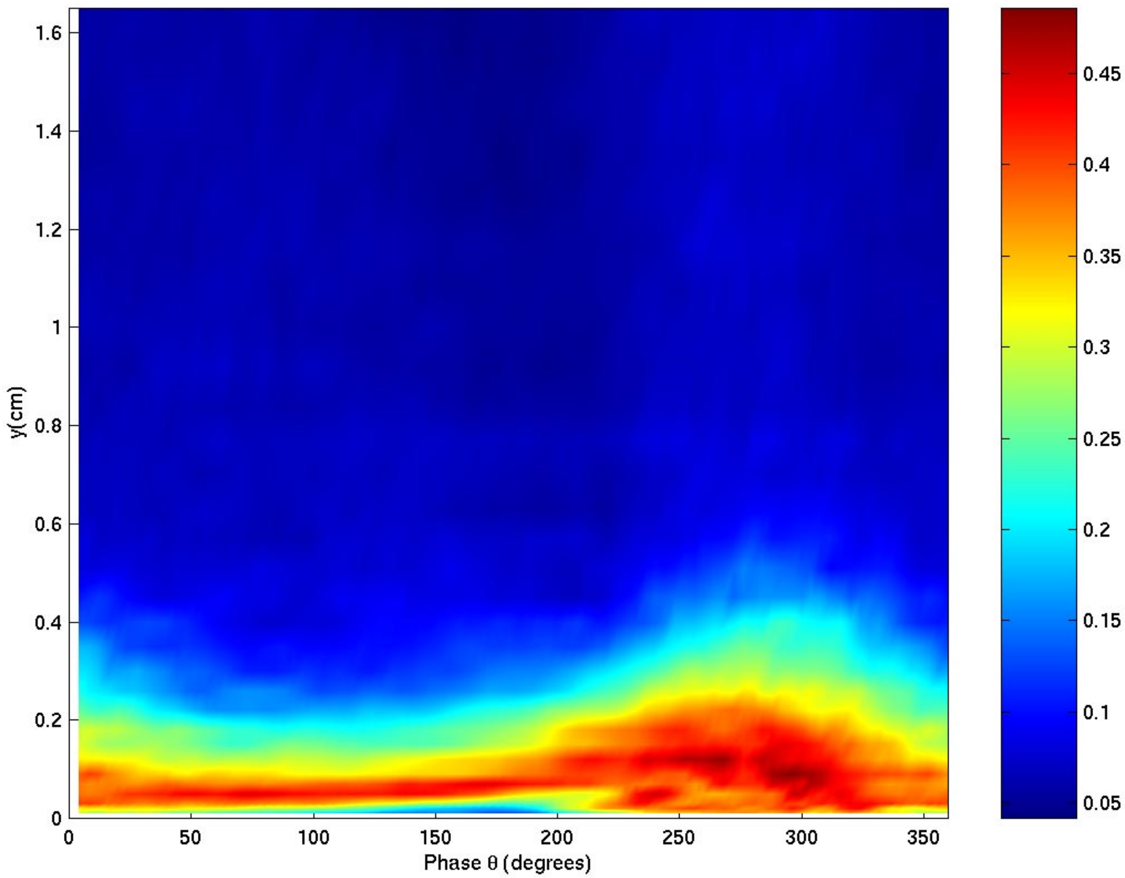
Ensemble Average Turbulence Intensity $\widetilde{TI}(y,t)$ at 46.67% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$



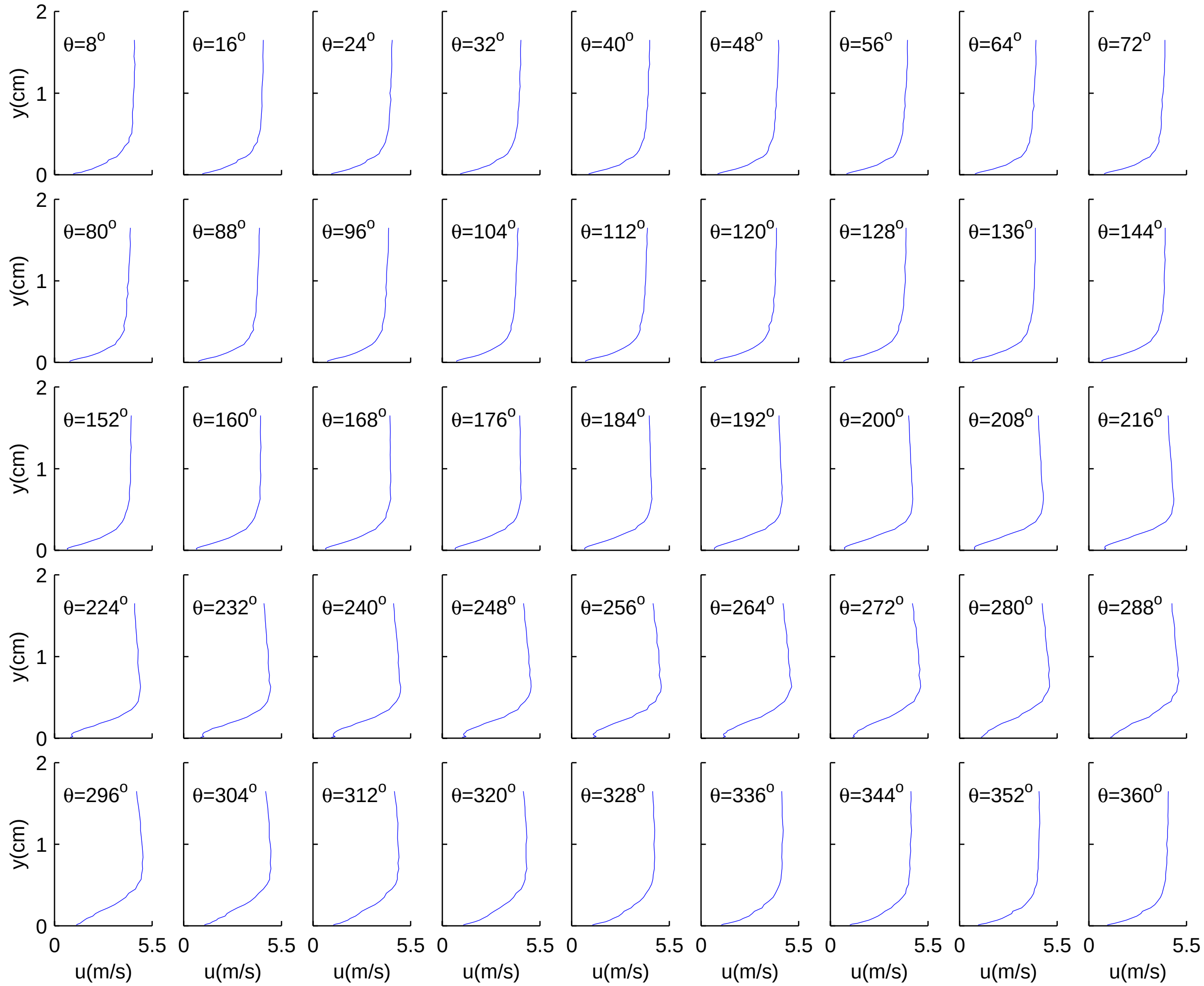
Ensemble Average Velocity $\tilde{u}(y,t)$ at 46.67% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$



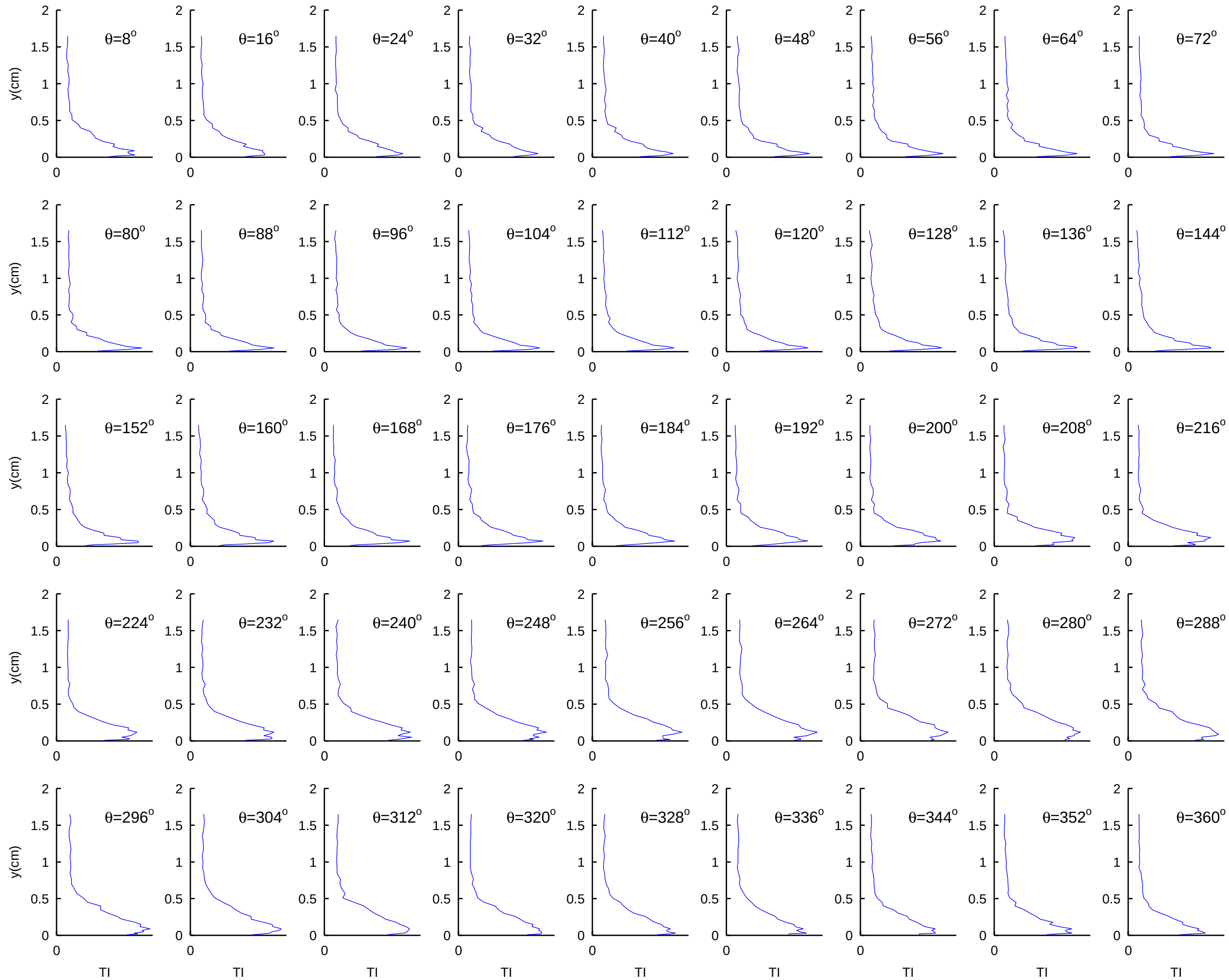
Ensemble Average Velocity $\tilde{u}(y,t)$ at 67.93% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$



Ensemble Average Turbulence Intensity $\widetilde{TI}(y,t)$ at 67.93% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$



Ensemble Average Velocity $\tilde{u}(y,t)$ at 67.93% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$



Ensemble Average Turbulence Intensity $\widetilde{TI}(y,t)$ at 67.93% of axial chord length, with $Re_c = 50,000$ and $FSTI = 2.5\%$

Animations

Animations in Quicktime format are available at

`http://www.me.umn.edu/divisions/tht/tcht/lpturbine`

DIRECT SIMULATION OF UNSTEADY WAKES AND TRANSITION IN A TURBINE PASSAGE

P.A. Durbin and X. Wu
Stanford University
Department of Mechanical Engineering
Stanford University, CA

Direct numerical simulations have been performed of unsteady wake effects and of transition on a flat plate and in a turbine passage. Passing wakes were simulated by sweeping a self-similar, turbulent wake across the entrance to the computational domain. Computations were performed on a highly parallel computer with on the order of 50million grid points. The geometry and flow conditions of the turbine passage correspond to the 'T106' blade being studied in a number of laboratory experiments.

Flat plate, zero pressure gradient bypass transition occurs through four stages. In the first, elongated regions of high or low velocity form near the wall. Secondly, the low velocity regions lift from the surface, producing a lifted, backward jet. This provides a receptivity path for for external turbulence to enter the boundary layer; the third stage is an instability of the lifted jet. In the final stage the instability cascades to small scale, locally filling the boundary layer with a turbulent spot. At this stage transition to turbulence has occured, although the spots subsequently evolve and merge to produce a fully turbulent boundary layer.

A second set of simulations addresses the development of wakes in a low pressure turbine passage. New vortical structures were observed to evolve within the wake as it traversed the passage. They were produced by interaction between the wake and the mean straining field. An intriguing asymmetry was observed between the suction and pressure sides of the passage. It can be explained by the relative orientation of the wake and rate of strain. Streamwise elongated vortices descend from the passage and lie along the pressure surface. Secondary vorticies are caused by the viscous boundary condition, leading to a set of surface vortices. Three-dimensional, small scale turbulence is amplified near the suction side. The unsteady, asymetric, vortical field will be illustrated and discussed for its relevance to predicting turbulence and transition in turbines.

Transition via spots occurs on the suction surface toward the rear edge. Some evidence was seen that in the absence of passing wakes more orderly transition occurs in the adverse pressure gradient region right before the trailing edge.

NASA/CP—2001-210888

Numerical Simulations of Passing Wakes and Transition

P. A. Durbin & X. Wu

Mechanical Engineering
Stanford University

Minnowbrook III

sponsor: DOE, Accelerated Strategic Computing Initiative

Code:

Finite-volume, staggered grid, incompressible

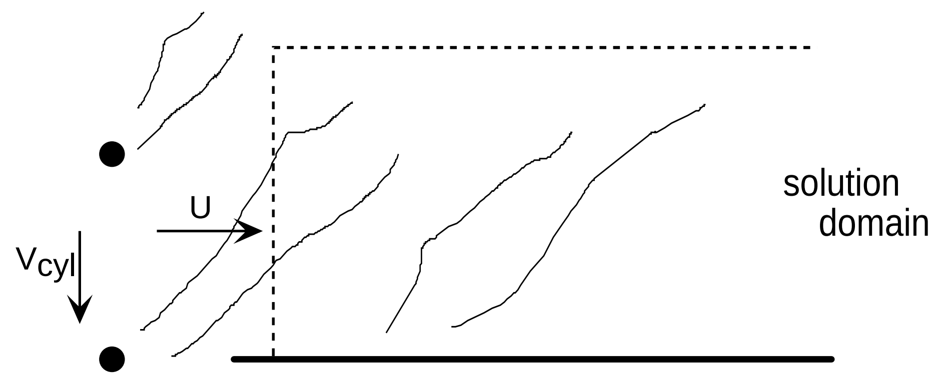
Admas-Bashforth for convection term/Crank-Nicolson for viscous

FFT, multi-grid for Poisson

Cases:

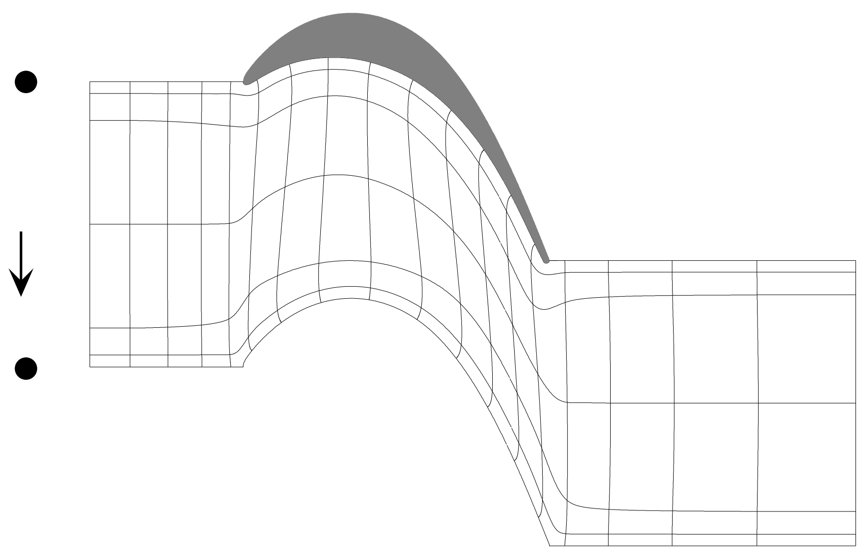
Flat plate, ZPG transition

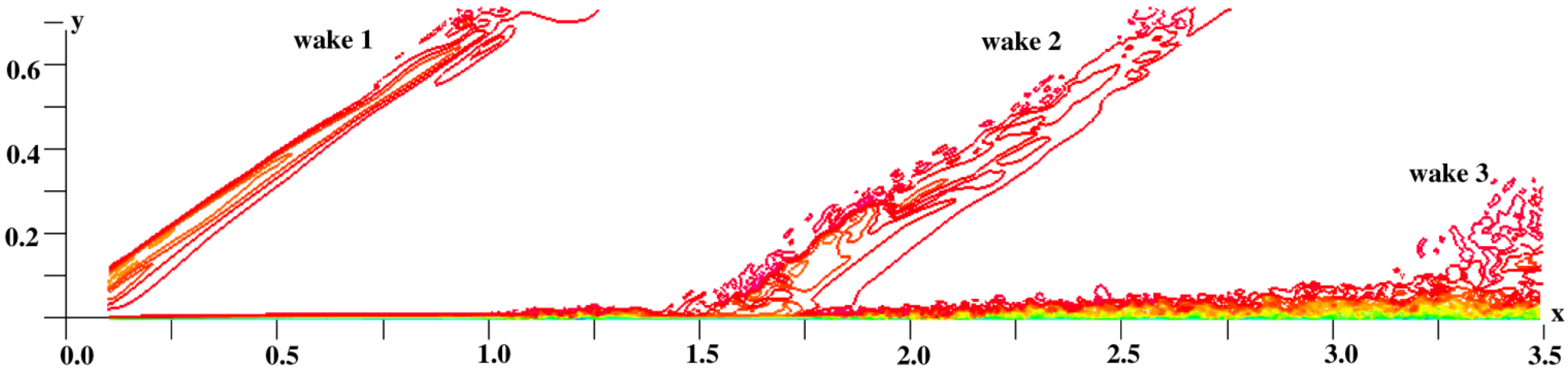
(1024×400×128 grid)

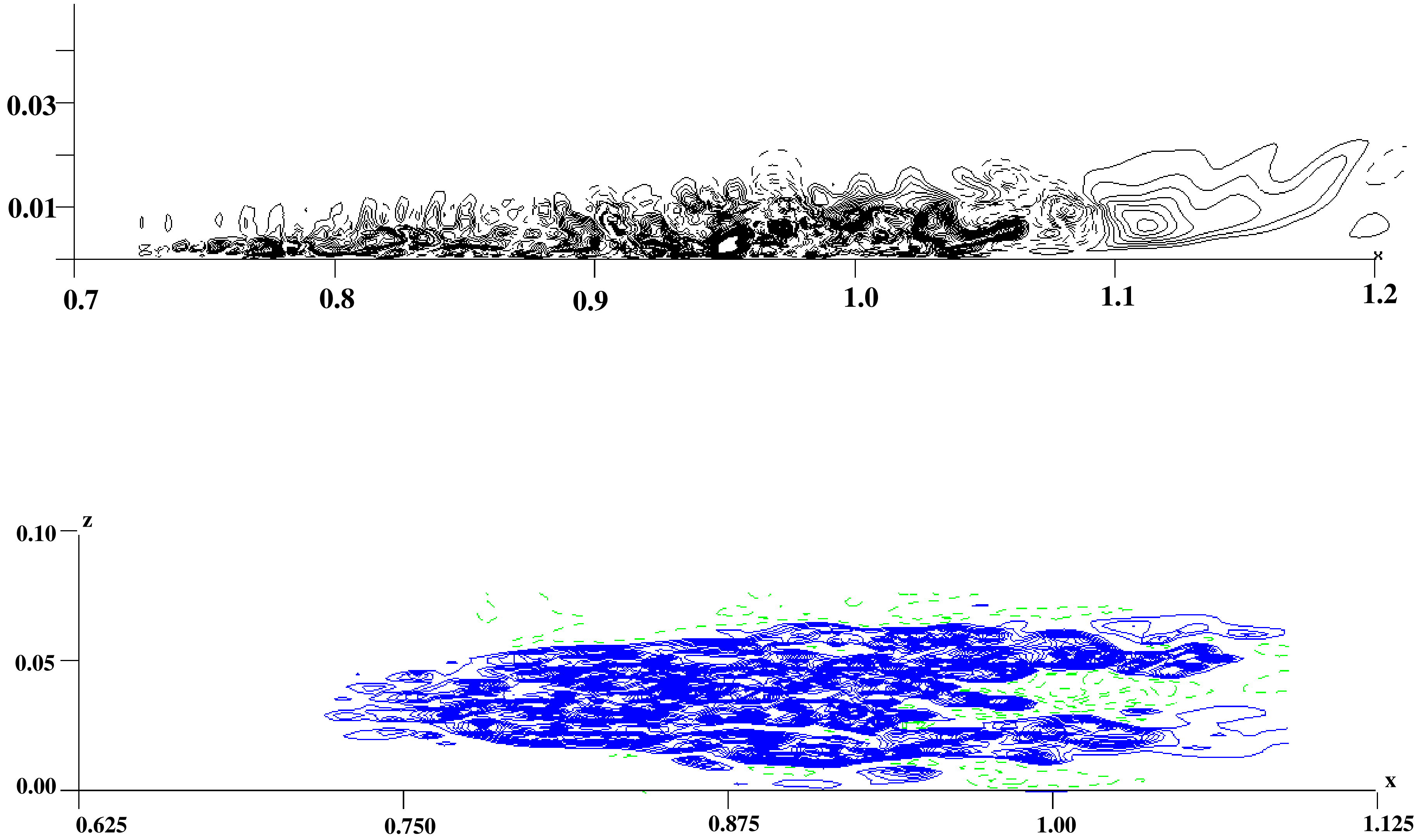


Turbine passage (T106)

(1153×385×129 grid)

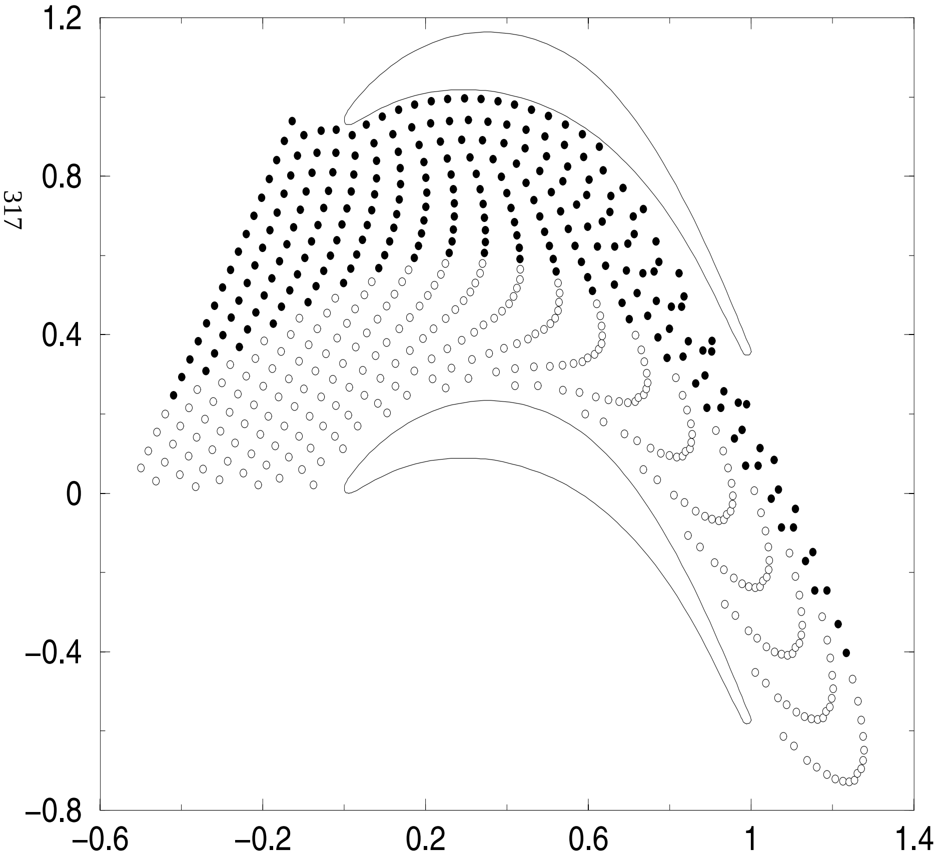


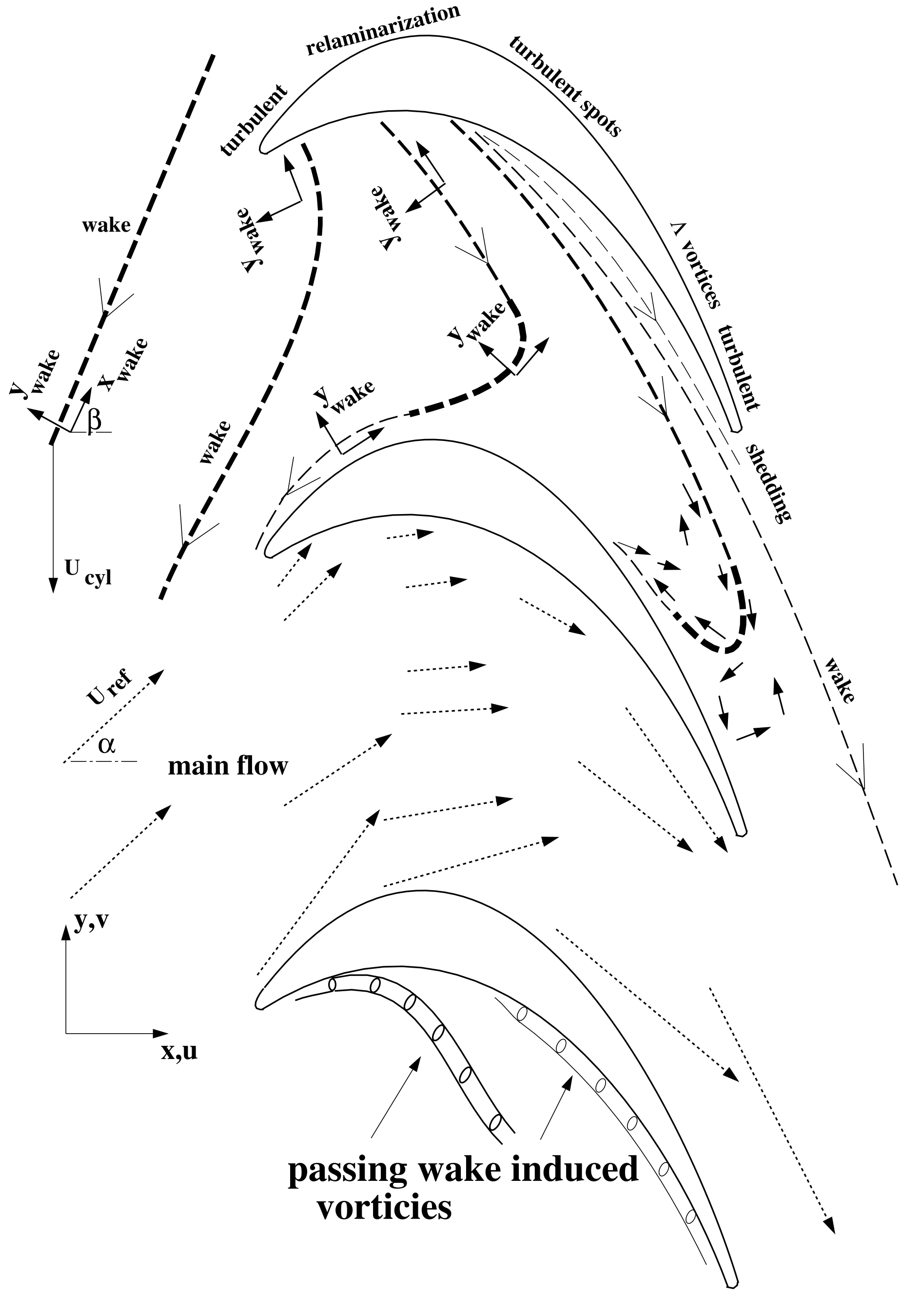

wake 1
wake 2
wake 3
y
0.6
0.4
0.2
x
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

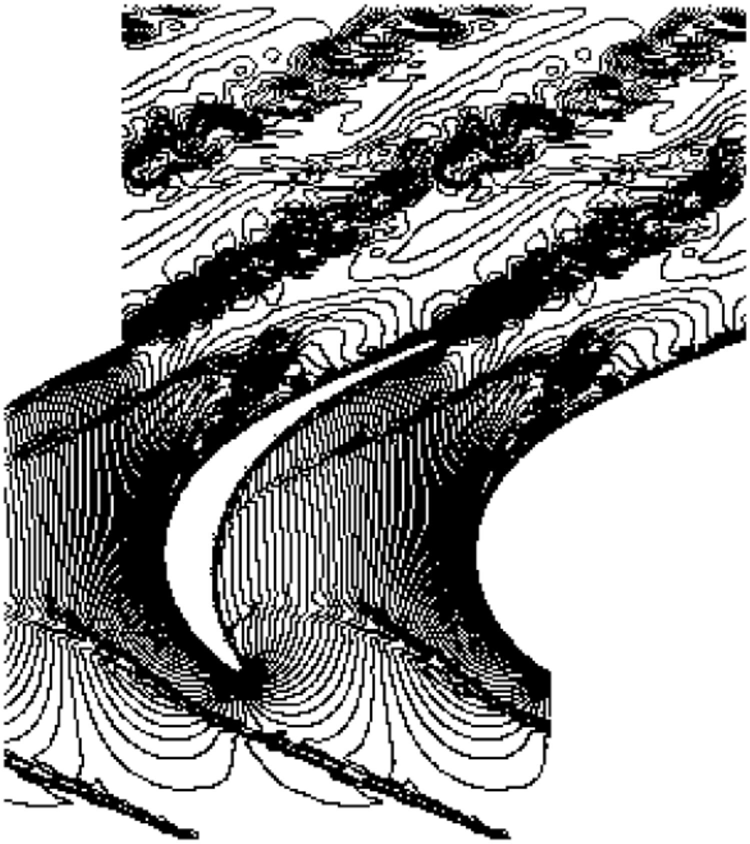
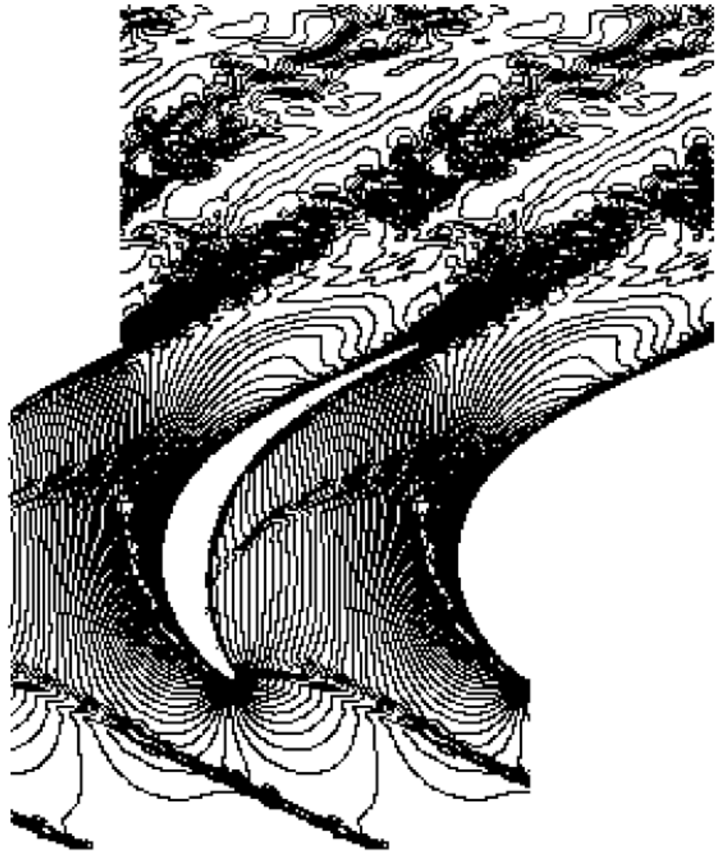
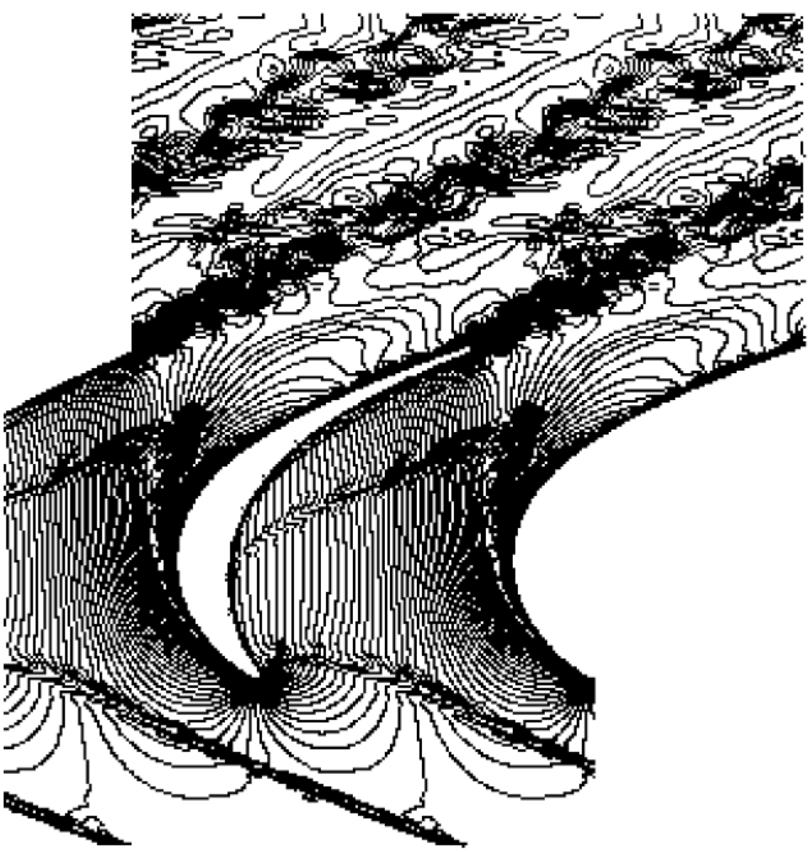
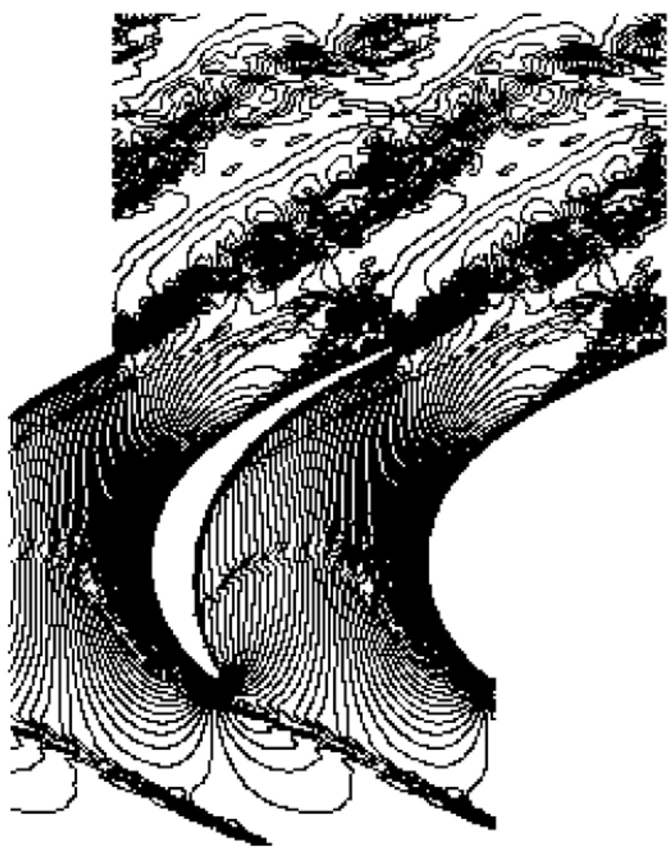


Wake induced turbulent spots

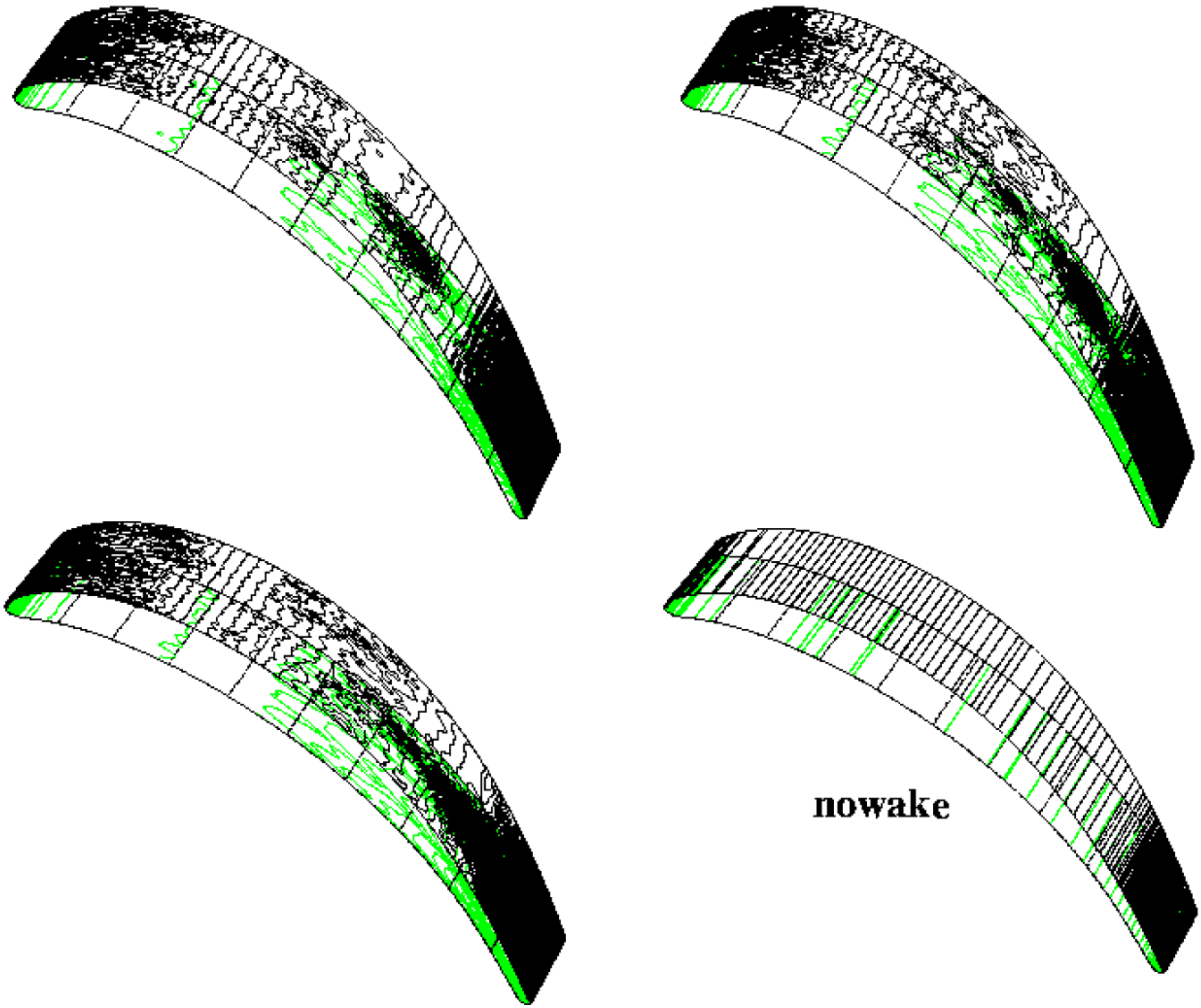
passive particle tracking in mean flow field



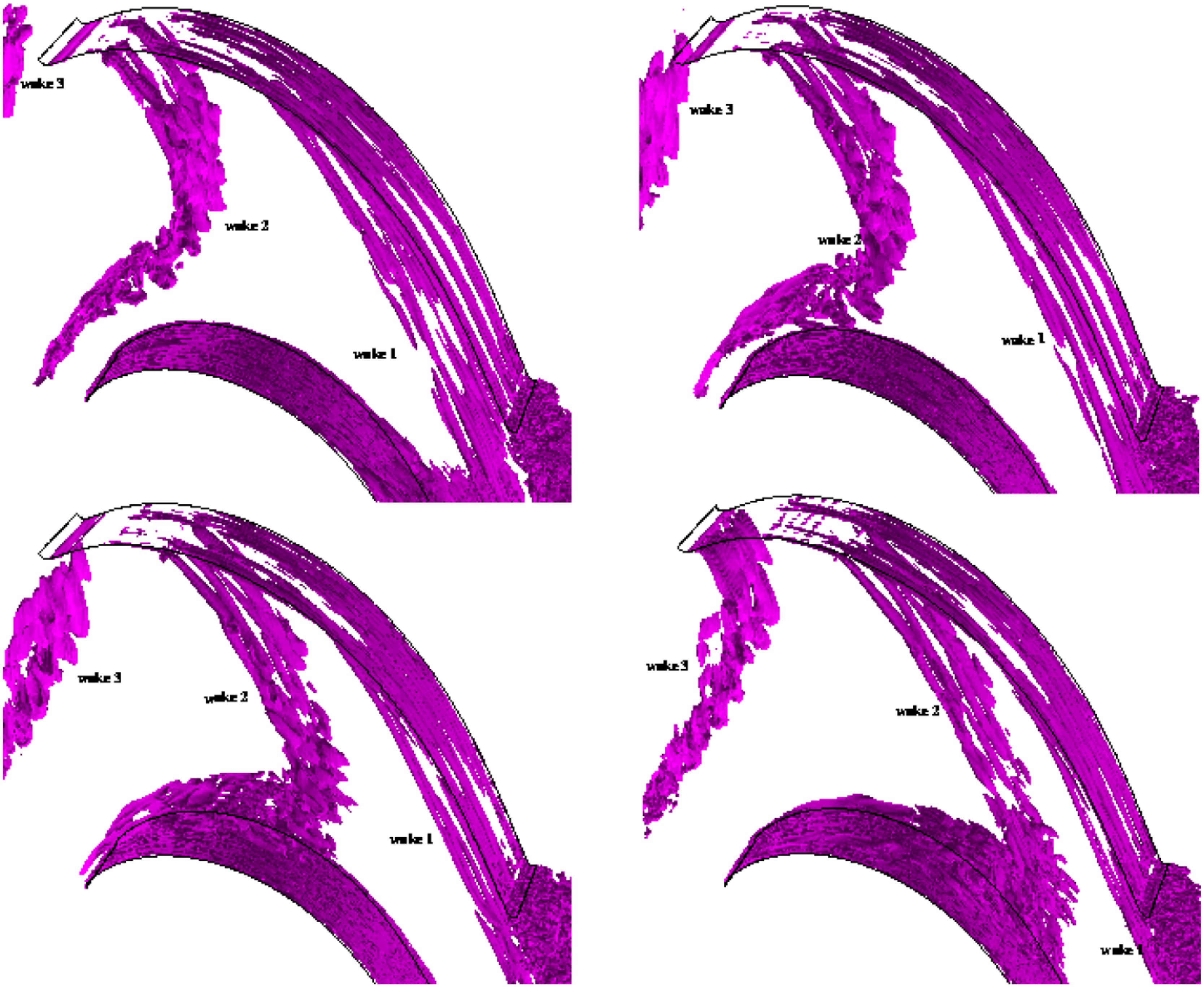


v velocity component near blade surface at 3 instants



regions of negative λ2 at four instants



UNSTEADY STATOR-ROW FLOW WITH WAKE PASSINGS

Frank T. Smith and Linzhong Li
University College
Department of Mathematics
London, U.K.

This ongoing work is aimed primarily at the understanding and modelling of the unsteady flow through a vertical periodic row (stack) of stationary quasi-stator blades, as affected by the wakes from a row of quasi-rotor blades upstream which are also vertically periodic but moving downward.

The periodic wake itself is first found to generate a pressure drop ahead of the stator row.

The subsequent unsteady motion within the stator row is taken to be two-dimensional and to be periodic in the vertical co-ordinate, to allow for the blade to blade interactions. This is accompanied, in a first shot, by an assumption of thin-layer and slowly-varying behaviour in order to capture the global properties of the stator motion via rapid numerical sweeps, as far as possible in a forward-marching manner.

The global properties include substantial regions of adverse pressure gradient over the rear of the typical blade and almost steady separations which periodically (in time) are made unsteady by the passage of the wakes. The wakes and the stator motions can be computed together, allowing for the interactive rows.

As a second shot, the influences of non-slow behaviour are incorporated in the overall approach by means of temporal or spatial lagging of their effects, for example through the normal pressure gradients, again in an attempt to keep the global numerical sweeps as rapid as possible. The effects of the typical wake thickness, the Reynolds number and the temporal period have been studied, among other main features. The above theory and computation is for laminar incompressible flow but should be extendable to turbulent and compressible flow also.

The consequent development of spots initially localised and at low amplitudes is described in allied papers, particularly in the regions of adverse pressure gradient or flow reversal generated on the blade as above. The effects of vortical wake passing as an initiator, followed by nonlinear evolution, nonparallel flow evolution and the three-dimensional responses are included in the spot analysis.

UNSTEADY STATOR-ROW FLOW WITH WAKE PASSINGS

Frank T Smith and Linzhong Li : Mathematics Dept, University College London, UK.
Thanks to the Leverhulme Trust for partial support.

Contents: INTRODUCTION.ROTOR WAKES.STATOR FLOWS.SENSITIVE AREAS AND LOCAL EFFECTS.CONCLUSIONS.

A . INTRODUCTION.

The approach taken here is to provide rapid, direct, forward-marching calculations of rotor wakes and their subsequent flow through stator blades. This is intended to capture swiftly much of the global physics in blade-blade and blade-wake interactions, with vertical periodicity, and avoid many little local features. The forward marching due to parabolicity is in the local flow direction and in time, as far as possible. Slender-flow viscous-inviscid equations are used throughout, across the whole rotor wake and whole stator gap. The calculations, which at heart are based on a slow-variation assumption, can be used to compare with or complement lengthy direct numerical simulation methods.

Some encouragement for this approach is gained from recent comparisons at moderate Reynolds number Re between direct simulations and slender-flow theory, as shown in figure 1(a,b) for the context of branching flow. Background results for wakes and their entry into a blade row downstream are exemplified by those in figure 2, which indicate a relatively wide region of vorticity disturbance in the stator flow context.

The slender-flow approach is applied in figures 3-8 below for incompressible laminar flow as a start. All quantities used are scaled on a representative streamwise velocity U and length L, with Re equal to UL / (kinematic viscosity).

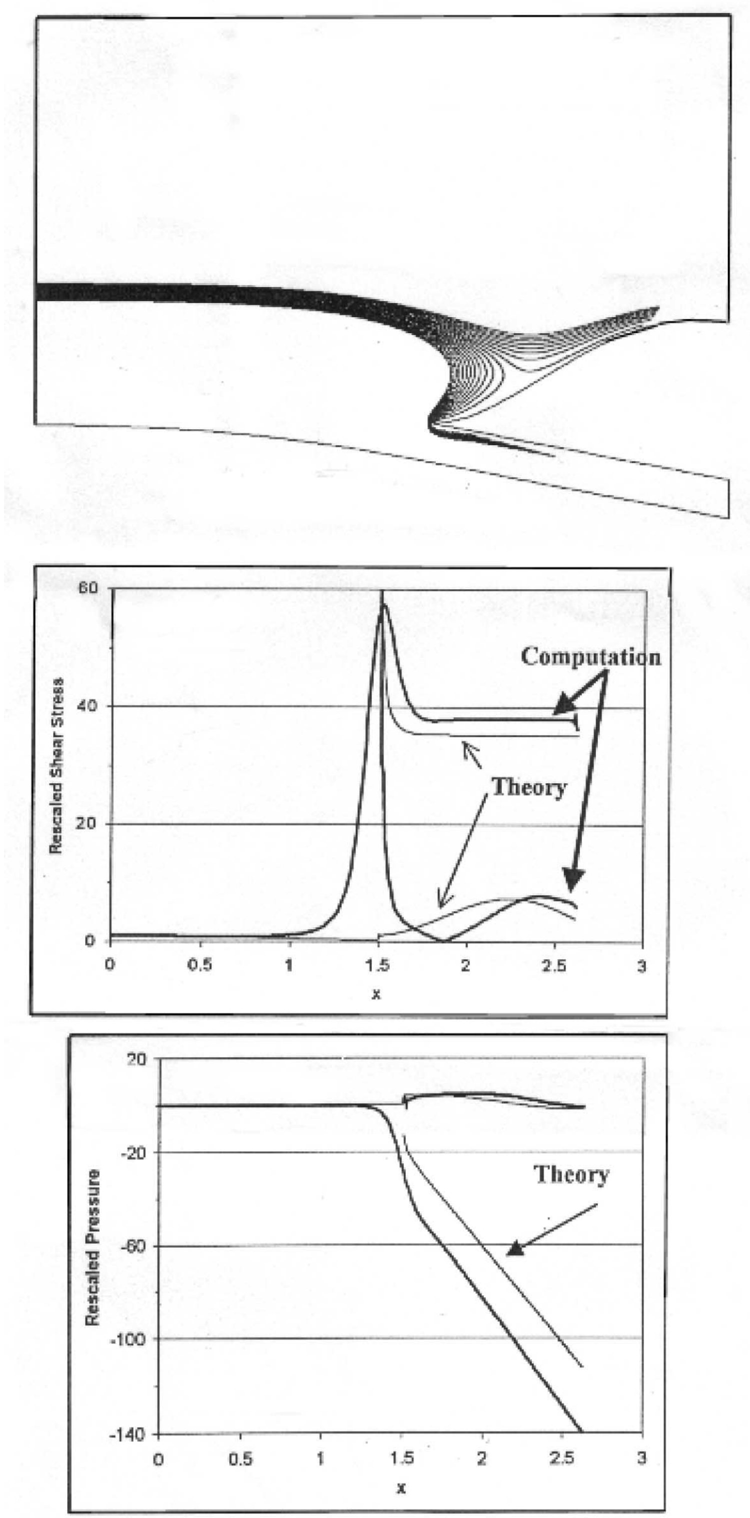


Figure 1. Comparisons between slender-flow theory and direct simulation, for the branching-gap geometry shown (along with the simulated streamlines) in (a); the specified flow on left, upper, and right boundaries is uniform shear flow (b), (c) show comparisons for the rescaled wall shear and pressure p vs streamwise distance x, at Re of 222. From Smith, Ovenden, Franke, and Doorly (2000, submitted to J Fluid Mech).

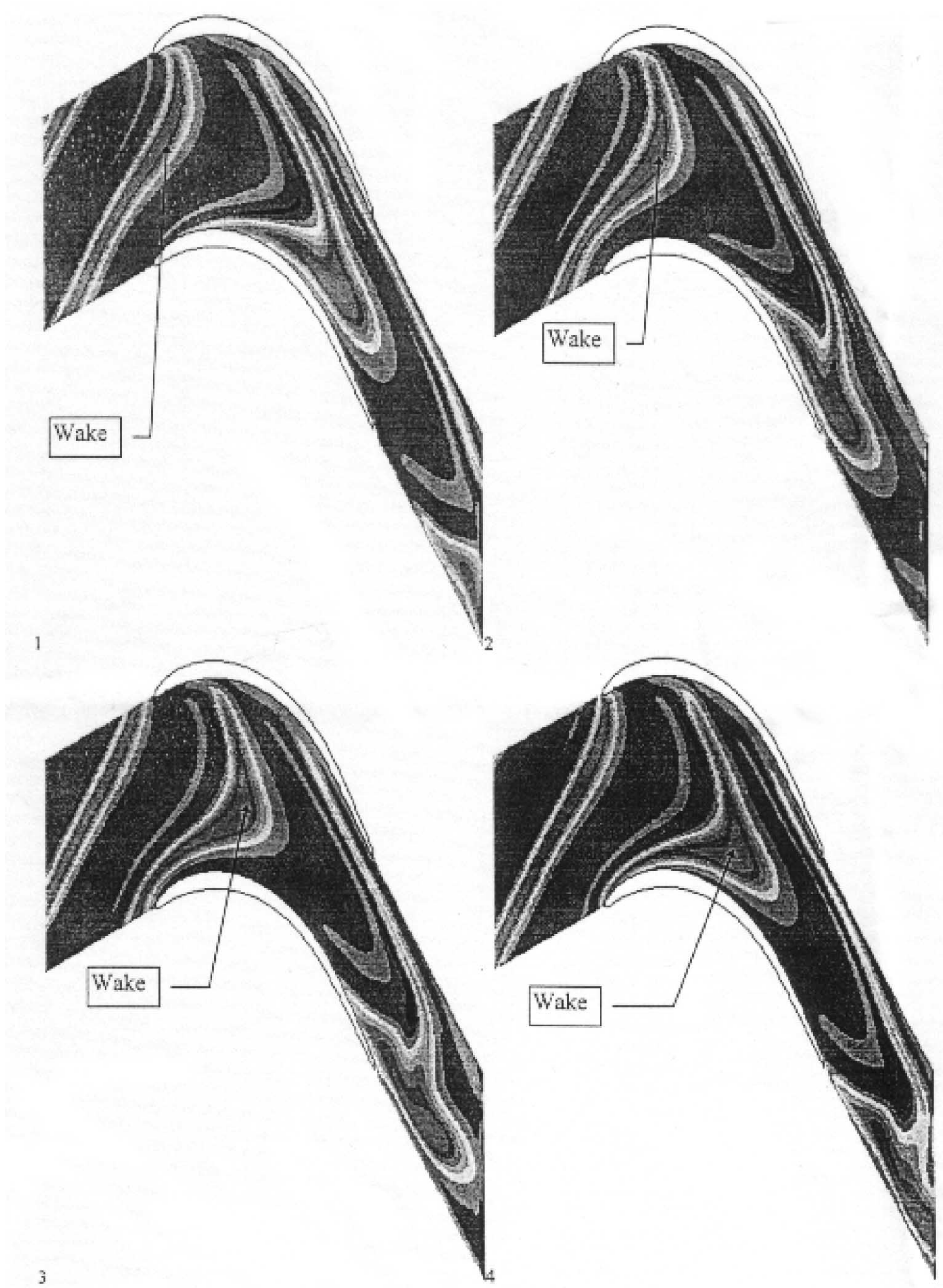


Figure 2. As background, computed inviscid time-marching predictions from Hodson and Dawes (1996): predicted entropy contours during wake-blade interaction.

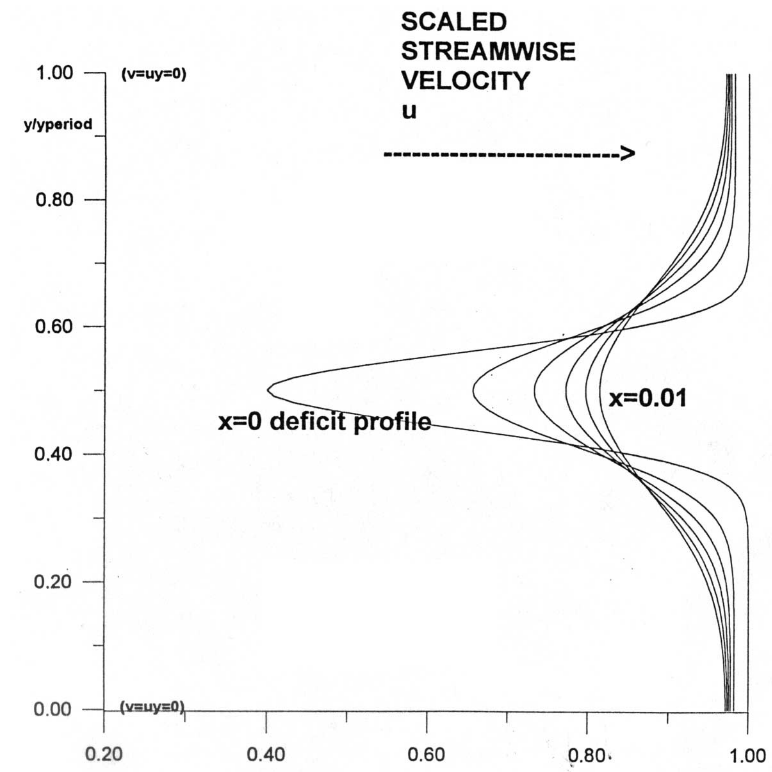
B . WAKES.

In a downward moving frame, periodicity imposed in the vertical direction y means that we need to allow p, the nondimensional pressure variation, to be nonzero. This is in internal motion; by contrast, in external motion the pressure variation would be zero and the vertical period would be an unknown.

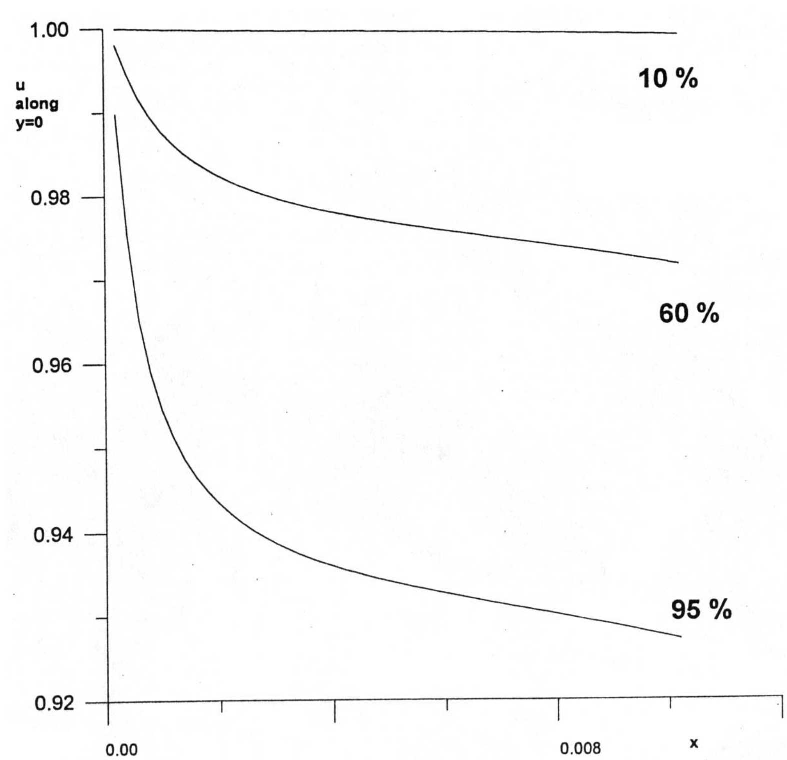
The governing equations are the slender-flow equations of continuity and streamwise momentum $uu_x + vu_y = -p'(x) + u_{yy} / Re$, including the unknown p'(x) force, while the boundary conditions imposed are for vertical periodicity in y and for a given starting profile at an initial x value.

The vertical periodicity is found to yield an adverse pressure gradient along the wake(s), the size of the pressure gradient depending on the starting conditions.
It also raises some concern about the experimental use of two-dimensional models without periodicity.

Examples of the present wake results with symmetry (after a Prandtl transposition if necessary) are shown in figure 3(a-d).

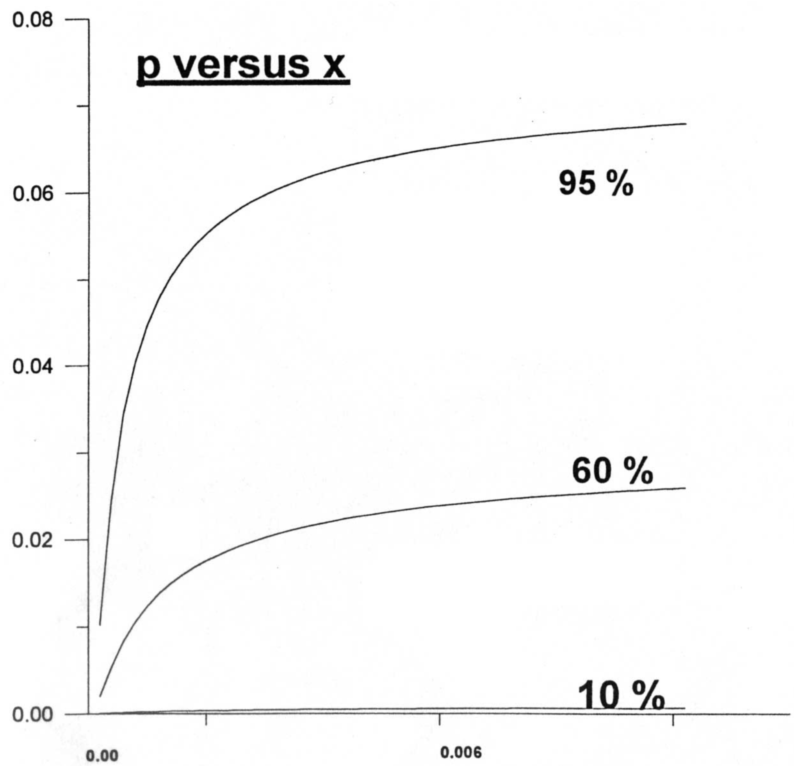


(a)

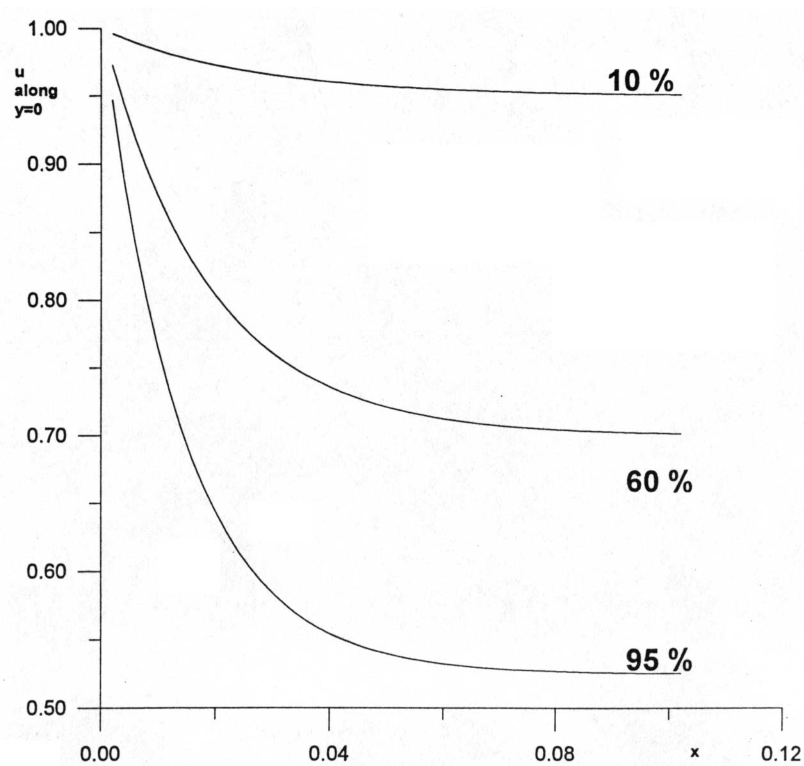


(b)

Figure 3. Wake configuration, periodic in y, with u given at x=0 (say) and v, u_y zero at y=0,1 (say). (a) Streamwise velocity profiles u at various x stations in the wake, after a 60% deficit profile at the start. The scaled y-period is unity. (b) Showing u along y=0 vs x, for 95%, 60%, and 10% deficits at start at x=0.



(c)



(d)

Figure 3. Wake configuration, periodic in y, with u given at x=0 (say) and v, u_y zero at y=0,1 (say). (c) As (b) but giving p vs x. (d) As (b) but for fuller starting profiles, with 95%, 60%, 10% deficits.

C . STATOR FLOWS.

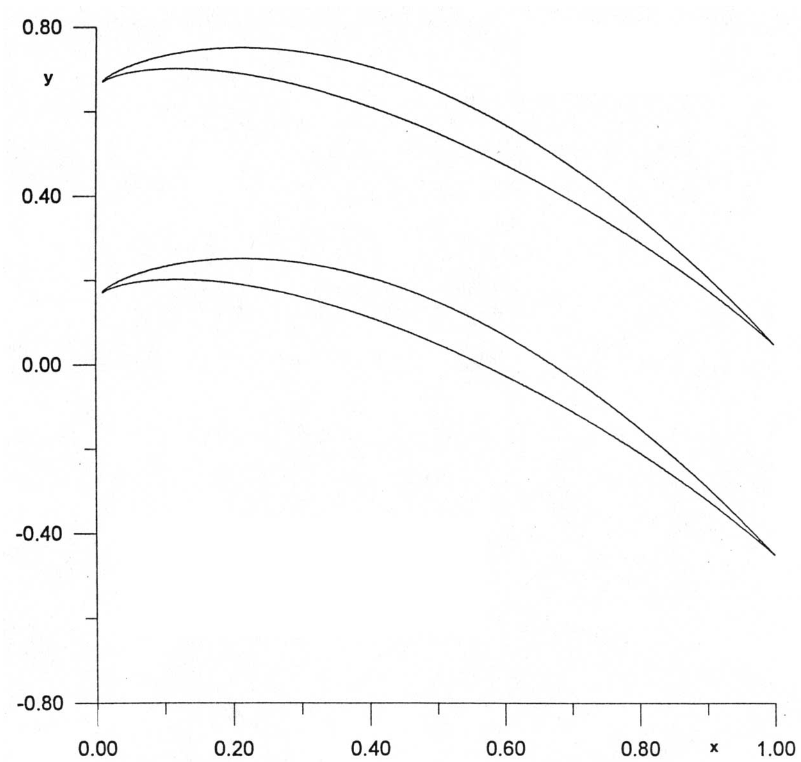
Figure 4(a) presents the configuration, as the wake profiles at entry make the representative stator row flow unsteady periodically (in time), and the typical stator surface shapes studied so far. The governing equations throughout the row are the unsteady versions of those for the wake previously, with p now dependent on x, t, but the boundary conditions require no slip at the upper and lower blade surfaces. A check on the (lagged) effects of non-slenderness and on the influence of normal pressure gradients due to the gap curvature is provided in figure 4(b,c).

Steady results with and without separation are given in figure 5(a,b).

Unsteady results for various conditions are in figures 6(a-c), 7(a-d) and 8(a-d).

Comments on the findings are the following. These global properties include substantial regions of adverse pressure gradient over the rear of the typical blade and almost steady separation. Studies have been made of varying Re, the temporal period and the typical wake thickness. For example the steady flow results in figure 5 show the position x_{min} of minimum p and position x_{sep} of flow reversal/separation coming together as Re increases. In the unsteady case however the pressure gradient is altered substantially. Inflexion points abound, showing two or more vertical length scales and suggesting study of inviscid instability later. Wake effects are seen to travel through the stator flow solution. Exit (i.e. stator trailing edge) profiles are unaffected for a finite time until the wake effect travels through. Local nonlinear breakup and short-scale oscillations become apparent for more disturbed motions.

(a)



(b)

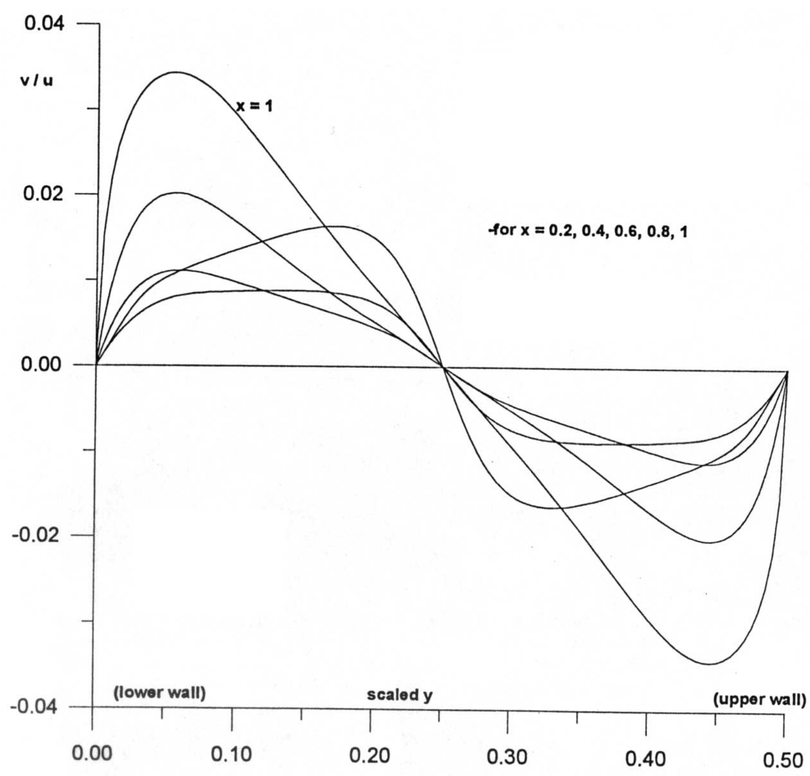


Figure 4. (a) Typical shapes in blade row passage taken in the present calculations, with gap ratio 0.5. The representative entry velocity profile has a 60% wake deficit: fixed in the steady case but moving downward with constant speed in the unsteady case. (b) A check on slenderness, in terms of v / u profiles vs y / ($2y_{max}$).

(c)

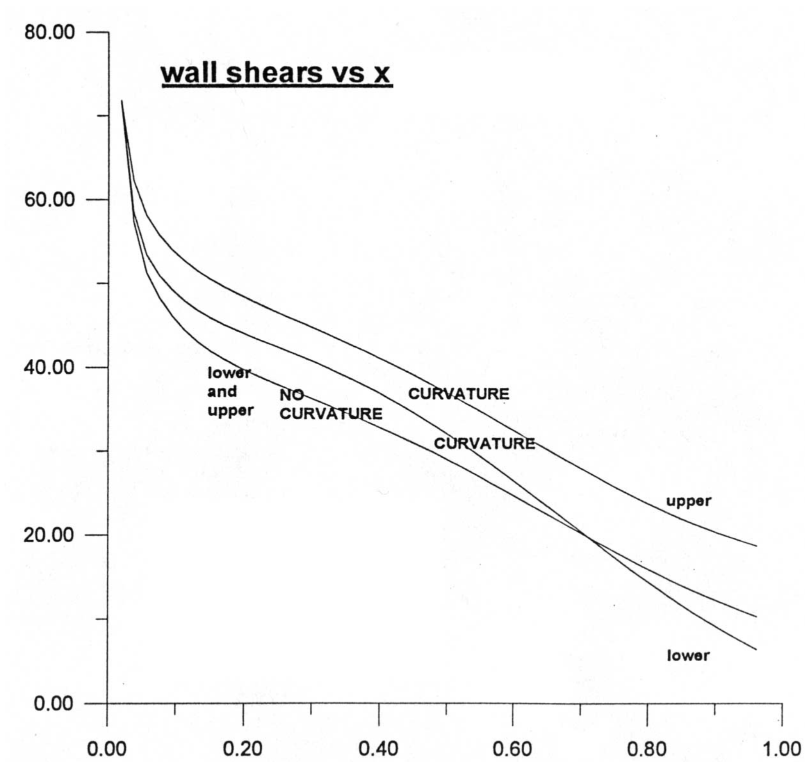
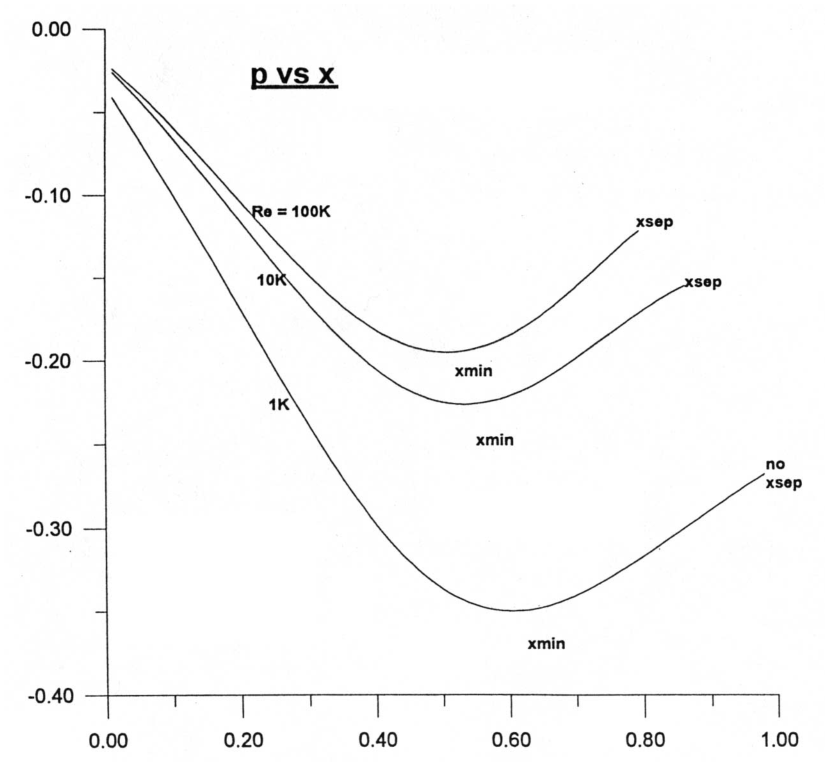
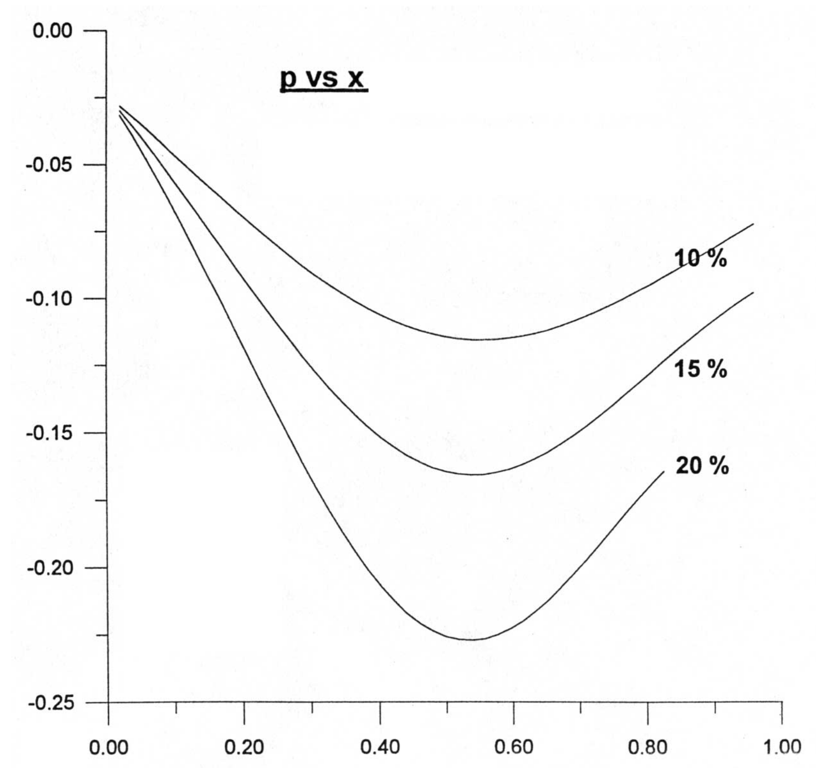


Figure 4. (c) Showing typical normal pressure gradient effects due to blade-row curvature.



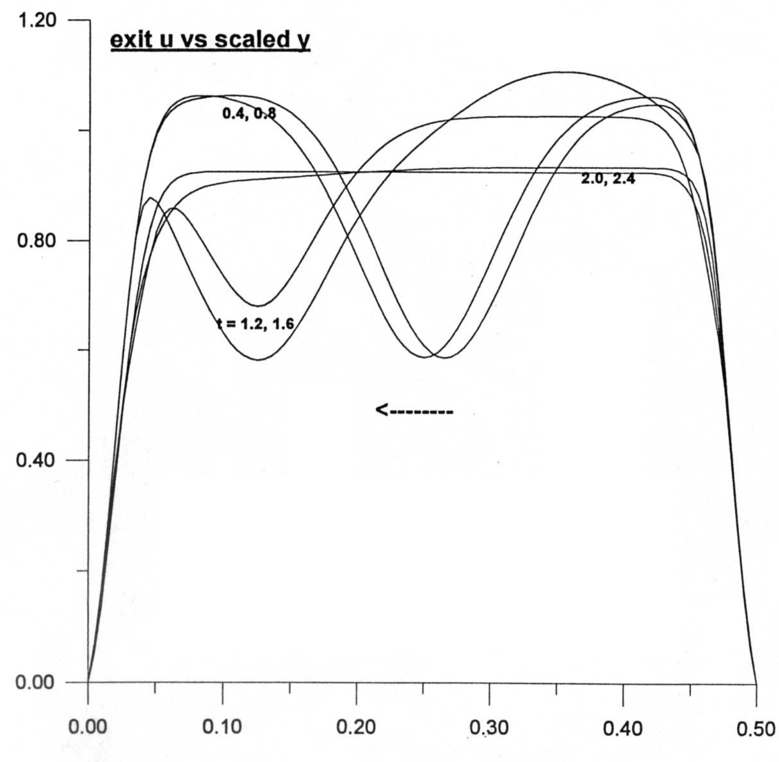
(a)



(b)

Figure 5. Steady flow calculations. (a) p vs x for a fixed geometry and entry profile, but varying Re from 1K to 100K. Note approach of x_{min} to position of minimum gap width, and of x_{sep} to x_{min}, as Re increases. (b) Effect of varying gap width on p vs x, for fixed Re=10K and fixed entry profile, maximum percentage reductions in gap width are shown.

(a)



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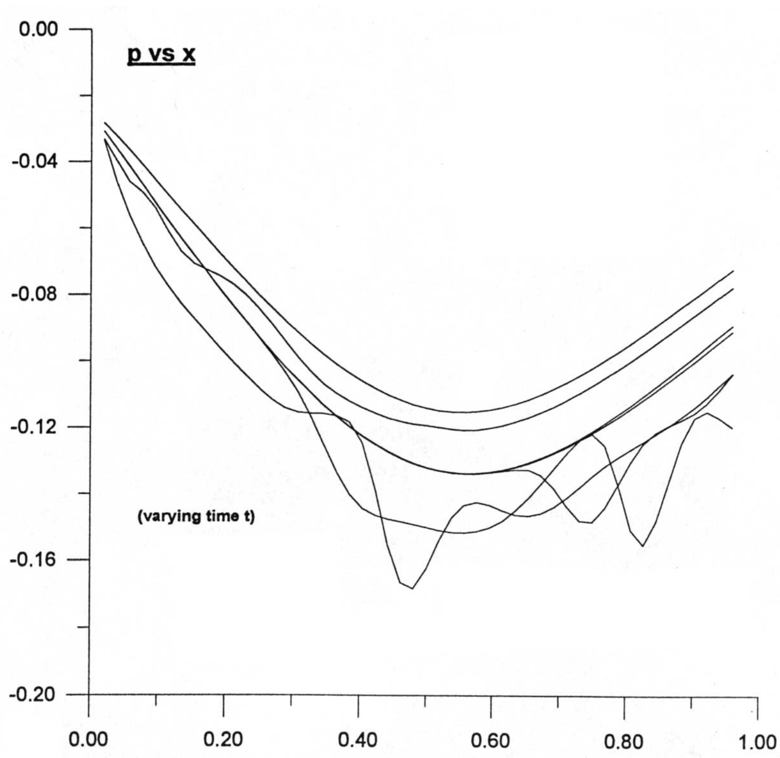


Figure 6. Showing unsteady blade-row results over 2 wake passings. (a) The exit u profiles at x=1, vs $y / (2y_{max})$, for scaled times t=0.4, 0.8, 1.2, 1.6, 2.0, 2.4. (b) p vs x at same times and at t=0.

(c)

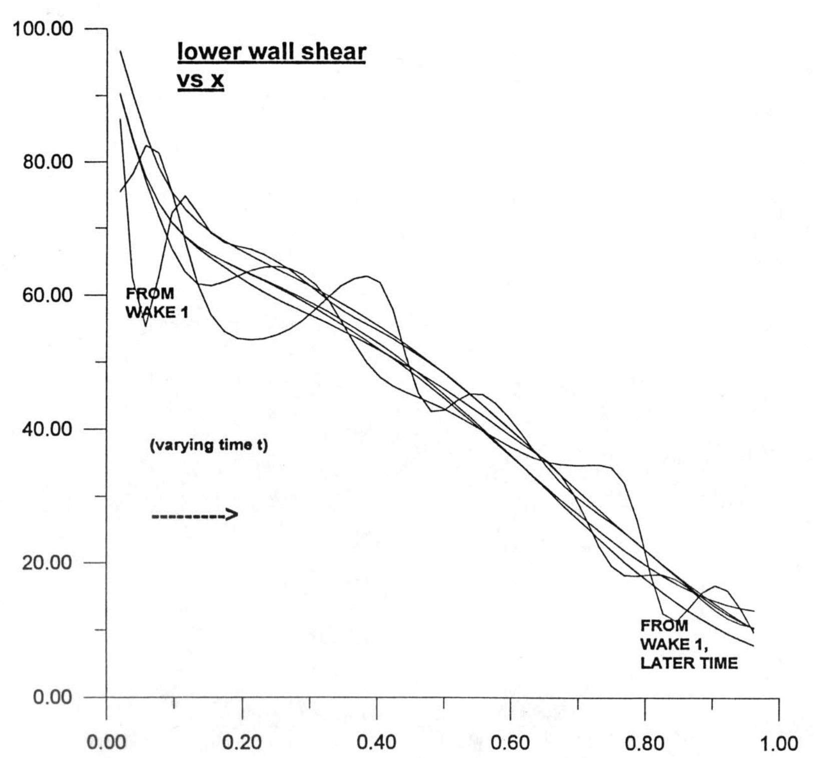
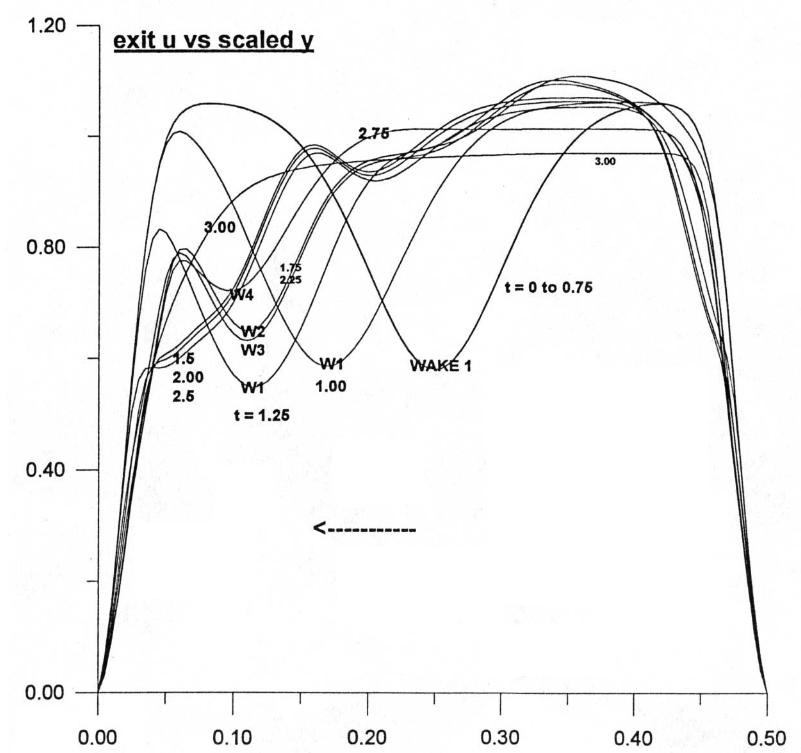
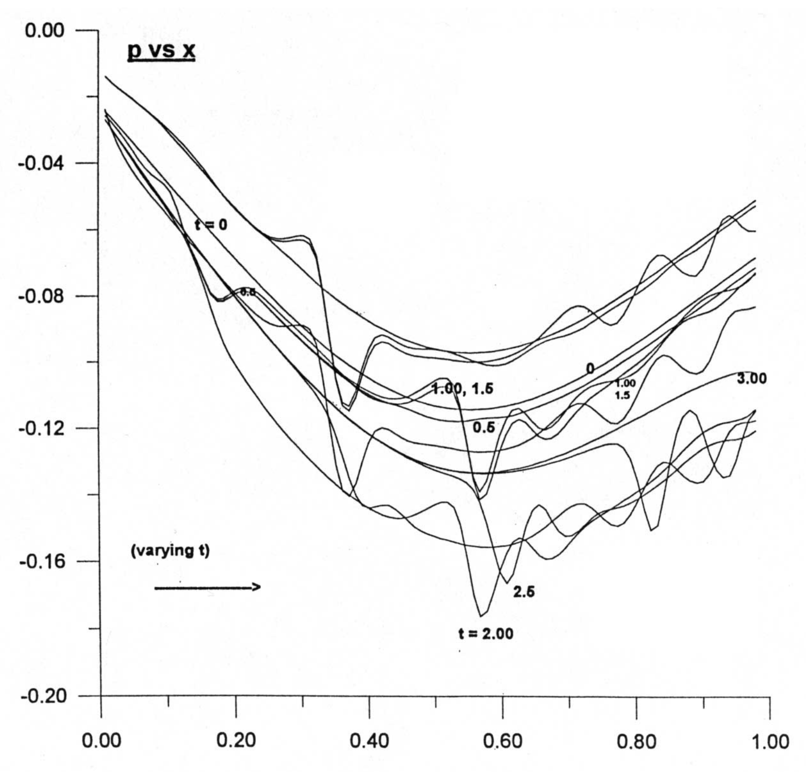


Figure 6. Showing unsteady blade-row results over 2 wake passings. (c) Lower wall shear vs x at same times.



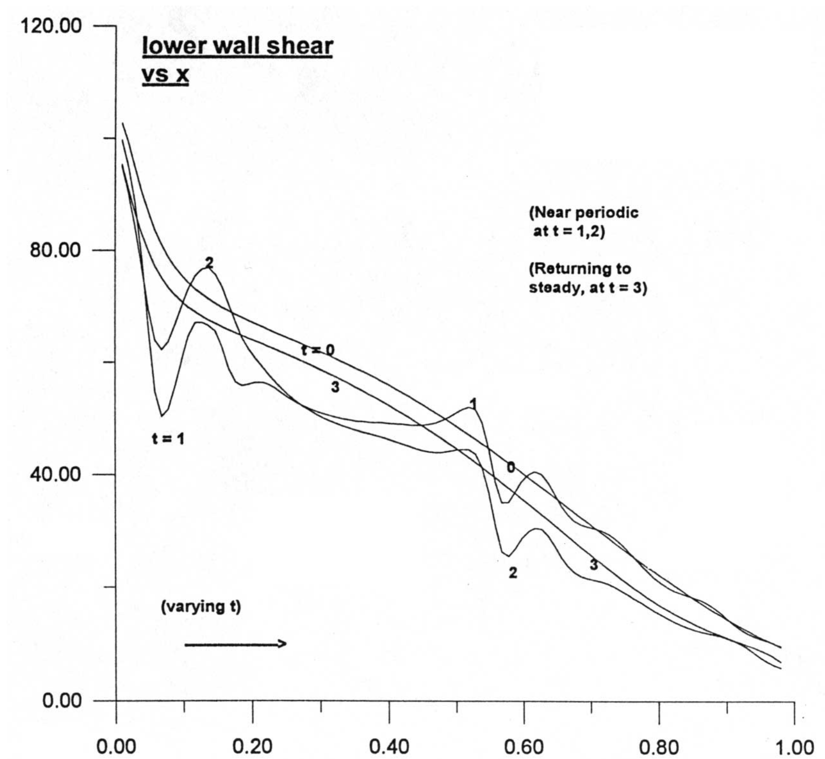
(a)



(b)

Figure 7. Over period of 4 wakes, starting from steady state at t=0. (a) Exit u vs y / $(2y_{max})$ for t=0 to 3, indicating passage of 4 wakes. (b) p vs x over same times.

(c)



(d)

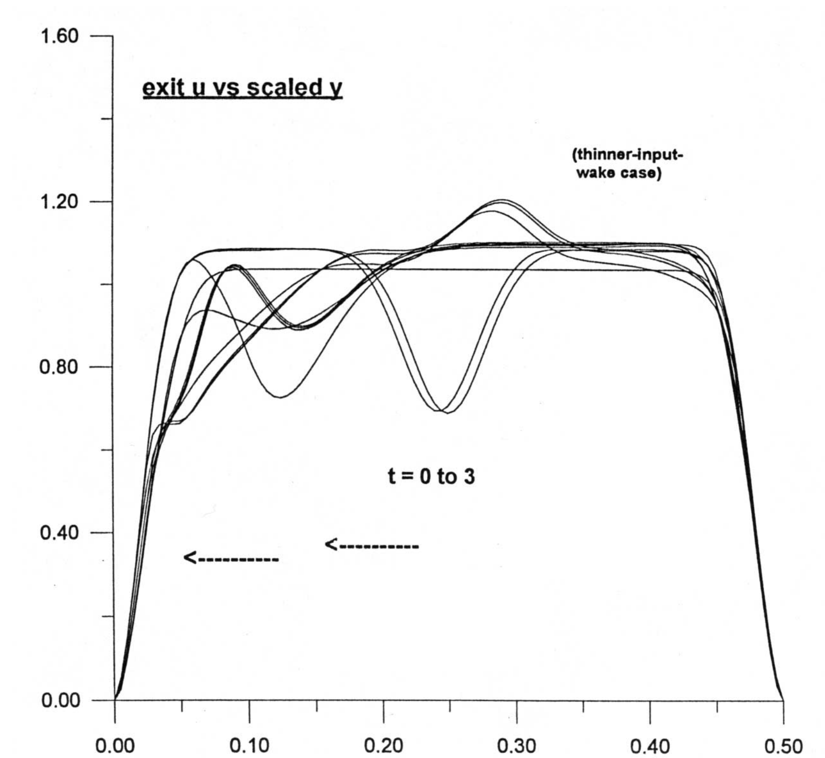
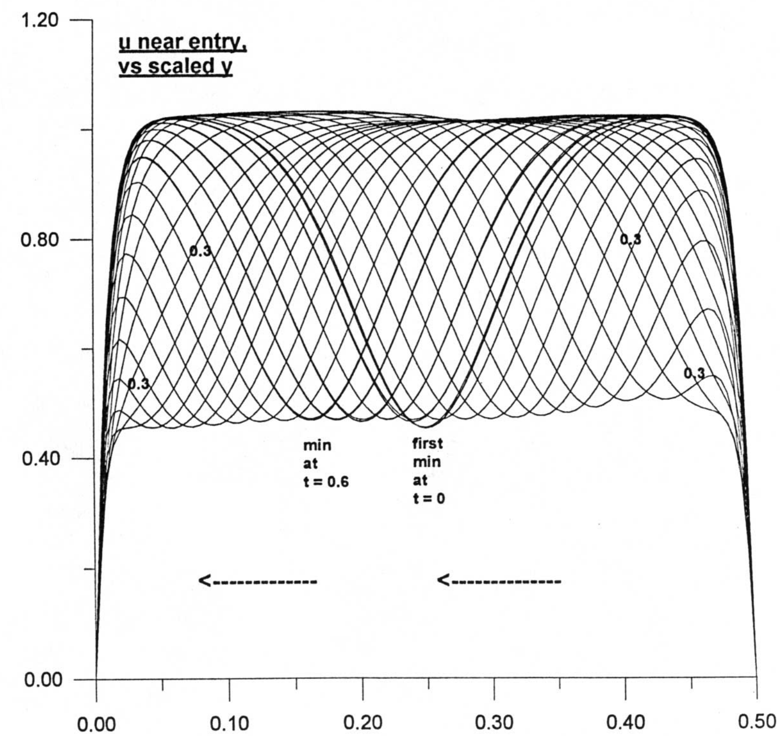


Figure 7. Over period of 4 wakes, starting from steady state at t=0. (c) Lower-wall shear. (d) As (a) but for a thinner (in y) deficit in entry velocity profile.

(a)



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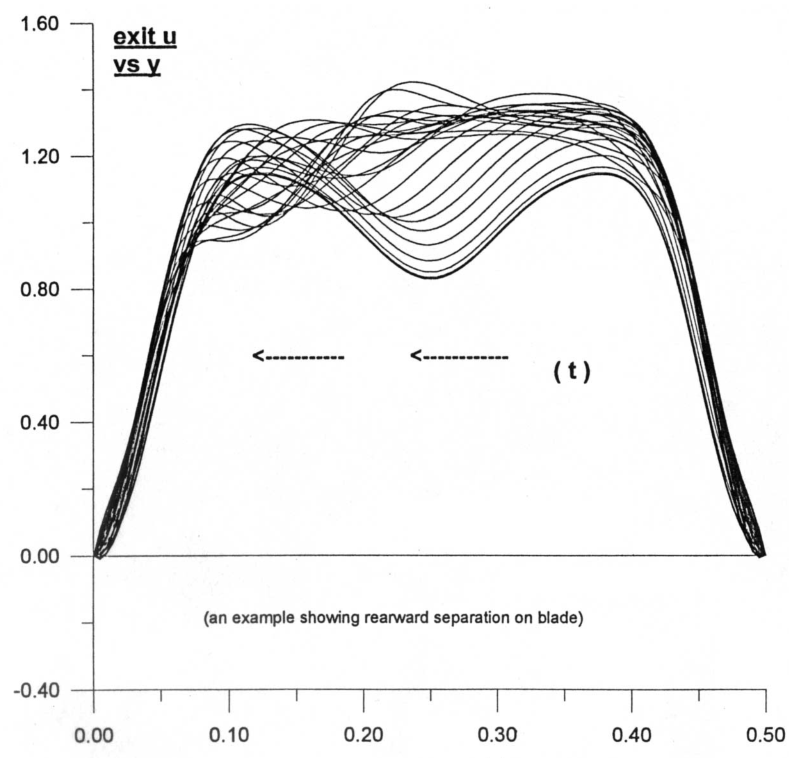
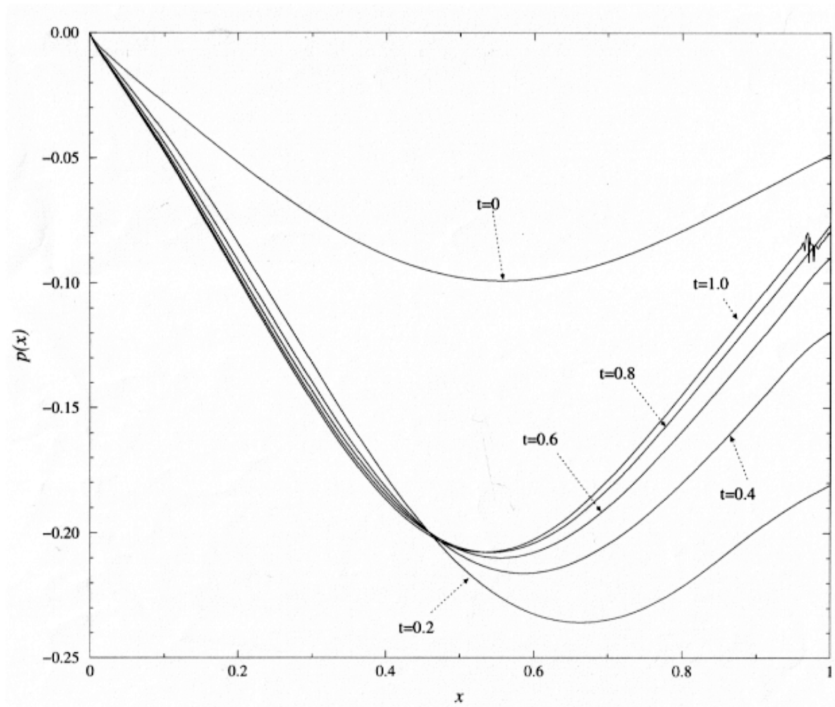


Figure 8. (a) Velocity profiles just downstream of row entry: u at x=0.04 vs y / ($2y_{max}$), for increasing t as indicated. (b) As (a) but at the row exit: u at x=1 vs y / ($2y_{max}$), for times t from 0 to 1.6.

PRESSURE p vs x

(c)



SCALED WALL SHEAR vs x

(d)

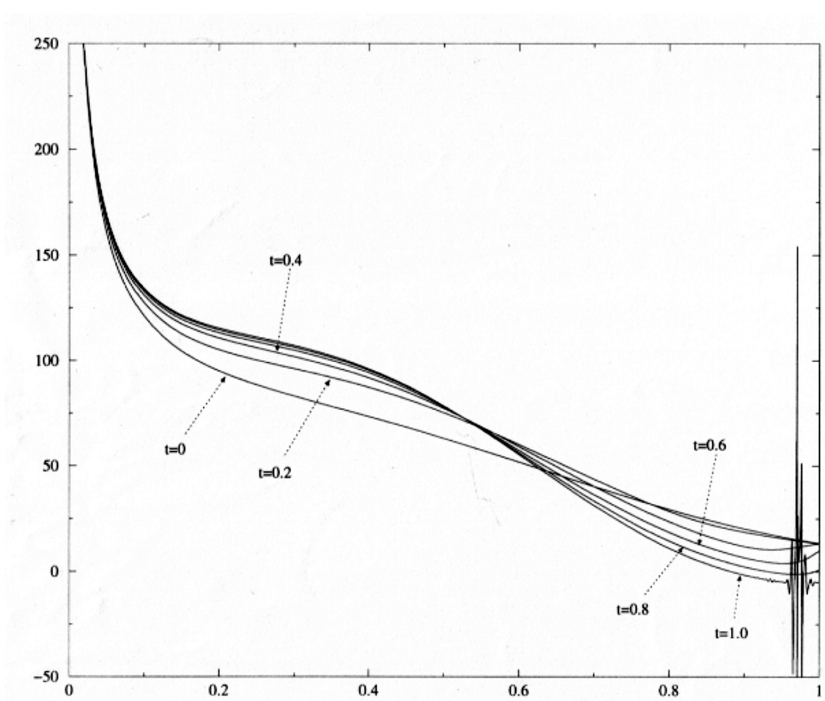


Figure 8. (c) Typical refined calculations at increased disturbance levels: pressures at increasing t, showing rapid growth associated with local breakup. (d) Lower-wall shears at increasing t.

D . SENSITIVE AREAS / LOCAL EFFECTS.

By and large these danger areas for the global calculations and/or other local effects also concern transition, unsteady wake-boundary layer interaction and formation of spots. These areas, depicted in figure 9, are associated with 1-4 below.

1. Regions of adverse pressure gradient beyond the x_{min} point.
2. Separating flow stability/transition.
3. Stability/transition of an evolving boundary layer.
4. Inflexional instability and deep transition, either from classical wake/jet instability or from whole velocity profiles (see figures 6-8 above) right across the gap.

The calculations in B, C above gloss over effects1, 3 and part of 2, 4.

Recent results from theoretical work with Susan Brown show remarkable shapes for spots under pressure gradients or in separating flow: see figure 10(a,b). Other related papers on spots under pressure gradients are by Brown and Smith (1999, Quart J Mech Applied Math), Smith and Timoshin (2000, submitted to J Fluid Mech), the latter of which includes a determination of calmed region properties.

E. CONCLUSIONS.

(i) Rapid calculations have been done for whole wake-stator-row flow.
The rotor wake, as it is in a contained flow, generates an adverse pressure gradient on its own ahead of the stator row.
The wake deficits that then enter the stator row can be substantial in the calculations.

(ii) The results give global viscous-inviscid properties.
Much of the stator flow response revolves around an inviscid adjustment of the incoming wake vorticity but supplemented by viscous effects in initially thin layers. This is why the slender-flow approach can work then.

(iii) Some local features are overlooked, some not.
E.g. the results show global recovery times, but they also show localised breakup, this nonlinear breakup being of the whole flow.

(iv) Extend to turbulent modelled flows, compressibility, three dimensions.

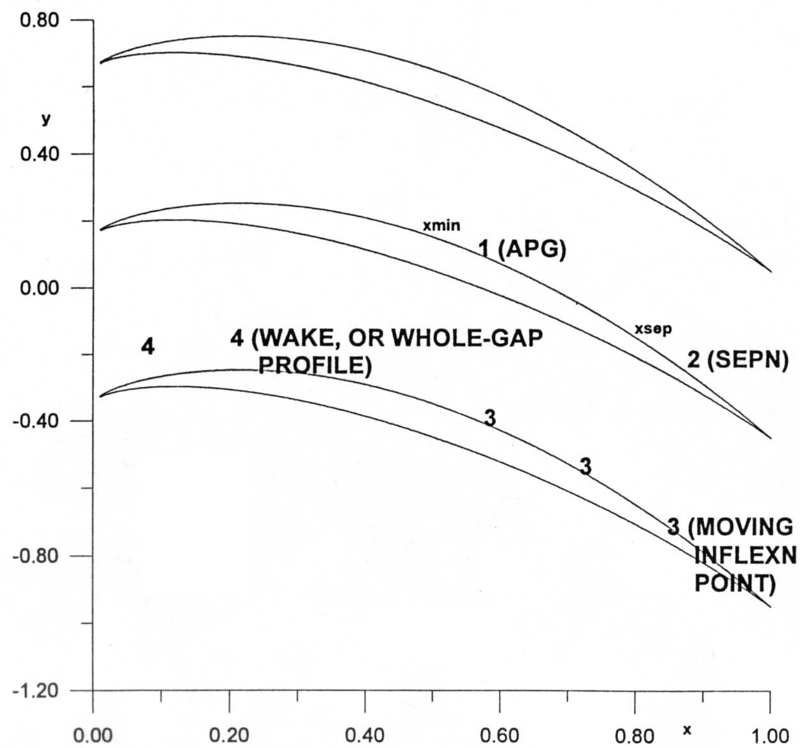
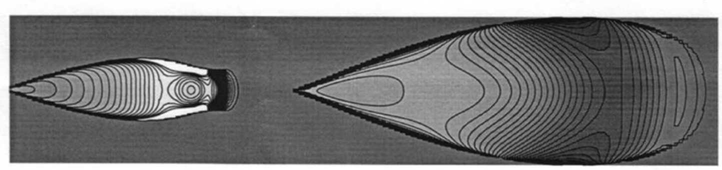


Figure 9. Indicating the sensitive areas / local effects on a representative blade row according to slender-flow calculations.

(a)



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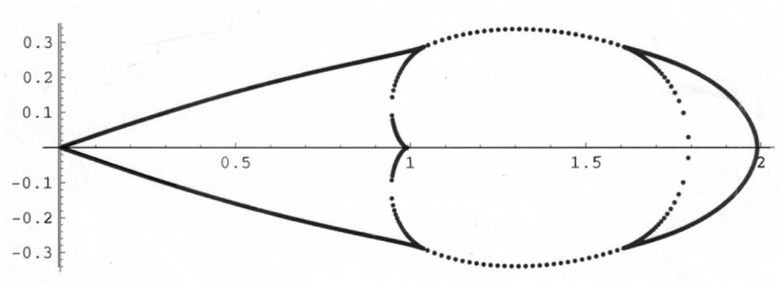

Figure 10. Spot predictions under (a) a favorable and (b) a small adverse pressure gradient, for straight-line basic profiles. Exponential growth arises inside the dotted curve in (b), but only algebraic growth in (a).

RELAXATION FOLLOWING WAKE IMPINGEMENT ON REATTACHING FLOW

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Department of Engineering
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Experiments are in progress aimed at direct comparisons between triggered turbulent spots and wake-induced turbulent patches on a flat plate in a low-speed wind tunnel. These are being conducted under strong adverse pressure gradients giving alternative conditions of a long laminar separation bubble, an incipient laminar separation and an early natural transition, as determined by small changes in free-stream Reynolds number. Good progress has been made on the experiments involving triggered spots and work has commenced on wake-induced turbulent patches.

The purpose is to gain an appreciation of turbulent spot behavior under an adverse pressure gradient as a foundation for the improved modeling of wake-induced turbulent patches in predictions of transitional boundary layer flows on axial turbomachine blading.

A substantial experimental program on triggered spots has now been completed for the long separation bubble and incipient laminar separation cases. This will give two new points which broadly confirm the existing Solomon, Walker, Gostelow spot-spreading correlation for transition length.

Preliminary boundary layer traverses are presented for the case involving wake impingement on the reattachment region of a laminar separation bubble. These show the similarity between the wake interaction and the triggered turbulent spot and also the strong effect of the calmed region behind the wake interaction. The calmed region prevails behind any such disturbance whether two-dimensional or three-dimensional. Unsteady transition phenomena occurring as a result of wake interaction events on compressor and turbine blading are consistent with the behavior of triggered turbulent spots on a flat plate. Experiments on turbulent spots are directly applicable to the complex flows on compressor and turbine blading. The overall effect of the wake interaction, and the resulting calmed region, is to delay the transition process and to stabilize the boundary layer against separation.

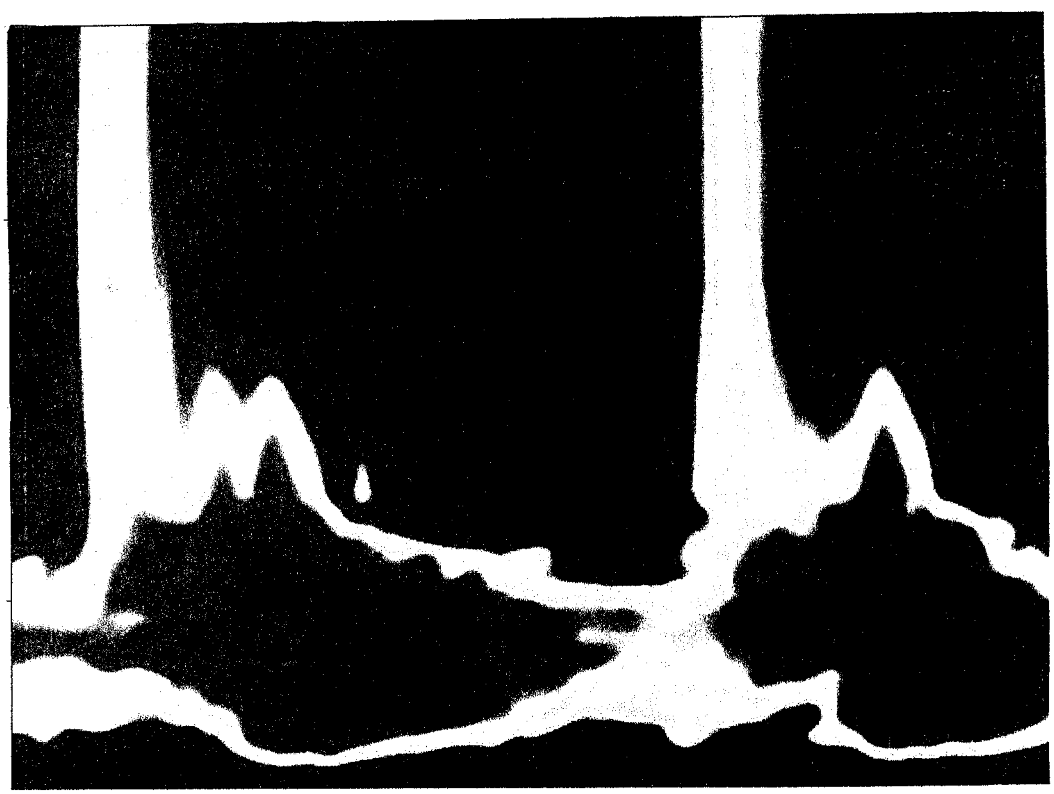
The velocity profiles show that within the impinging wake, the rms disturbance level is strong but there is little velocity perturbation from the incoming laminar layer profile. The turbulent patch behind the wake is more characteristic of a turbulent layer and shows a strong velocity perturbation from the laminar layer velocity profile. The calmed region is strong and has a more stable velocity profile than a steady laminar boundary layer under the same local pressure gradient; the amplitude of Tollmien-Schlichting (T-S) instabilities is therefore temporarily reduced and the progression to harmonic breakdown and turbulence delayed. Turbulence from the surrounding boundary layer eventually contaminates the region leading to its destruction, but this process may be quite protracted. Because of its increased wall shear stress the calmed region flow is also more resistant to separation, and this may have beneficial consequences for stall margin.

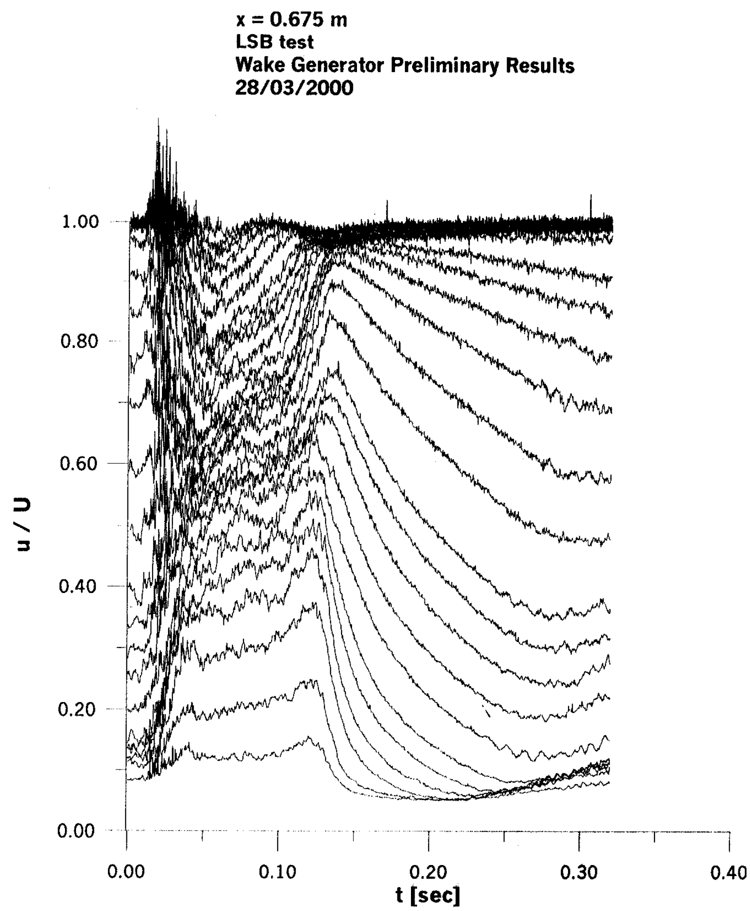
Similarities have been investigated between transition through spots on a flat plate and wake-induced turbulent patches on turbine and compressor blades. In triggered spots on a flat plate transition proceeds by natural growth; small disturbance, to wave packet, to developed spot. Flat plates, turbine cascades and rotating compressor all show natural transition with strong amplification of T-S waves. Harmonic development to turbulence then develops. The instabilities are amplified by strong adverse pressure gradients.

Relaxation Following Wake Impingement on Reattaching Flow

Paul Gostelow, Nic Allen,
Alberto D'Ovidio and James Harkins

University of Leicester




x = 0.675 m
LSB test
Wake Generator Preliminary Results
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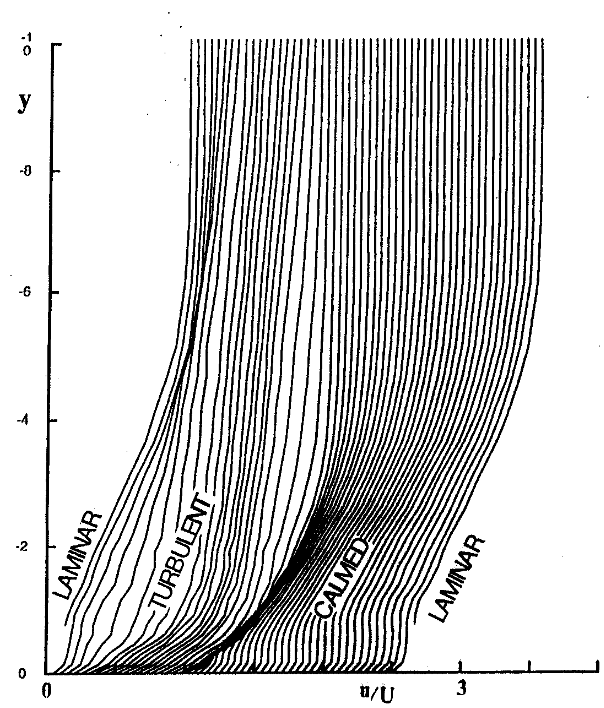
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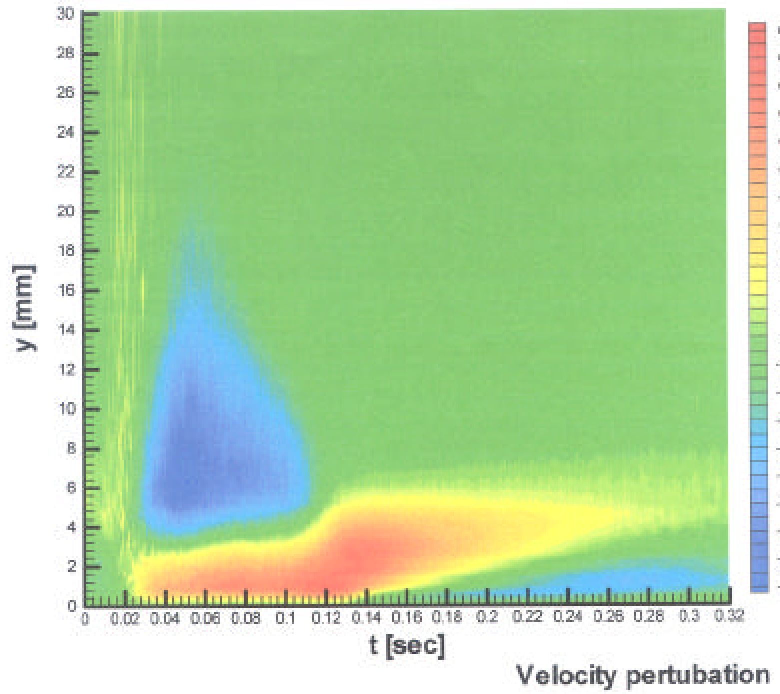
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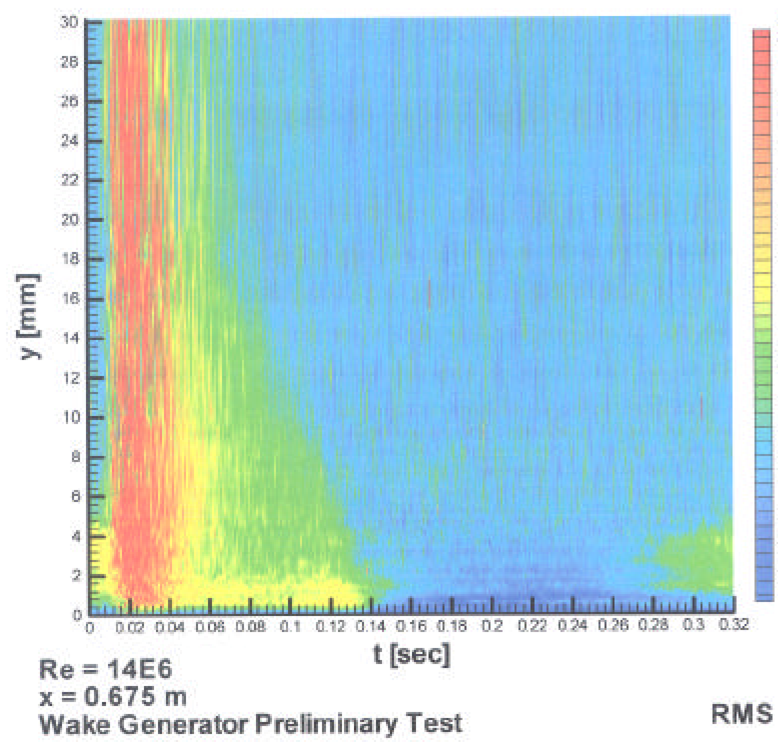
Vp
Velocity pertubation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RMS
Re = 14E6
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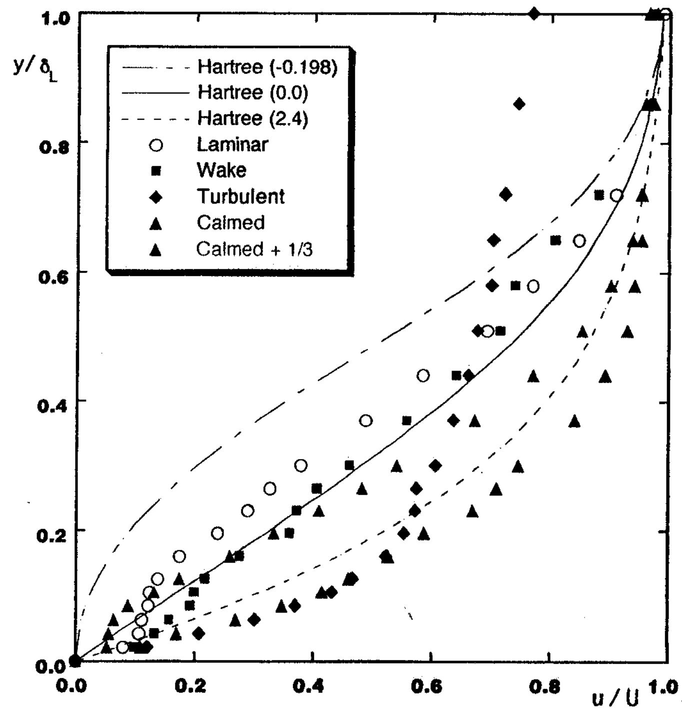
Wake Generator Preliminary Test
RMS



Conclusions and *Further Work*

A substantial experimental program on triggered spots has been completed for long laminar separation bubble and incipient laminar separation cases; this will give two new points on the spot spreading angle correlation curve.

These broadly confirm the existing Solomon, Walker, Gostelow spot-spreading correlation for transition length.

Preliminary tests have been undertaken with a rod-generated wake. The results show similarities with both a triggered spot and the turbulent patch behind an impinging compressor rotor wake.

Velocity profiles show:
(i) within the impinging wake, there is a high rms disturbance level, but little velocity perturbation from laminar,
(ii) turbulent patch behind wake shows strong velocity pertubation,
(iii) then very strong and stable calmed region.

Further work - investigation of streamise development of wake-induced turbulent patches, frequency parameter variation effects on calmed region and laminar separation bubble interaction.

LEADING-EDGE RECEPTIVITY TO VORTICAL DISTURBANCES

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Aerospace and Mechanical Engineering Department
Hessert Center for Aerospace Research
Notre Dame, IN

The amplitude response of Klebanoff modes near the leading edge of a flat plate was studied for different amplitudes and scales of free-stream turbulence. The leading edge geometry consisted of 6:1 and 12:1 ellipses which were matched to a flat plate. The free-stream turbulence conditions were set using perforated grids and screens with different hole and mesh sizes. These were carefully selected so that combinations of turbulence intensities and scales could be independently changed. The free-stream turbulence conditions were documented for the grids and screens in terms of the total r.m.s, and spectra of streamwise velocity fluctuations. The turbulence conditions at the leading edge were changed by placing the plate at different streamwise distances from the grid or screen. The response of the boundary layer near the leading edge was then measured through wall-normal profiles of the mean and r.m.s. velocity fluctuations. The r.m.s. distributions and streamwise development agreed well with those associated with the Klebanoff mode. These were then used to determine an input-output response of the Klebanoff mode amplitude with the free-stream turbulence level. The results showed two regions: a 2:1 amplitude response for $u'/U_\infty \leq 0.5\%$ and a 4:1 response when $u'/U_\infty > 0.5\%$. In both cases, the response appeared to be linear.

LEADING-EDGE RECEPTIVITY TO VORTICAL DISTURBANCES

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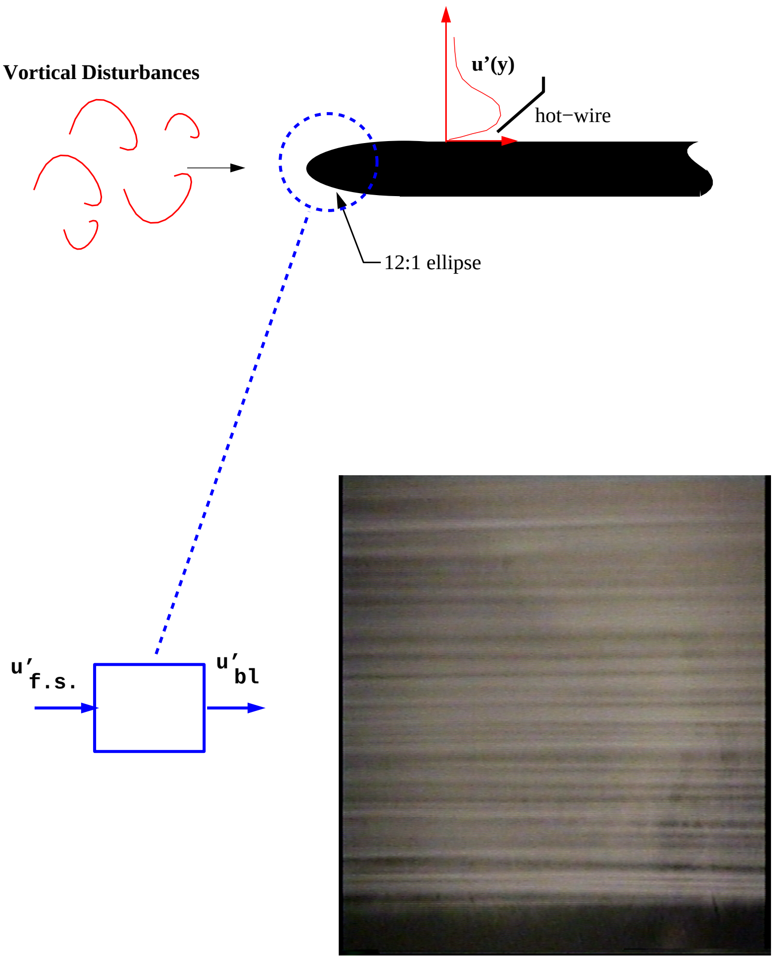
OBJECTIVE:

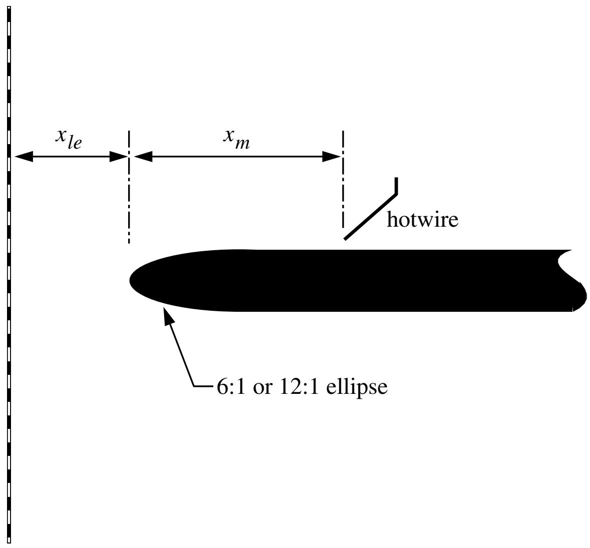
- To investigate the effect of different intensities and scales of free-stream turbulence, and leading edge geometry, on the amplitude of Klebanoff modes in a 2-D boundary layer.
  - Could be used for an **indirect** measure of free-stream turbulence levels in harsh wind-tunnel environments.



APPROACH:

- Experimental conditions similar to Kendall (1985,1990).
  - 6:1 and 12:1 elliptic leading edge on a flat plate.
  - Comparable range of measurement Re_x.
  - Hot-wire and microphone sensors.

- Numerical simulation analog by Bertolotti (1997).



$$U_\infty(x_m) = 8.5 \text{ m/s; Plate thickness} = 2.21 \text{ cm}$$
$$x_m = 25.4 \text{ cm}, \ Re_{\delta^*} \simeq 495$$
$$15\text{cm} \leq x_{le} \leq 2.31\text{m}$$
$$19 \leq x_{le}/M \leq 834$$

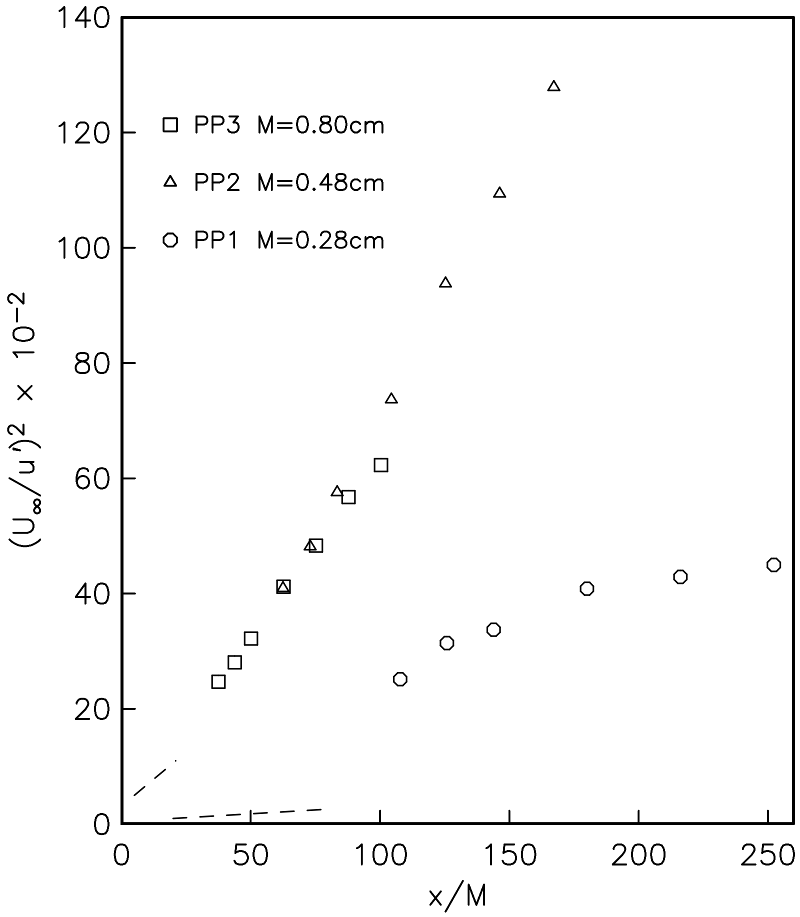
Characteristics of Perforated Grids used for Controlling Free-stream Turbulence

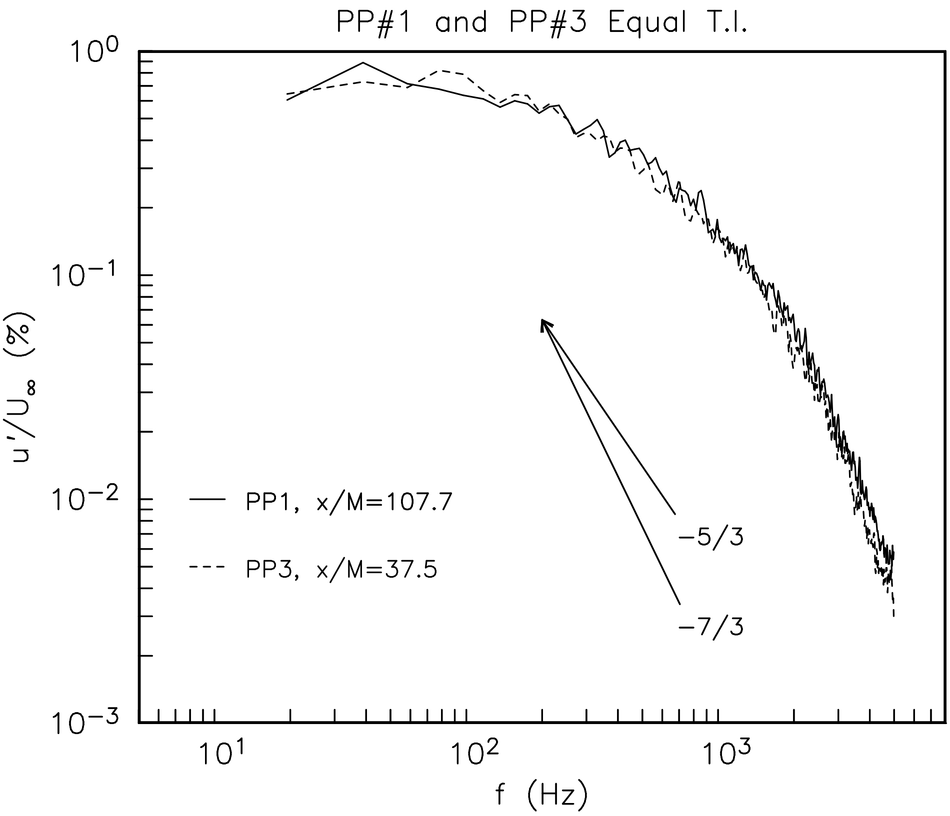
Designation	Hole Diam. (d) (in.)	Mesh (M) (in.)	Solidity (σ) (in.)
PP #1	0.0625	0.109	0.70
PP #2	0.1400	0.188	0.49
PP #3	0.250	0.313	0.42

note: All grids are 0.063in thick, steel.

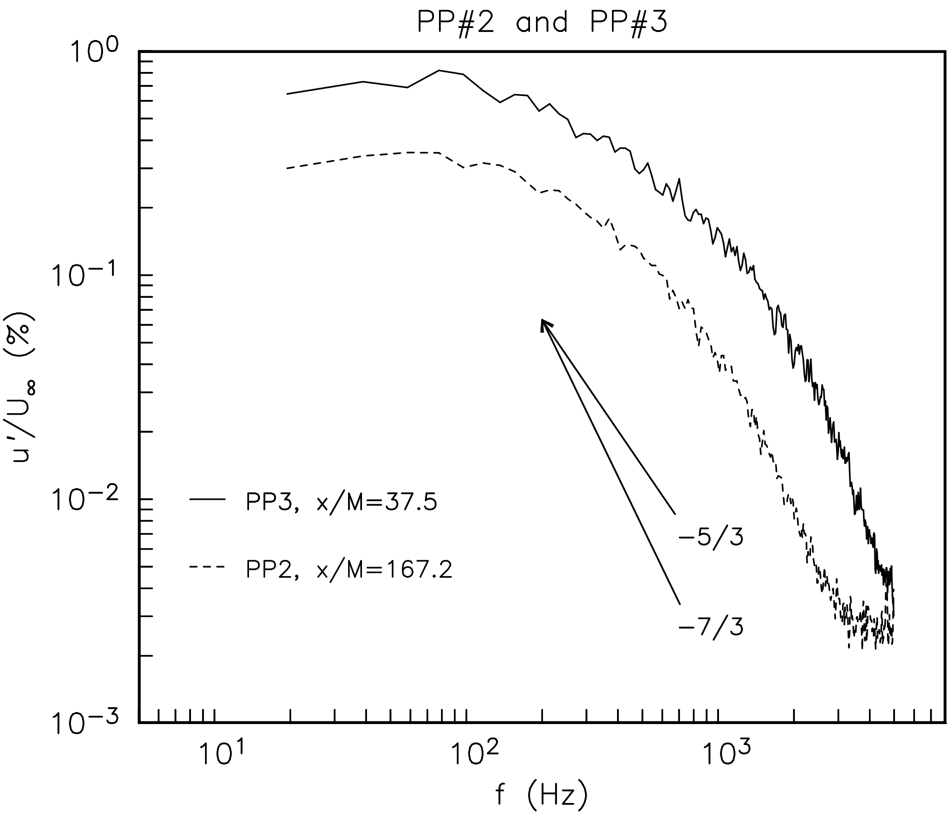
Characteristics of Screen used for Controlling Free-stream Turbulence

Designation	Wire Diam. (d) (in.)	Mesh (M) (in.)	Solidity (σ) (in.)
S #1	0.0065	30×32	0.36

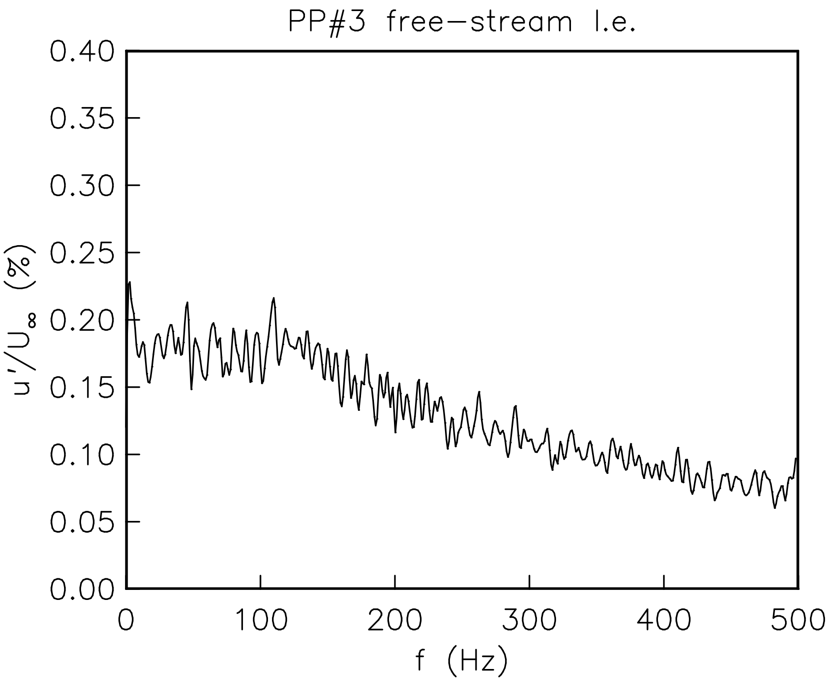

140
120
100
80
60
40
20
0
$(U_\infty/u')^2 \times 10^{-2}$
PP3 M=0.80cm
PP2 M=0.48cm
PP1 M=0.28cm
0
50
100
150
200
250
x/M

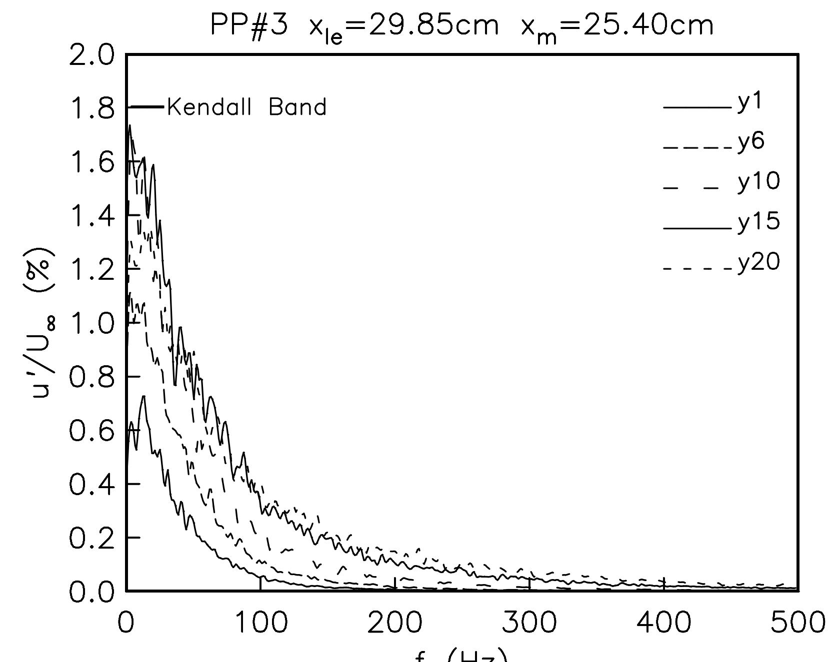


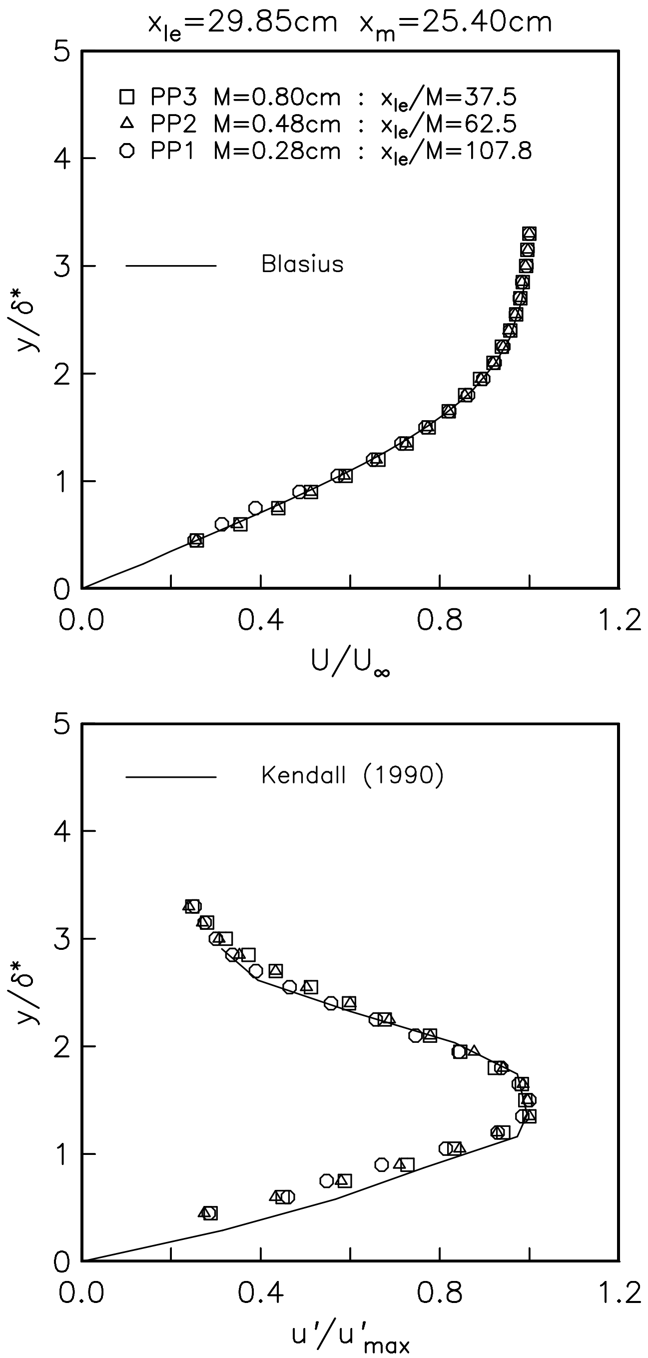
PP#1 and PP#3 Equal T.I.
u'/U∞ (%)
f (Hz)
PP1, x/M=107.7
PP3, x/M=37.5
−5/3
−7/3



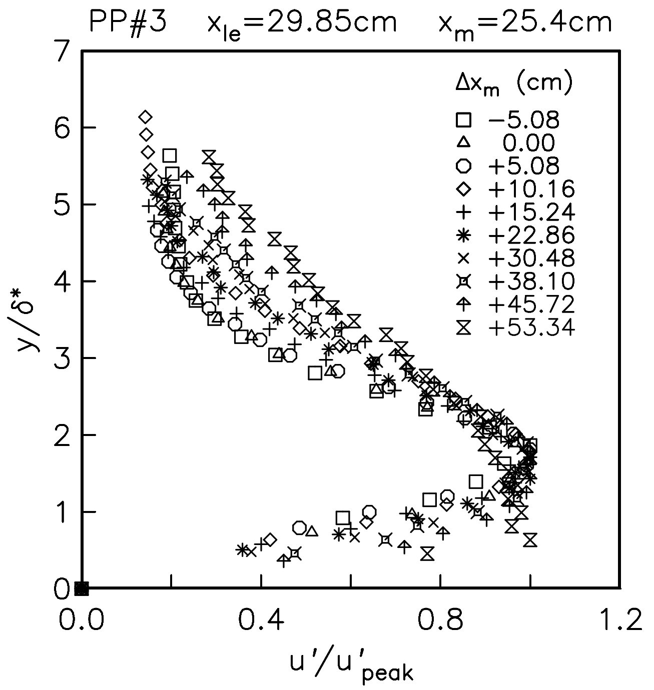
PP#2 and PP#3
10^0
10^{-1}
10^{-2}
10^{-3}
u'/U∞ (%)
PP3, x/M=37.5
PP2, x/M=167.2
−5/3
−7/3
10^1
10^2
10^3
f (Hz)

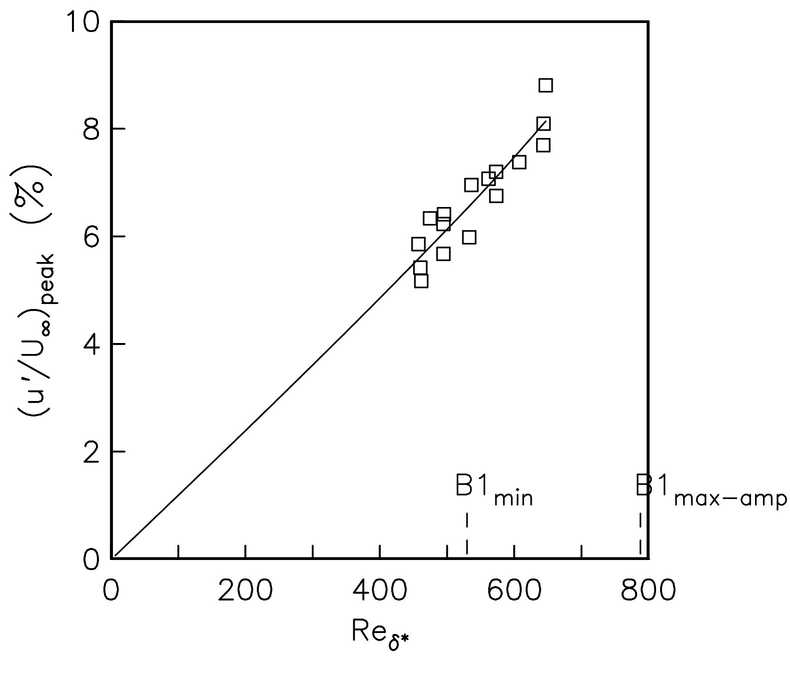

PP#3 free-stream l.e.
u'/U∞ (%)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
100
200
300
400
500
f (Hz)

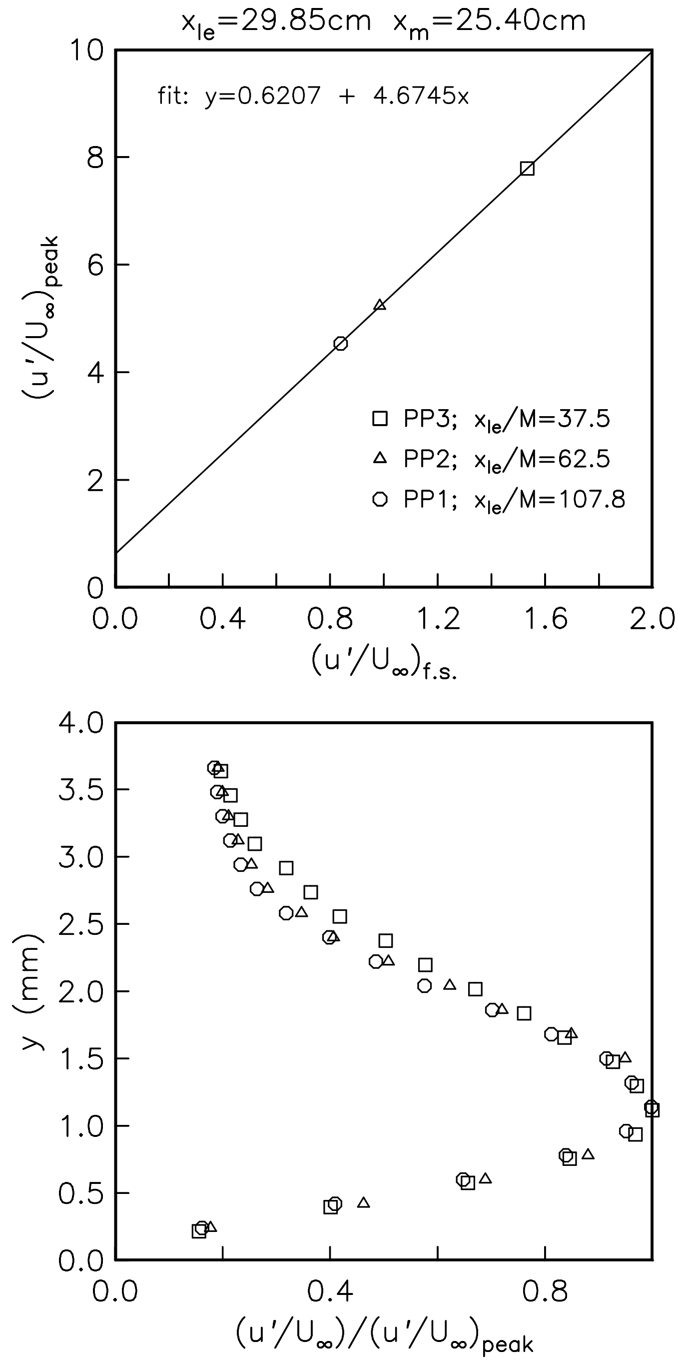

PP#3 x_le=29.85cm x_m=25.40cm
Kendall Band
y1
y6
y10
y15
y20
u'/U∞ (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
100
200
300
400
500
f (Hz)

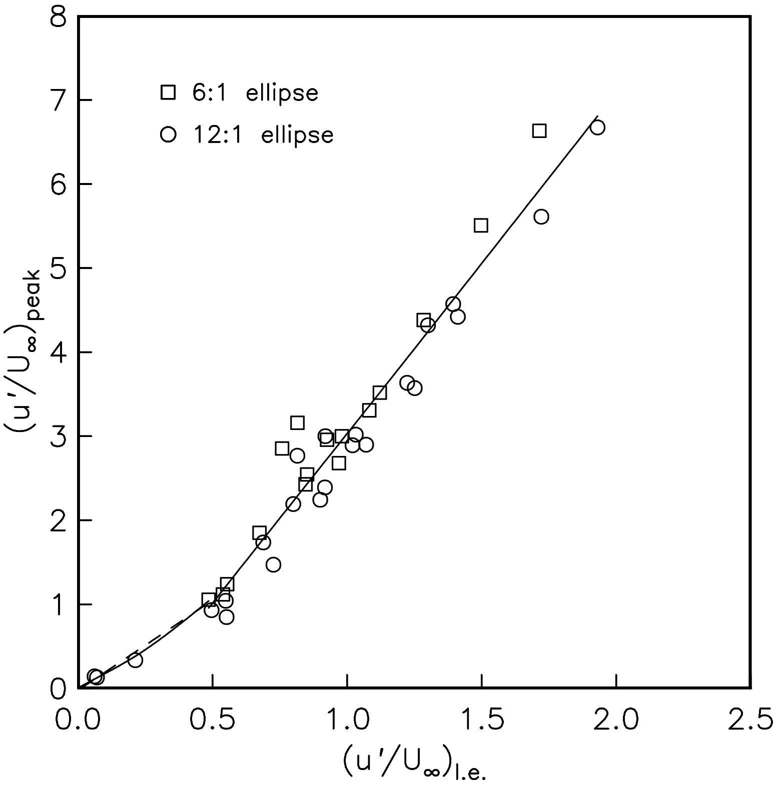


x_le=29.85cm x_m=25.40cm
PP3 M=0.80cm : x_le/M=37.5
PP2 M=0.48cm : x_le/M=62.5
PP1 M=0.28cm : x_le/M=107.8
Blasius
y/δ*
U/U∞
Kendall (1990)
y/δ*
u'/u'max


PP#3 x_{le}=29.85cm x_m=25.4cm
Δx_m (cm)
−5.08
0.00
+5.08
+10.16
+15.24
+22.86
+30.48
+38.10
+45.72
+53.34
y/δ*
u′/u′peak
0.0
0.4
0.8
1.2
0
1
2
3
4
5
6
7


(u′/U∞)peak (%)
Re_{δ^*}
B1min
B1max−amp
0
200
400
600
800
0
2
4
6
8
10


x_le=29.85cm x_m=25.40cm
fit: y=0.6207 + 4.6745x
PP3; x_le/M=37.5
PP2; x_le/M=62.5
PP1; x_le/M=107.8
(u'/U∞)peak
(u'/U∞)f.s.
0 2 4 6 8 10
0.0 0.4 0.8 1.2 1.6 2.0
y (mm)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
0.0 0.4 0.8
(u'/U∞)/(u'/U∞)peak



8
7
6
5
4
3
2
1
0
6:1 ellipse
12:1 ellipse
$(u'/U_\infty)_{peak}$
0.0
0.5
1.0
1.5
2.0
2.5
$(u'/U_\infty)_{l.e.}$

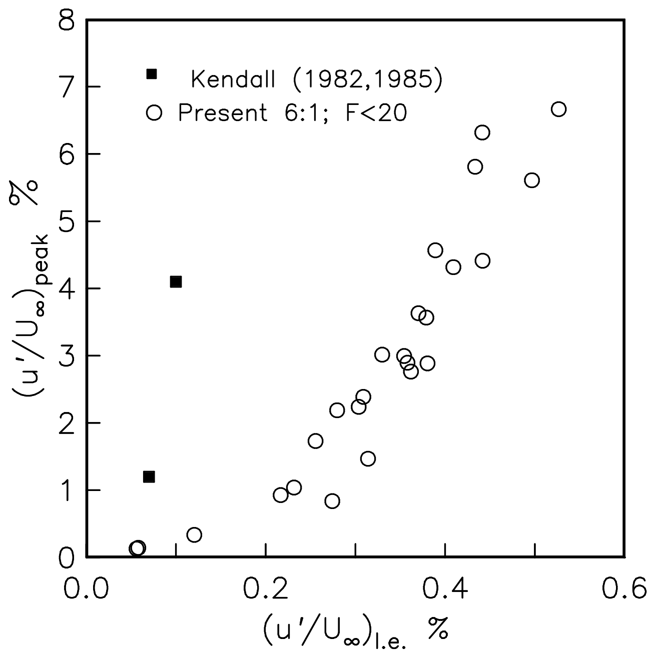
SUMMARY:

- We found excellent agreement with past experiments on effects of free-stream turbulence by Kendall (1985,1990) **in terms of**:
  - Amplification of low-frequency band.
  - Single-peaked $u'(y)$ distribution, maximum at $y/\delta^* \simeq 1.5$.
  - Independent of l.e. aspect ratio: 6:1 versus 12:1 ellipse.

- In terms of “receptivity” to vortical disturbances:

  – We observed an offset or two-sloped I/O relation.

  – Examination of Kendall’s (1985) results showed **something similar**.



- ISSUES: Isotropic turbulence <u>vs</u> predominant ω_z.

EXPERIMENTAL INVESTIGATION OF SEPARATED AND TRANSITIONAL BOUNDARY LAYERS UNDER LOW-PRESSURE TURBINE AIRFOIL CONDITIONS

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Modern low-pressure turbine airfoils are subject to increasingly stronger pressure gradients as designers impose higher loading in an effort to improve efficiency and to reduce part count. The adverse pressure gradients on the suction side of these airfoils can lead to boundary-layer separation, particularly under cruise conditions. Separation bubbles, notably those which fail to reattach, can result in a significant degradation of engine efficiency.[1,2,3] Accurate prediction of separation and reattachment is hence crucial to improved turbine design. This requires an improved understanding of the transition flow physics. Transition may begin before or after separation, depending on the Reynolds number and other flow conditions, has a strong influence on subsequent reattachment, and may even eliminate separation. Further complicating the problem are the high free-stream turbulence levels in a real engine environment, the strong pressure gradients along the airfoils, the curvature of the airfoils, and the unsteadiness associated with wake passing from upstream stages. Because of the complicated flow situation, transition in these devices can take many paths that can coexist, vary in importance, and possibly also interact, at different locations and instances in time.

The present work was carried out in an attempt to systematically sort out some of these issues. Detailed velocity measurements were made along a flat plate subject to the same nominal dimensionless pressure gradient as the suction side of a modern low-pressure turbine airfoil ('Pak-B'). The Reynolds number based on wetted plate length and nominal exit velocity, *Re*, was varied from $50,000$ to $300,000$, covering cruise to takeoff conditions. Low, 0.2%, and high, 7%, inlet free-stream turbulence intensities were set using passive grids. These turbulence levels correspond to about 0.2% and 2.5% turbulence intensity in the test section when normalized with the exit velocity. The Reynolds number and free-stream turbulence level do not have a significant effect on the location of boundary-layer separation unless they are high enough to induce transition upstream of separation. The location and extent of the transition zone, in contrast, depend strongly on *Re* and TI. The beginning of reattachment closely follows the onset of transition. Under low free-stream turbulence conditions the boundary layer is laminar at separation and then begins to exhibit fluctuations in a finite frequency band in the shear layer over the separation bubble. These fluctuations are due to instability waves. The fluctuations grow in magnitude, higher harmonics are generated, and finally lead to a breakdown to turbulence. Transition begins in the shear layer, but quickly spreads to the near wall region and causes the boundary layer to reattach. The transition is rapid and the resulting turbulence contains a full range of high and low frequencies. Under high free-stream turbulence conditions, slowly growing low-frequency fluctuations are induced in the pre-transitional boundary layer by the free-stream.[4,5,6] The separation bubbles are considerably thinner than in the low TI cases, resulting in thinner boundary layers at the end of the test wall. At Re=50,000 and 100,000, the pre-transitional boundary layer separates at about the same location as in the low TI cases. Transition occurs through a bypass[7] mode, begins upstream of the corresponding low-TI location, and proceeds in a manner similar to that of an attached boundary layer. Under high TI at Re=200,000 and 300,000, transition begins before separation. The boundary layer may separate, but if it does the separation bubble is very short and does not significantly affect the downstream development of the boundary layer. A comparison is made to previous work[8] in a simulated cascade.

[1] Hourmouziadis, J., 1989, "Aerodynamic Design of Low Pressure Turbines," AGARD Lecture Series, 167.
[2] Mayle, R.E., 1991, "The Role of Laminar-Turbulent Transition in Gas Turbine Engines," *ASME J. of Turbomachinery*, Vol. 113, pp. 509-537.
[3] Sharma, O.P., Ni, R.H. and Tanrikut, S., 1994, "Unsteady Flow in Turbines," AGARD-LS-195, Paper No. 5.
[4] Dryden, H.L., 1936, "Air flow in the boundary layer near a plate," NACA Report 562.
[5] Blair, M. F., 1992, "Boundary-Layer Transition in Accelerating Flow With Intense Freestream Turbulence: Part 1—Disturbances Upstream of Transition Onset," *J. Fluids Engineering*, Vol. 114, pp. 313-321.
[6] Volino, R.J., 1998a, "Wavelet Analysis of Transitional Flow Data Under High Free-Stream Turbulence Conditions," ASME paper 98-GT-289.
[7] Morkovin, M. V., 1978, "Instability, Transition to Turbulence and Predictability," *NATO AGARDograph No. 236*.
[8] Qiu, S. and Simon, T.W., 1997, "An Experimental Investigation of Transition as Applied to Low Pressure Turbine Suction Surface Flows," ASME paper 97-GT-455.

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Experimental Investigation of Separated And Transitional Boundary Layers Under Low-Pressure Turbine Airfoil Conditions

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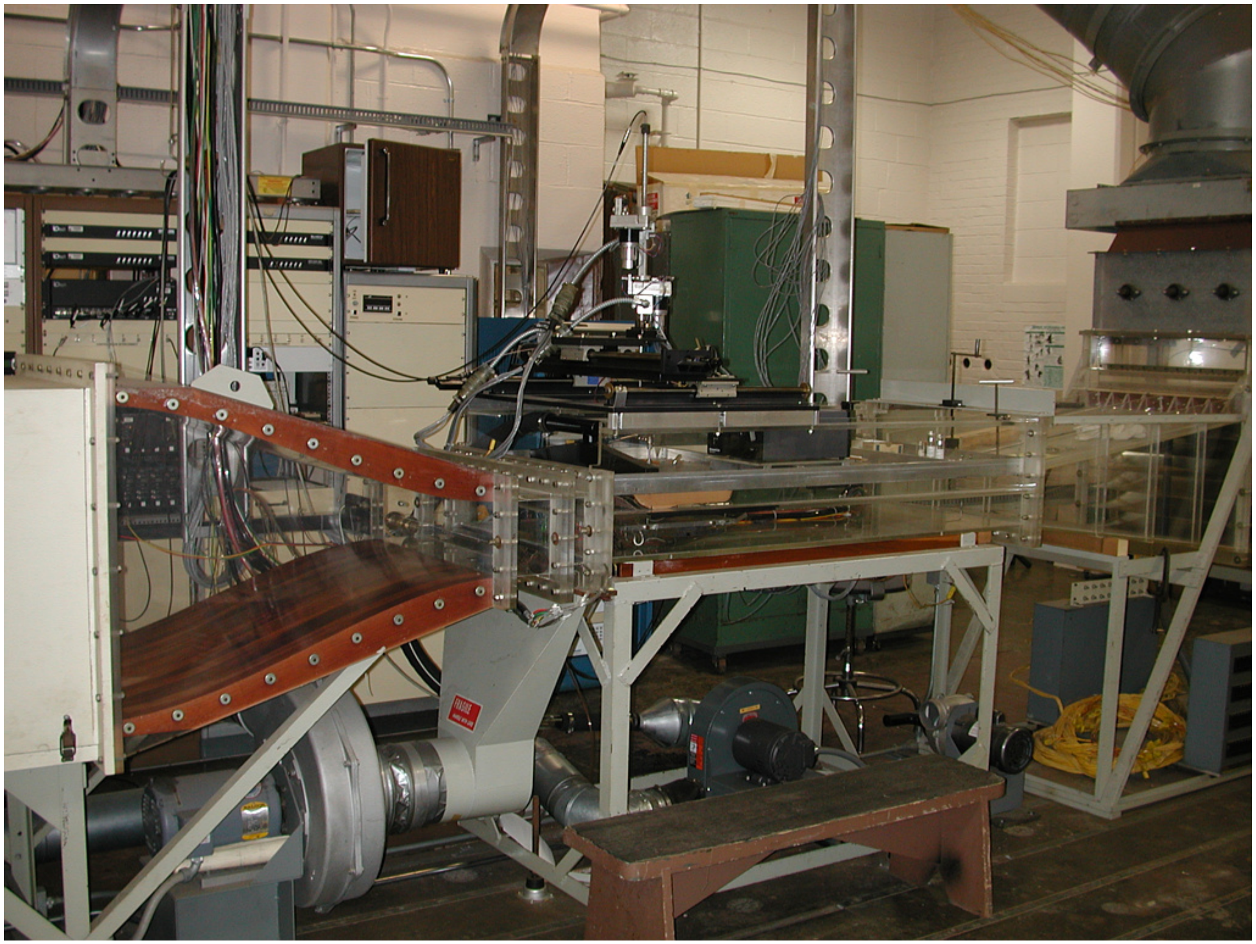
United States Naval Academy
Department of Mechanical Engineering, Annapolis, Maryland 21402

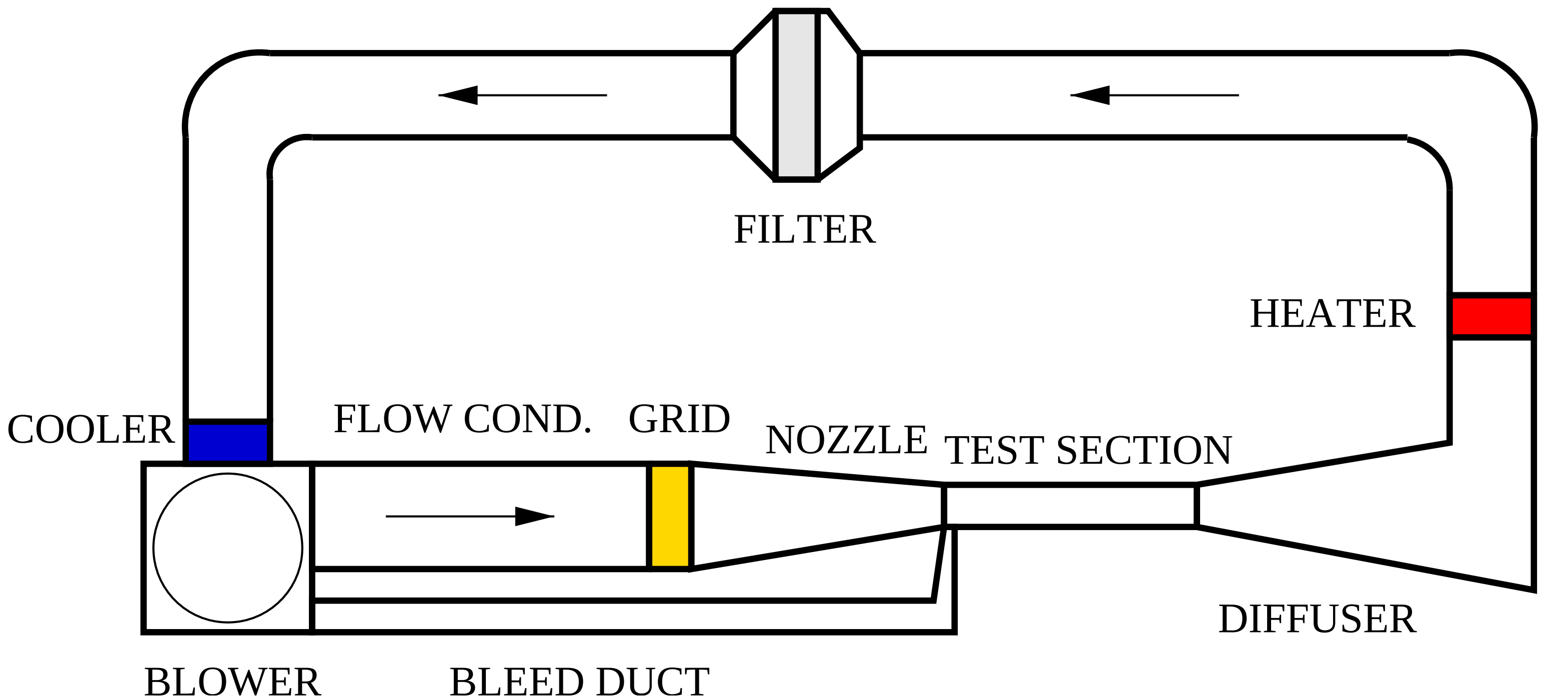
Minnowbrook III: Aug 20-23, 2000

NASA/CP—2001-210888

CW-7 FACILITY at NASA GRC

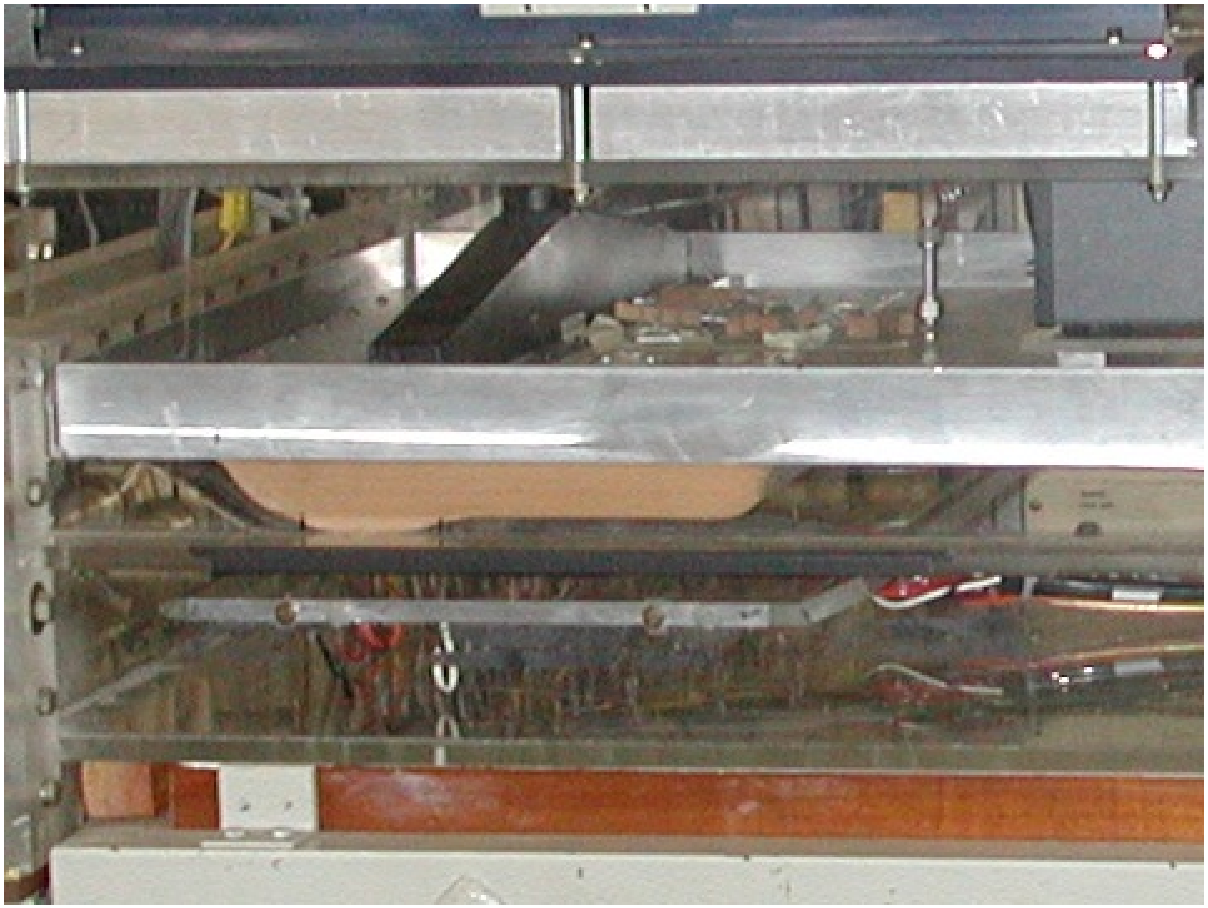


CW-7 FACILITY at NASA GRC

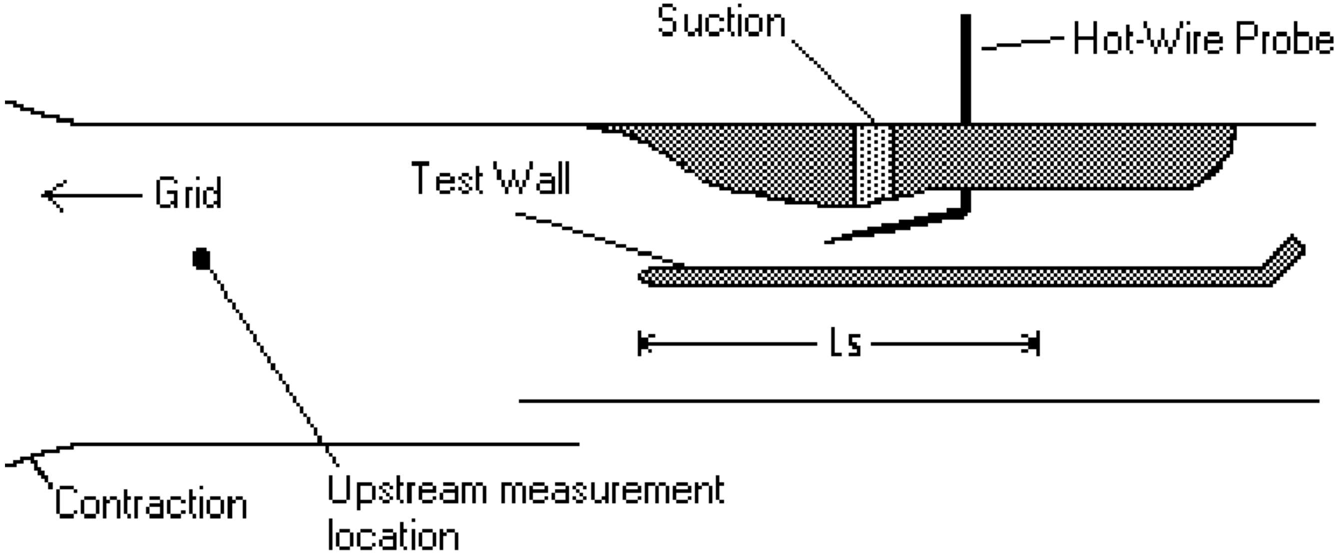


- CLOSED-LOOP WIND TUNNEL WITH COOLING/HEATING
  - BLEED DUCT AND HEATER NOT USED

CW-7 TEST SECTION



CW-7 TEST SECTION



- CONTOURED UPPER WALL IN TEST SECTION $\Rightarrow C_p$
- FLAT PLATE SIMULATING BLADE

CASES

test matrix

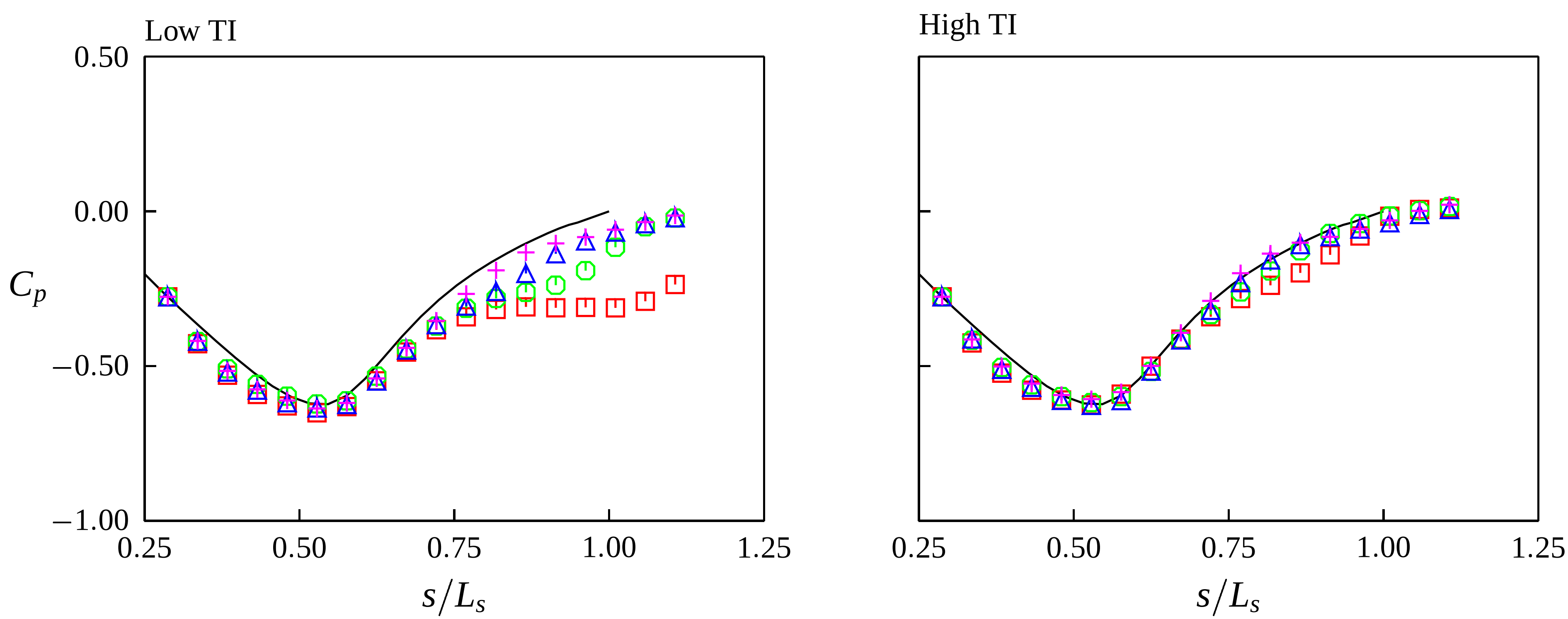
	Re=50,000	Re=300,000
Low TI	•	•
High TI	•	•

nominal turbulence intensities

	inlet (normalized by inlet velocity)	test-section freestream (normalized by exit velocity)
Low TI	0.2%	0.2%
High TI	7%	2.5%

- passive grid upstream of contraction for high-TI case

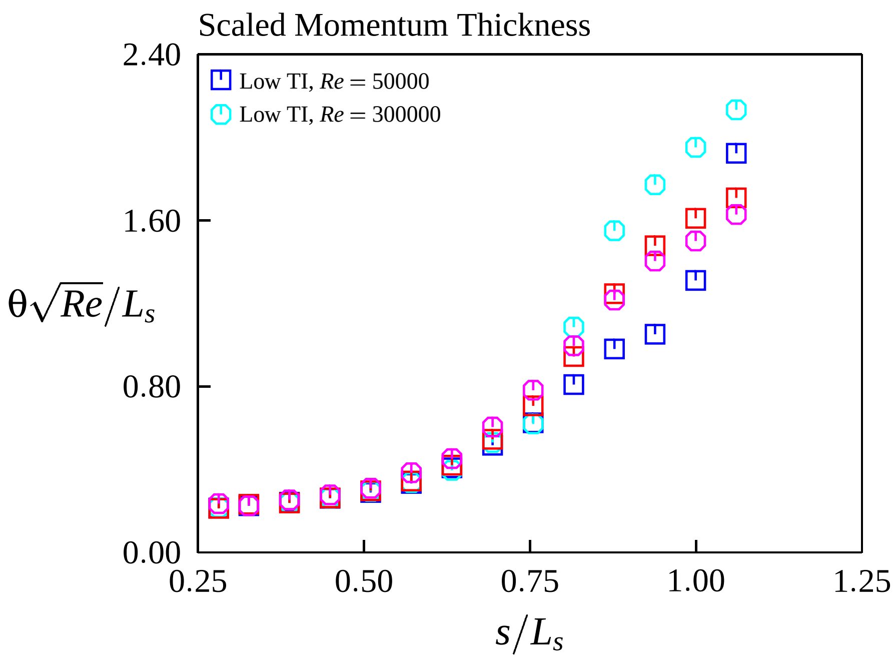
FIXED HEIGHT STREAMWISE HOT-WIRE SURVEYS

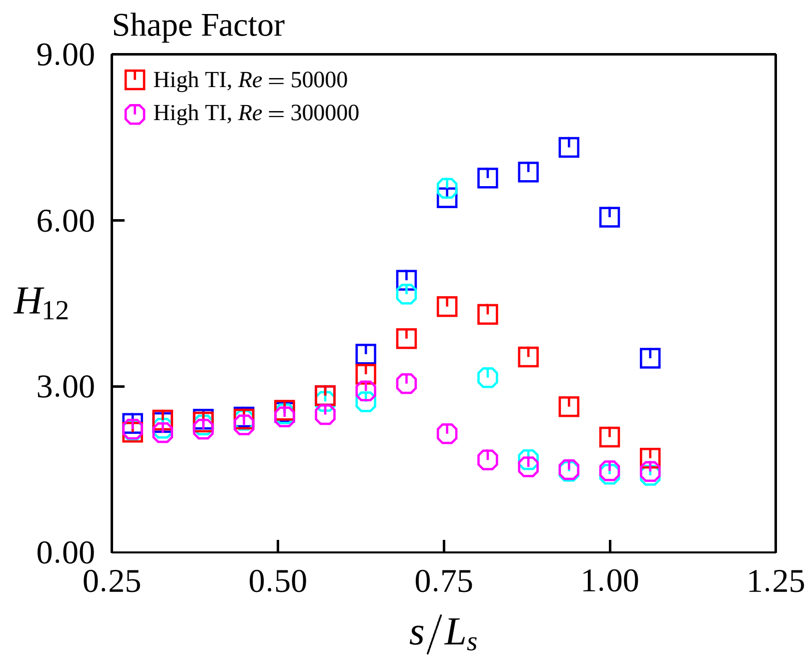


- $Re \equiv U_e L_s/\nu =$ 50000, 100000, 200000, and 300000

STREAMWISE STATIONS

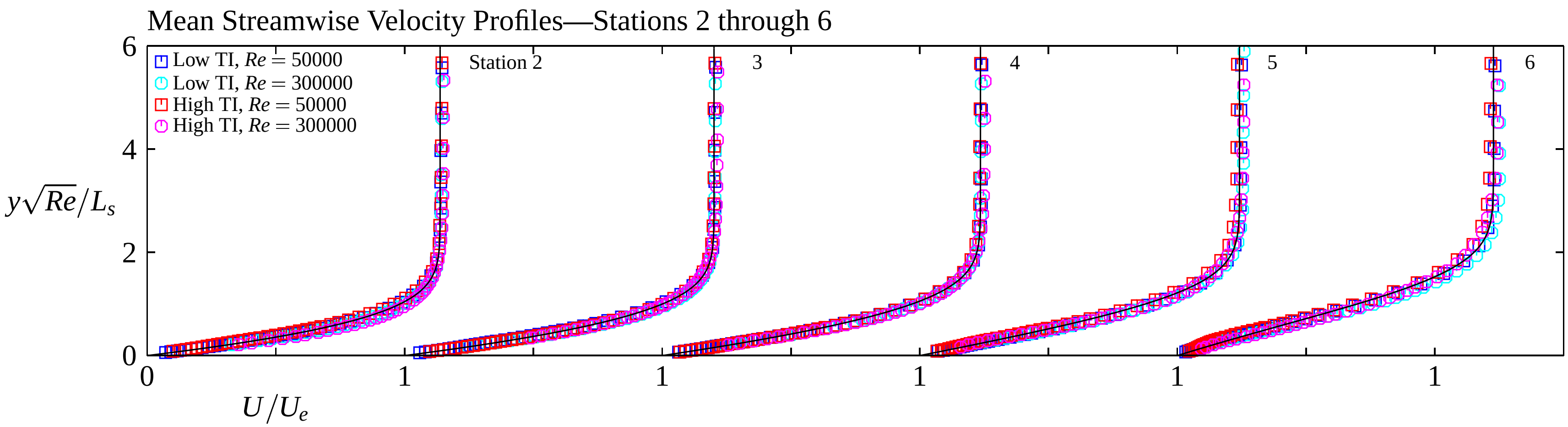
Station	1	2	3	4	5	6	7
s/L_s	0.28	0.33	0.39	0.45	0.51	0.57	0.63
Station	8	9	10	11	12	13	14
s/L_s	0.69	0.75	0.81	0.88	0.94	1.00	1.06





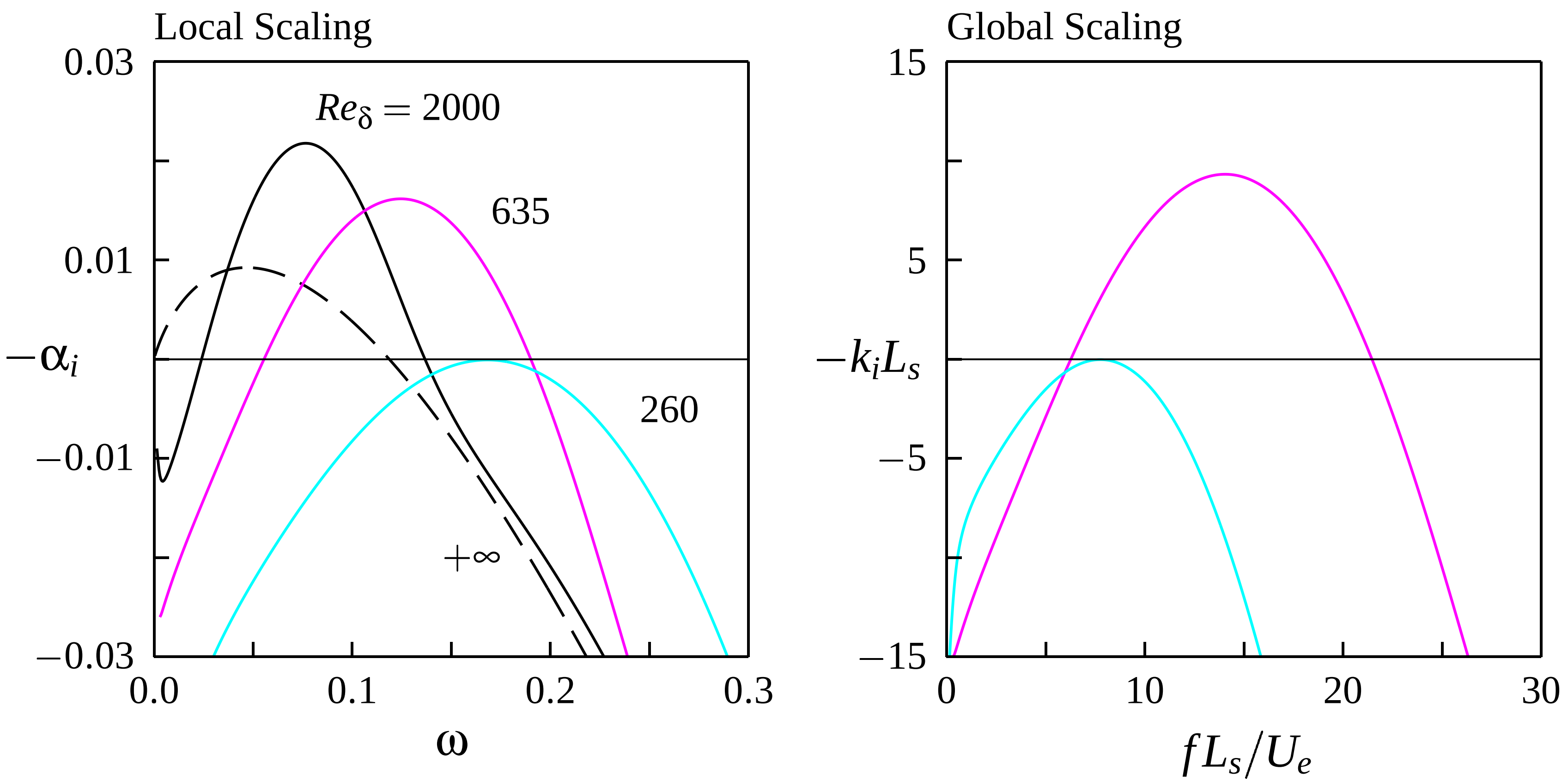
LOCAL FALKNER-SKAN FIT

Station	1	2	3	4	5	6
s/L_s	0.28	0.33	0.39	0.45	0.51	0.57
m_{FS}	0.751	0.386	0.259	0.141	0.034	-.0339
Re_δ (Low Re)	114±6	138±4	154±4	176±1	207±4	261±4
Re_δ (High Re)	298±16	311±4	367±7	429±8	511±9	637±14



- For $m_{FS} = 0$, $Re_{\delta_c} = 520$ (linear stability theory)

LINEAR STABILITY RESULTS FOR STATION 6



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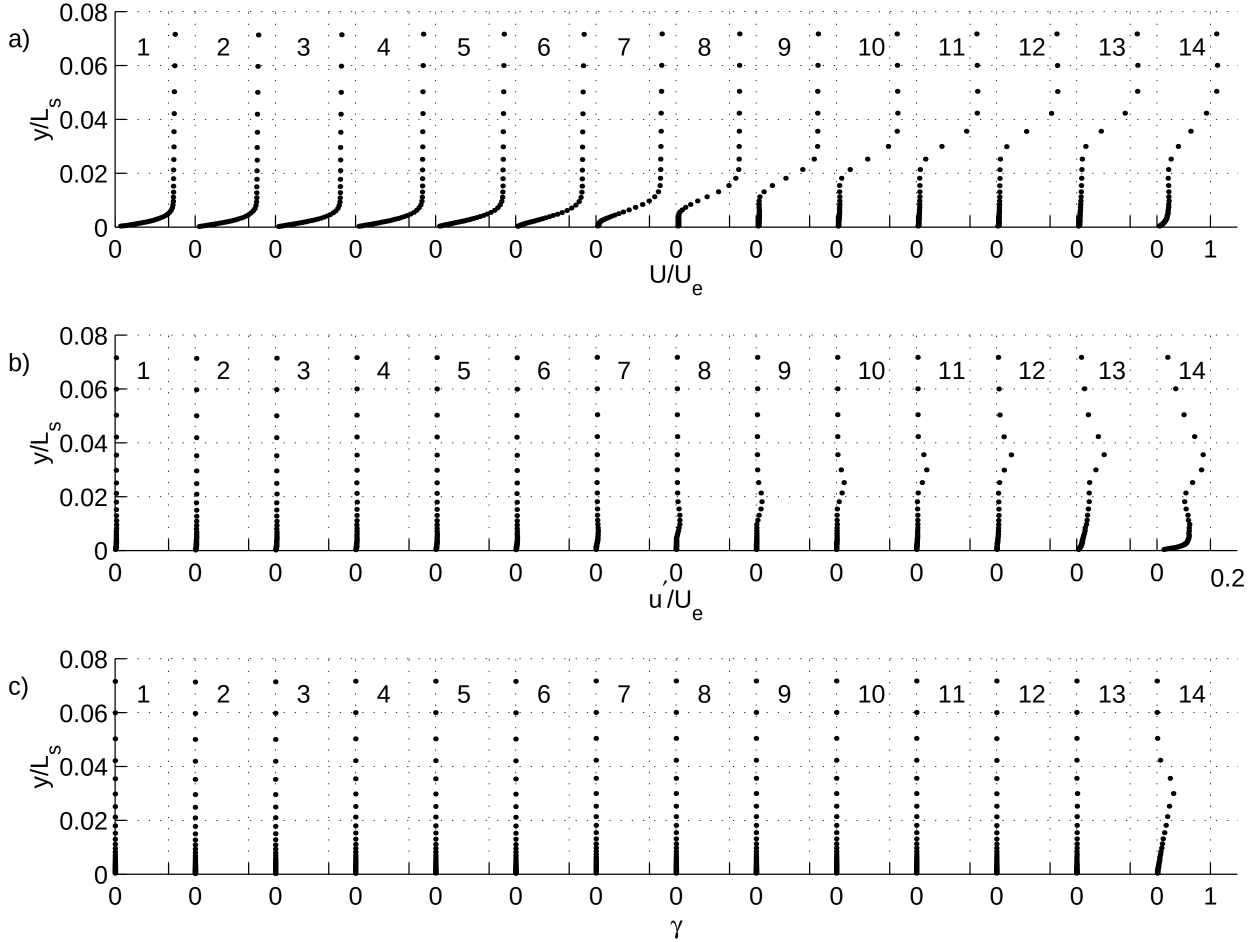
Re=50000—LOW TI



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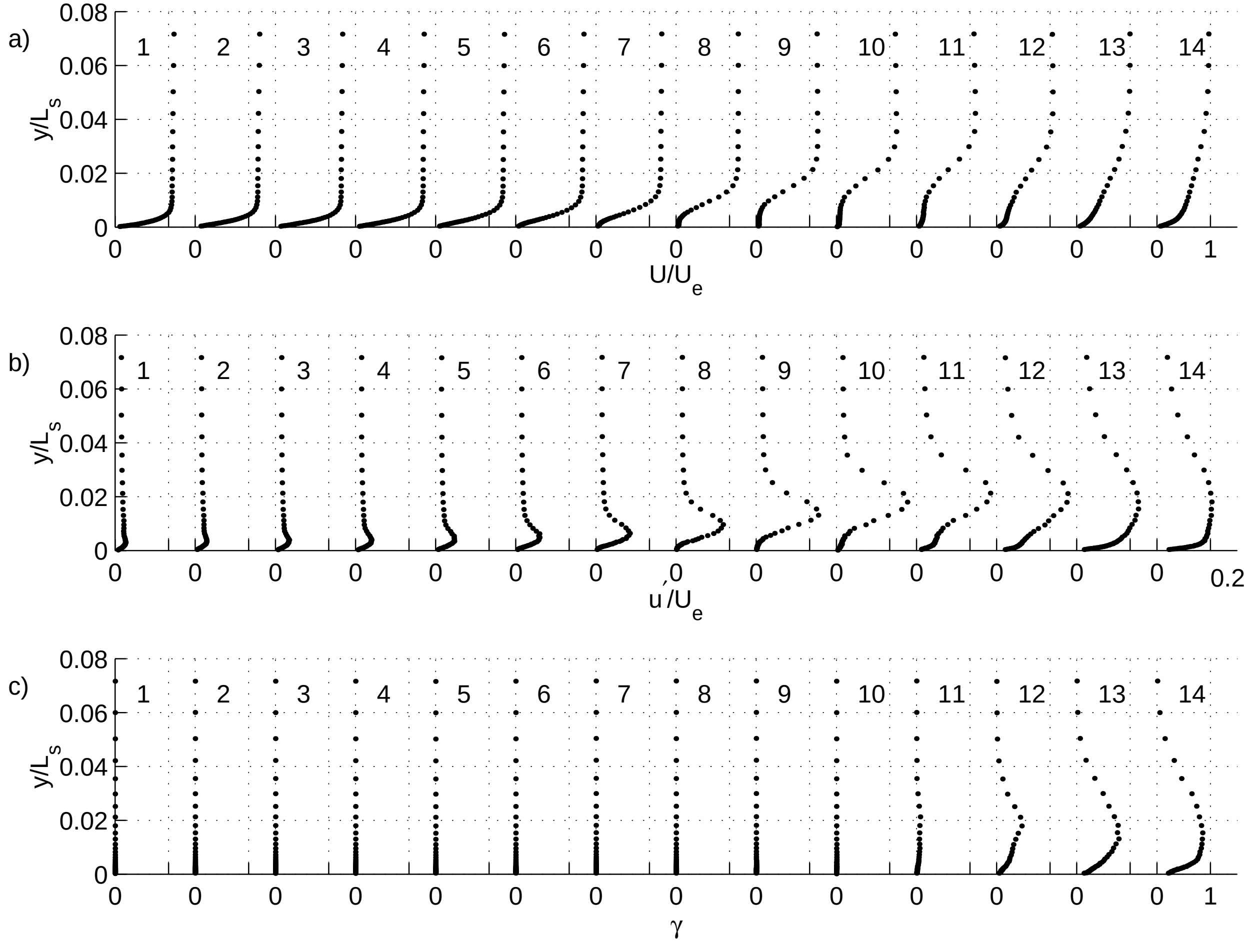
Re=50000—HIGH TI



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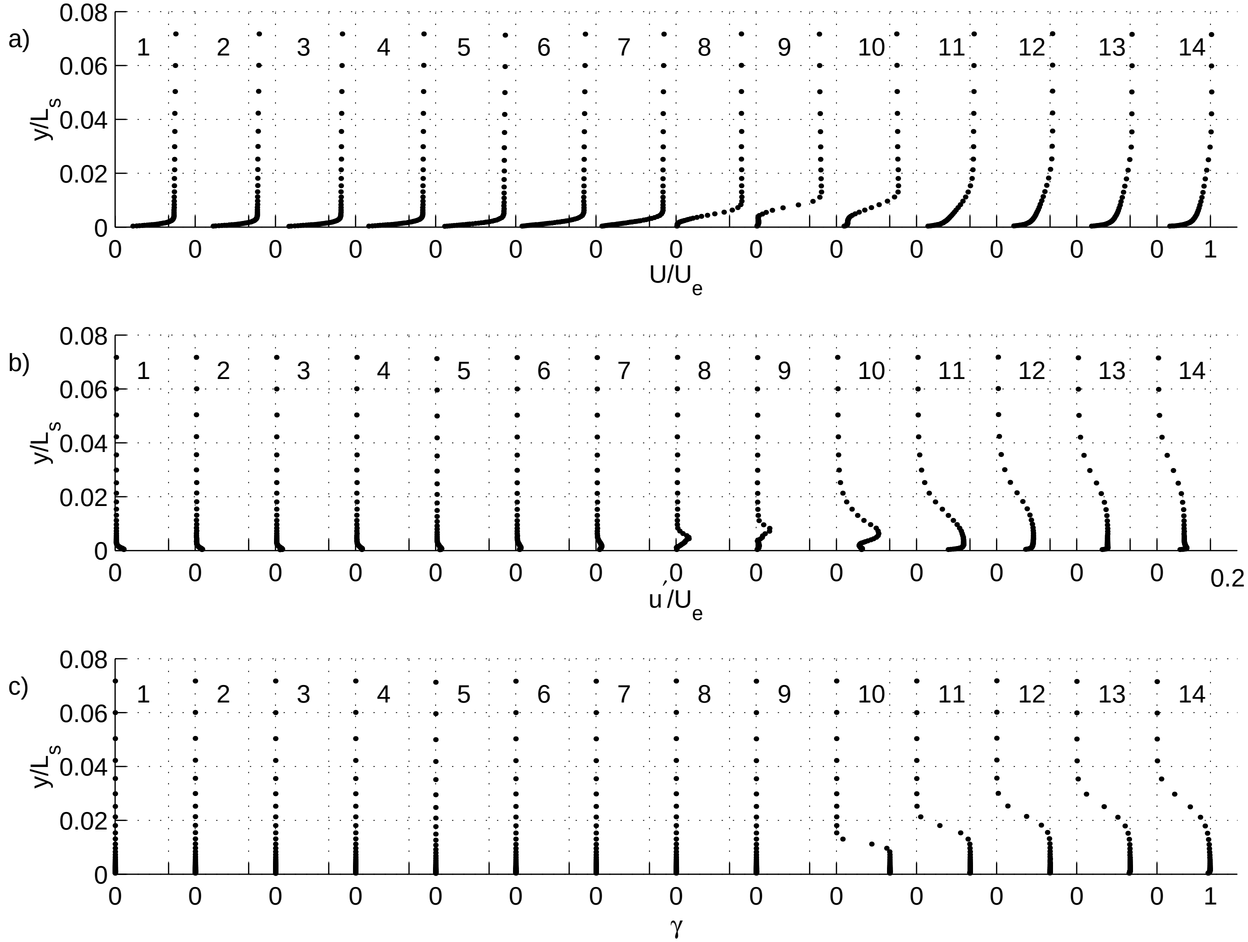
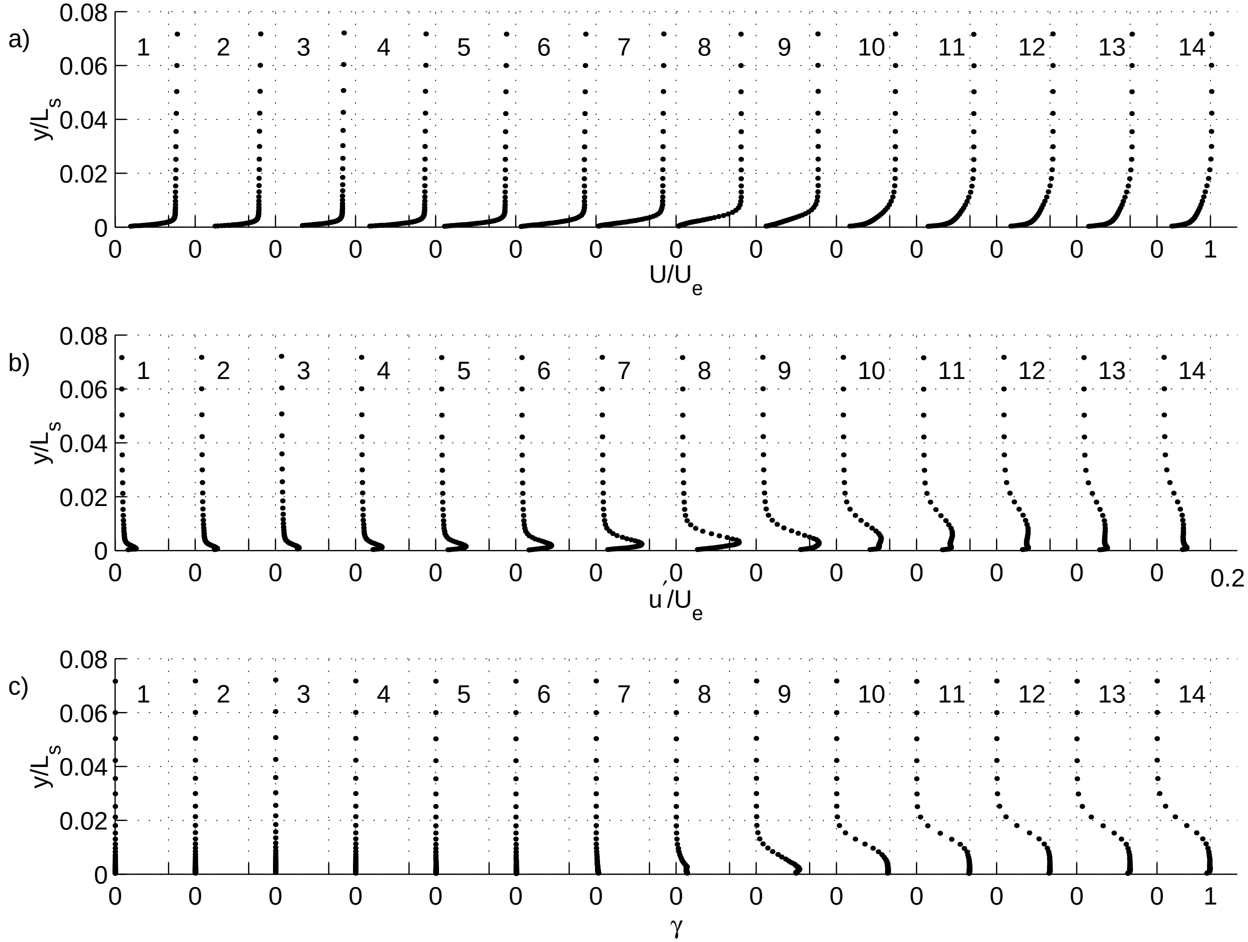
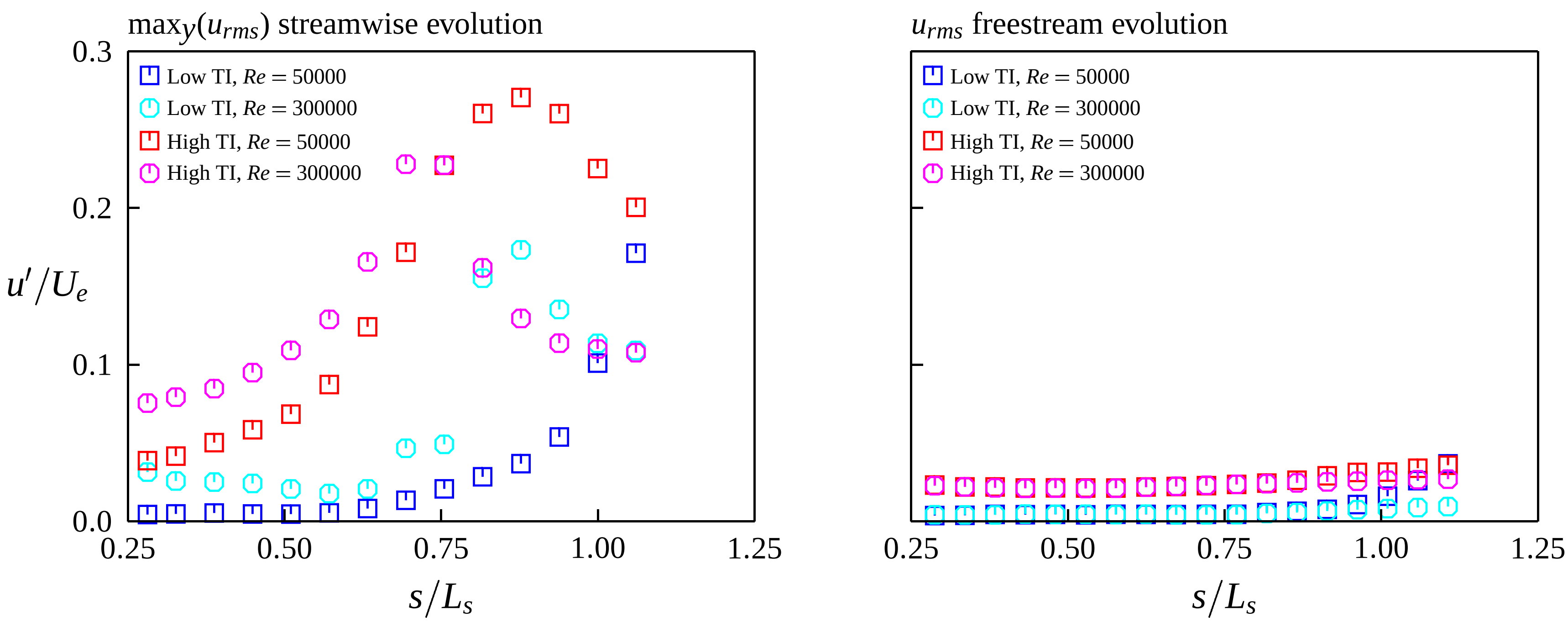
Re=300000—LOW TI



Re=300000—HIGH TI

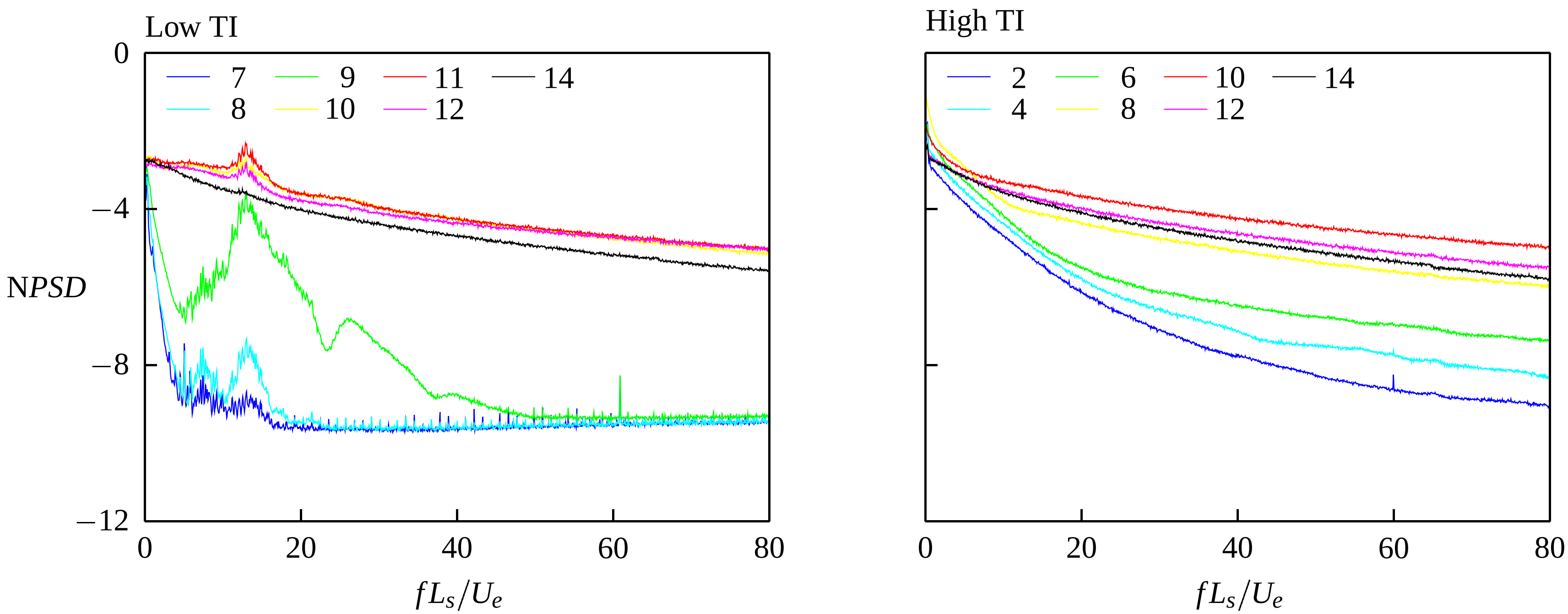


STREAMWISE U_RMS EVOLUTION



- KLEBANOFF MODE GROWTH AND EFFECTS CLEARLY EVIDENT

Re=300000—POWER SPECTRAL DENSITY



- SHEAR-LAYER INSTABILITY FOR LOW TI CASE
- SPECTRA SIMILAR AFTER TRANSITION/RE-ATTACHMENT

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SEPARATION AND TRANSITION LOCATIONS

s=separation, ts=transition start, r=reattachment, te=transition end.

Re	s (s/L_S) / Re_θ	ts and r (s/L_S) / Re_θ	te (s/L_S) / Re_θ
Low TI			
50000	0.63/106	1.0-1.06/344-501	–
100000	0.66/177	0.88-0.94/363-642	0.94-1.0/642-680
200000	0.67/260	0.76-0.82/344-423	0.82-0.88/423-704
300000	0.67/314	0.76-0.82/406-675	0.76-0.82/406-675
High TI			
50000	0.63/111	0.85/271	1.11/383
100000	0.63/158	0.78/230	0.92/477
200000	–	0.72/322	0.85/533
300000	–	0.66/336	0.82/592

Simon, Qui, and Yuan (2000)

TI	s s/L_S	ts s/L_S	r s/L_S	te s/L_S	Re $\times 10^3$
0.5%	0.50-0.54	0.79-0.68	n/a-0.79	n/a-0.72	$50, 100, 200$
2.5%	0.53-0.54	0.65/0.72-0.57	0.89-0.70	n/a-0.67	$50, 100, 200$
10%	0.54-0.55	0.61-0.56	0.83-0.75	n/a-0.80	$50, 100$

- differences may be due to curvature effects or actual C_p differences

SUMMARY

- Re and TI do not significantly affect separation unless they are high enough to case transition upstream of separation

- Location and extent of transition zone depends strongly on Re and TI

- Low TI: Laminar separation, transition in separation-bubble shear layer, and re-attachement

- High TI: Sequence similar to that in an attached boundary layer even when separation occurs—Klebanoff modes and/or bypass transition

- Generally good agreement with previous study, but some differences:
  - ◇ separation location—may be due to curvature effects or actual C_p
  - ◇ transition locations—may be due to intermittency procedures

GLOBAL INSTABILITIES IN LAMINAR SEPARATED BOUNDARY LAYER FLOW

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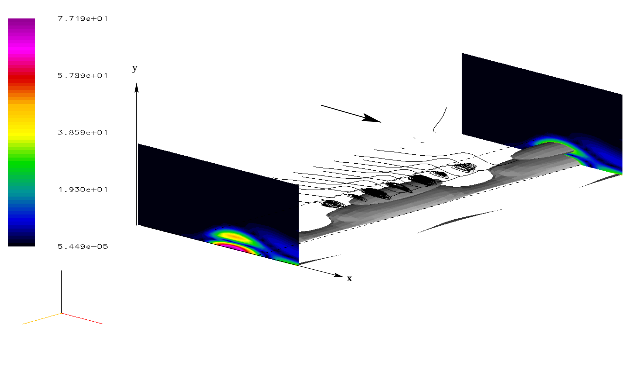
DLR Institute of Fluid Mechanics
Göttingen, Germany

Over decades separated transitional flow control has focussed on amplification of *incoming* Tollmien-Schlichting (TS)-like disturbances and ignored the possibility of *own* ('eigen')-disturbances being generated by the flow itself. Evidence is accumulating that global flow instability is active in canonical laminar separated flow configurations. Failure to control this instability mechanism will render separated flow control methodologies which are based on TS-frequency information incomplete as far as travelling disturbances are concerned and inadequate for control of stationary global instabilities. In order to explore the question of existence of global linear instability in a model flow relevant to aerodynamics and turbomachinery alike, namely a laminar separation bubble set up by an analytically known adverse pressure gradient in incompressible flow, the related partial derivative nonsymmetric generalised eigenvalue problem has been solved[1]. Both stationary and pairs of travelling linear instabilities have been discovered, which are distinct from known solutions of the Orr-Sommerfeld equation (OSE) or the linear parabolised stability equations (PSE) instability theories, and can both become unstable at flow parameters presented by Theofilis[1]. The disturbance vorticity $\hat{\zeta}$ of the most unstable stationary global mode is dominated by the streamwise disturbance velocity component; $|\hat{\zeta}|$ is visualised in the following figure by a single isosurface of this quantity, drawn at an arbitrarily defined level such that the dominant features of the instability in question are illustrated. The flow direction is indicated by the arrow and the steady laminar separation and reattachment boundaries determined by the basic state are marked by dashed lines. One spanwise periodicity is shown. The innocuous primary separation line and the three-dimensionalisation of the primary reattachment line on account of the global instability mechanism is to be seen in this result. Of the two layers of particles released into the flow that nearer the wall, at the height of the primary separation bubble, is seen to be trapped in the neighbourhood of reattachment on account of the global instability mechanism.



Besides issues revolving around flow control, the instability mechanism discovered may well be related with and shed light to the phenomenon of vortex-shedding by laminar separation bubbles; a detailed discussion of this issue is presented by Theofilis *et al.*[2] In our opinion, the significance of the present findings warrants further investigation into this problem. In order to address the issues of global instability of flows with large-scale separation on configurations relevant to both external aerodynamics and turbomachinery a new algorithm based on spectral/hp element technology[3] has been developed and validated. Results will be presented in due course.

[1] Theofilis, V. 1999 "Global linear instabilities in laminar separated boundary layer flow", IUTAM *Laminar–Turbulent Transition Symposium V*, Sedona, AZ, USA, (W. Saric and H. Fasel eds.), to appear.

[2] Theofilis, V., Hein, S., and Dallmann, U. Ch. 2000 "On the origins of unsteadiness and three-dimensionality in a laminar separation bubble". *Phil. Trans. Roy. Soc. A* **358**, to appear.

[3] Karniadakis, G. Em. and Sherwin, S. J. 1999 "Spectral/hp Element Methods for CFD". Oxford University Press.

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Global linear instabilities

in laminar separated (boundary layer) flow

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Göttingen
GERMANY

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Roadmap

Introduction

motivation and problemacy

Methodology

global linear instability analysis

Global Linear Instability Results

validations

3D instability of Briley’s steady 2D laminar reparation bubble

Summary and Outlook

(unsteady) turbulent flow (in turbomachines)

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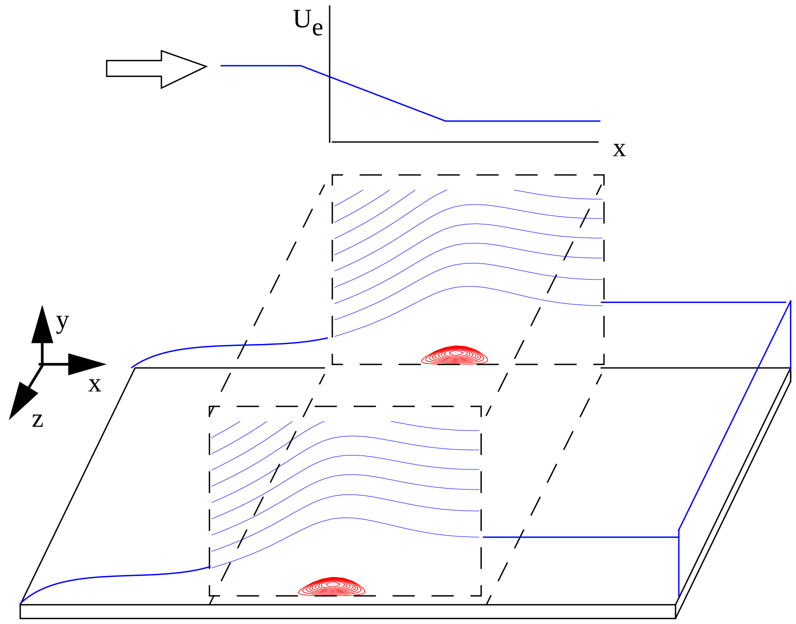
A steady laminar separation bubble



$$\mathbf{U} = (\,U(x,y),\, V(x,y),\, 0\,)$$

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Introduction

Motivation

Understand
the processes of unsteadiness and
three-dimensionalisation of the two-dimensional **steady laminar**
separation bubble flow

Extend
our understanding into **unsteady laminar** and **turbulent**
separated boundary layer flow

Control
separated internal and external flow

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Introduction

Problemacy

Does our understanding of **shear-layer instability** suffice to achieve our objectives?

In other words,

Does the bubble **amplify** oncoming disturbances **only**, or

Do unstable disturbances **originate** inside the bubble ?

What are the **structural changes** experienced by the steady laminar flow on account of either of the above mechanisms ?

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Methodology

Interpret our objectives in terms of global linear flow instability:

Formulate and solve numerically the global linear eigenvalue problem, assuming **homogeneity** in **one** and **resolving two** spatial directions

Focus on a semi-analytically known model basic steady-state

Compare/contrast the global eigenvalue problem results with local (OSE) and nonlocal (PSE) instability analyses

Compare with DNS and experiment

The partial derivative eigenvalue problem

Decompose any flow quantity as $\mathbf{q}(x,y,z,t) = \bar{\mathbf{q}}(x,y) + \varepsilon\ \hat{\mathbf{q}}(x,y)\ e^{i\,[\beta z - \omega t]} + c.c.$

and substitute into the governing equations. The eigenvalue problem

$$
\begin{aligned}
[\mathcal{L} - (\mathcal{D}_x \bar{u})]\,\hat{u} - (\mathcal{D}_y \bar{u})\hat{v} - \mathcal{D}_x \hat{p} &= \tilde{\omega}\ \hat{u}, \\
-(\mathcal{D}_x \bar{v})\hat{u} + [\mathcal{L} - (\mathcal{D}_y \bar{v})]\,\hat{v} - \mathcal{D}_y \hat{p} &= \tilde{\omega}\ \hat{v}, \\
+\mathcal{L}\tilde{w} - \beta \hat{p} &= \tilde{\omega}\ \tilde{w}, \\
\mathcal{D}_x \hat{u} + \mathcal{D}_y \hat{v} - \beta \tilde{w} &= 0.
\end{aligned}
$$

results, where

$$
\mathcal{L} = (1/\mathrm{Re})\left(\mathcal{D}_x^2 + \mathcal{D}_y^2 - \beta^2\right) - \bar{u}\mathcal{D}_x - \bar{v}\mathcal{D}_y,
$$

$$
\mathcal{D}_x = \partial/\partial x,\ \ \mathcal{D}_x^2 = \partial^2/\partial x^2,\ \ \mathcal{D}_y = \partial/\partial y,\ \ \mathcal{D}_y^2 = \partial^2/\partial y^2,
$$

and

$$
\tilde{\omega} = i\ \omega
$$

$$
\tilde{w} = i\ \hat{w}
$$

The partial derivative eigenvalue problem

The eigenvalue problem

$$\mathbf{A}\hat{\mathbf{q}} = \tilde{\omega}\,\mathbf{B}\,\hat{\mathbf{q}}$$

must be solved for the determination of $\tilde{\omega}$ (temporal growth rate) and spatial structure of $\hat{\mathbf{q}}$ (global eigenvector) once β is specified

The two-dimensional steady laminar basic flow $\bar{\mathbf{q}}$ is obtained by DNS

Global linear instability results

were obtained using

- a spectrally-accurate basic flow
- primitive-variable formulation of the EVP
- real formulation of the EVP
- boundary conditions

Wall & Far-field boundaries: **Homogeneous Dirichlet**

Inflow boundary: **Homogeneous Dirichlet**

Outflow boundary: **Extrapolation**

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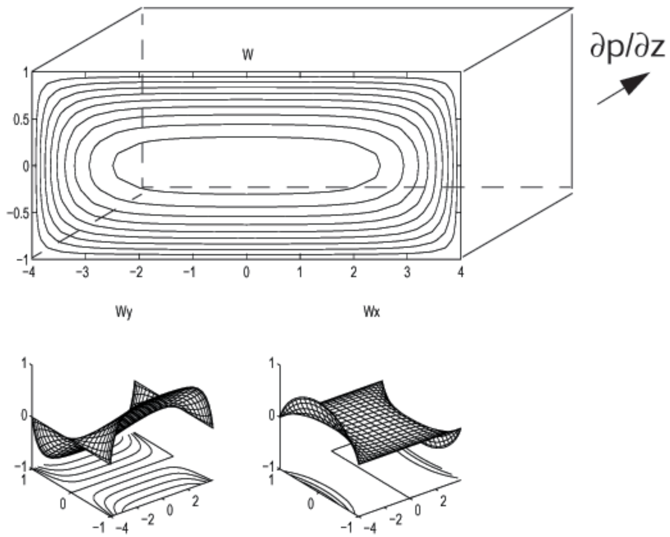
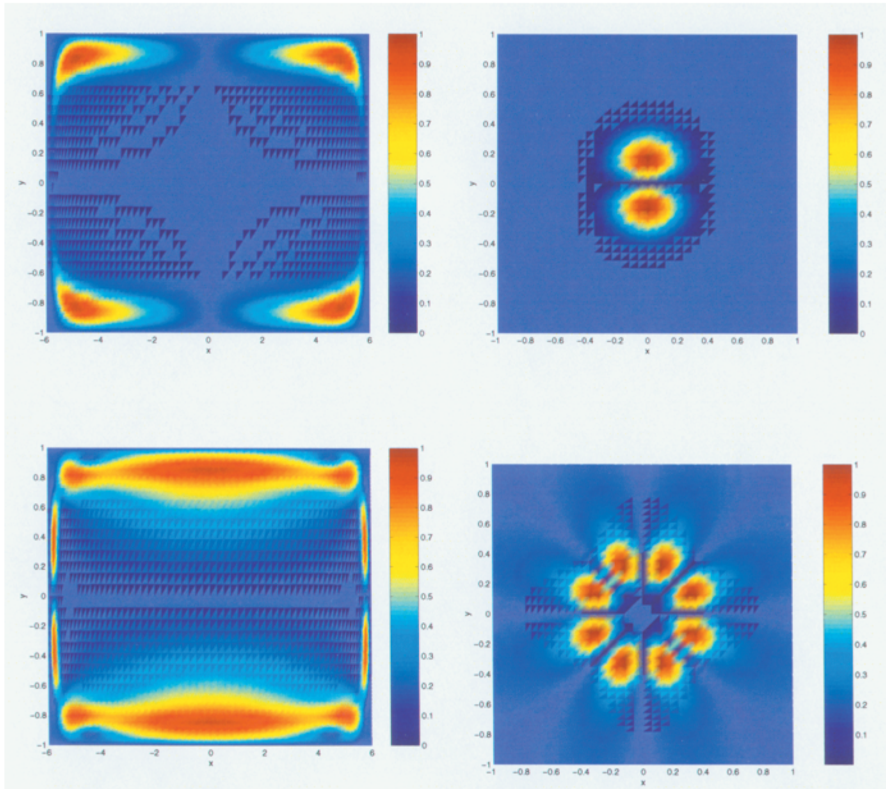
Validation results

primitive variables EVP formulation:
the **rectangular duct**





(Tatsumi & Yoshimura; JFM **212** 1990,
Th; Aero Sci. Technol. **4** 2000)

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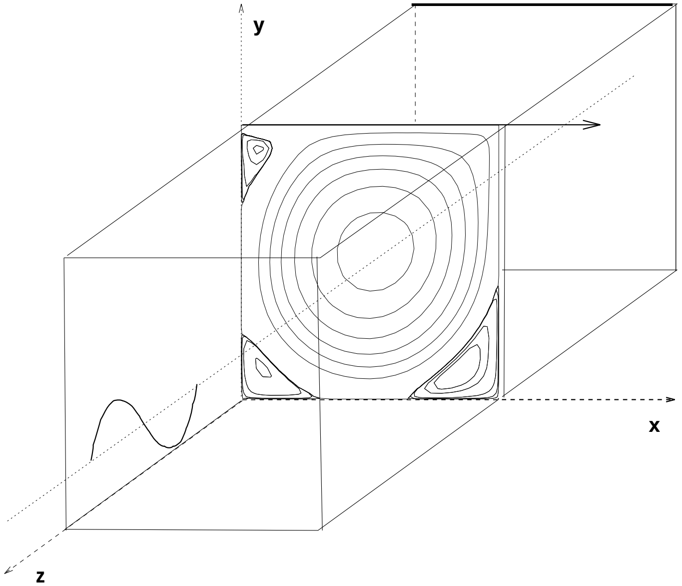
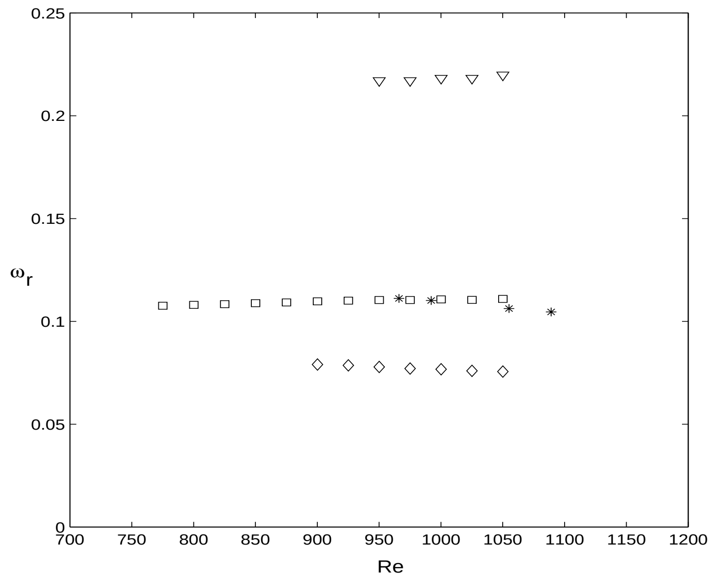
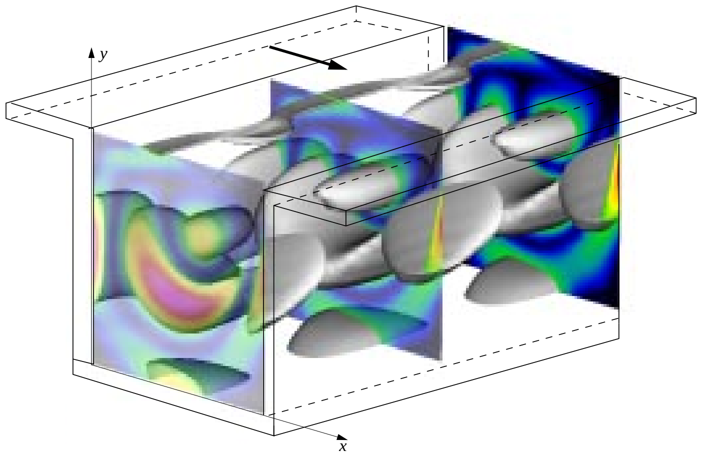
Validation results

real EVP formulation:
the **driven cavity**



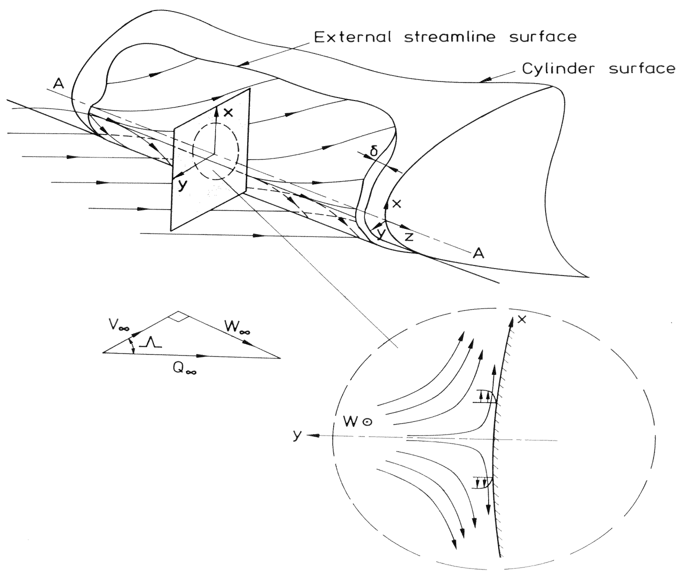
(Benson & Aidun; Phys Fluids A **4** 1992, Th; AIAA 2000-1965)



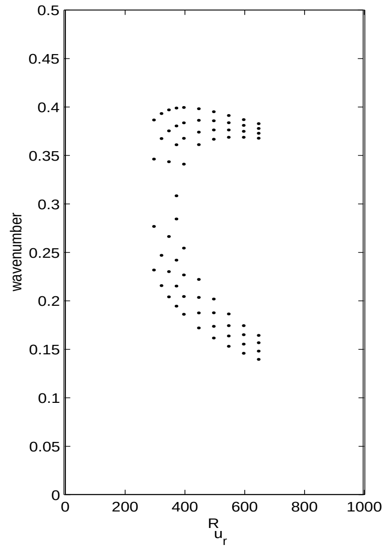


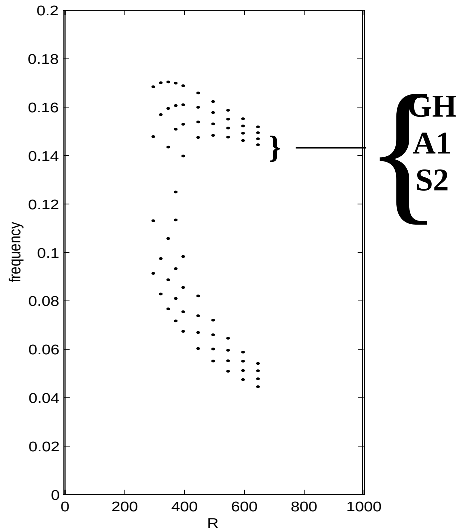
Validation results

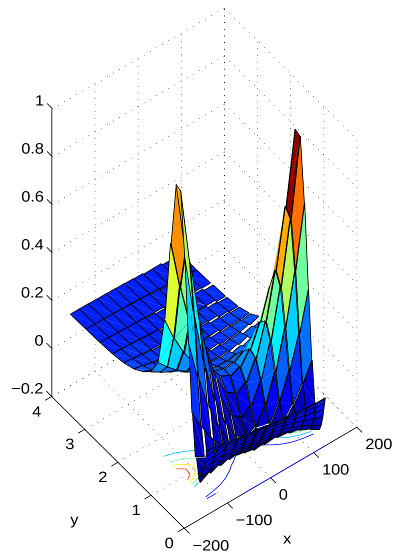
outflow boundary conditions:
the **swept Hiemenz flow**

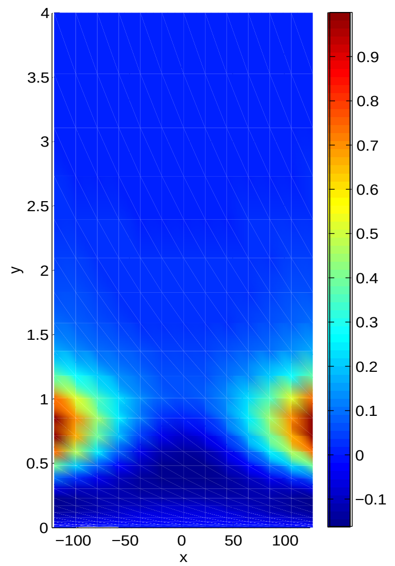


(Lin & Malik; JFM **311** 1996;
Th, Obrist, Dallmann 2000)



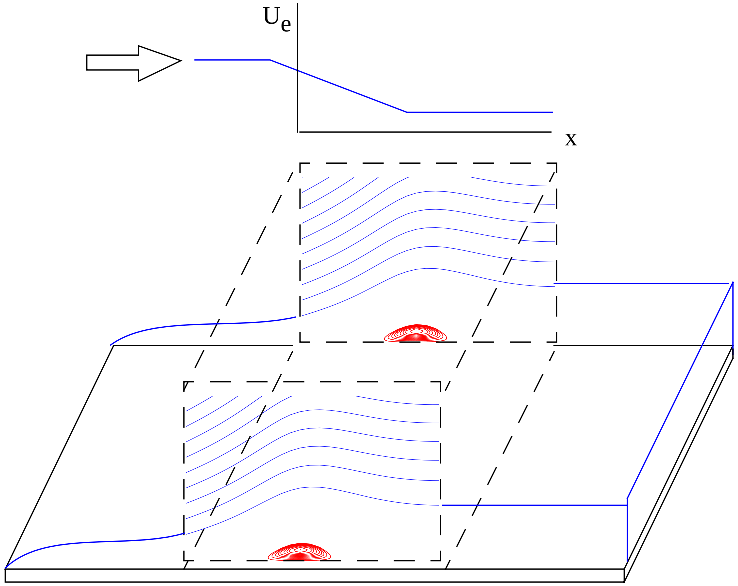


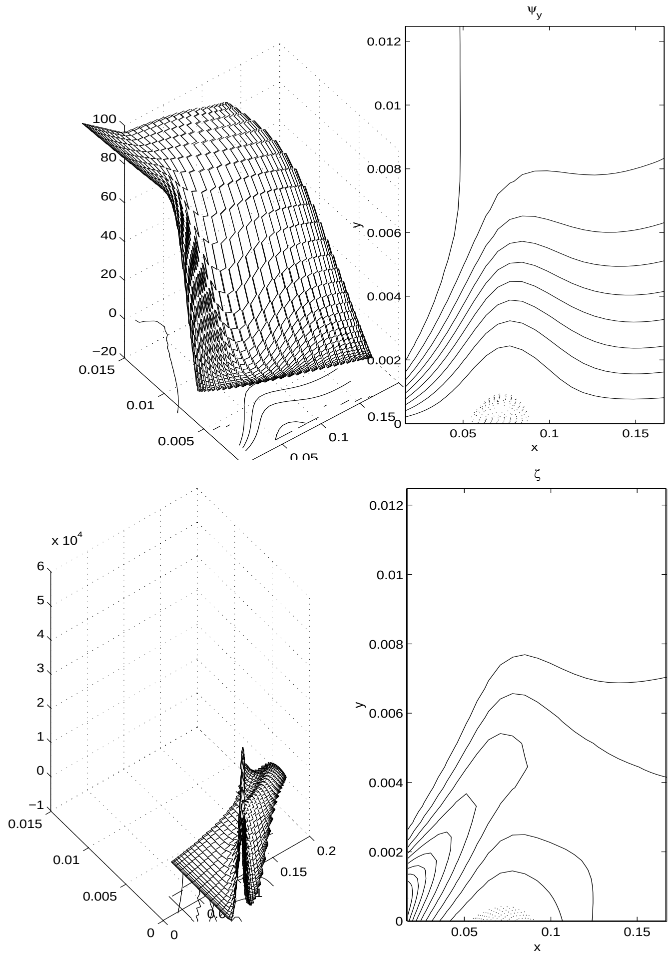




Separation bubble

Basic Flow (Briley 1971)

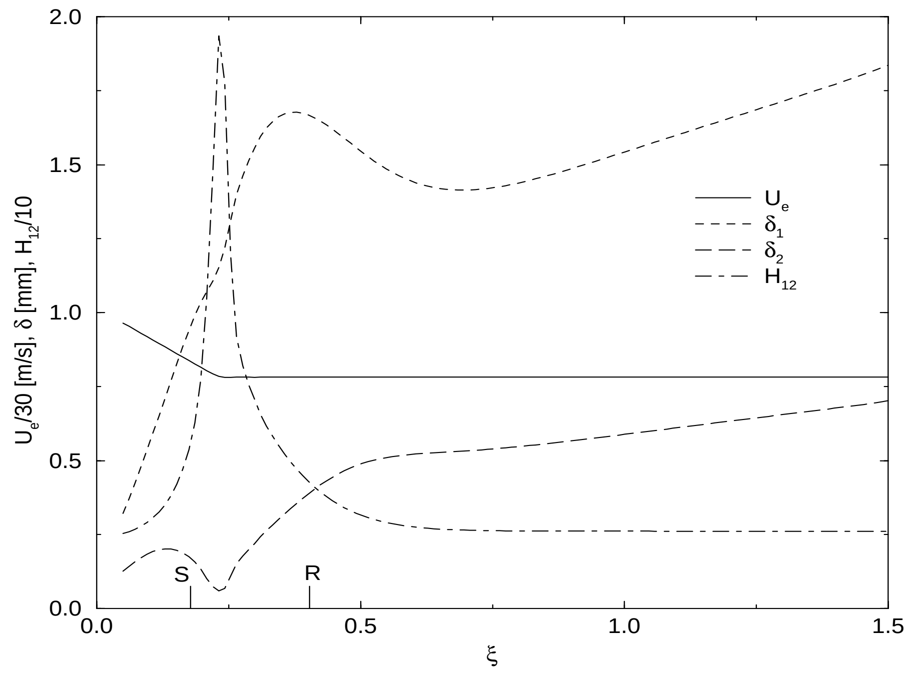




(Th, Hein, Dallmann; Phil Trans Roy Soc A London **358**, 2000)

SB basic flow results (Cebeci Stewartson 1983)

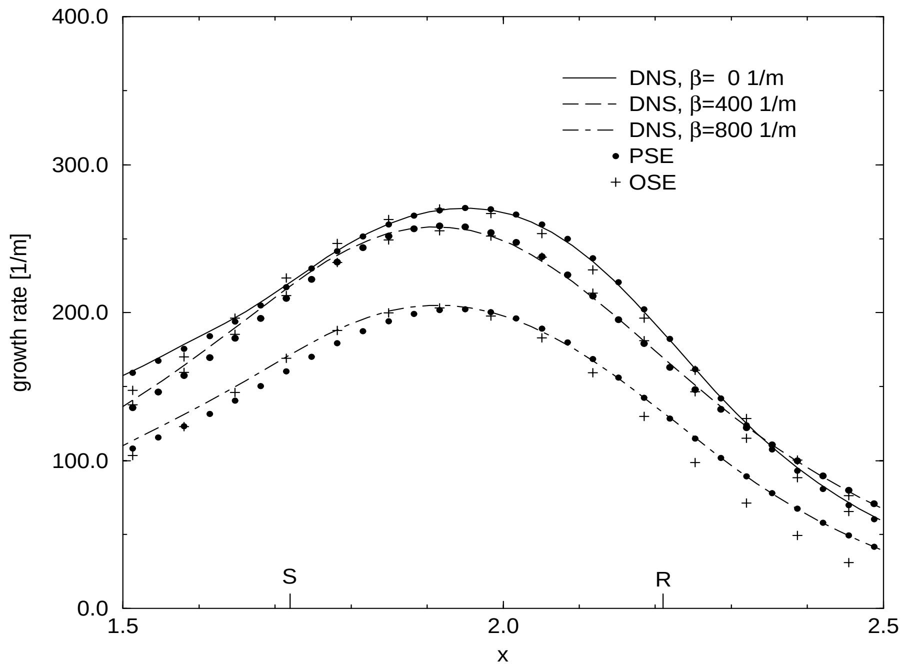
Integral quantities



(Th, Hein, Dallmann; Phil Trans Roy Soc A London **358**, 2000)

OSE/PSE (shear-layer) linear instability results

The laminar separation bubble **amplifies incoming** disturbances



(Th, Hein, Dallmann; Phil Trans Roy Soc A London **358**, 2000)

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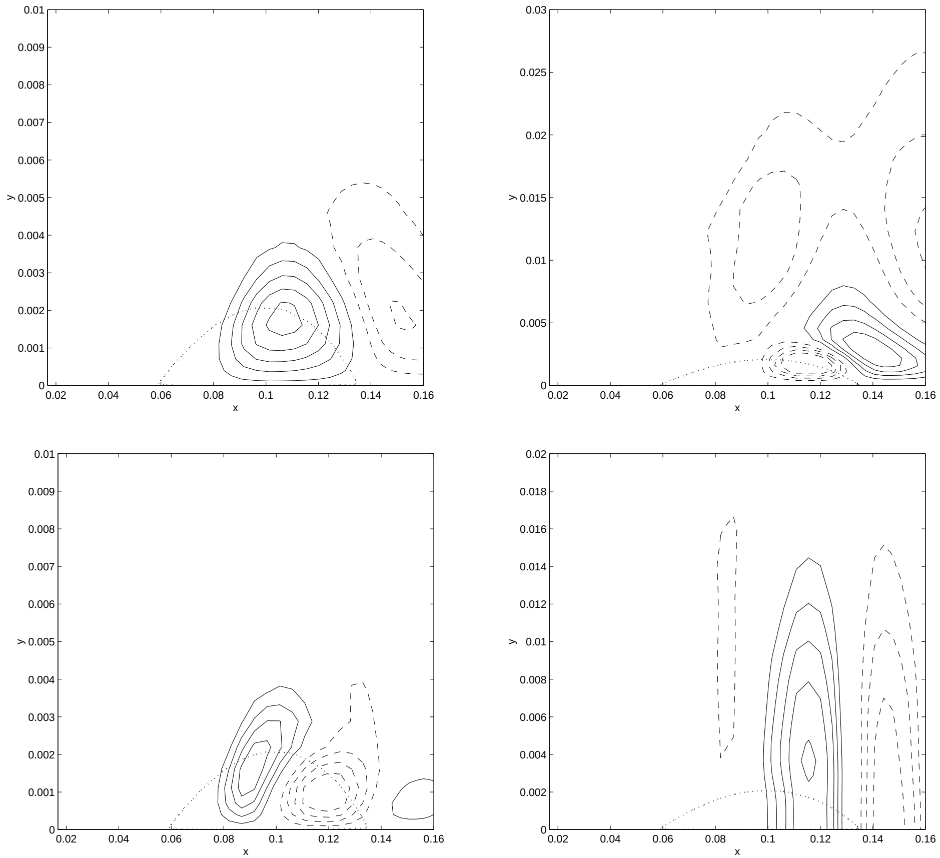
Global linear instability results

The laminar separation bubble **generates own** (eigen-)disturbances



(Th, Hein, Dallmann; Phil Trans Roy Soc A London **358**, 2000)

Global linear instability results

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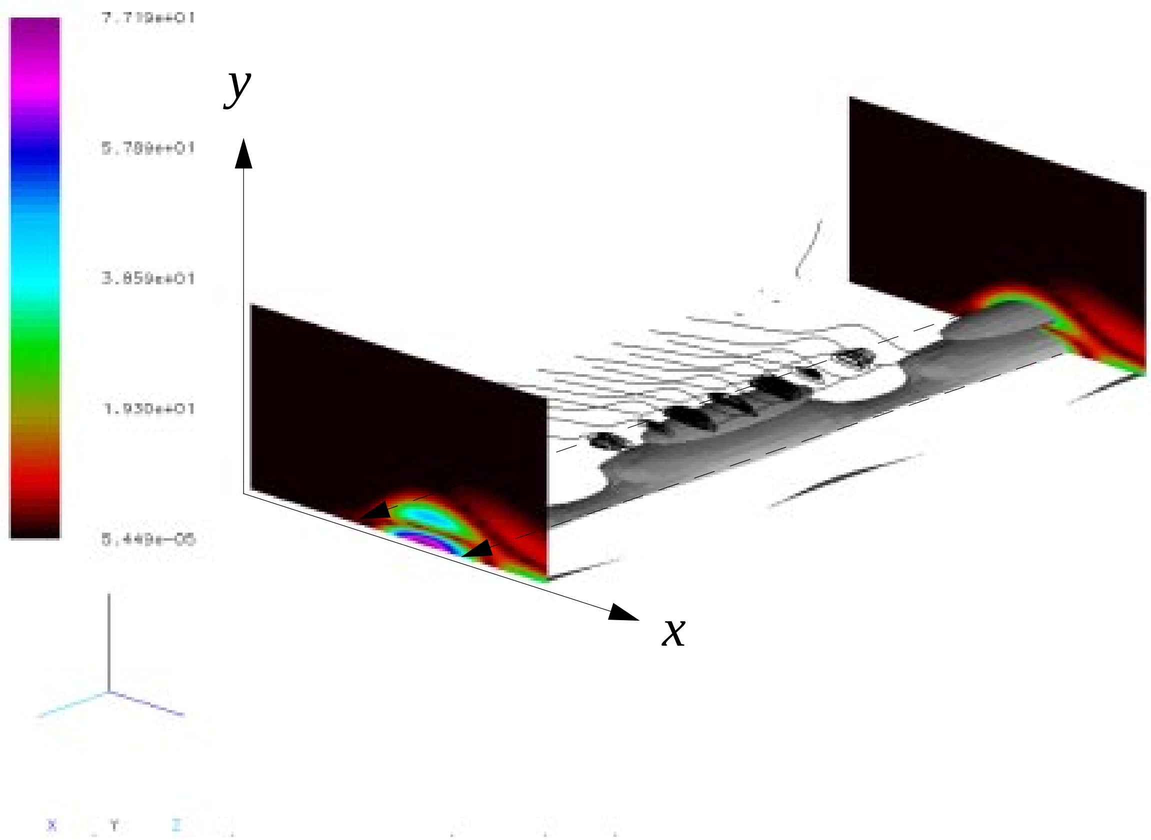

(Th; IUTAM Laminar-Turbulent Transition Symposium V, Sedona 1999)

Summary

The laminar separation bubble has the potential to **generate** and **amplify** global (i.e. large-scale, non-wave-like) linear instability, in the absence of incoming disturbances

The global instability **co-exists** with TS-like instabilities

Flow control should take **both** mechanisms into account

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Outlook

Prerequisites for:
Turbomachinery/external aerodynamics applications

Global instability analysis of **unsteady laminar** basic flow:
Floquet theory (Herbert 198X, Barkley & Henderson 1996)

Global instability analysis of **turbulent** basic flow:
The triple decomposition concept (Reau & Tumin 2000)

Outlook

Theory

A **new** spectral/*hp* element global instability analysis **solver** has been validated (with Imperial/Warwick)

Experiments

and global instability analysis of **turbulent** (TAU/Arizona) or **unsteady** (ITAM) **flows** and associated DNS (IAG)

ACTIVE CONTROL OF A TRANSITIONAL SEPARATION BUBBLE AT LOW REYNOLDS NUMBER AND ELEVATED FREE-STREAM TURBULENCE

B. Nishri, A. Seifert, and I. Wygnanski
Tel-Aviv University
Faculty of Engineering
Department of Fluid Mechanics and Heat Transfer
Tel-Aviv, Israel

Laminar Separation of low Reynolds number adverse pressure gradient boundary layers, with subsequent turbulent reattachment frequently occurs on airfoils and on low-pressure turbine blades. It is responsible for a reduction in efficiency due to an increase in pressure drag. Elevated free-stream turbulence (FST), enhances mixing above the separation bubble and thus promotes earlier reattachment. However, in most low Reynolds number applications, elevated FST does not eliminate the bubble altogether. Therefore, one may improve the performance by actively reducing the size of the separation bubble.

Experimental studies shown that laminar, transitional and turbulent separation bubbles can be effectively controlled by periodic excitation at low levels of FST. The control method relies on the successive introduction of coherent structures at frequencies that generate between one to four vortices at any instant above the bubble. These vortices amplify while propagating downstream, they enhance the mixing and thus promote reattachment. The fact that this method is successful for fully turbulent shear-layers served as a basis for attempting its application in the presence of elevated FST. A feasibility study was performed and reported (Bachar, Ashpis and Wygnanski, APS/DFD meeting '98) showing that active separation control is not hindered by the presence of elevated free-stream turbulence.

Current tests use an apparatus that contains a large, transitional separation bubble, situated near the leading edge of a flat-plate (Fig. 1), because the existence of a strong adverse pressure gradient. Active control, using periodic excitation via acoustic forcing from the tunnel wall (Fig. 1), is used to reduce the mean bubble size. The FST is increased by placing a grid at various distances upstream of the test plate leading edge (LE). The level of the FST varies from 0.3% to 11% (Fig. 2) depending on the position of the grid. Fig. 3 shows the turbulence length scale (using cross correlation between two hot-wires) for various FST levels. The spectral content of the oscillations in the free-stream and in the separated shear layer, were carefully documented in the presence and in the absence of "active flow control". Fig. 4 demonstrates the effect of the FST on the spectral content of the uncontrolled velocity inside and just outside the boundary layer, close to the LE. The effect of the elevated FST on the manner in which the separated shear layer is modified by the periodic excitation is documented as well. Further measurements include surface pressure distributions (Fig. 5 shows the effect of the FST on the mean Cp's) as well as mean and fluctuating velocity profiles that are phase locked to the excitation..

Preliminary results indicate that the average dimension of the bubble can be significantly reduced, even in the presence of elevated FST. This particularly true at the low frequency of excitation (e.g. 20Hz, corresponding to F^+_B=1, where the reduced frequency is based on the length of the baseline bubble and the free-stream velocity) when there is a large disparity of scales between the free stream turbulence and the imposed oscillation. At an excitation frequency of 80Hz, the effect of AFC was reduced as the FST increased. See Fig. 6 for controlled Cp's. The effect of acoustic excitation from the tunnel wall was found to be similar to the effect of a vibrating ribbon placed near the LE of the plate (Fig. 7)

It is believed that the application of active flow control to low Reynolds number axial flow machinery has great potential for improving efficiency of a single rotor-stator stage therefore enabling a reduction of overall number of stages simplifying future design. (see Fig. 8 for provisional conclusions)

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Active Control of a Transitional Separation Bubble at Low Reynolds Number and Elevated Free-Stream Turbulence

B. Nishri, A. Seifert and I. Wygnanski

Tel-Aviv University

Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

Experimental Setup

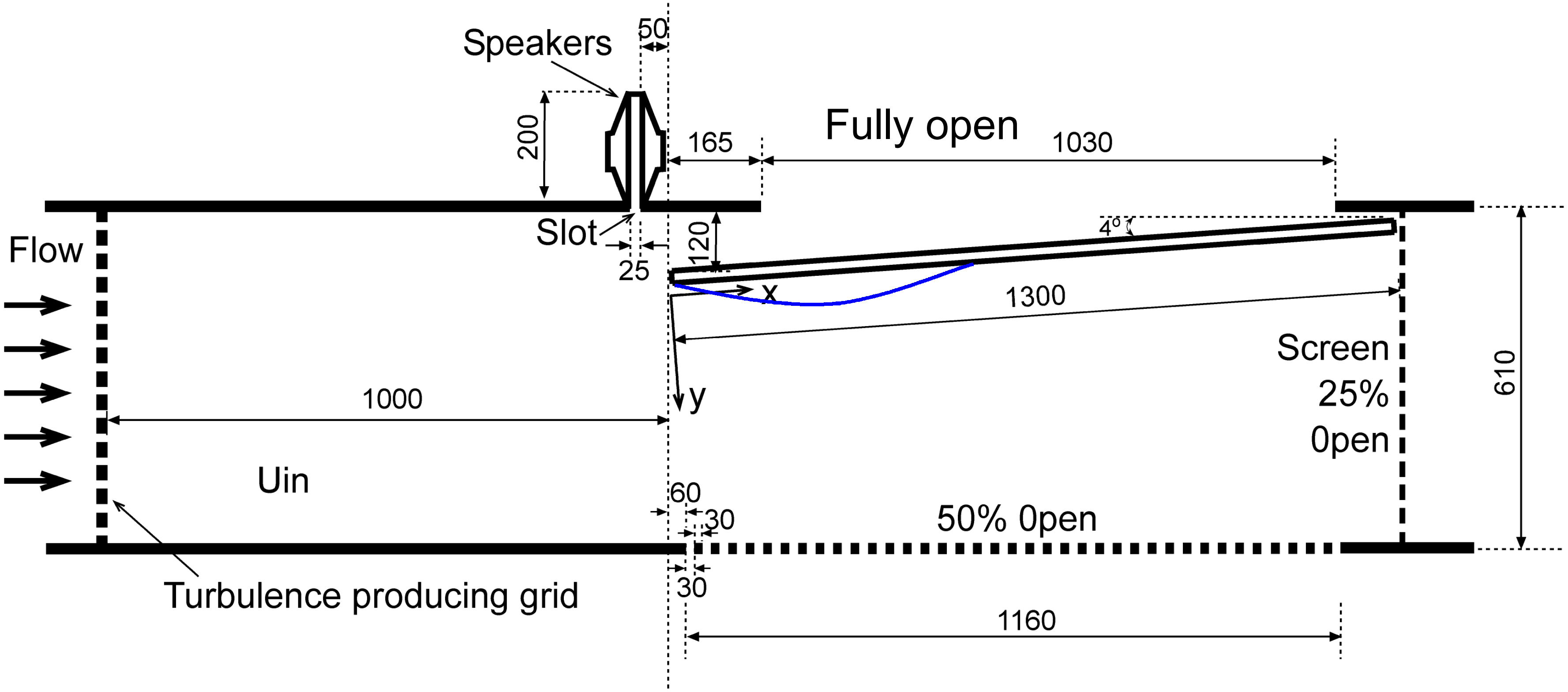

Fig. 1

Note: Test section H=915mm, Openings on sidewalls: only at central 700mm

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Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

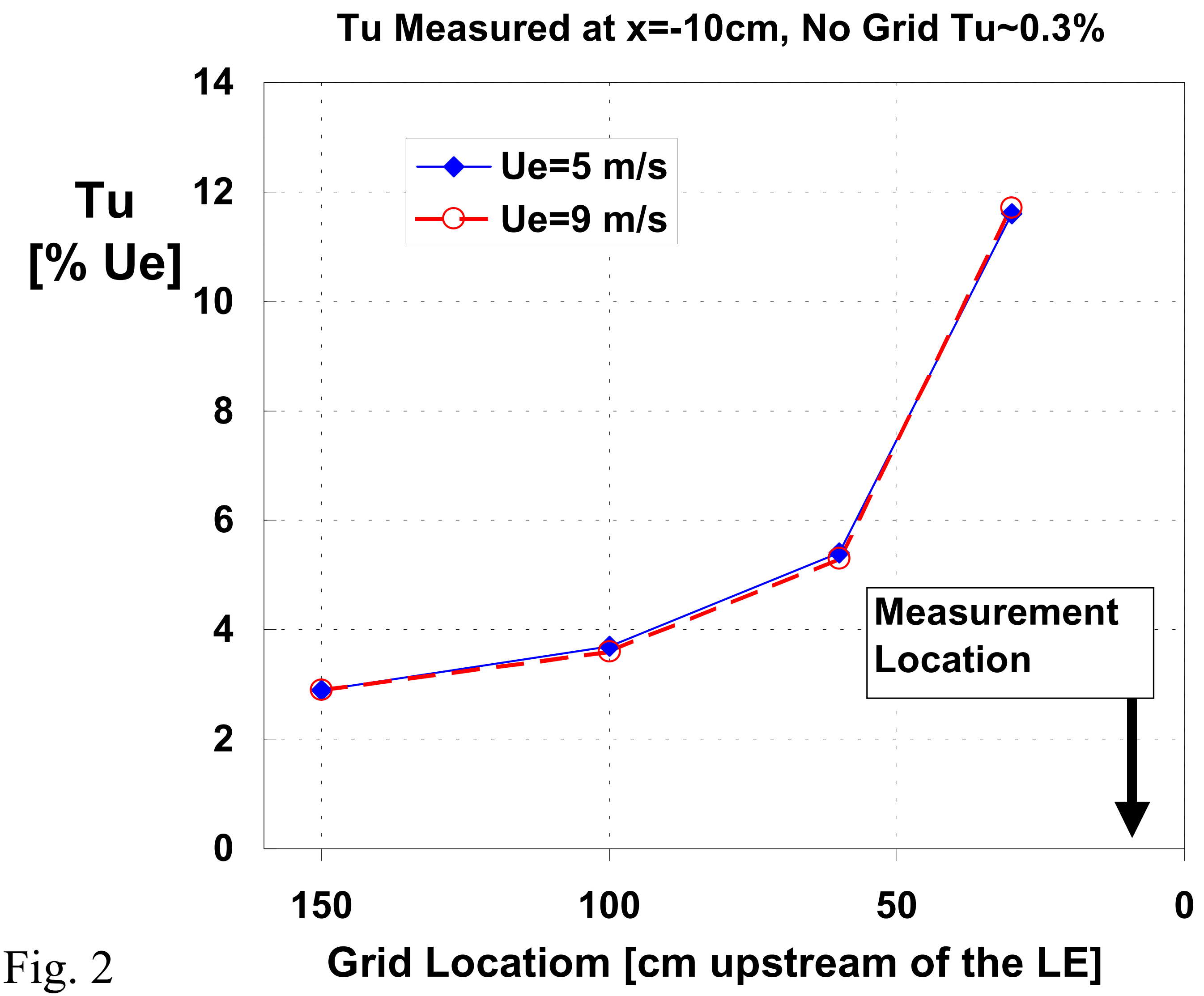

Fig. 2

Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

Turbulent Scales vs. Bubble Scales?

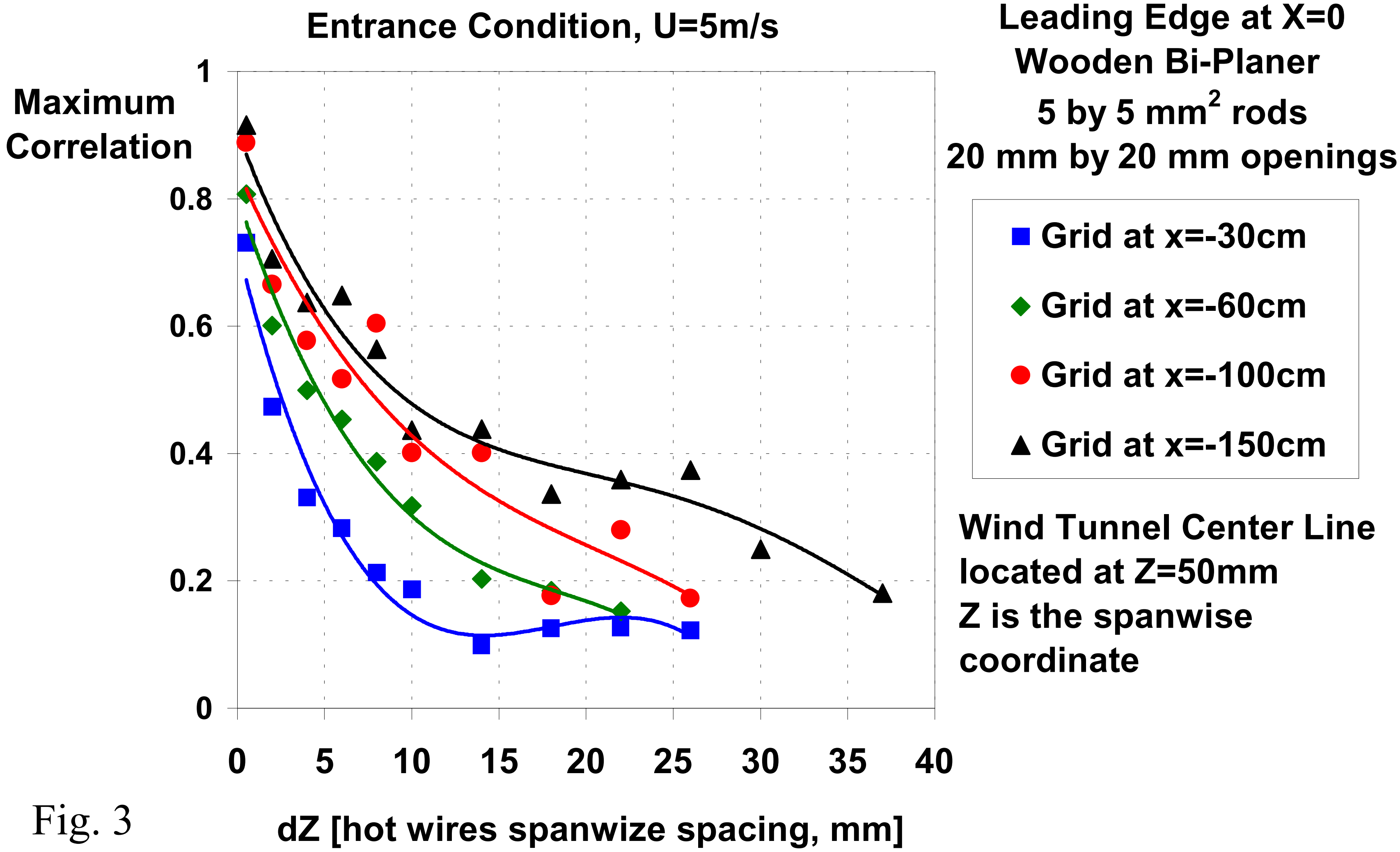

Fig. 3

Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

Separation is (probably) Laminar, but Transition takes place very quickly
Elevated FST – Shear layer turbulent at LE

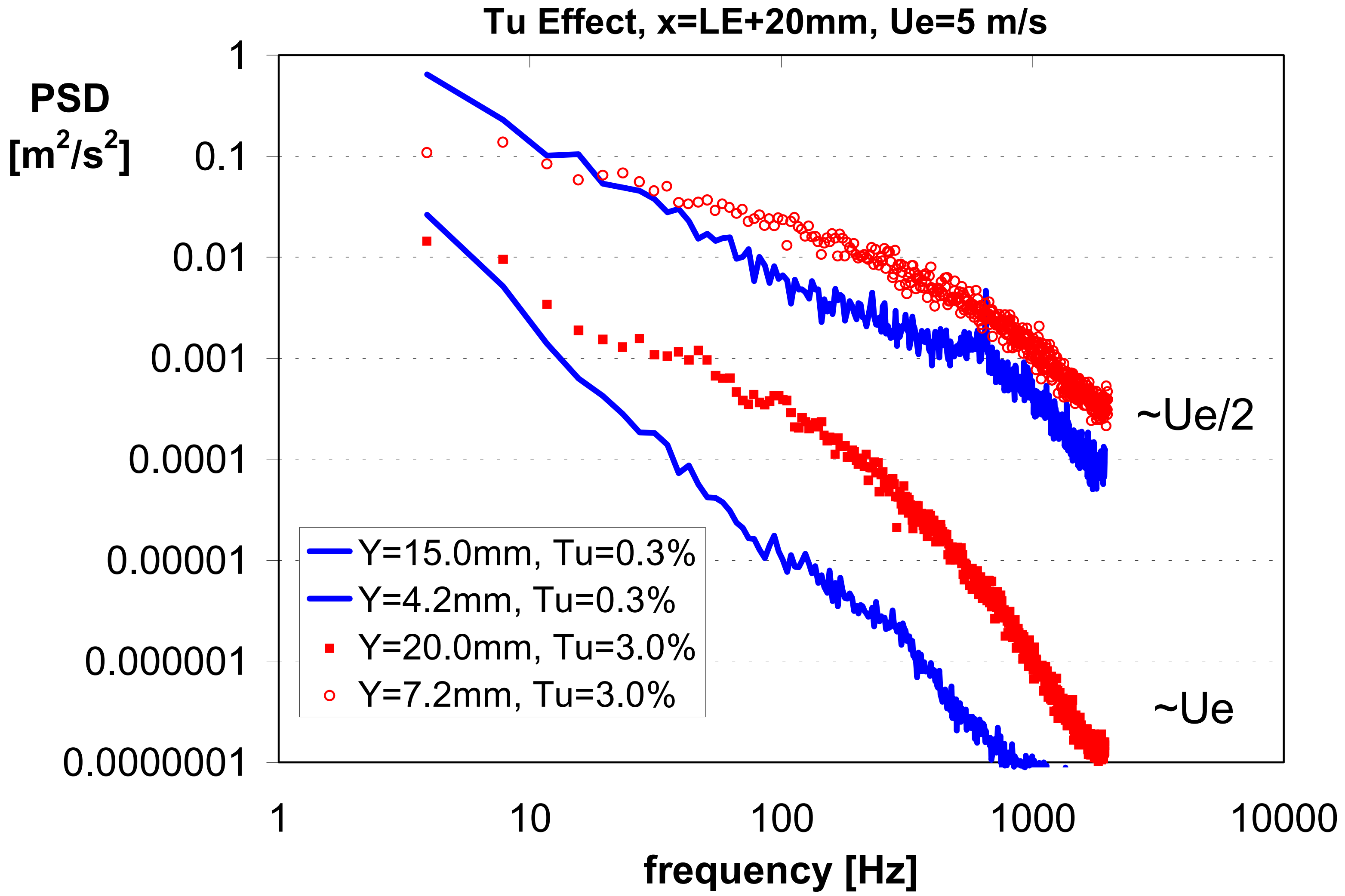

Fig. 4

Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

Significant Effect on Pressure Recovery Rate only for Tu=11%

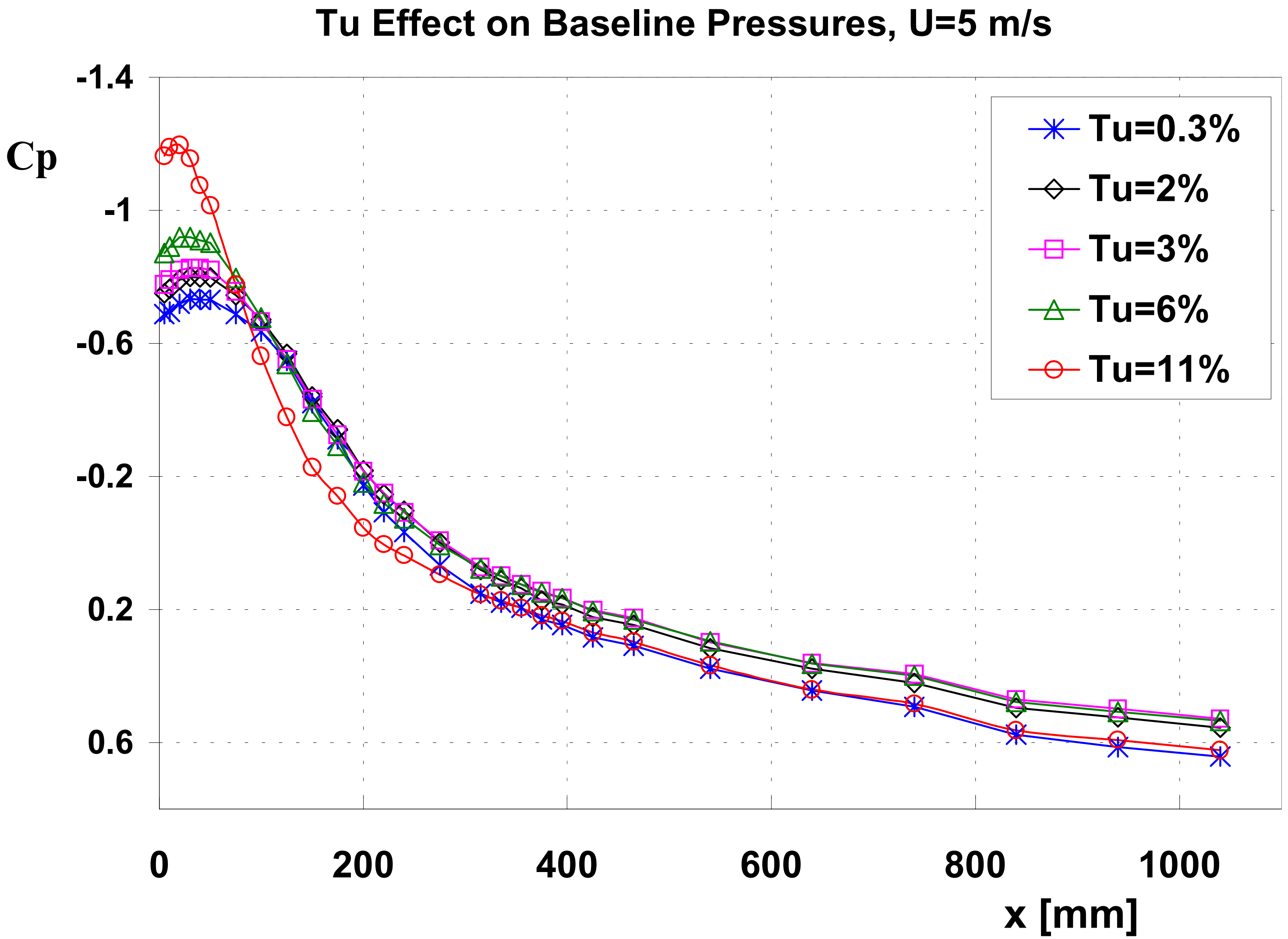

Fig. 5

Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

Effects of Acoustic Excitation:

Hi F+ completely eliminates Bubble at Low Tu, but reduced efficacy at Hi Tu

Low F+ Maintains its Effectiveness at Hi Tu (Effects the bubble Global instability?)

Mean Reattachment position – x of P"=0

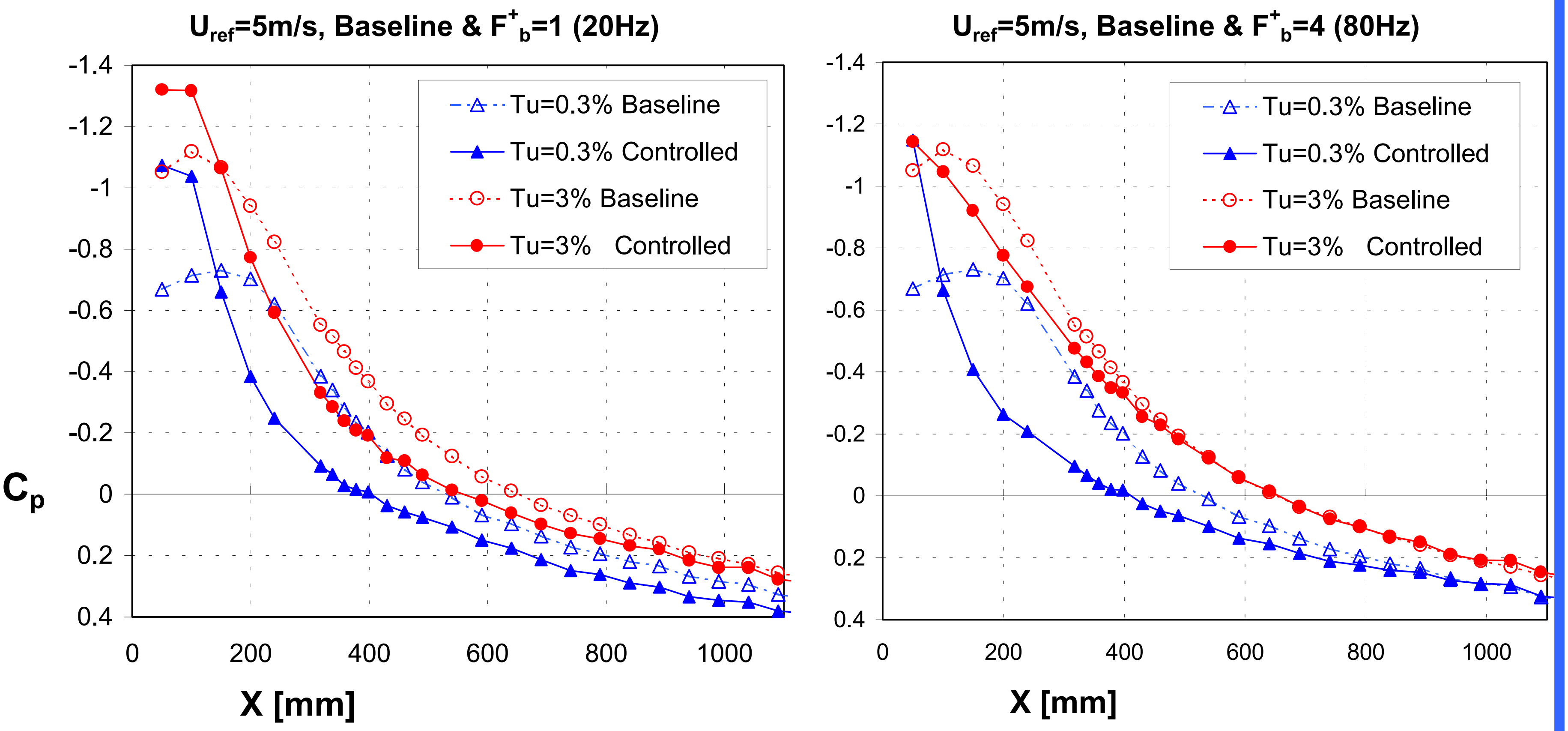

Fig. 6

Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

Effects of Vibrating Ribbon at LE: Similar to that of Acoustic Excitation, Tu=0.3%

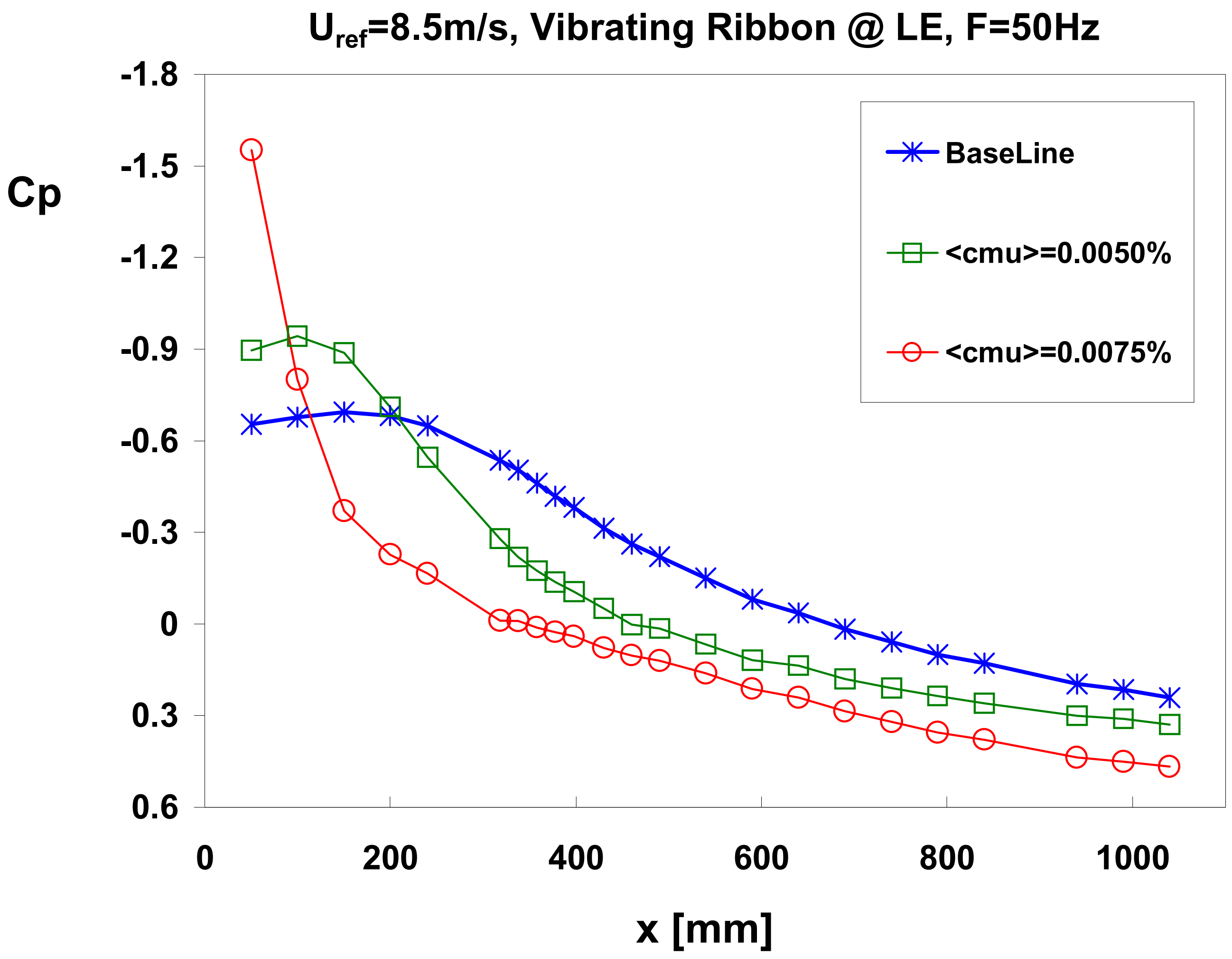

Fig. 7

Separation Bubble Active Flow Control – Nishri, Wygnanski & Seifert

Provisional Conclusions

Elevated F.S.T. Reduces Bubble size – reducing the potential for improvement by AFC

AFC using F^{+}~1 effective for reducing bubble size at Elevated F.S.T.

Effectiveness maintained at low frequencies that interact with the bubble global instability at elevated F.S.T.

Fig. 8

STABILITY, TRANSITION, AND REATTACHMENT CHARACTERISTICS OF A SEPARATION BUBBLE IN UNSTEADY FLOW

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Berlin University of Technology
Berlin, Germany

Highly loaded turbomachinery airfoils in high lift low pressure turbines as well as in compressors approaching stall demonstrate transition of the suction side boundary layer via a separation bubble. Close control of this transition process is necessary to avoid full separation with dramatic effects on performance and stability.

The transition of the free shear layer is strongly affected by two unsteady external phenomena:

- the velocity defect in the wake of upstream blade rows and
- the increased turbulence levels within this wake

In most experiments both phenomena are effective simultaneously and it is not possible to determine their relative relevance. Experiments with a large-scale low-speed facility offer the opportunity of combining a closely controlled main flow with a detailed resolution of the shear layer. Such experiments have been performed in a suction type wind tunnel with a rotating flap and a contoured wall to generate the necessary pressure distribution on a flat plate. The effects of the velocity defect of the wake alone are studied in a low-turbulence environment. Typical parameters have been selected from earlier high speed turbine tests.

The results offered for discussion include

- A comparison of the response of the separation bubble to steady and periodic main flow.
- The development of instability waves in the free shear layer and visualization of the transition process over a full period of the main flow fluctuation applying phase-averaging to single hot wire signals.
- The characteristic "frequency packages" of the instability waves
- The observed phase shift between the main flow and the separation bubble in the region of transition and reattachment.
- The effect of Strouhal-no. on the location of transition initiation along the velocity wave of the periodic main flow.

Minnowbrook III
Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows

Stability, Transition and Reattachment Characteristics of a Separation Bubble

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Hourmouziadis@TU-Berlin.de

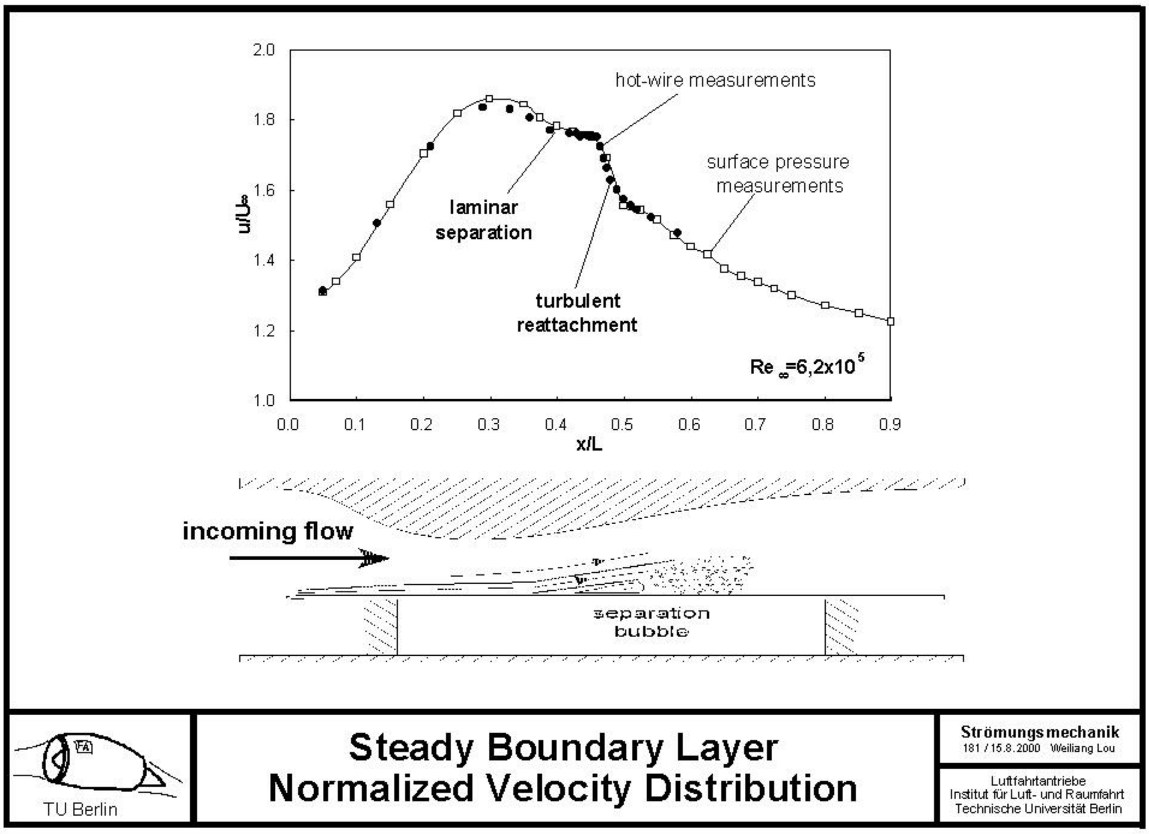
Experimental Facility

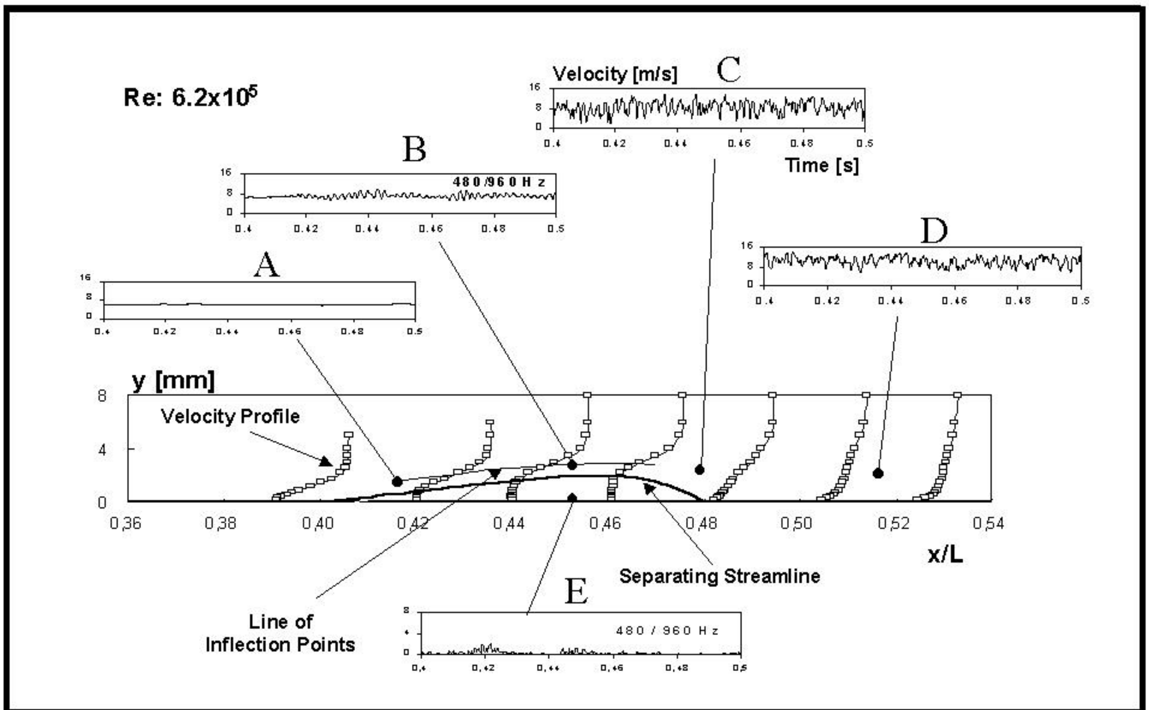
Separation bubble behaviour

- Steady and unsteady hot wire signal analysis

- Steady and unsteady instability characteristics

- Phase shift between main flow and separation



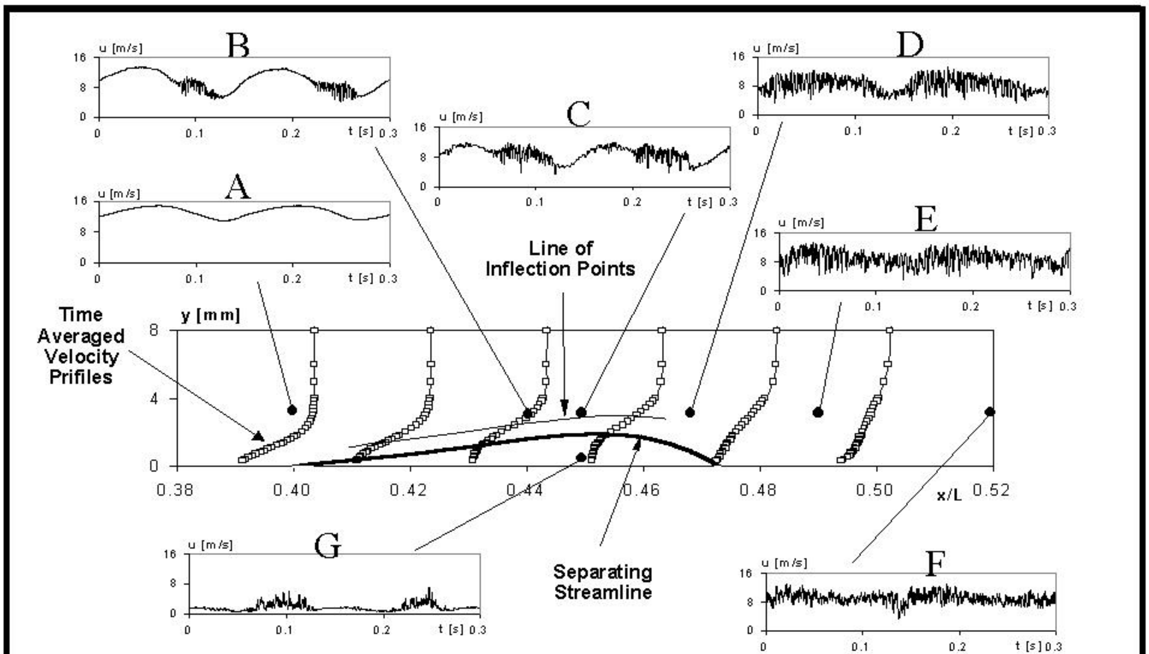


TU Berlin

Steady Flow Separation Bubble Velocity Profiles

Strömungsmechanik
176 / 14.8.2000 Weiliang Lou

Luftfahrtantriebe
Institut für Luft- und Raumfahrt
Technische Universität Berlin



Weiliang Lou, Jean Hourmouziadis
Jet Propulsion Laboratory, Berlin University of Technology
Separation Bubbles under Steady and Periodic-Unsteady Conditions
46th ASME International Gas Turbine & Aeroengine Congress, Munich, Germany, 8.-11.5.2000, 2000-GG-0270

TU Berlin

Unsteady Flow Separation Bubble Velocity Profiles

Strömungsmechanik
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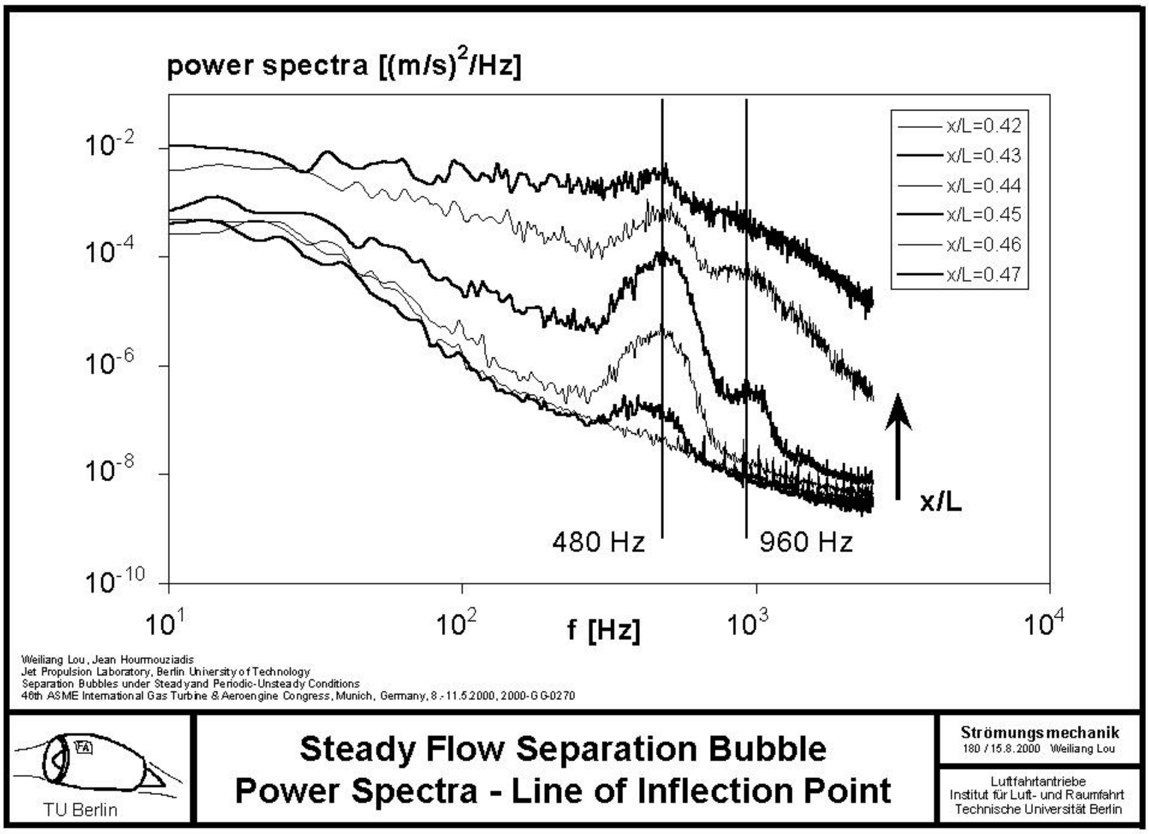
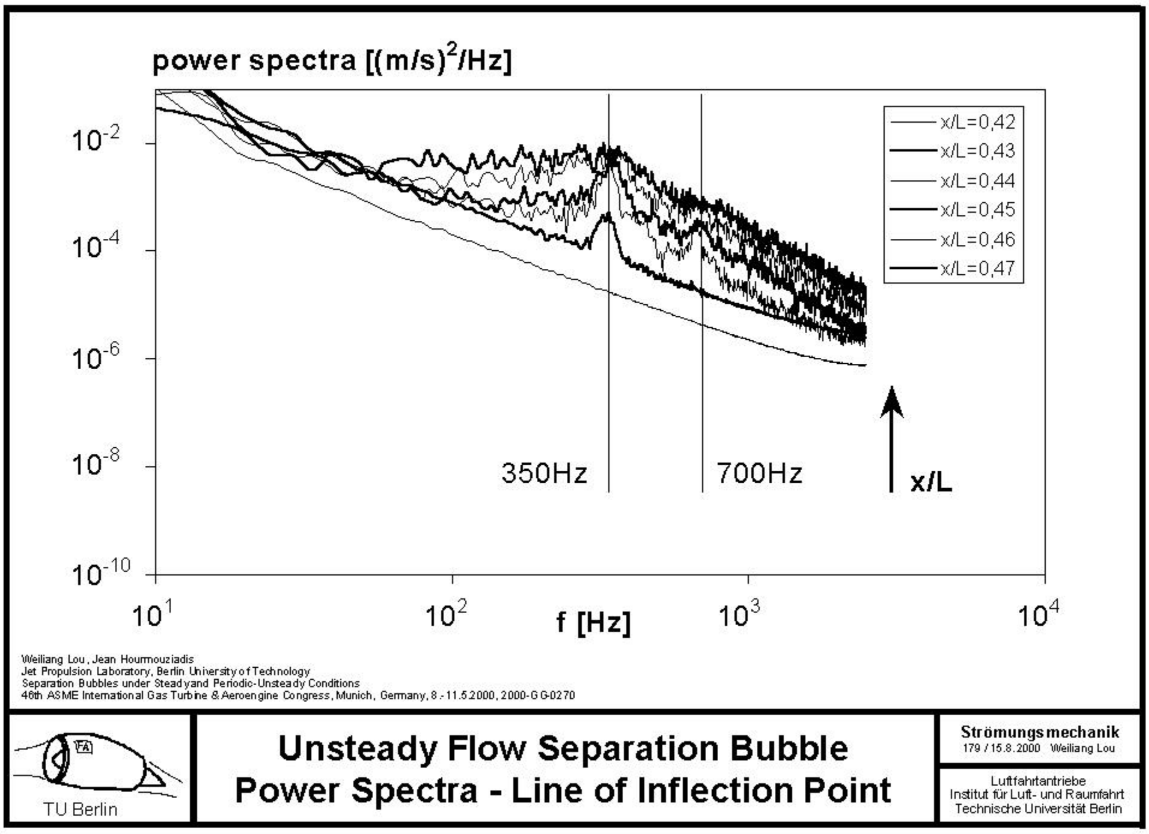

power spectra [(m/s)²/Hz]
10-2
10-4
10-6
10-8
10-10
x/L=0.42
x/L=0.43
x/L=0.44
x/L=0.45
x/L=0.46
x/L=0.47
x/L
480 Hz
960 Hz
10¹
10²
f [Hz]
10³
10⁴
Weiliang Lou, Jean Hourmouziadis
Jet Propulsion Laboratory, Berlin University of Technology
Separation Bubbles under Steady and Periodic-Unsteady Conditions
46th ASME International Gas Turbine & Aeroengine Congress, Munich, Germany, 8.-11.5.2000, 2000-GG-0270
TU Berlin
Steady Flow Separation Bubble
Power Spectra - Line of Inflection Point
Strömungsmechanik
180 / 15.8.2000 Weiliang Lou
Luftfahrtantriebe
Institut für Luft- und Raumfahrt
Technische Universität Berlin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10-2
10-4
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x/L=0,43
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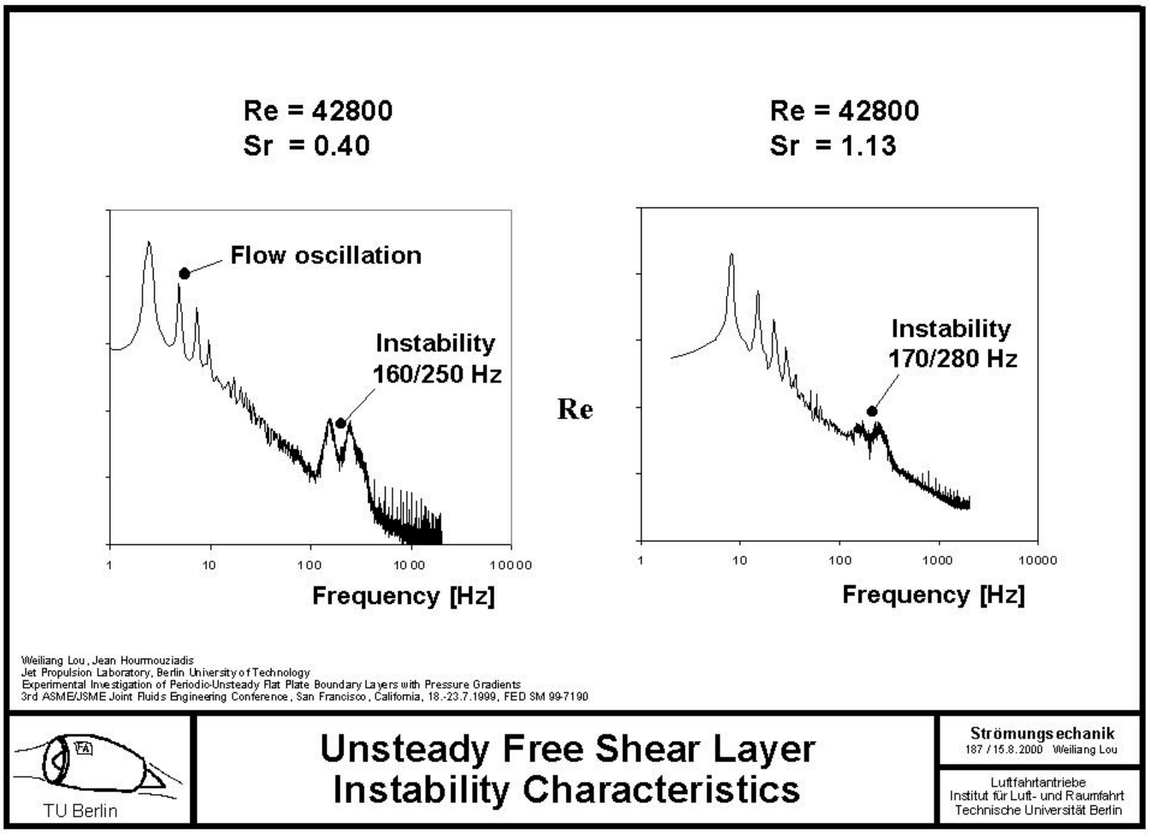
x/L=0,45
x/L=0,46
x/L=0,47
350Hz
700Hz
x/L
10¹
10²
f [Hz]
10³
10⁴
Weiliang Lou, Jean Hourmouziadis
Jet Propulsion Laboratory, Berlin University of Technology
Separation Bubbles under Steady and Periodic-Unsteady Conditions
46th ASME International Gas Turbine & Aeroengine Congress, Munich, Germany, 8.-11.5.2000, 2000-GG-0270
TU Berlin
Unsteady Flow Separation Bubble
Power Spectra - Line of Inflection Point
Strömungsmechanik
179 / 15.8.2000 Weiliang Lou
Luftfahrtantriebe
Institut für Luft- und Raumfahrt
Technische Universität Berlin



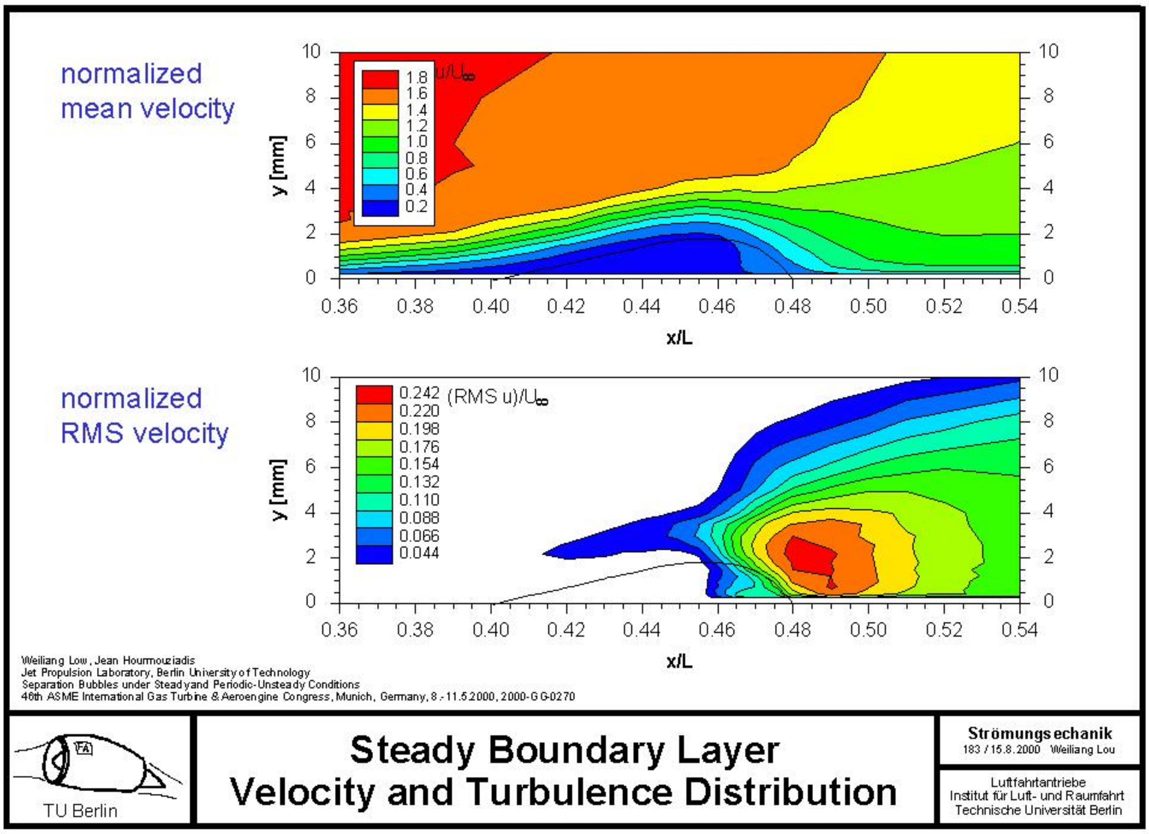
Stability and Transition of the Free Shear Layer

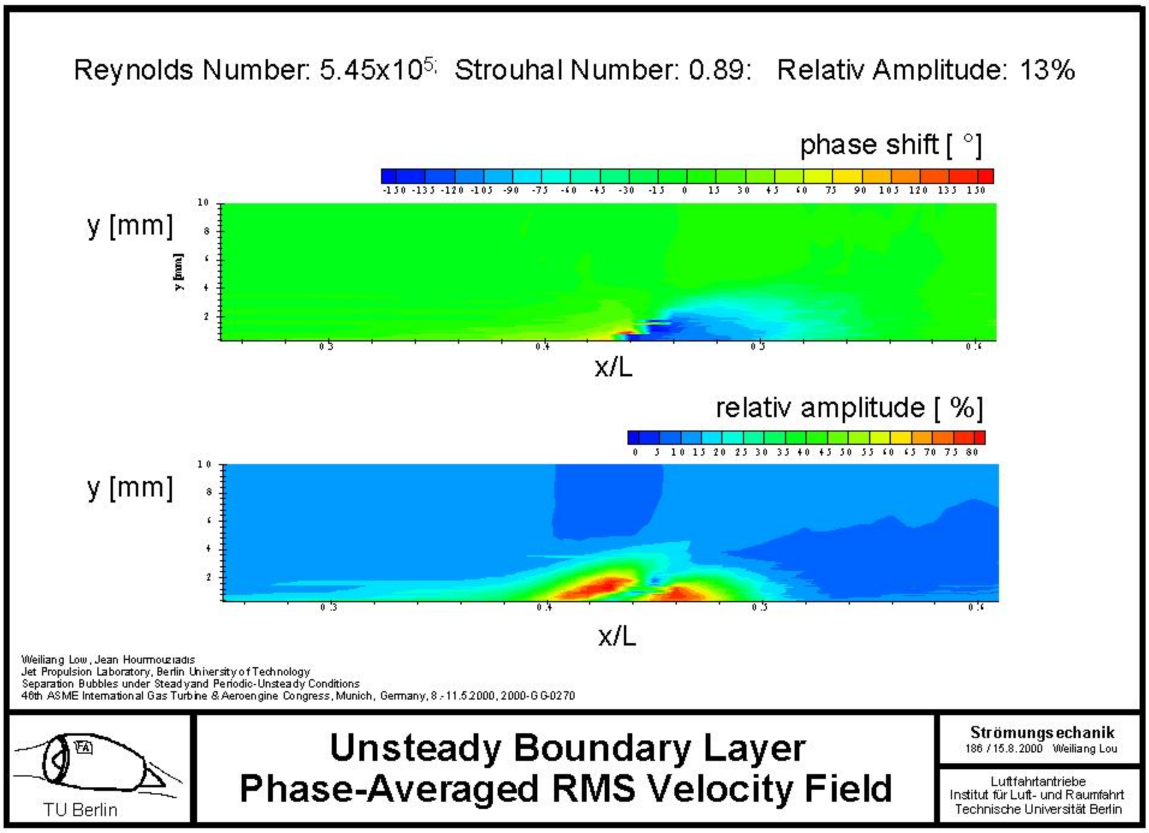
Instability waves appear very early in the separated shear layer, far upstream of transition.

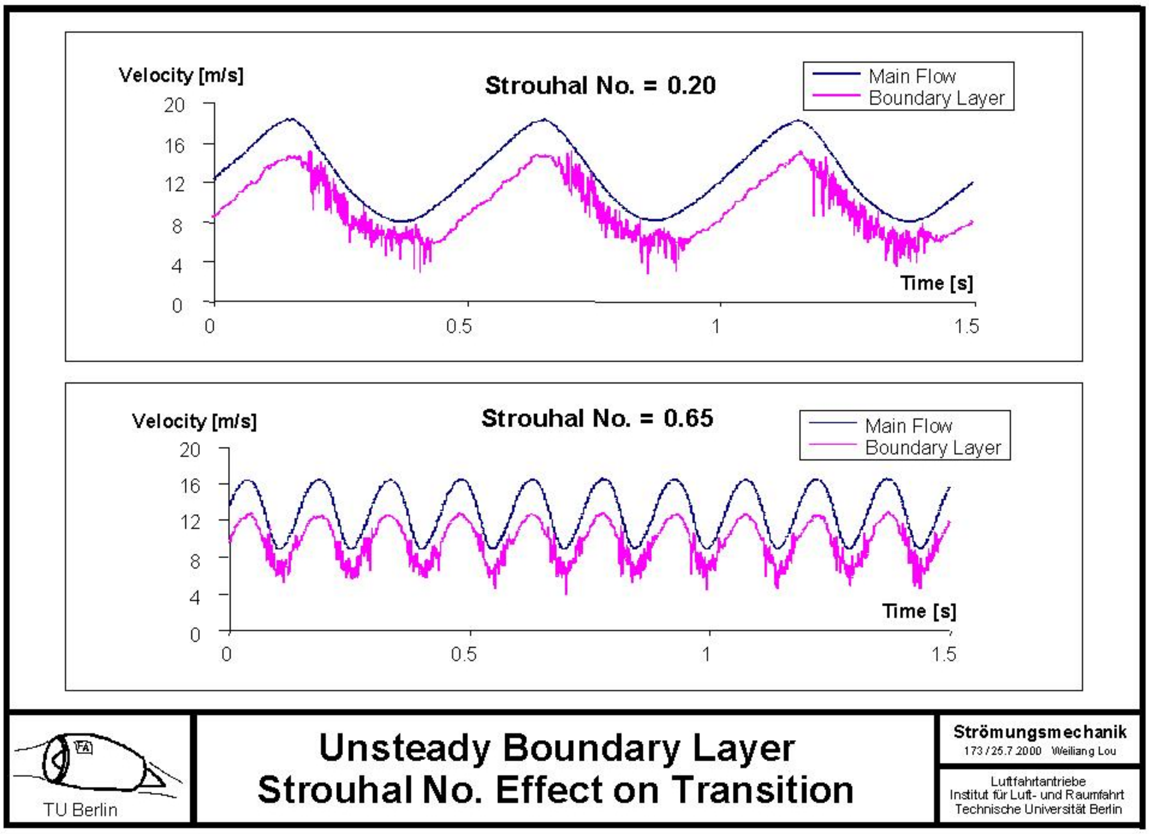
Both in the steady and the unsteady case two somewhat smeared out instability peaks are observed in the power spectra, the higher frequency not always being a harmonic of the lower one.

The frequencies of the instability waves depend strongly on theReynolds no. level. The effect of the Strouhal no. appears to be minor.

Transition progresses very rapidly after initiation and is complete much earlier than known for the attached boundary layer.


normalized
mean velocity
u/U∞
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
y [mm]
x/L
normalized
RMS velocity
(RMS u)/U∞
0.242
0.220
0.198
0.176
0.154
0.132
0.110
0.088
0.066
0.044
Weiliang Low, Jean Hourmouziadis
Jet Propulsion Laboratory, Berlin University of Technology
Separation Bubbles under Steady and Periodic-Unsteady Conditions
46th ASME International Gas Turbine & Aeroengine Congress, Munich, Germany, 8.-11.5.2000, 2000-GT-0270
TU Berlin
Steady Boundary Layer
Velocity and Turbulence Distribution
Strömungsechanik
183 / 15.8.2000 Weiliang Lou
Luftfahrtantriebe
Institut für Luft- und Raumfahrt
Technische Universität Berlin


Reynolds Number: 5.45x10^5; Strouhal Number: 0.89; Relativ Amplitude: 13%
phase shift [°]
y [mm]
x/L
relativ amplitude [%]
y [mm]
x/L
Weiliang Low, Jean Hourmouziadis
Jet Propulsion Laboratory, Berlin University of Technology
Separation Bubbles under Steady and Periodic-Unsteady Conditions
46th ASME International Gas Turbine & Aeroengine Congress, Munich, Germany, 8.-11.5.2000, 2000-GT-0270
TU Berlin
Unsteady Boundary Layer
Phase-Averaged RMS Velocity Field
Strömungsechanik
186 / 15.8.2000 Weiliang Lou
Luftfahrtantriebe
Institut für Luft- und Raumfahrt
Technische Universität Berlin



Conclusions

Instability waves in the separated laminar shear layer initiate in the region of the (time-averaged flow) inflection points of the velocity profiles indicating inviscid rather than viscous instability.

At the same avarage Reynolds no. the separation bubble in unsteady flow is shorter and thinner than in steady flow.

There is a considerable phase shift between the main flow and the response of the separation bubble (Transition and Reattachment).

The location of transition initiation along the velocity wave of the periodic main flow depends strongly on the Strouhal no.

Reference

Joint German research programm : "Periodically Unsteady Turbomachinery Flow"

http://www.TurboFlow.TU-Berlin.de

SIMULATIONS OF BOUNDARY LAYER DEVELOPMENT IN LOW-PRESSURE TURBINES

Daniel J. Dorney*
Virginia Commonwealth University
Department of Mechanical Engineering
Richmond, VA

Experimental data from jet-engine tests have indicated that turbine efficiencies at takeoff can be as much as two points higher than those at cruise conditions. Recent studies have shown that low Reynolds number effects contribute to the lower efficiencies at cruise conditions. The goal of the current effort is to implement/improve existing turbulence models, natural transition models, intermittency function models and bubble transition models into two- and three- dimensional Navier-Stokes analyses. Numerical simulations have been performed for several geometries, including a low-pressure turbine cascade and a two-stage low-pressure turbine. The simulations were performed for several Reynolds numbers and turbulence levels. The predicted results have been compared with experimental airfoil loadings and boundary layer quantities. The comparisons indicate that relatively simple models can be used to predict the effects of Reynolds number variations in a low-pressure turbine environment.

*present address: NASA Marshall Space Flight Center, Fluid Dynamics Analysis Group–TD64, Huntsville, AL

NASA/CP—2001-210888

Simulations of Boundary Layer Development in Low-Pressure Turbines

Daniel J. Dorney
Virginia Commonwealth University
Richmond, VA

Minnowbrook III Workshop
22 Aug 2000

NASA/CP—2001-210888

Outline

- Motivation
- Numerical method
- Test cases
  - PAK-B cascade (WP/AFB)
  - LSRT two-stage turbine (GE)
- Conclusions

Motivation

- Implement/improve turbulence and transition models for design and analysis
- Strive for simplicity!

Numerical Method

- Time-dependent, 3rd-order accurate Navier-Stokes codes (Q3D and 3D)
- Highly-modified Baldwin-Lomax turbulence model
- Abu-Ghannam & Shaw, Mayle transition models
- Dhawan-Narasihma, Solomon-Gostelow-Walker intermittency function correlations
- Modified Roberts' correlation (separated flow)

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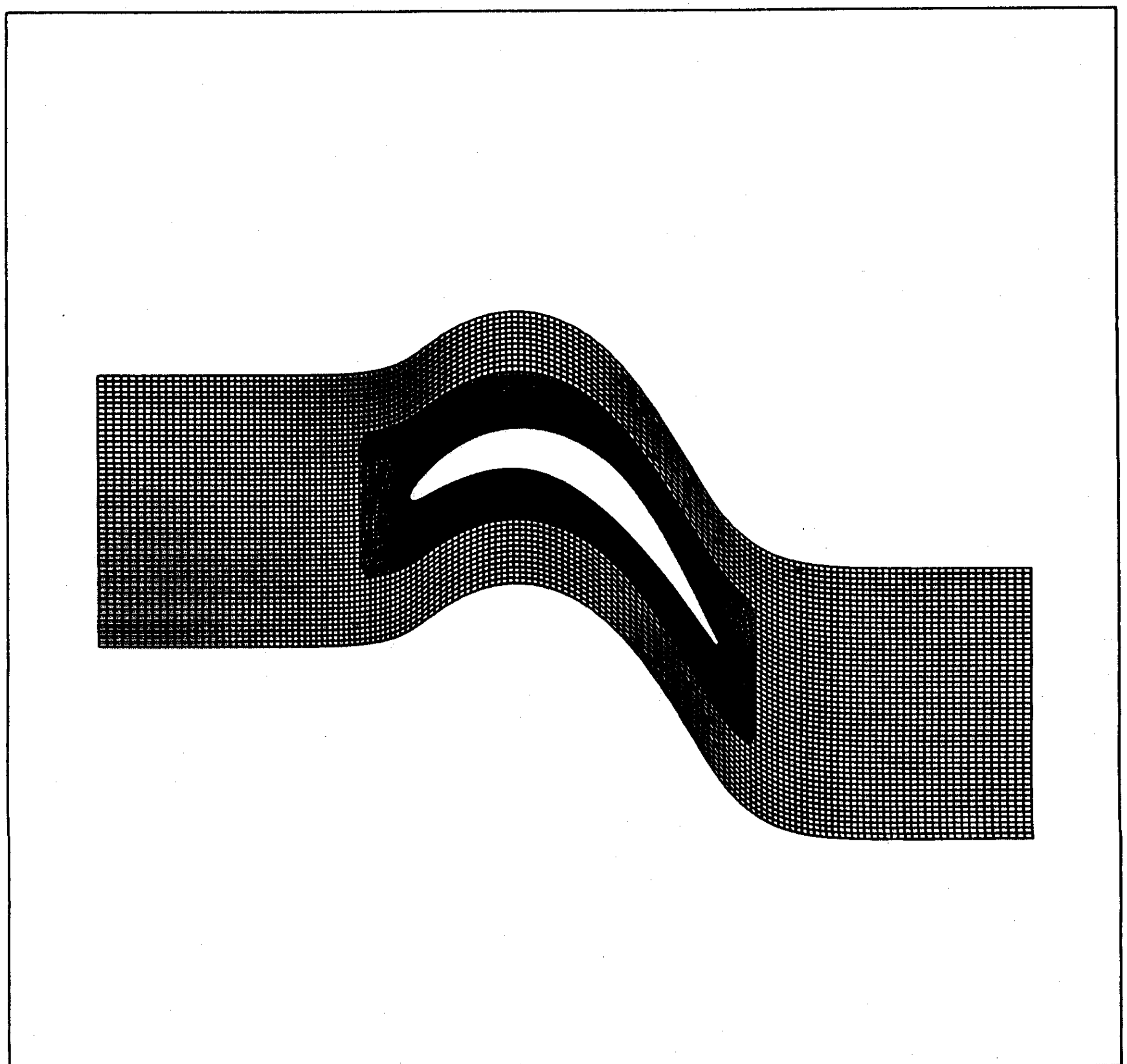
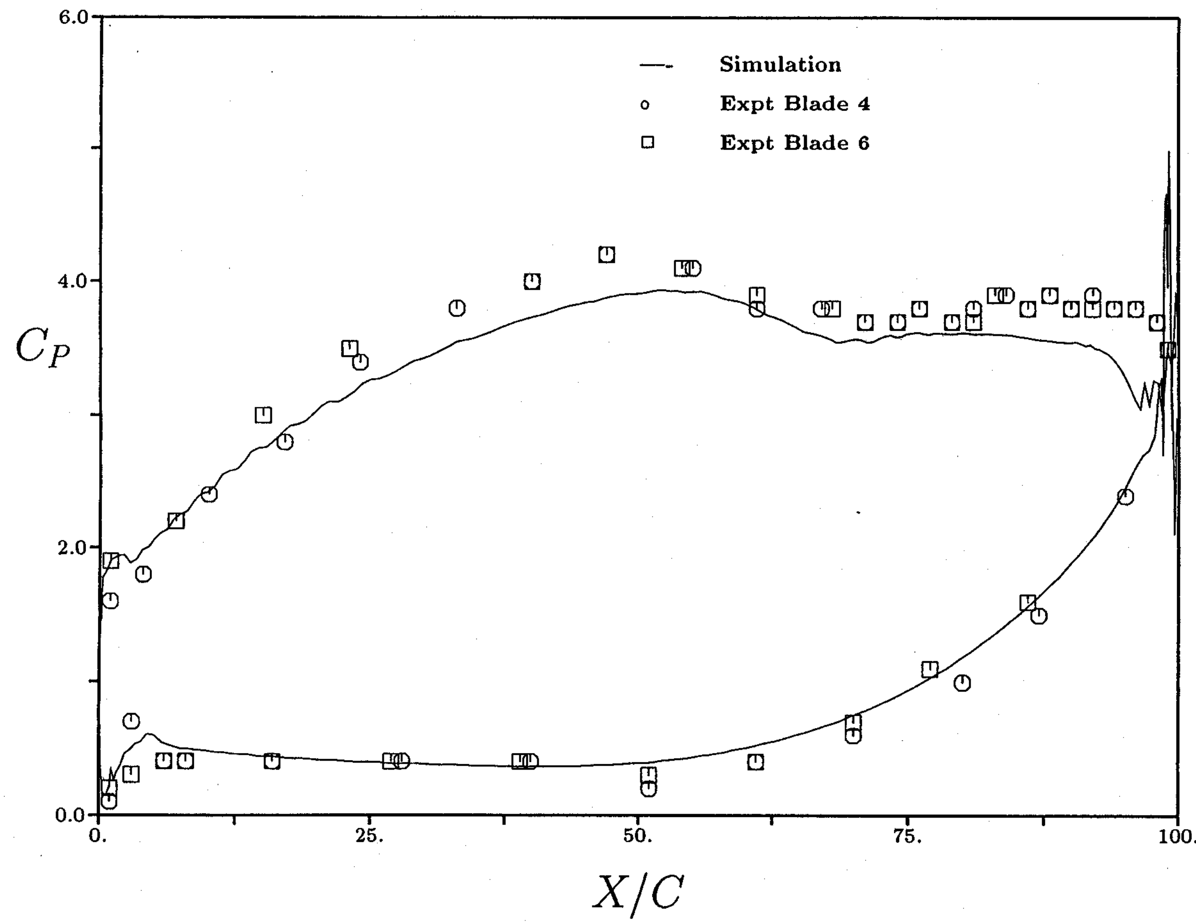
PAK-B Cascade

- Tested at WP/AFB
- Re=50k, 100k, 200k
- Tu=1%, 4%
- Airfoil loadings, velocity profiles, losses
- Computational grids
  - 351x51 O-grid
  - 150x51 H-grid
  - 25,551 total grid points

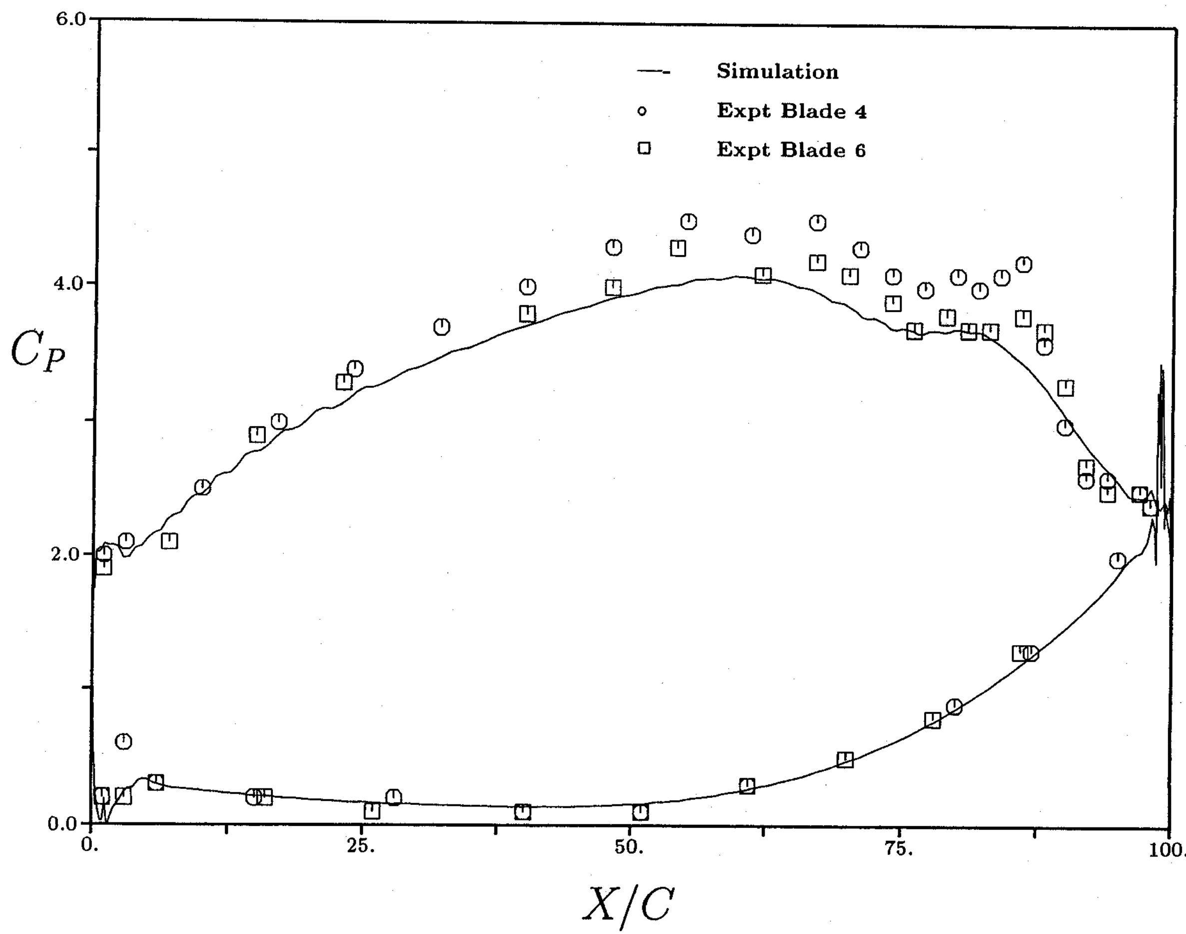
COMPUTATIONAL GRID



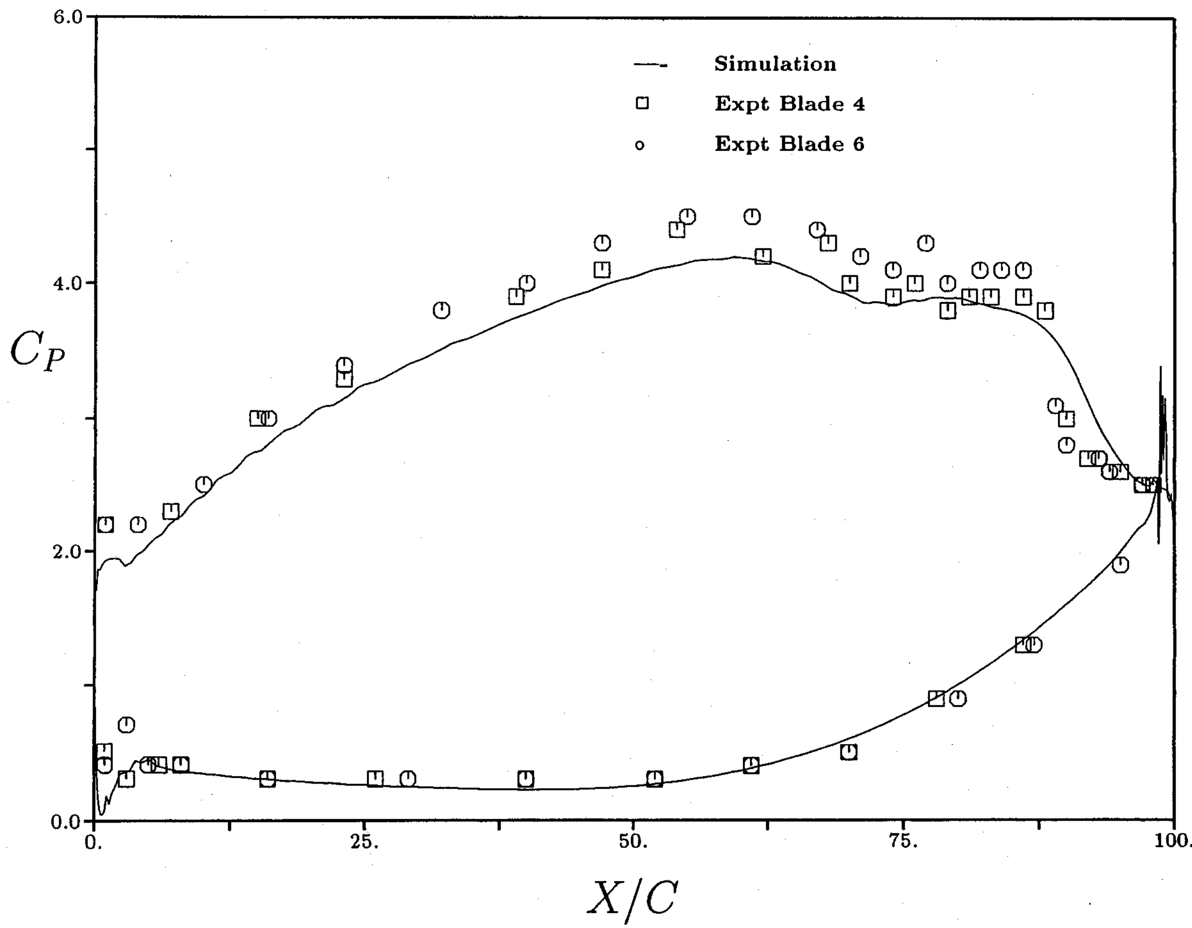
Loading - Re=50k - Tu=1%



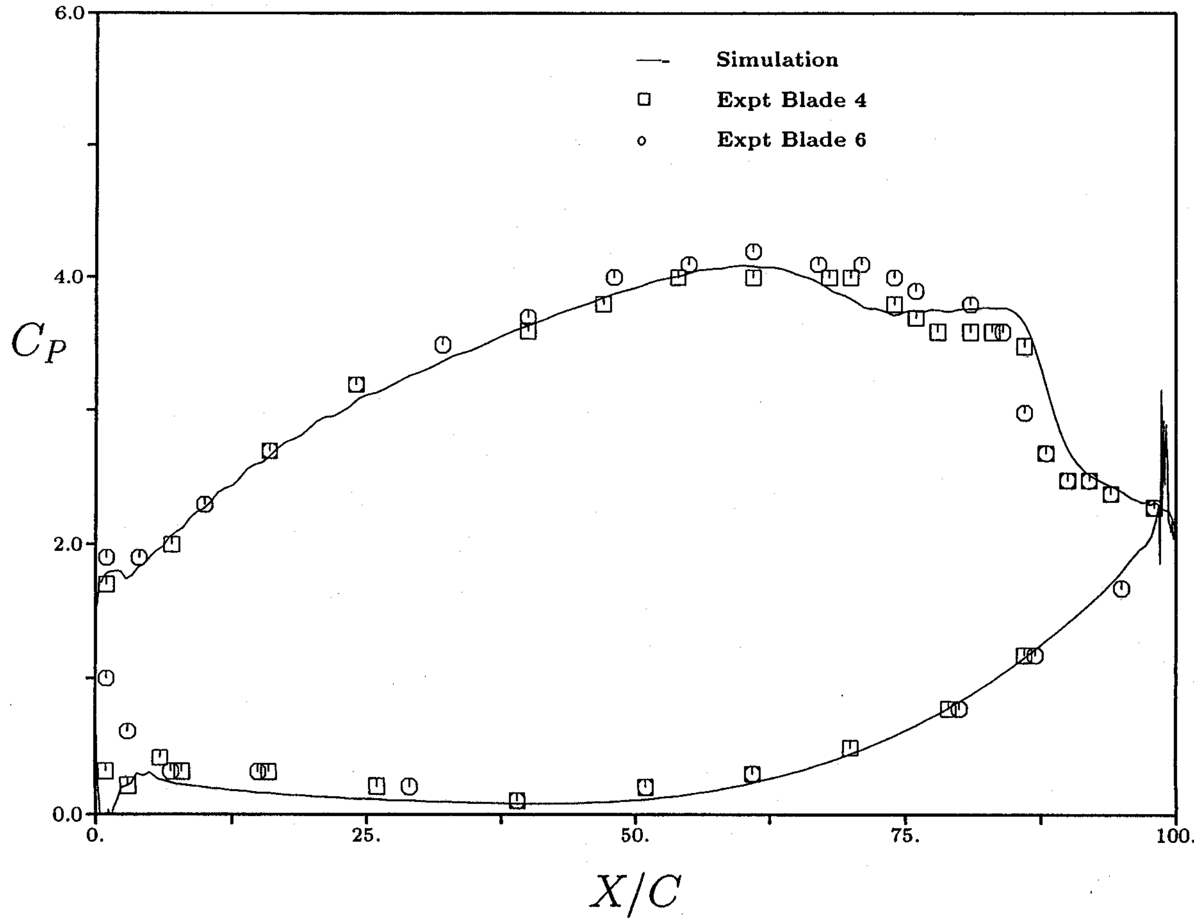
Loading - Re=50k - Tu=4%



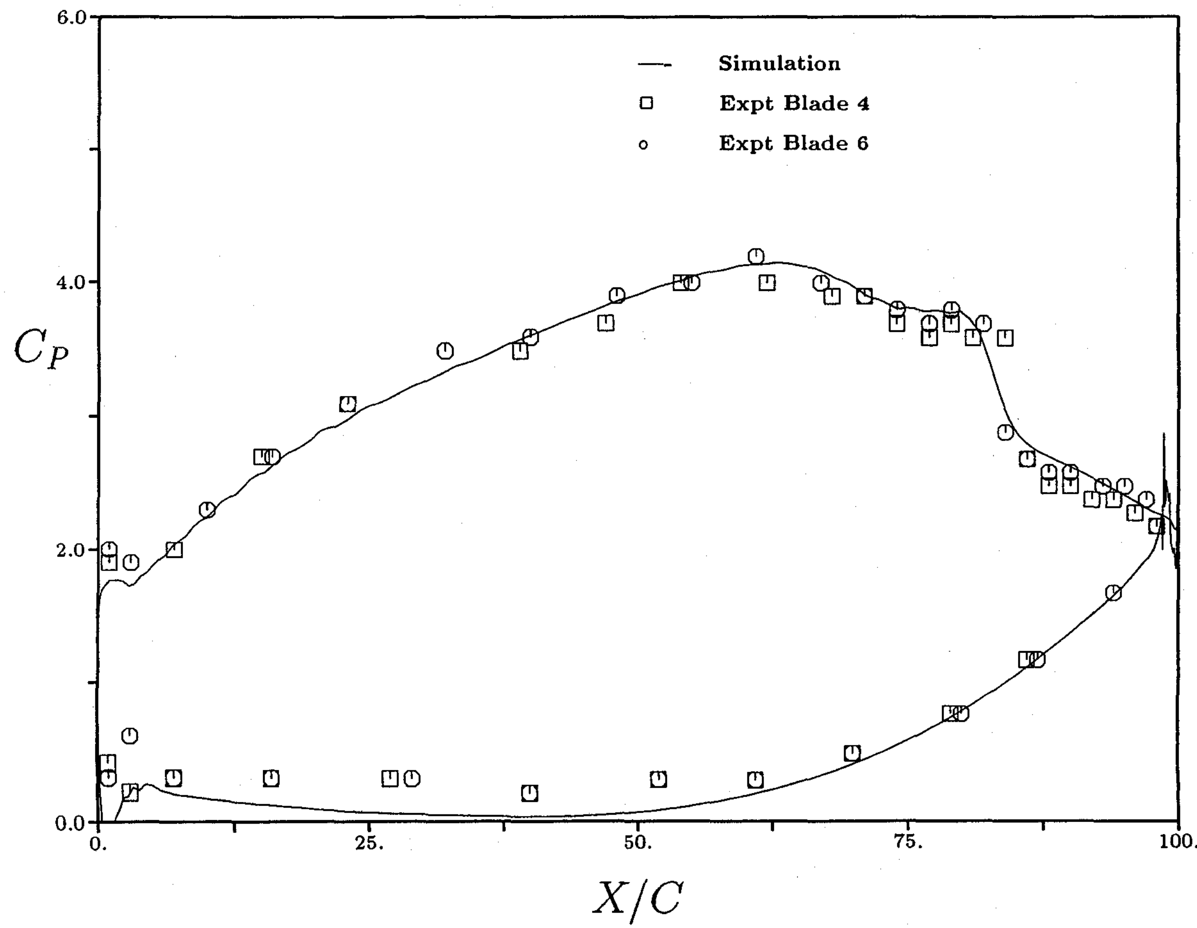
Loading - Re=100k - Tu=1%



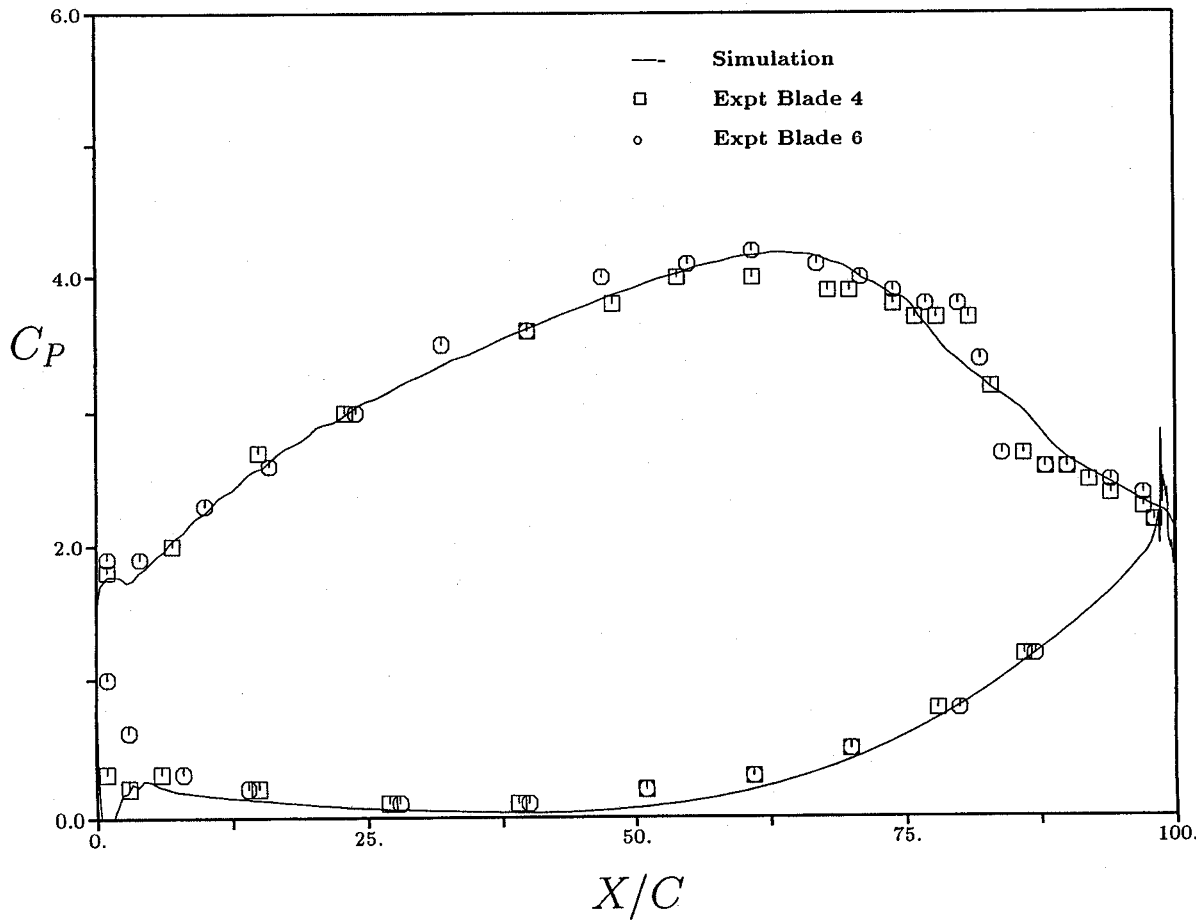
Loading - Re=100k - Tu=4%



Loading - Re=200k - Tu=1%



Loading - Re=200k - Tu=4%



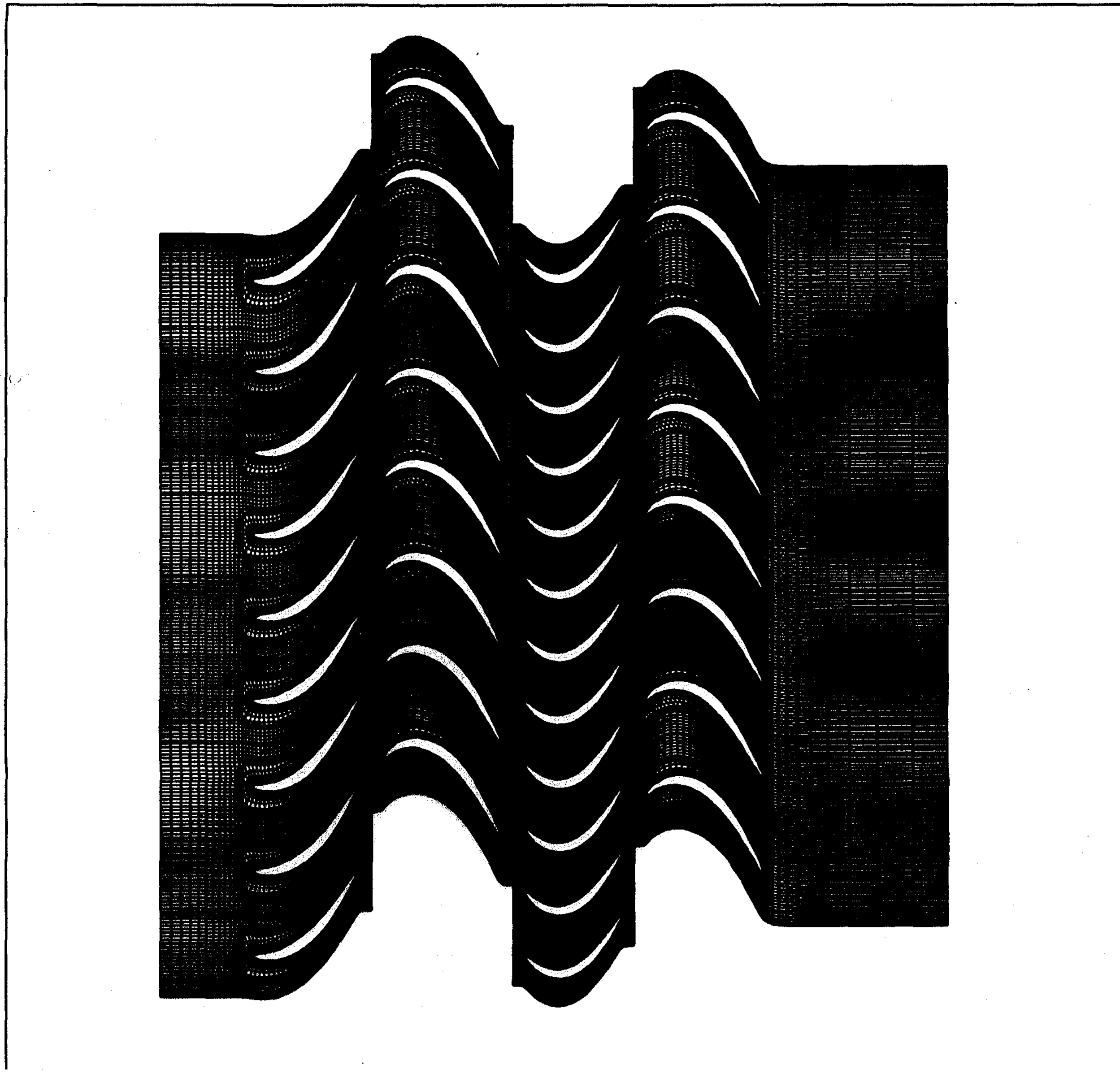
Two-Stage LSRT Turbine

- Tested at GE
- Takeoff/cruise Reynolds numbers
- Tu=3%
- Airfoil loadings, boundary layer quantities
- Computations
  - 9/8/12/8 airfoil count
  - 935,589 total grid points

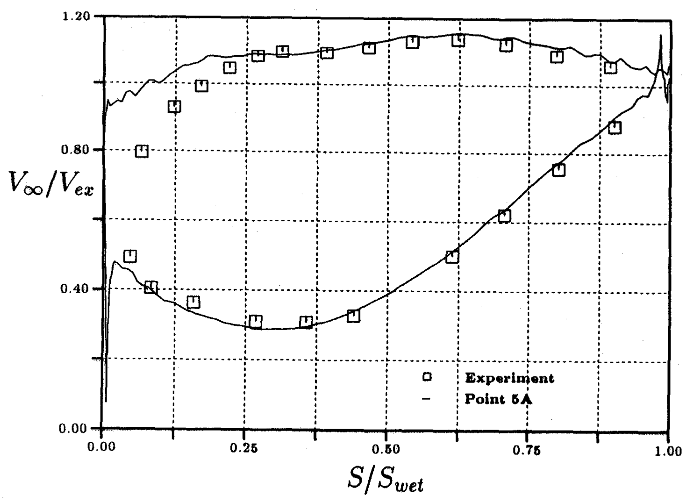
COMPUTATIONAL MODELS

- Computational blade counts
  - 72-72-108-72 (3-3-4-3); ~ 400,000 points
  - 81-72-108-72 (9-8-12-8); ~ 936,000 points
  - $y^+=1$ for all blade rows
- Simulations run for 10 characteristic cycles (1+ revolutions)
- Data time-averaged over one characteristic cyle

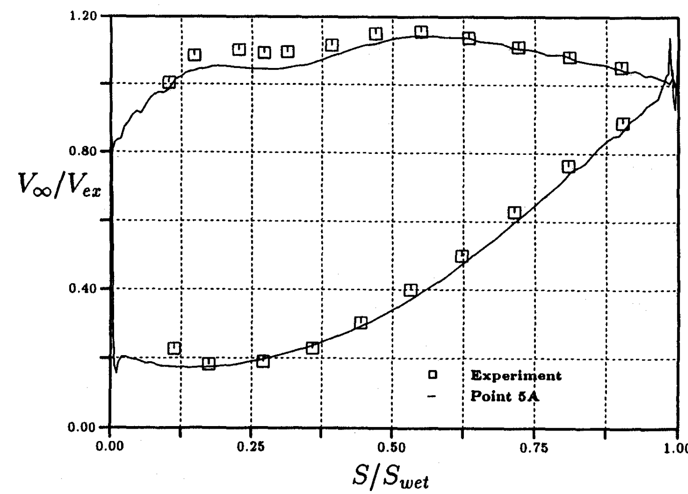
COMPUTATIONAL GRID



Normalized Loading - 5A

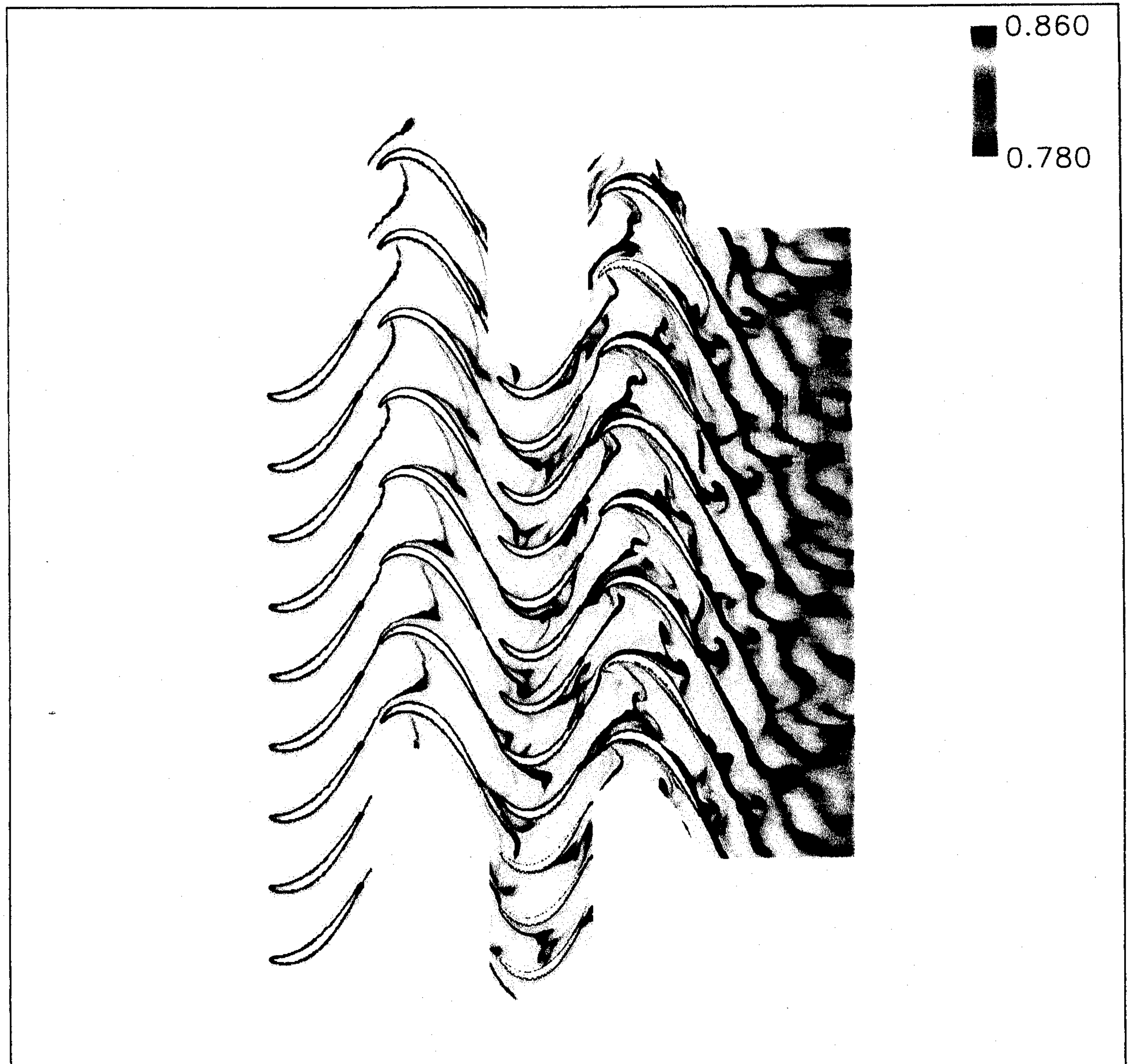


Nozzle -2

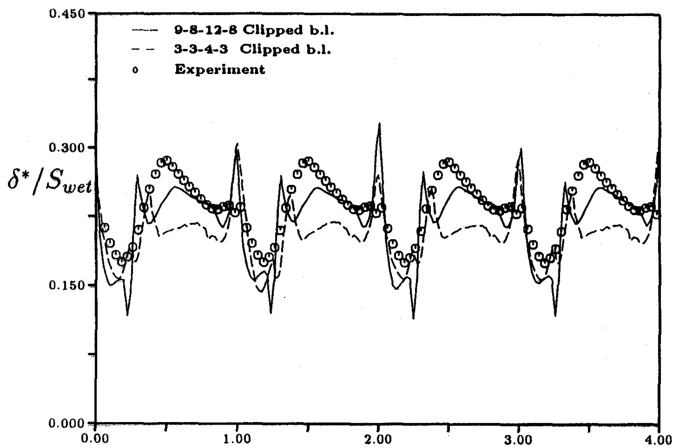


Rotor-2

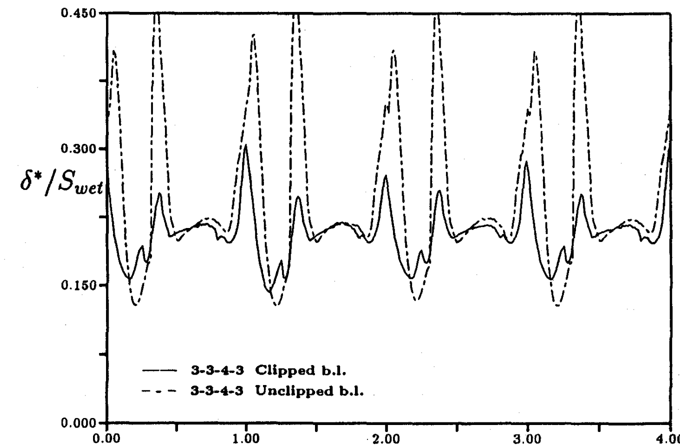
Instantaneous Entropy - 5A



Displacement Thickness - 5A - 82% SS

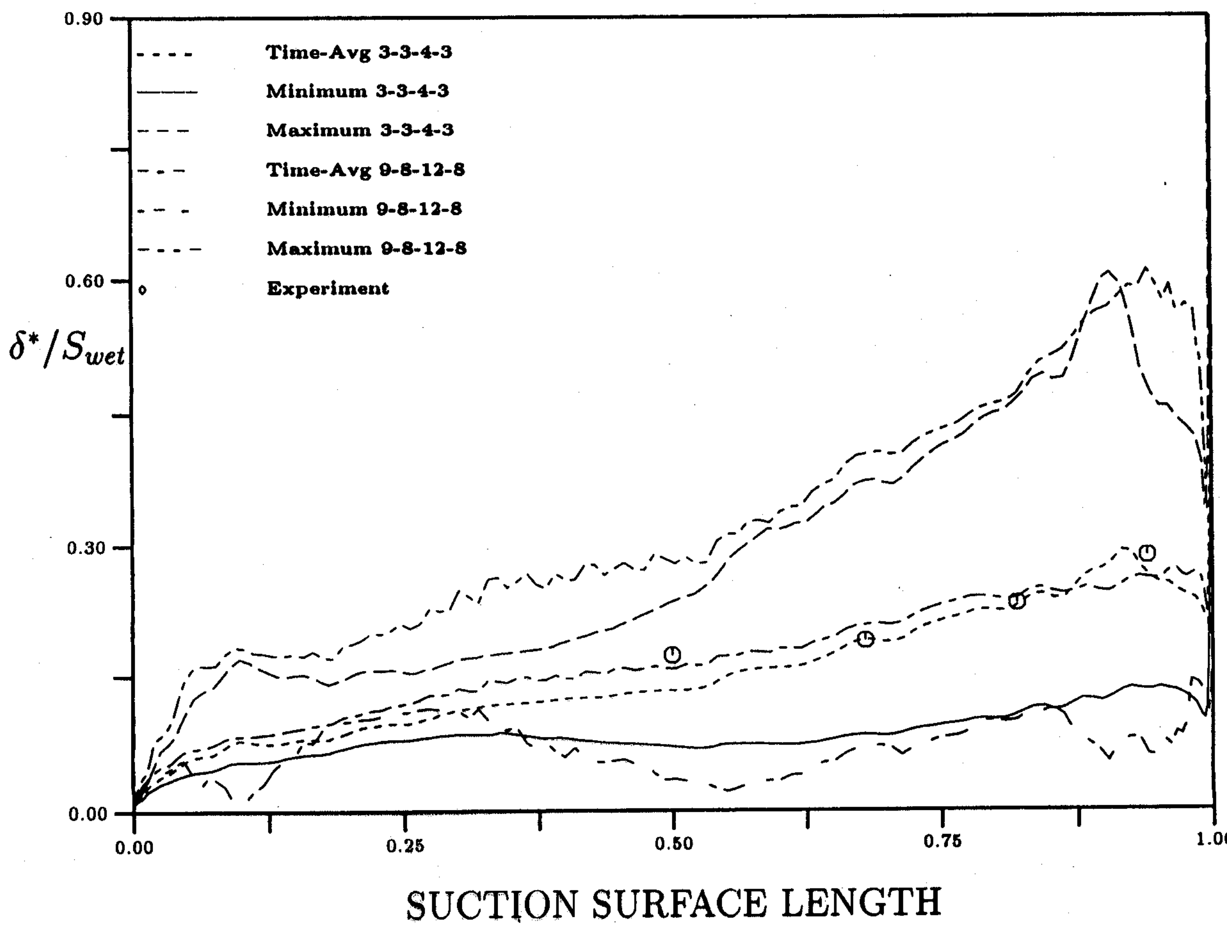


Blade Count

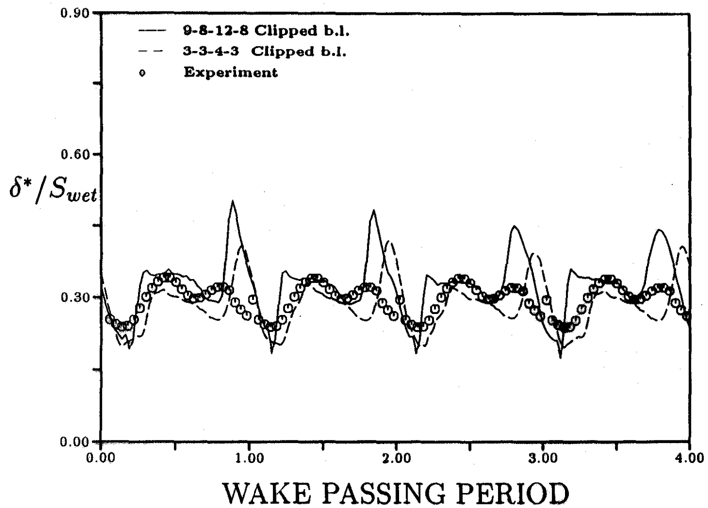


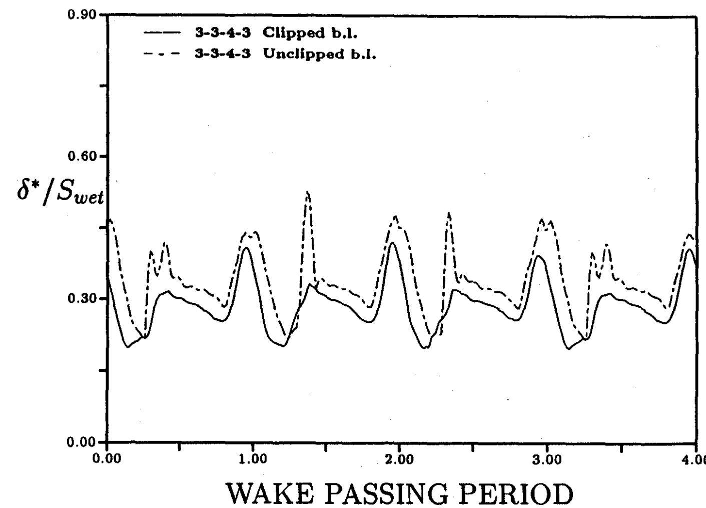
Clipping

Time-Avg Displacement Thickness - 5A



Displacement Thickness - 5D - 68% SS

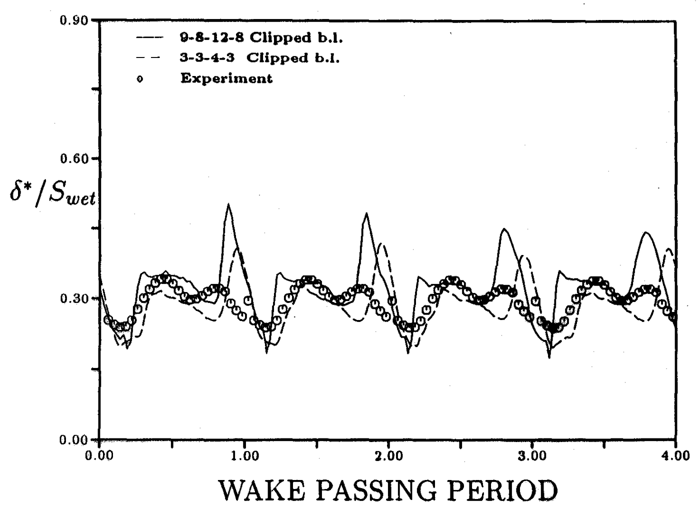




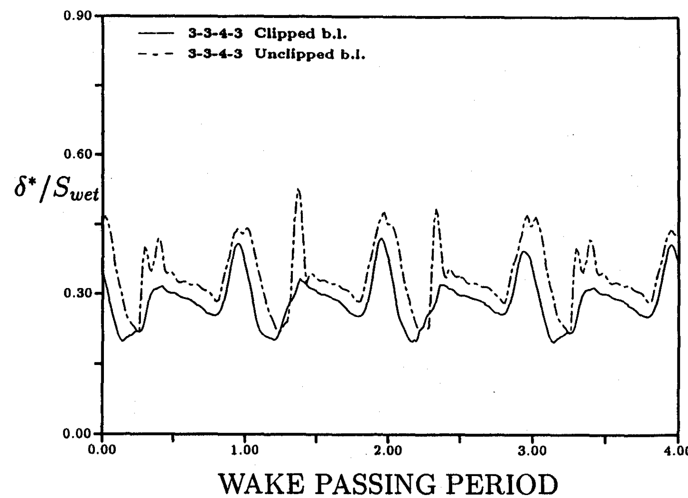
Blade Count

Clipping

Displacement Thickness - 5D - 68% SS



Blade Count



Clipping

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Conclusions

- Simple does work!
- Accurate cascade/stage simulations can be performed with rapid turn-around time (with no tweaking)
- Work continues on improving the physics and implementation of transition/turbulence models

EFFECT OF FAVORABLE PRESSURE GRADIENTS ON TURBINE BLADE PRESSURE SURFACE HEAT TRANSFER

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National Aeronautics and Space Administration
Glenn Research Center
Cleveland, OH

P.W. Giel
Dynacs Engineering Company, Inc.
Cleveland, OH

Recent measurements on a turbine rotor showed significant relaminarization effects. These effects were evident on the pressure surface heat transfer measurements. The character of the heat transfer varied with Reynolds number. Data were obtained for exit Reynolds numbers between 500,000 and 880,000. Tests were done with a high level of inlet turbulence, 7.5%. At lower Reynolds numbers the heat transfer was similar to that for laminar flow, but at a level higher than for laminar flow. At higher Reynolds numbers the heat transfer was similar to turbulent flow, when the acceleration parameter, K, was sufficiently small.

The proposed paper discusses the experimental results, and also discusses approaches to calculating the surface heat transfer for the blade surface. Calculations were done using a three-dimensional Navier-Stokes CFD analysis.

The results of these tests, when compared with previous blade tests in the same facility, illustrate modeling difficulties that were encountered in CFD predictions. The two blades were in many ways similar. However, the degree of agreement between the same analysis and the experimental data was significantly different. These differences are highlighted to illustrate where improvements in modeling approaches are needed for transitional flows.

NASA/CP—2001-210888

Effects of Favorable Pressure Gradients on Turbine Blade Pressure Surface Heat Transfer

Robert J. Boyle
NASA−Glenn Research Center

Paul W. Giel
Dynacs Engineering

Minnowbrook III − Workshop on Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows

August 20−23, 2000

OBJECTIVES

- Evaluate approaches for predicting relaminarization effects on turbine blade heat transfer

- Use Navier−Stokes analyses to evaluate approaches

- Identify an approach which gives best agreement with experimental data

APPROACH

- Incorporate boundary layer concept to relaminarize turbulent flow into 2D and 3D Navier−Stokes analyses (Chima, 1987,1991)

  - Steady state solution using Runge−Kutta time marching with implicit residual smoothing

  - Algebraic turbulence model, (Chima,1993)

  - Mayle's(1991) transition start model

  - Smith & Kuethe(1966) model for freestream turbulence effects

Modeling Approach

Use STAN5/Cebeci−Smith type strong favorable pressure gradient models, and explicit relaminarization model

- **STAN5 / Cebeci−Smith models**

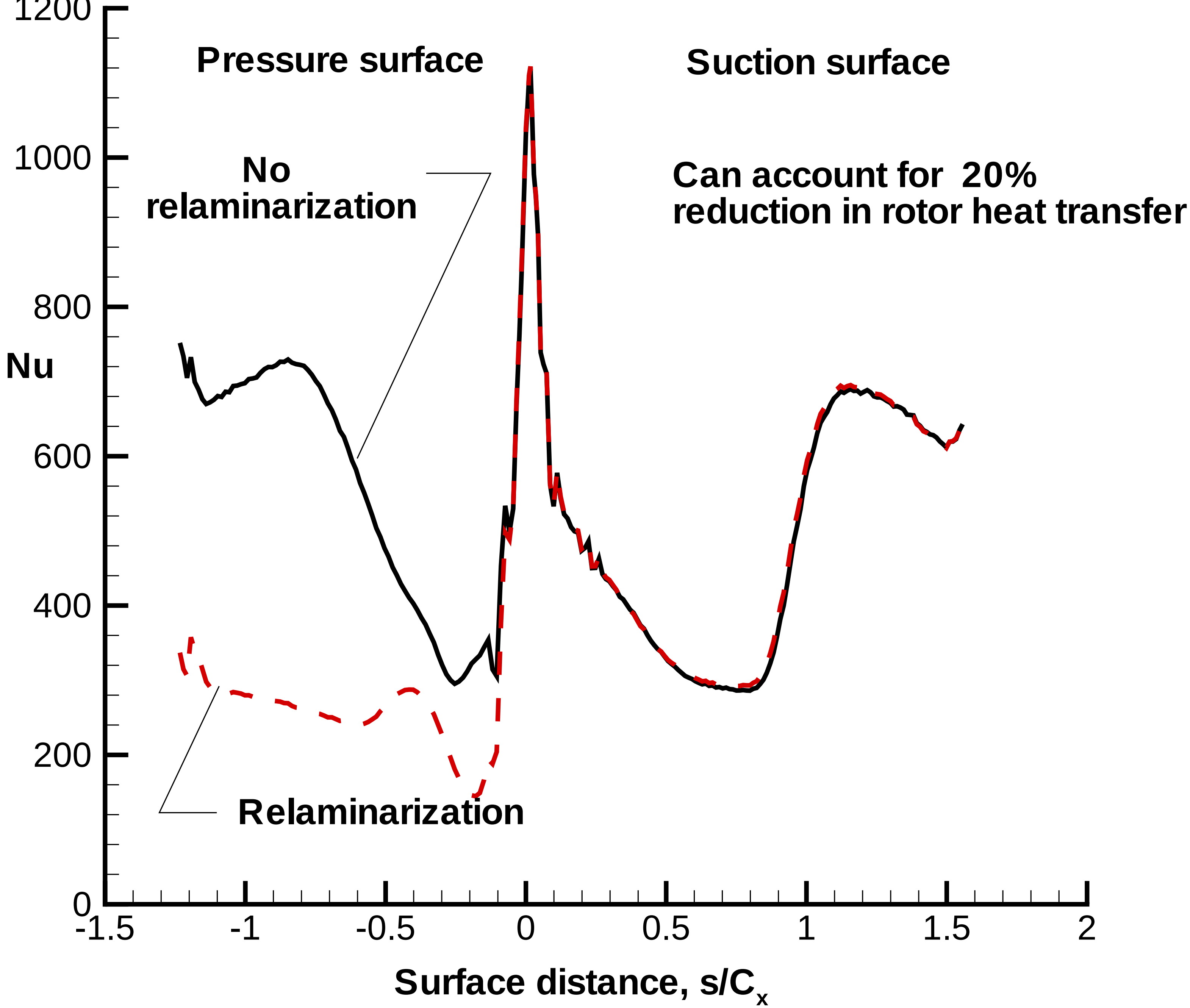
  Variable near−wall damping, $A^+=f(P^+_{eff})$

  Include the STAN5 lag term for P^+_{eff}

- **Explicit relaminarization model**

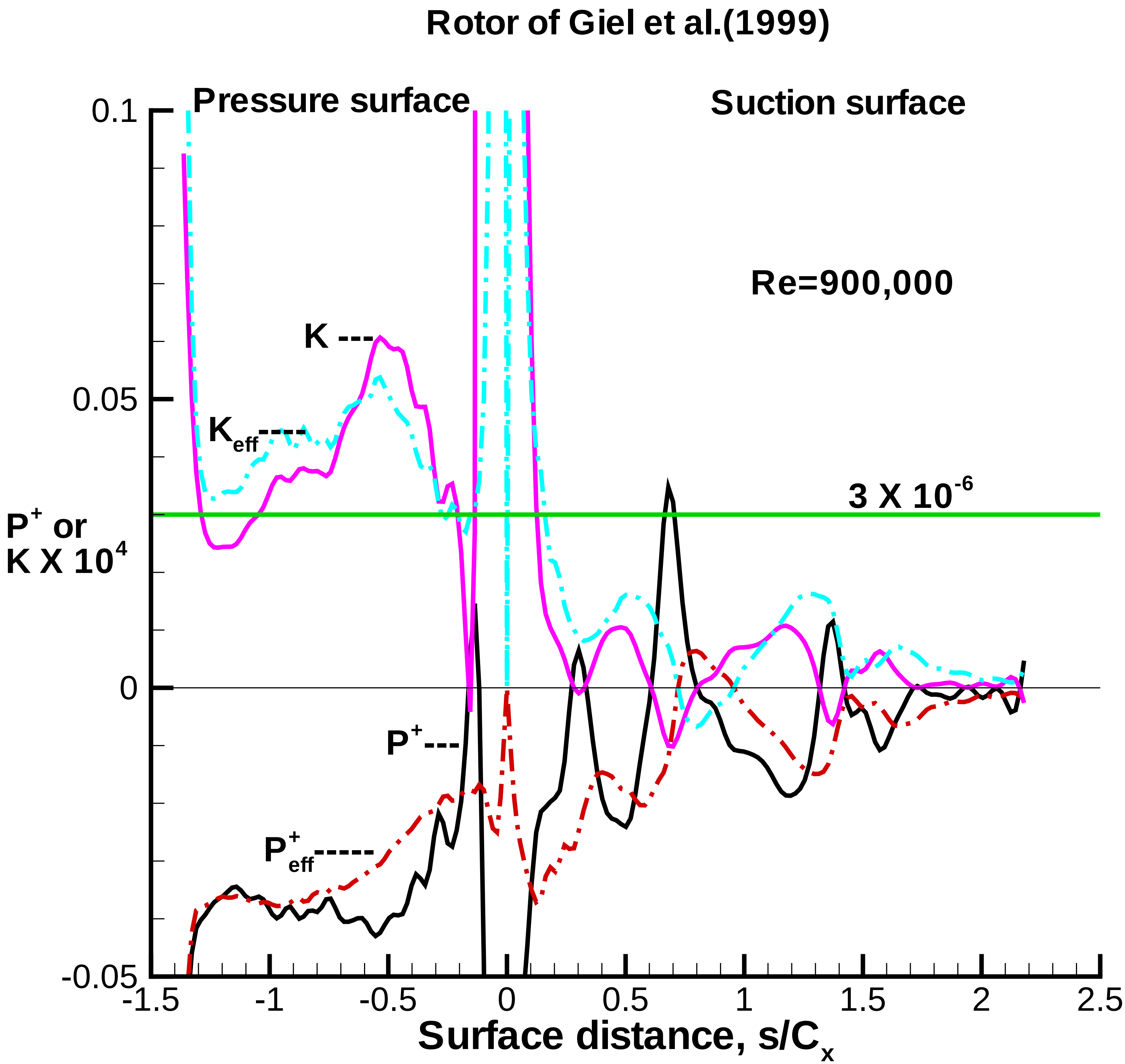
  Force relaminarization based on local value of the velocity gradient term,K

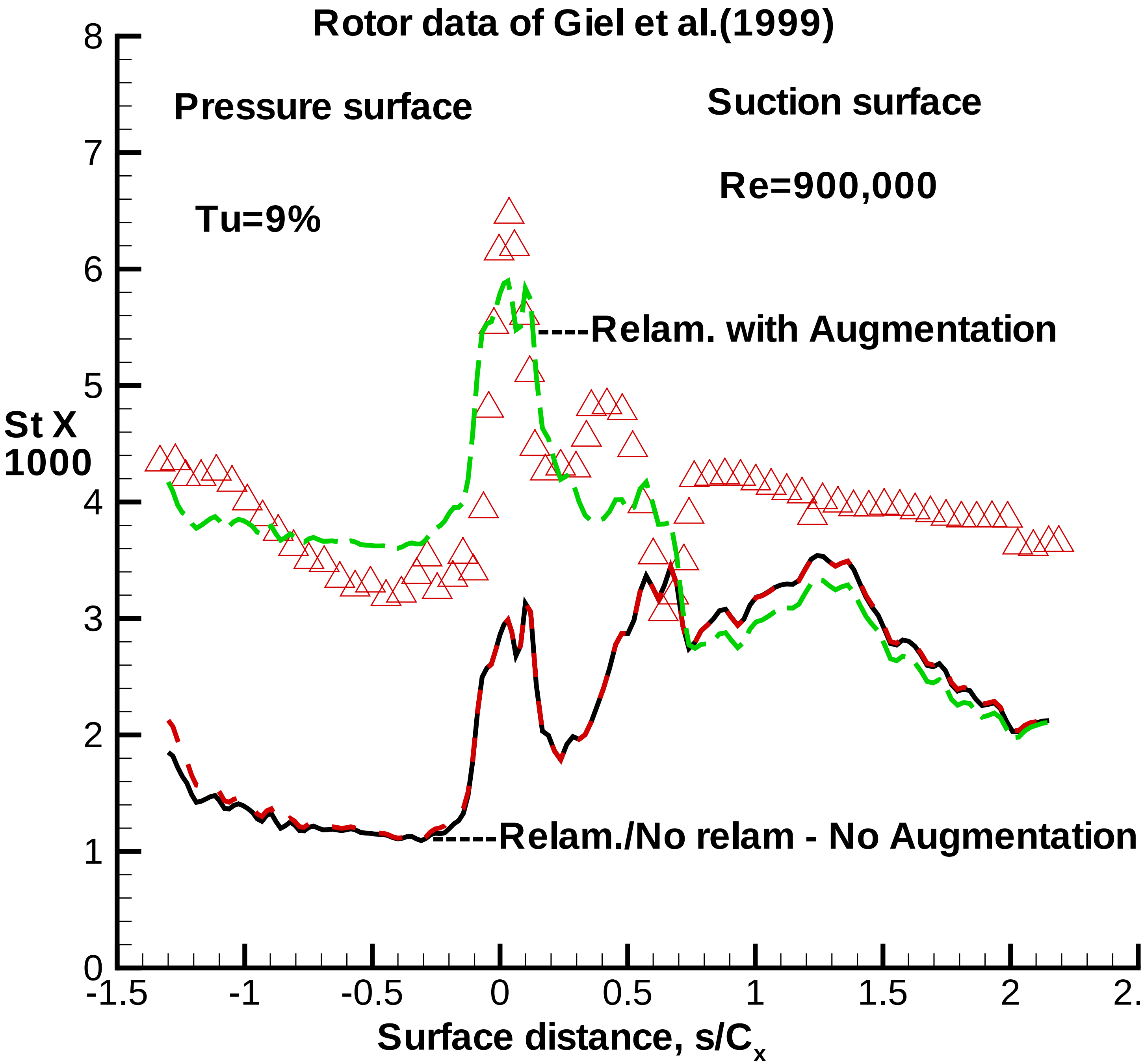
Effect of relaminarization on predicted heat transfer

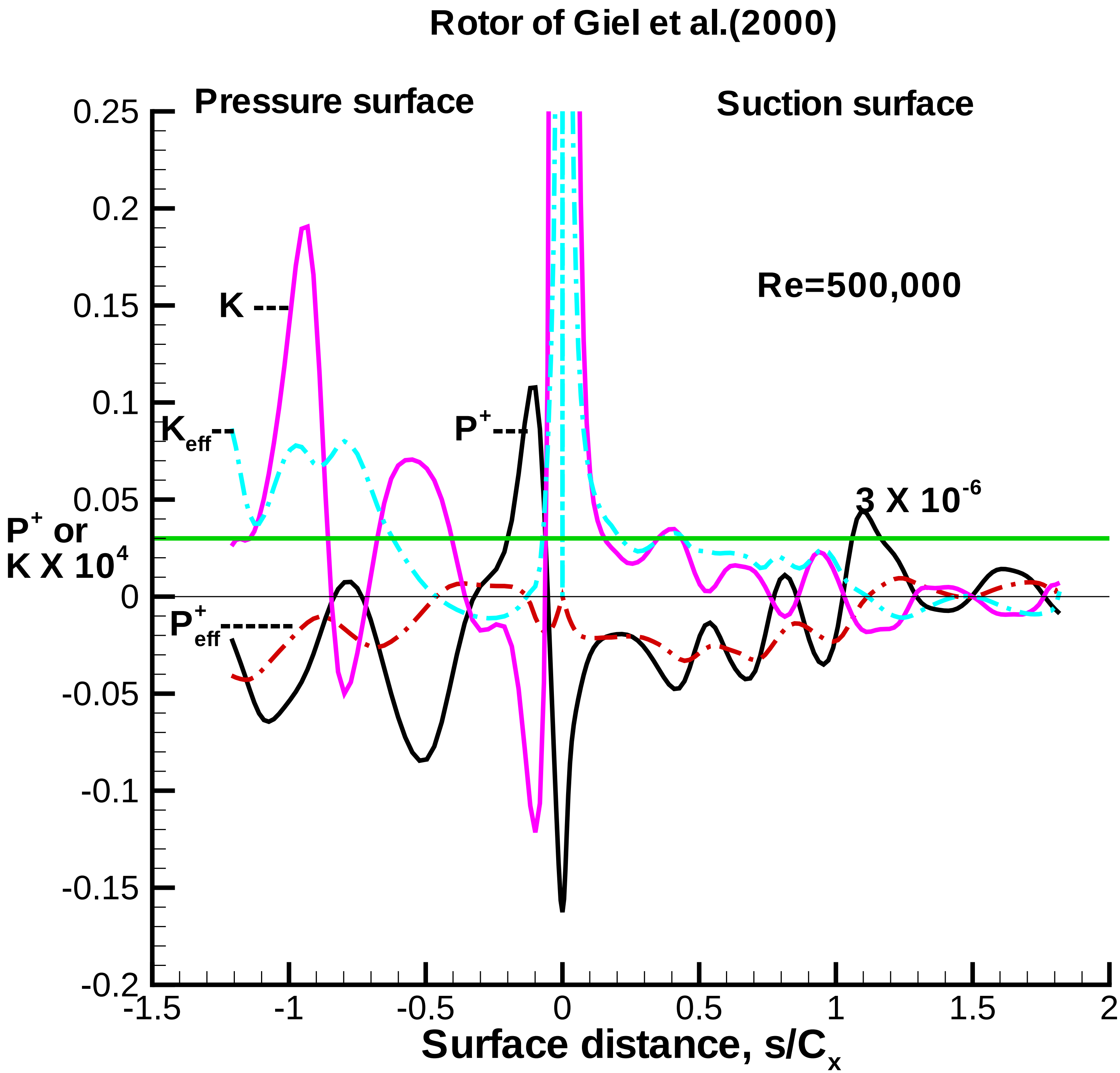


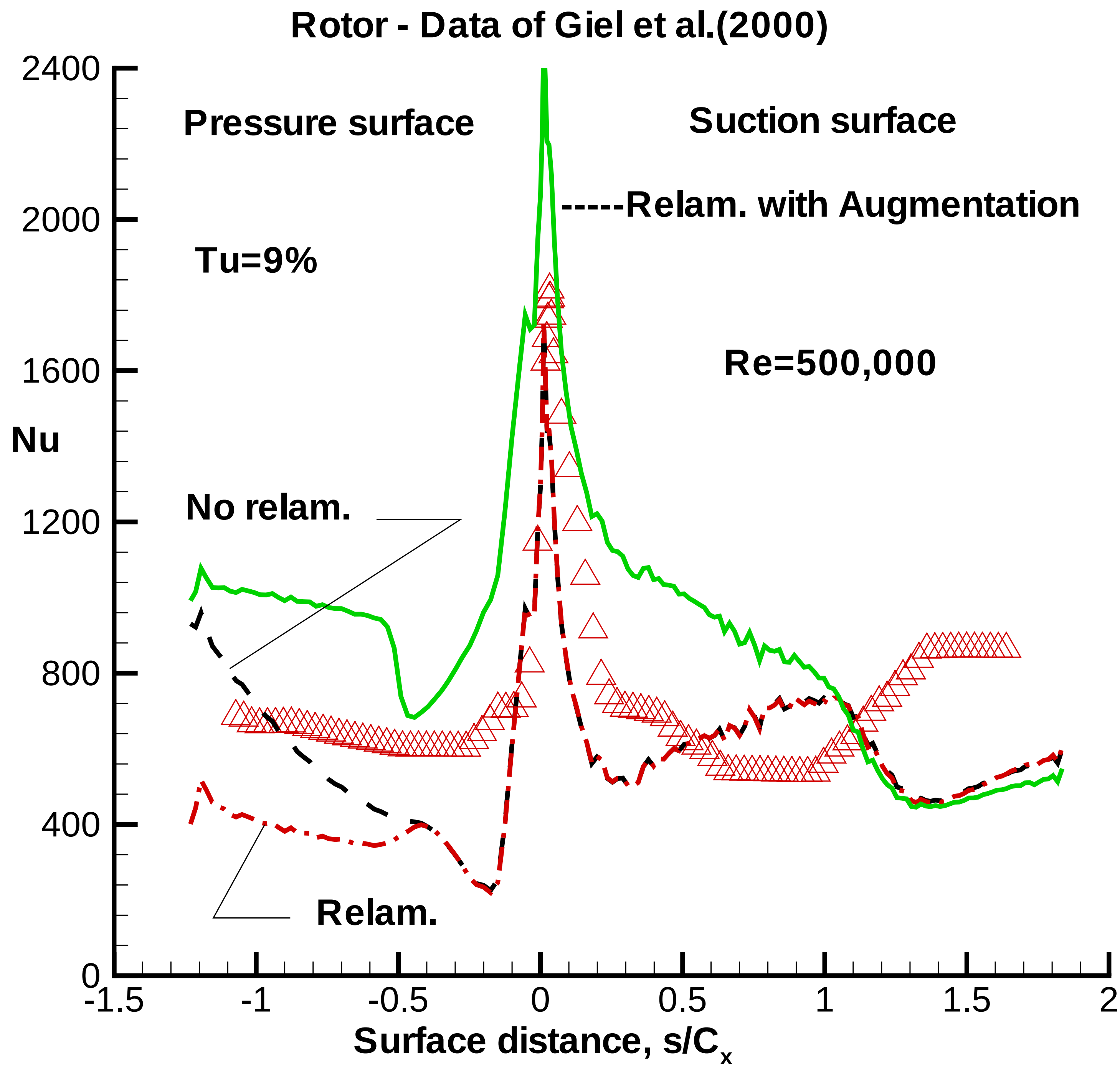
Description of rotor cases considered

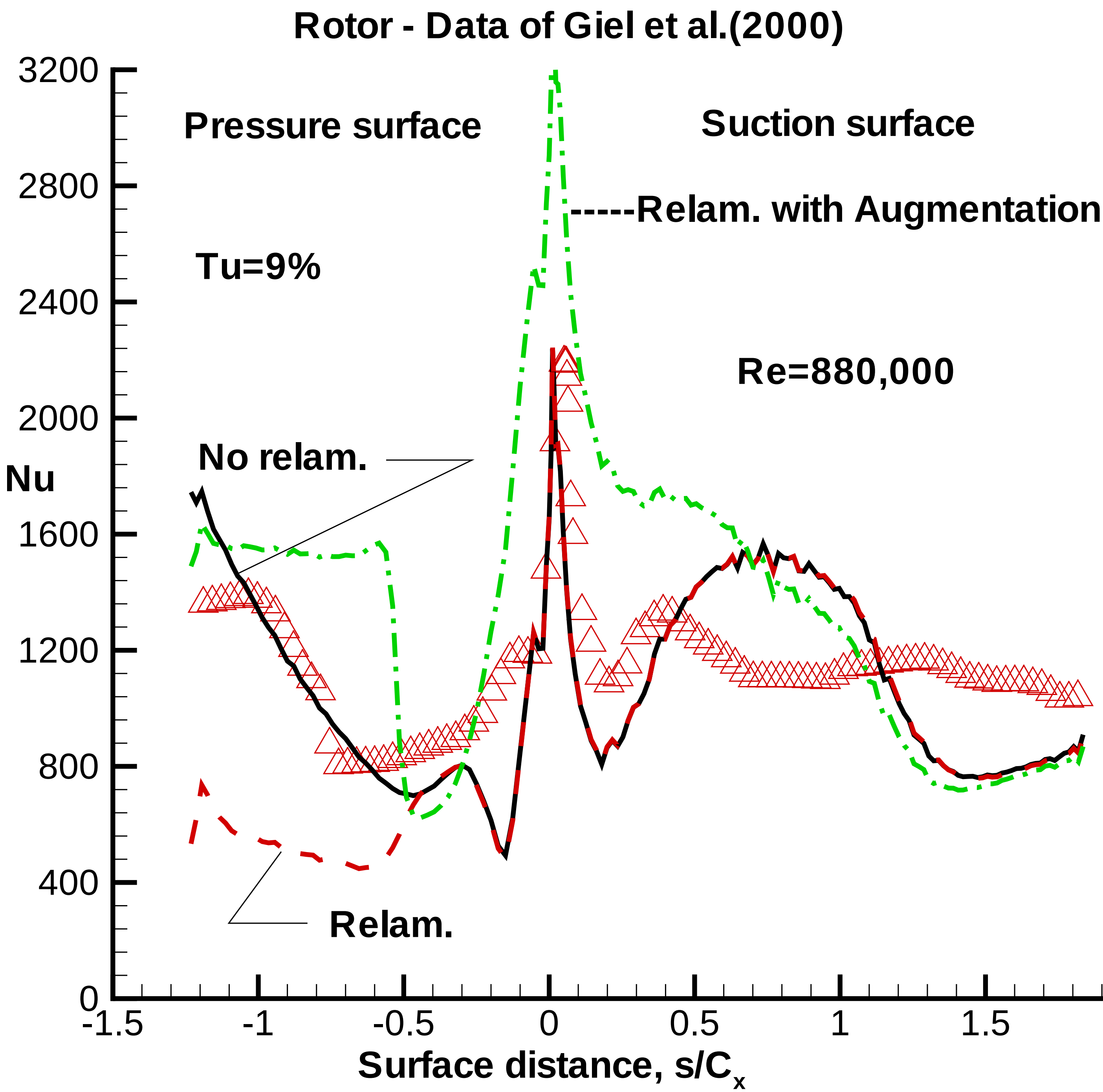
Re_2 X 10^5	M_2	Tw/Tg	Ref.	Comment
5.0, 8.8	0.7	1.07	Giel(2000)	Linear cascade 3D − NS
9.0	0.98	1.07	Giel(1999)	Linear cascade 3D − NS
5.4	1.1	0.70	Arts(1997)	Linear cascade Midspan − 2D
4.2 2.3	0.2 0.1	1.1	Blair(1994)	Rotating turbine Midspan − 2D

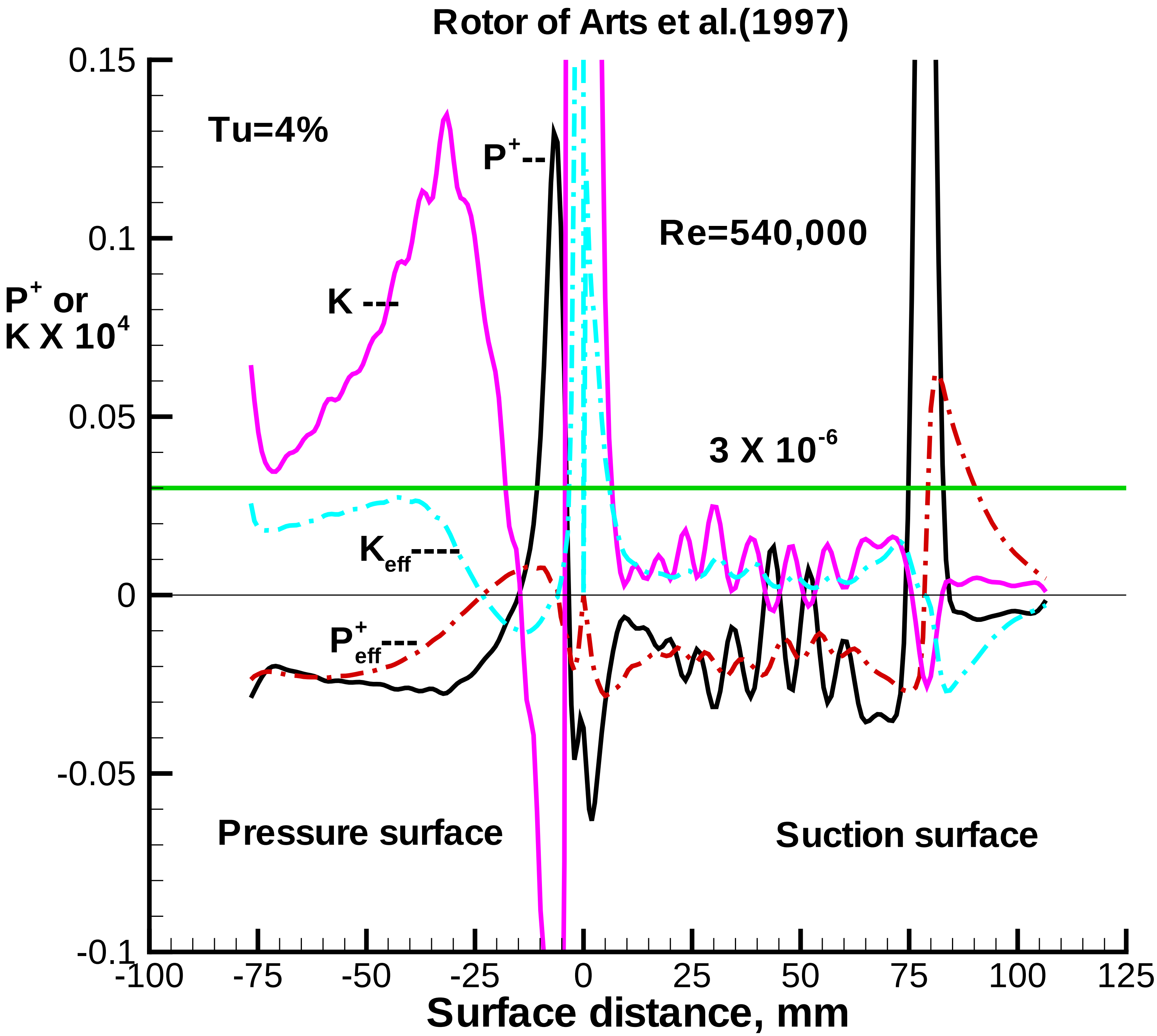

Rotor of Giel et al.(1999)
Pressure surface
Suction surface
Re=900,000
K ----
K_eff -----
3 X 10^-6
P+ or
K X 10^4
P+---
P+_eff-----
0.1
0.05
0
-0.05
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Surface distance, s/C_x

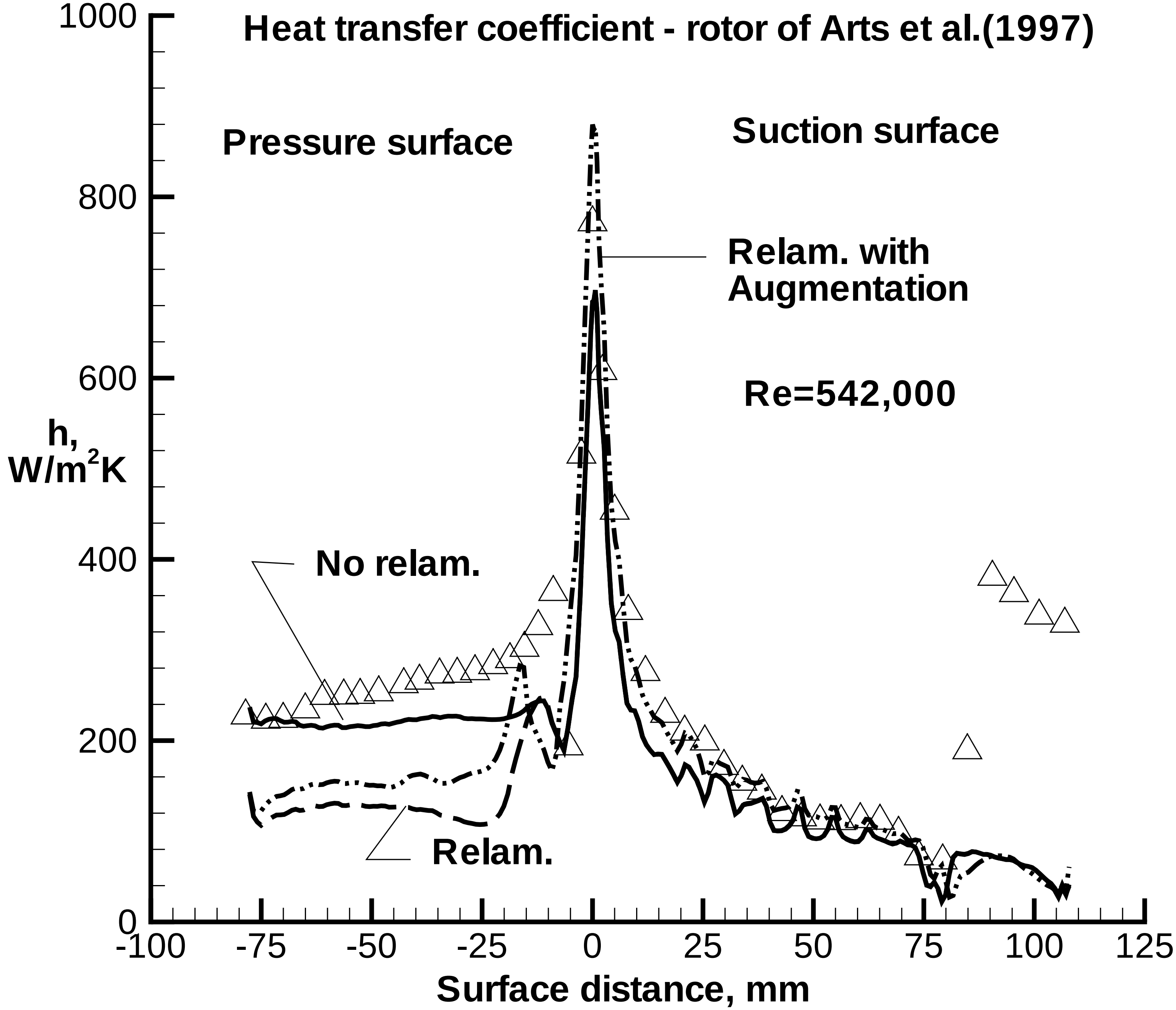

Rotor data of Giel et al.(1999)
Pressure surface
Suction surface
Re=900,000
Tu=9%
----Relam. with Augmentation
-----Relam./No relam - No Augmentation
St X 1000
8
7
6
5
4
3
2
1
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Surface distance, s/Cx

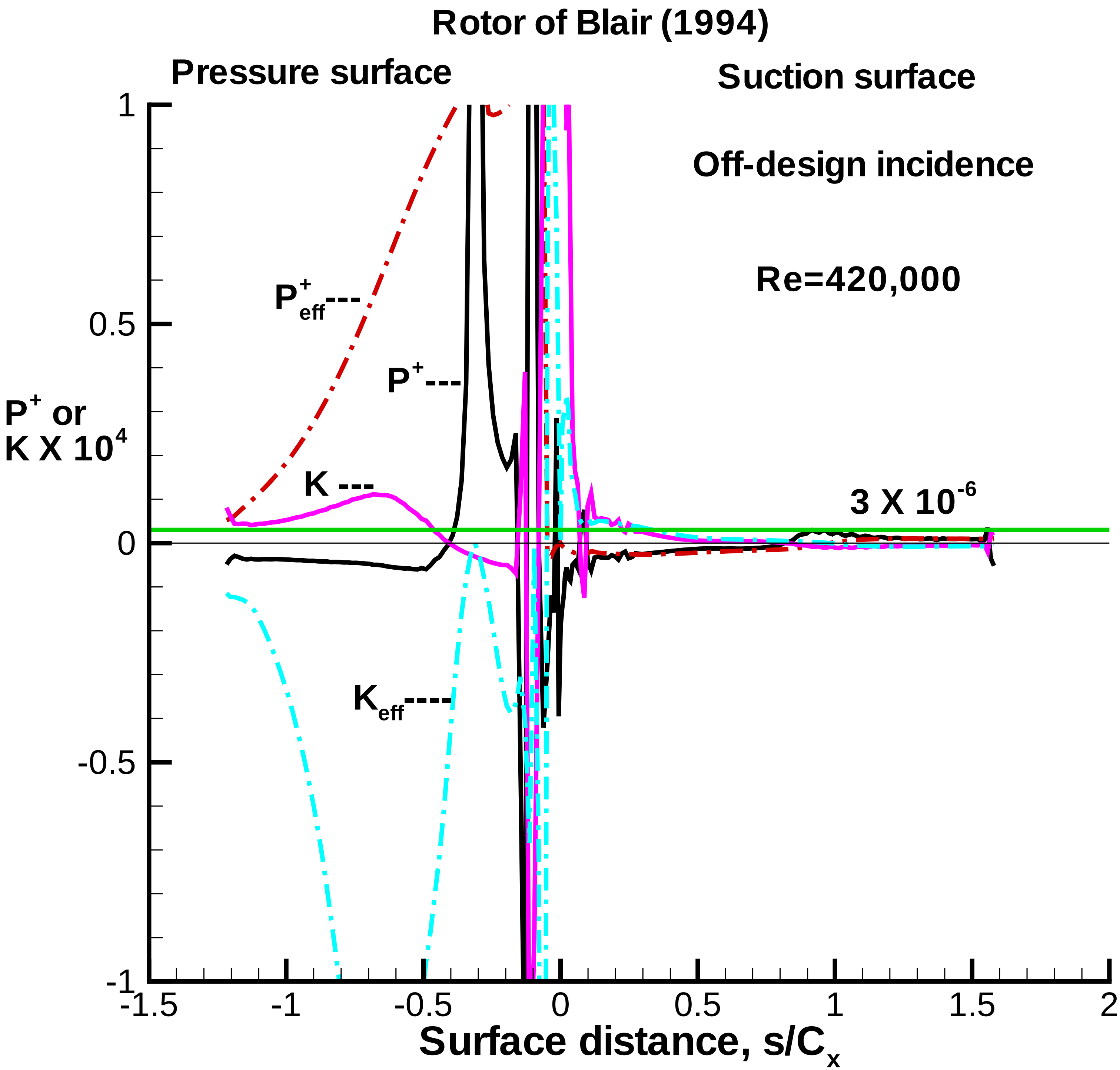

Rotor of Giel et al.(2000)
Pressure surface
Suction surface
Re=500,000
K ---
K_{eff}--
P^+---
P^+_{eff}-------
3 X 10^{-6}
P^+ or
K X 10^4
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Surface distance, s/C_x


Rotor - Data of Giel et al.(2000)
Pressure surface
Suction surface
-----Relam. with Augmentation
Tu=9%
Re=500,000
Nu
No relam.
Relam.
2400
2000
1600
1200
800
400
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
Surface distance, s/Cx

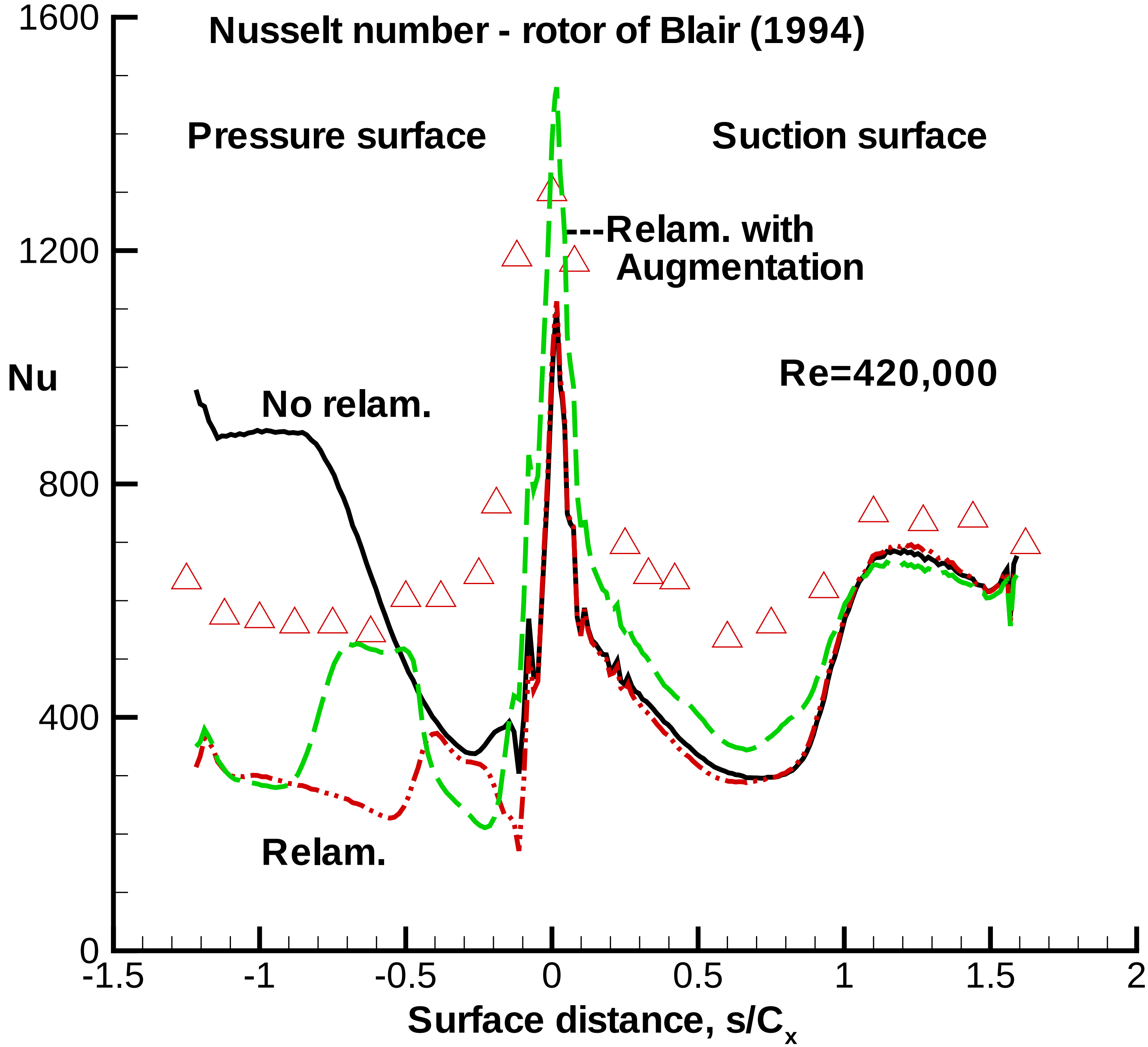

Rotor - Data of Giel et al.(2000)
Pressure surface
Suction surface
-----Relam. with Augmentation
Tu=9%
Re=880,000
No relam.
Nu
Relam.
3200
2800
2400
2000
1600
1200
800
400
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
Surface distance, s/Cx


Rotor of Arts et al.(1997)
Tu=4%
Re=540,000
P+ or
K X 10^4
P+ --
K ---
K_eff ----
P+_eff ----
3 X 10^-6
Pressure surface
Suction surface
0.15
0.1
0.05
0
-0.05
-0.1
-100
-75
-50
-25
0
25
50
75
100
125
Surface distance, mm

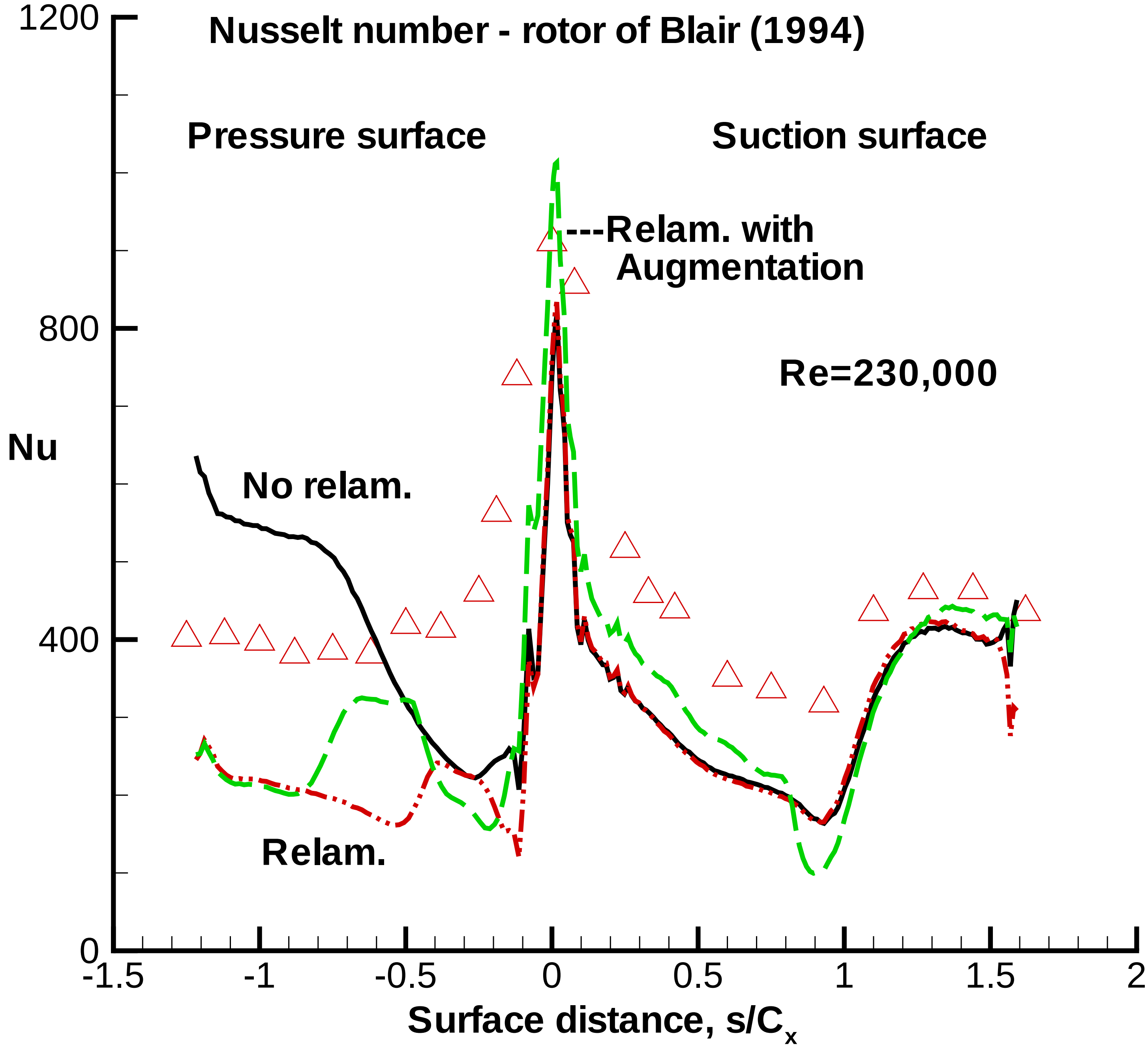

Heat transfer coefficient - rotor of Arts et al.(1997)
Pressure surface
Suction surface
Relam. with Augmentation
Re=542,000
No relam.
Relam.
h, W/m2K
Surface distance, mm
1000
800
600
400
200
0
-100
-75
-50
-25
0
25
50
75
100
125



Rotor of Blair (1994)
Pressure surface
Suction surface
Off-design incidence
Re=420,000
P^+_{eff}---
P^+---
K ---
K_{eff}----
3 X 10^{-6}
P^+ or
K X 10^4
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
1.5
2
Surface distance, s/C_x



Nusselt number - rotor of Blair (1994)
Pressure surface
Suction surface
---Relam. with Augmentation
Re=420,000
No relam.
Relam.
Nu
1600
1200
800
400
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
Surface distance, s/Cx


Nusselt number - rotor of Blair (1994)
Pressure surface
Suction surface
---Relam. with
Augmentation
Re=230,000
Nu
No relam.
Relam.
1200
800
400
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
Surface distance, s/C_x

CONCLUSIONS

- Predictions incorporating relaminarization effects can significantly improve agreement with exp. data

- The relaminarization criteria, K, should be calculated from a lag equation similar to that used for P^+

- Modification of the STAN5 type lag equation is needed to account for flows near separation.

Future work

- Incorporate a lag equation to calculate K
- Determine sensitivity of K to lag parameters –
  - Is a lag constant of 4000 appropriate?
  - Should the lag be f(Pressure gradient) or f(P^+)
- Is there a more appropriate model for freestream turbulence effects?
- Compare results with data for other datasets
- Present final results at ASME Gas Turbine Conference.

MIXED-FLOW TURBINE: STEADY AND UNSTEADY PERFORMANCE WITH DETAILED FLOW MEASUREMENTS

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Imperial College
Department of Mechanical Engineering
London, U.K.

Turbochargers are finding increasing application to automotive diesel engines as cost-effective means for improving their power output and efficiency, and reducing exhaust emissions; these requirements have led to the need for highly loaded turbocharger turbines. A mixed-flow turbine is capable of achieving its peak isentropic efficiency at reduced velocity ratios compared to a typical radial inflow turbine, it is therefore possible to improve the turbocharger/engine matching.

The steady and unsteady performance of a mixed flow turbocharger turbine with constant blade inlet angle has been investigated. The steady flow results indicated that the mixed–flow turbine obtains a peak efficiency (total–to–static) of 75% at a velocity ratio of 0.61, which is lower when compared to a typical radial inflow turbine (peaking at around a 0.7 velocity ratio). In the unsteady flow performance tests, the cycle average isentropic efficiencies are higher for the mixed flow geometry than in a radial turbine. A substantial deviation from the performance and flow characteristics of the equivalent steady–state tests commonly used in turbocharger turbine design has been found. The pulsations from the engine have been followed through the inlet pipe and around the volute; the pulse has been shown to propagate close to the speed of sound and not according to the bulk flow velocity as stated by some researchers.

The flow entering and exiting the blades has been quantified by a laser Doppler velocimetry system. The turbine test conditions corresponded to the peak efficiency point at 29,400 and 41,300 rpm. The results were resolved in a blade-to-blade sense to examine in greater detail the nature of the flow at turbocharger representative conditions.

The unsteady flow characteristics have been investigated at two flow pulse frequencies, corresponding to internal combustion engine speeds of 1600 and 2400 rpm. Four measurement planes have been investigated: one in the pipe feeding the volute, two in the volute (40^0 and 130^0 downstream of the tongue) and one at the exit of the turbine. The pulse propagation at these planes has been investigated; the effect of the different planes on the evaluation of the unsteady isentropic efficiency is shown to be significant. The rotor inlet and exit velocity triangle under pulsating flow conditions has demonstrated a deviation from the optimum conditions based on steady-flow analysis.

Minnobrook III Workshop: August 20-23, 2000

Unsteady and flow characteristics of mixed-flow turbocharger turbines

Ricardo Martinez-Botas

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NASA/CP—2001-210888

Summary

- Why turbocharging and mixed flow rotors?
- Experimental facility
- Unsteady performance
- Pulsating velocity measurements
- Concluding remarks/outstanding issues

Why turbocharging?

- applications in automotive industry (diesel engine 10 L)
- higher power output.
- indirect reduction of emissions.

Problems in turbocharging?

- high air/fuel ratio in diesel engines and use of inter cooler result in exhaust gas at lower temperature hence, need of high power from low energy gas.
- in a turbine rotor under pulsating flow, the maximum energy in the exhaust is available at high pressure, hence the turbine efficiency should peak at that pressure ratio.

Requirements: efficiency peaks at low velocity ratio

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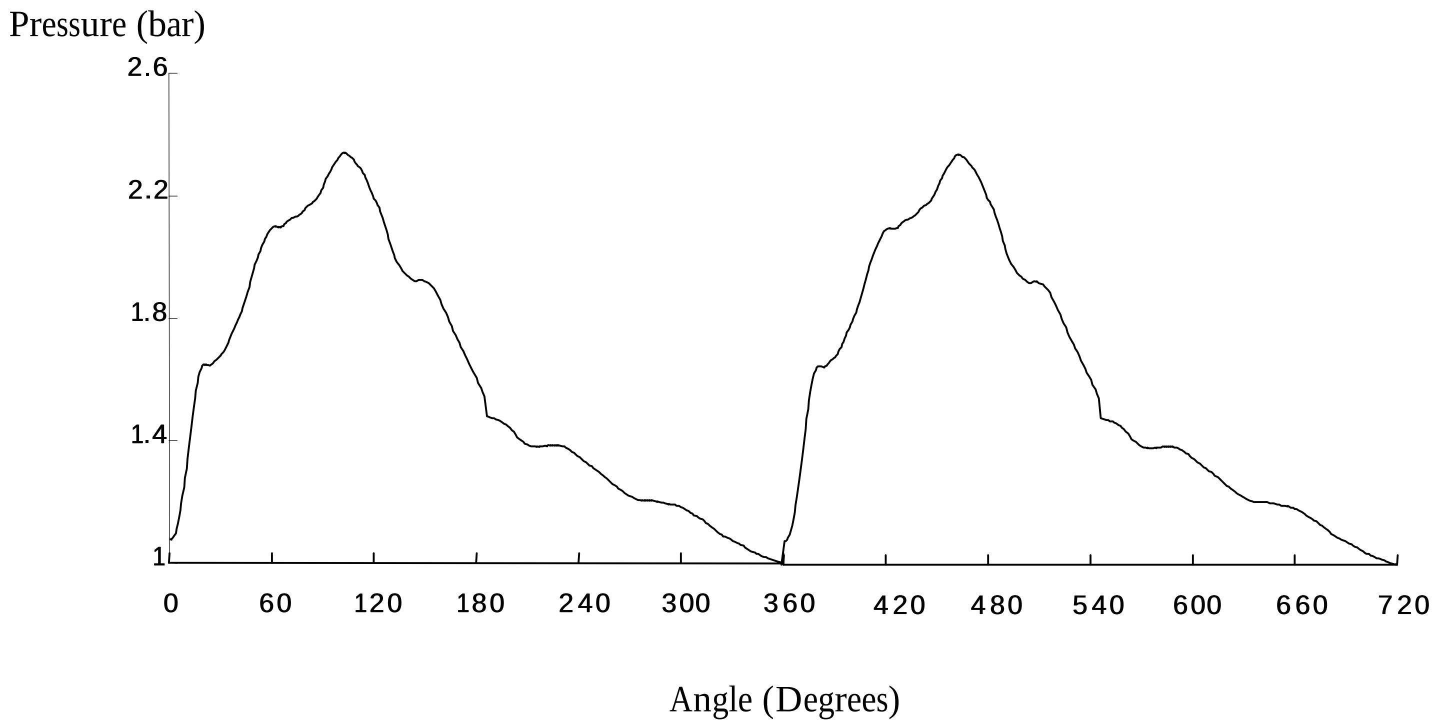
Pulses in an IC engine



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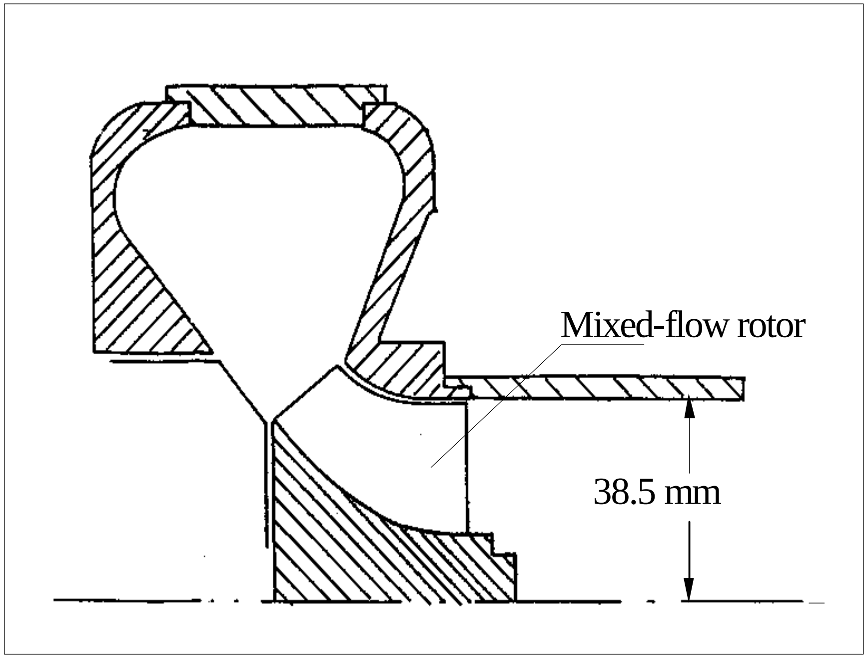
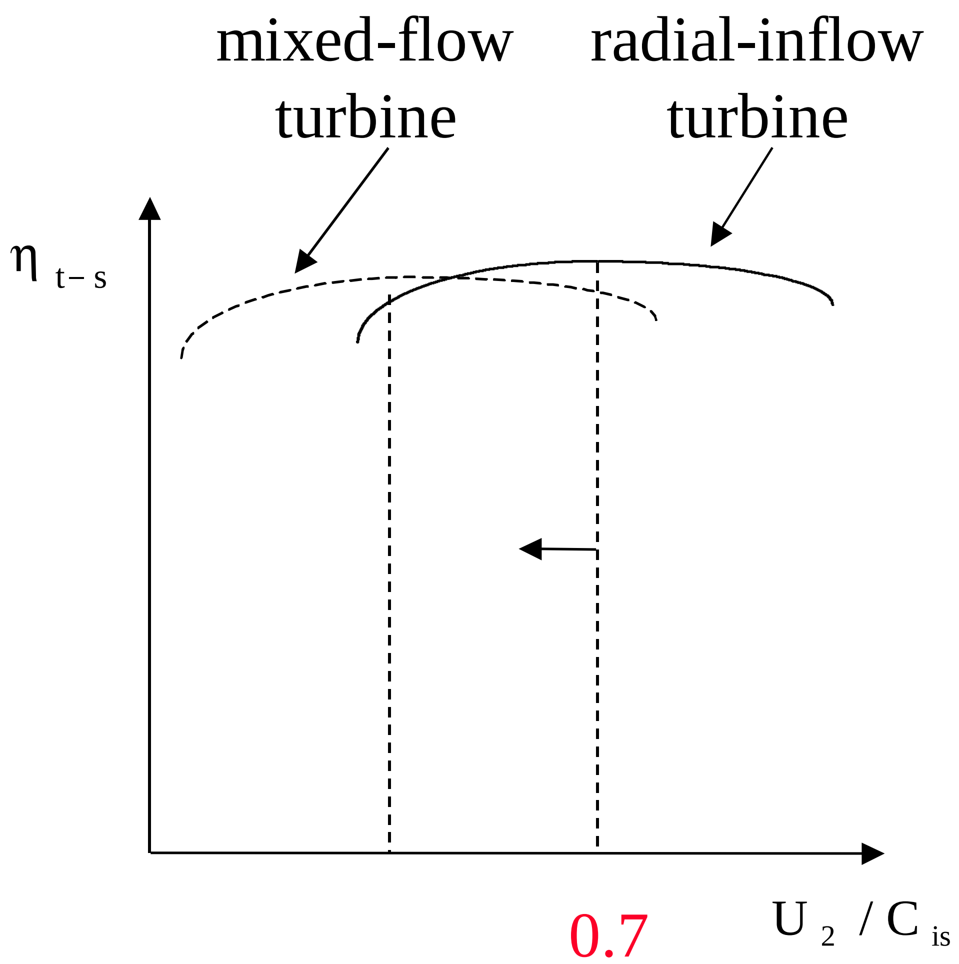
Mixed-flow turbine rotor



- Radial and axial direction of the inlet air flow
- Non-zero inlet blade angle, hence an extra degree of freedom
- Different inlet configurations
- Peak efficiency at lower velocity ratio

Mixed-flow turbine rotor



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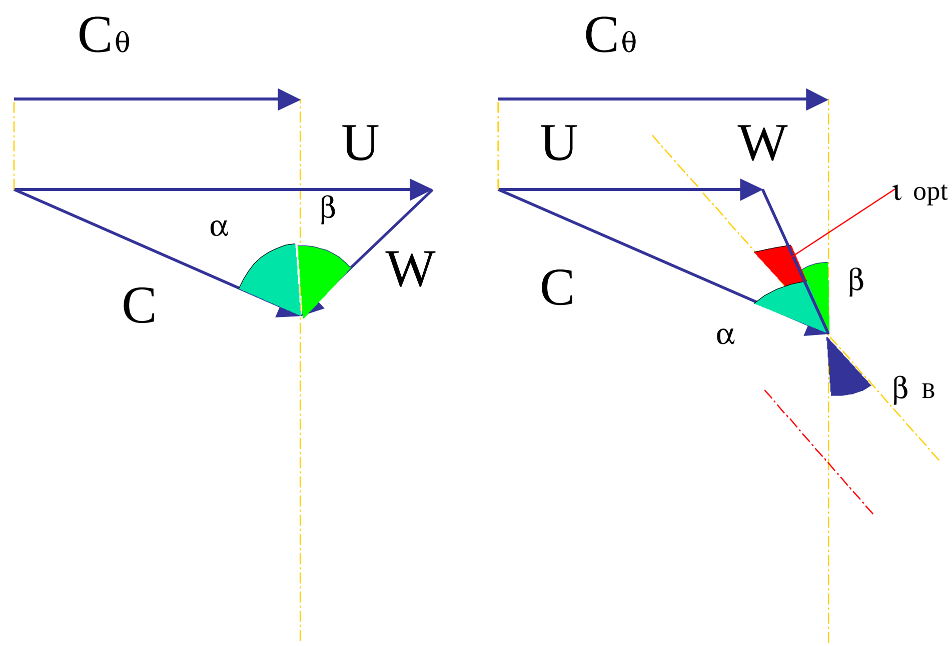
Mixed-flow turbine rotor



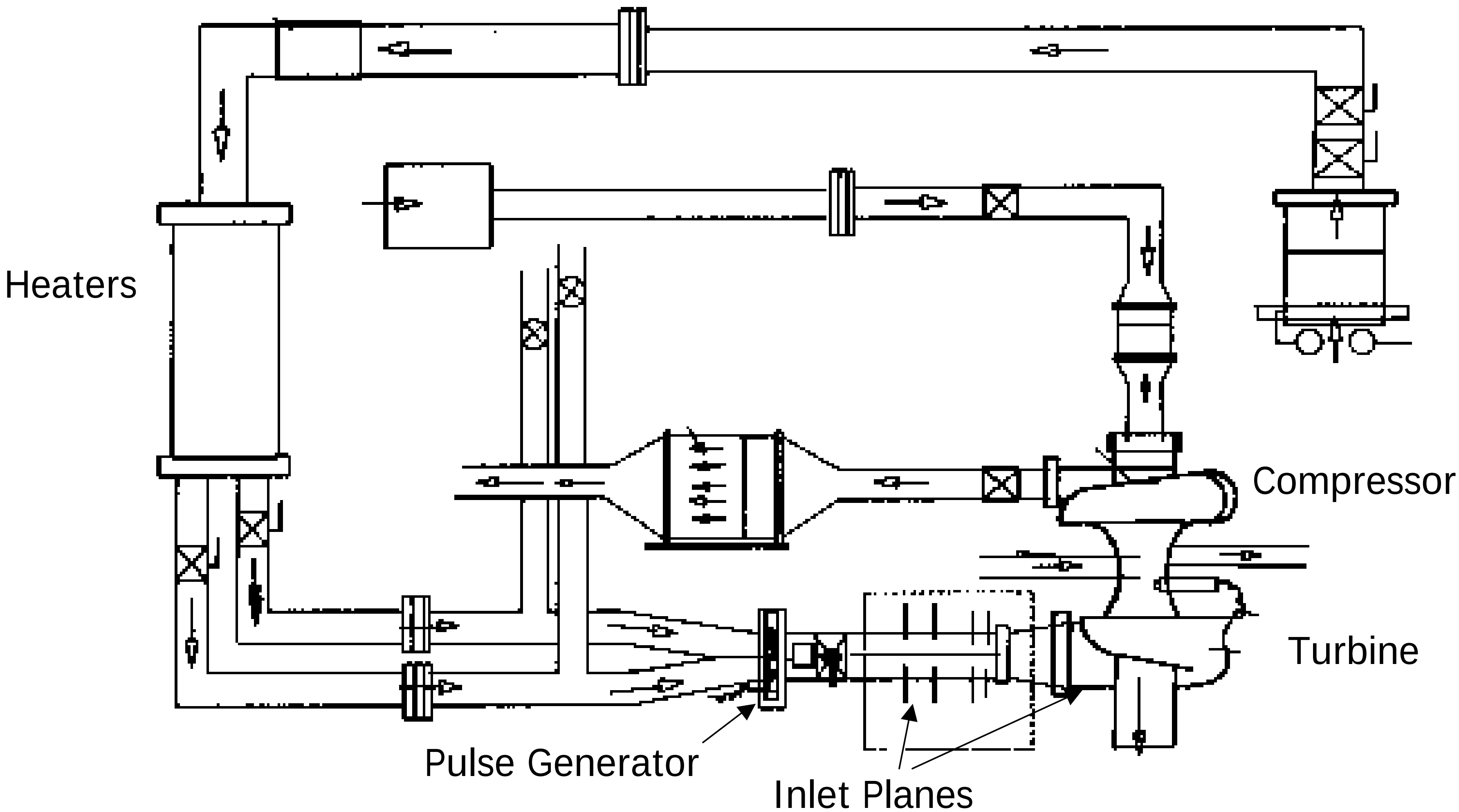
$\beta_{blade} = 0^o$

radial

$\beta_{blade} = +20^o$

mixed

Experimental apparatus



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Mixed flow rotor geometry

Rotor tip diameter	83.6 mm
Rotor inlet blade height	18 mm
Number of blades	12
Exducer tip diameter	78.6 mm
Exducer hub diameter	27 mm
Blade angle at exducer	-52 degrees

Constant incidence angle design

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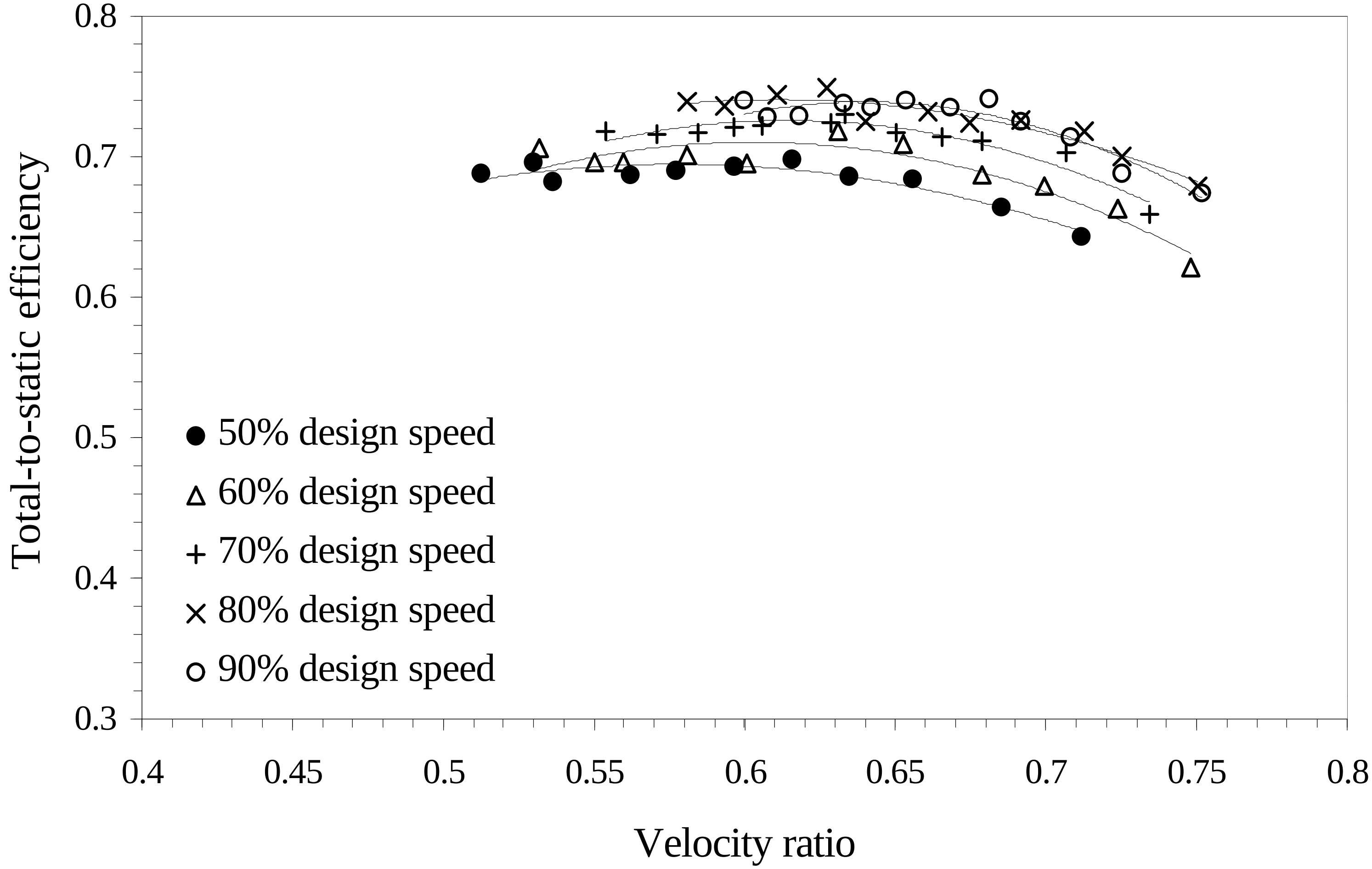
Test conditions (100% speed)

Inlet total temperature	344 K
Mass flow rate	0.678 kg/s
Rotational speed	59,828 rpm
Pressure ratio	2.91
Velocity ratio	0.61

Steady Flow Results



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Unsteady performance

Parameters measured.

Unsteady mass flow rate.

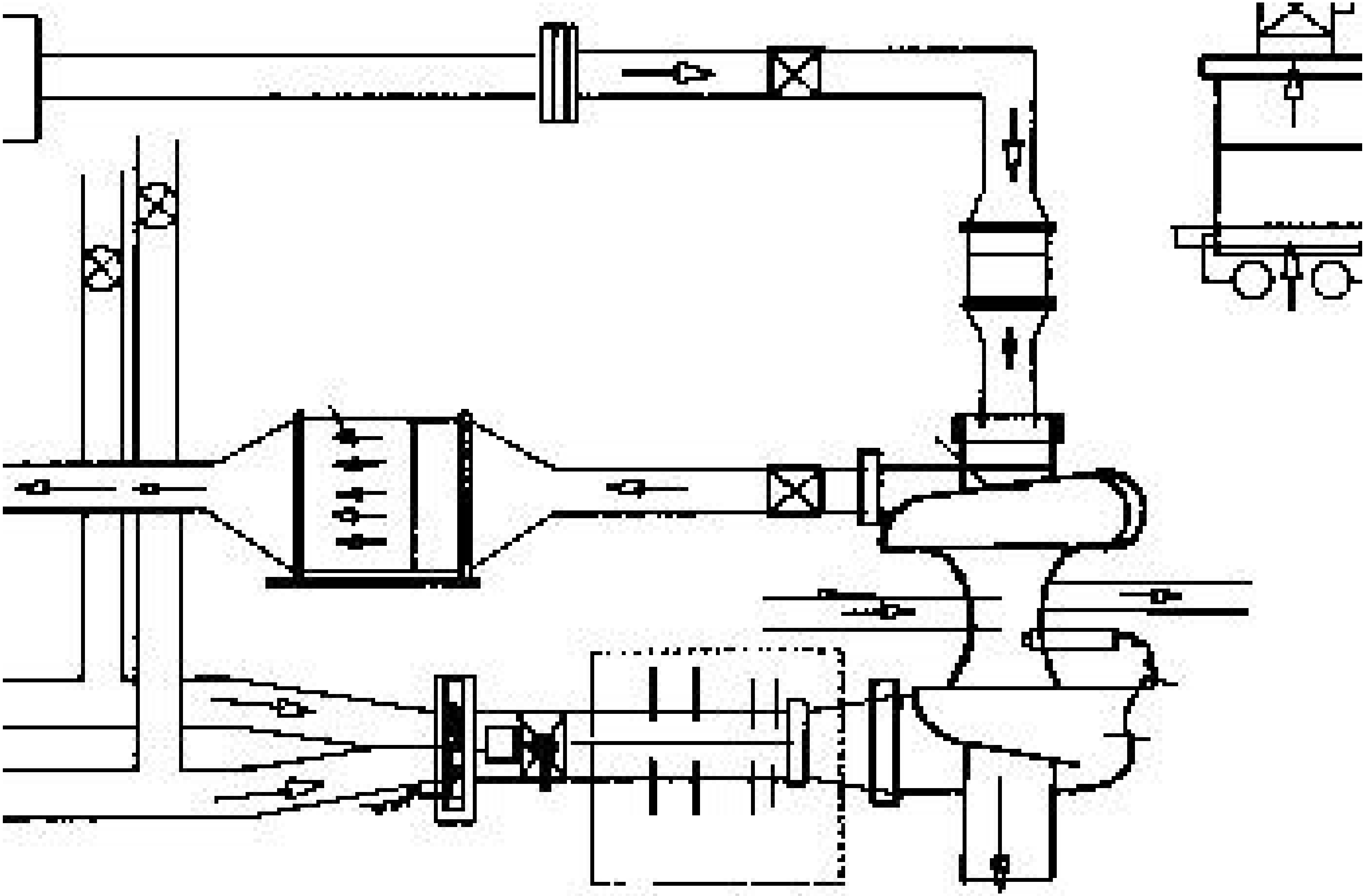
Unsteady efficiency?

Data Processing

- In order to calculate the instantaneous turbine efficiency all the parameters need to be measured at the same time. However, in the test rig the mass flow rate and the inlet pressure are measured at upstream of the turbine inlet.

- It is therefore necessary to shift the signal in order to evaluate the instantaneous performance of the turbine.

- The shifting time in the present study was based on the sonic velocity, that is, the velocity of the travelling pressure waves.



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Pulsating Flow Performance

Unsteady Performance

$$(m_{t-s})_{unsteady} = \frac{(\dot{W}_T)_{inst}}{\left(\dot{m}_{inst} \times \frac{C_{is}^2}{2}\right)}$$

Instantaneous Turbine Work

$$(\dot{W}_T)_{inst} = t_{inst} \times w_{inst}$$

Isentropic Expansion Velocity

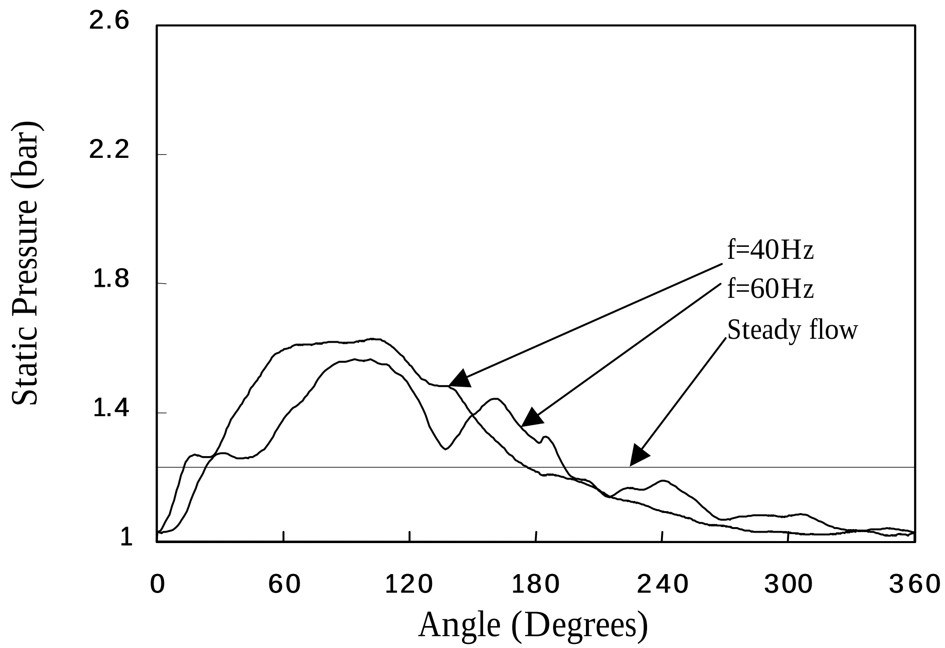
$$C_{is} = \sqrt{2\left(\int_{inlet}^{outlet} C_p dT - \tfrac{1}{2}u_1^2\right)}$$

Instantaneous Torque

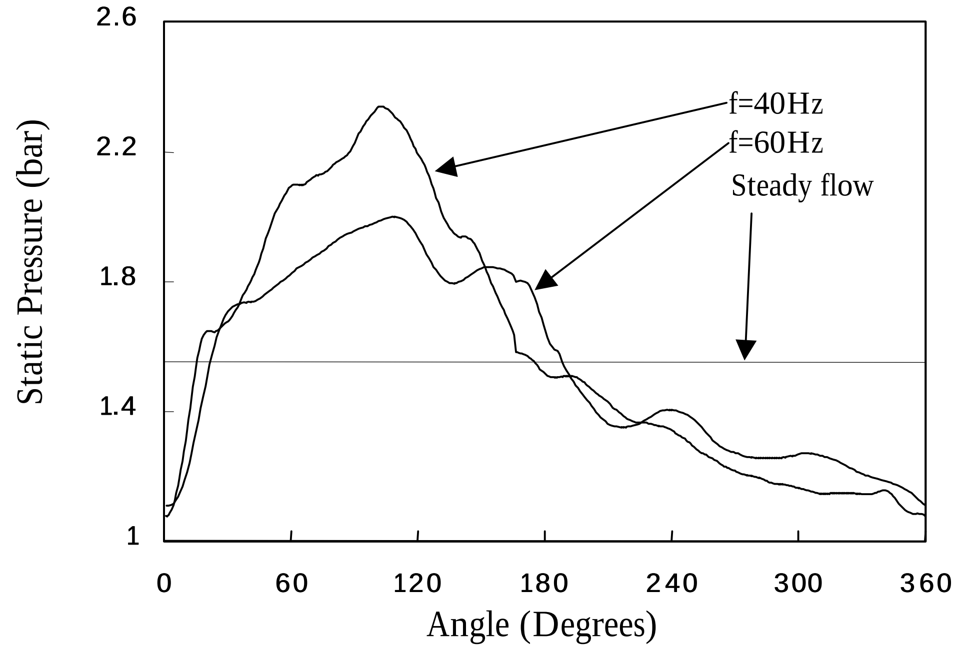
$$t_{inst} = \bar{t} + t'$$

$$t' = Ja = J\frac{d}{dt}\left(\frac{dq}{dt}\right)$$

Pressure traces

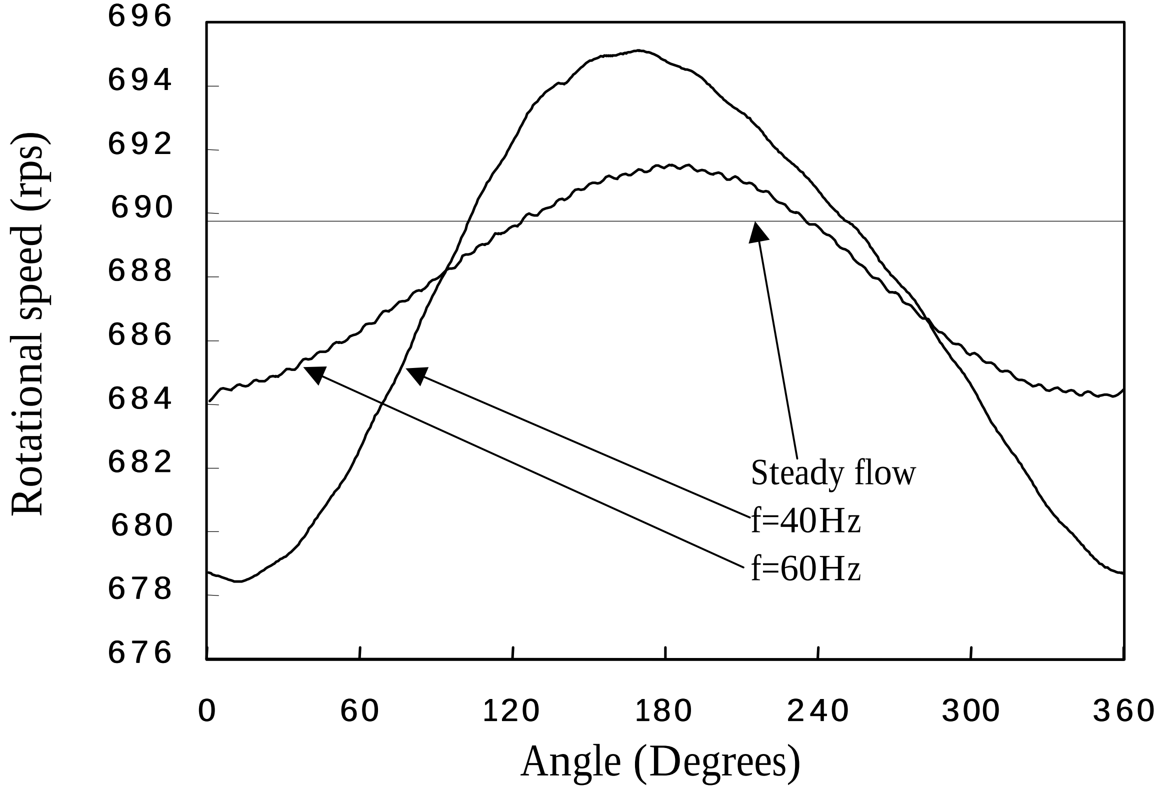


50% speed



70% speed

Rotational speed at 70%



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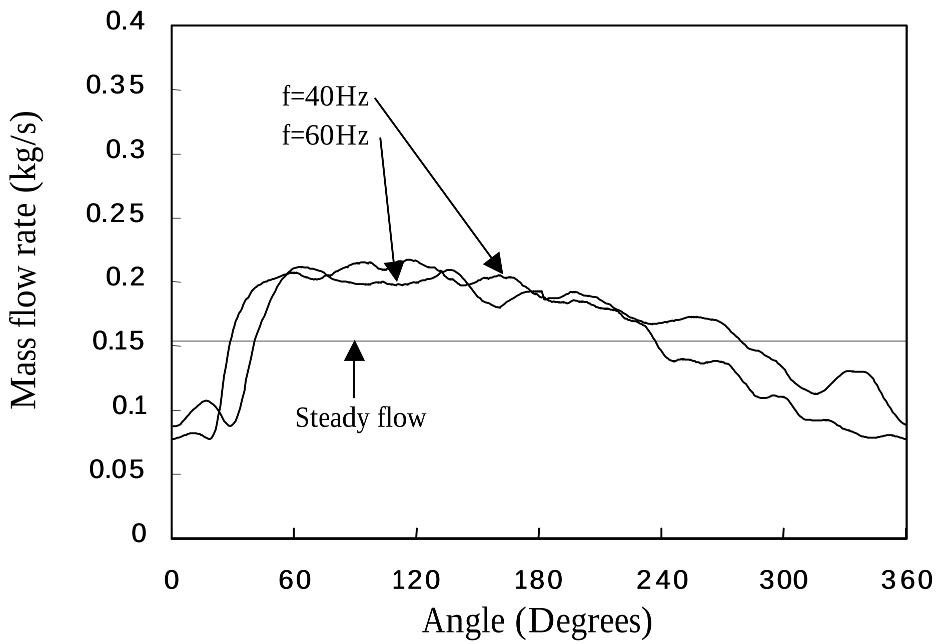
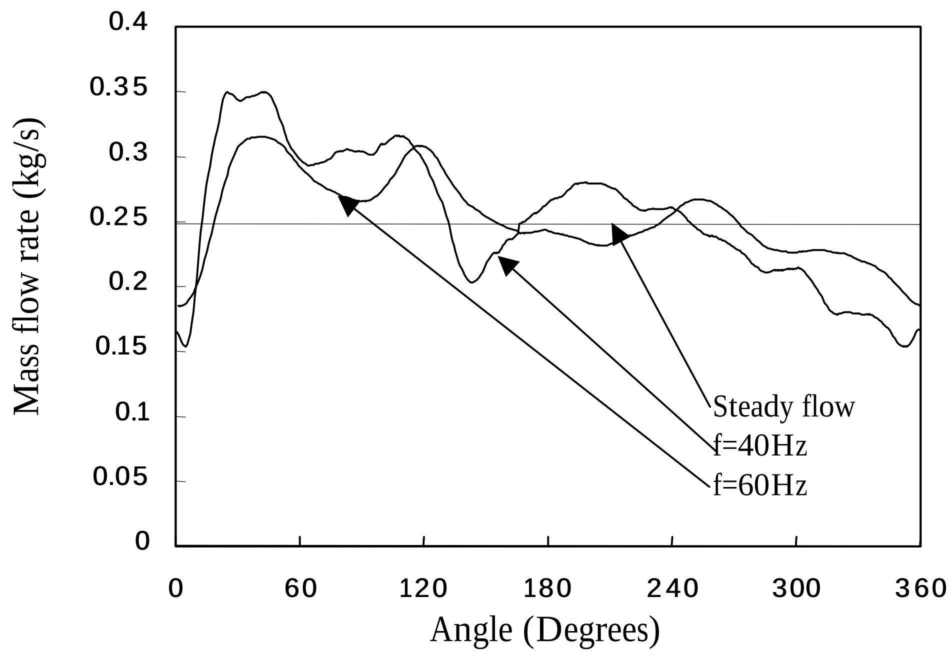
Instantaneous mass flow rate



50%

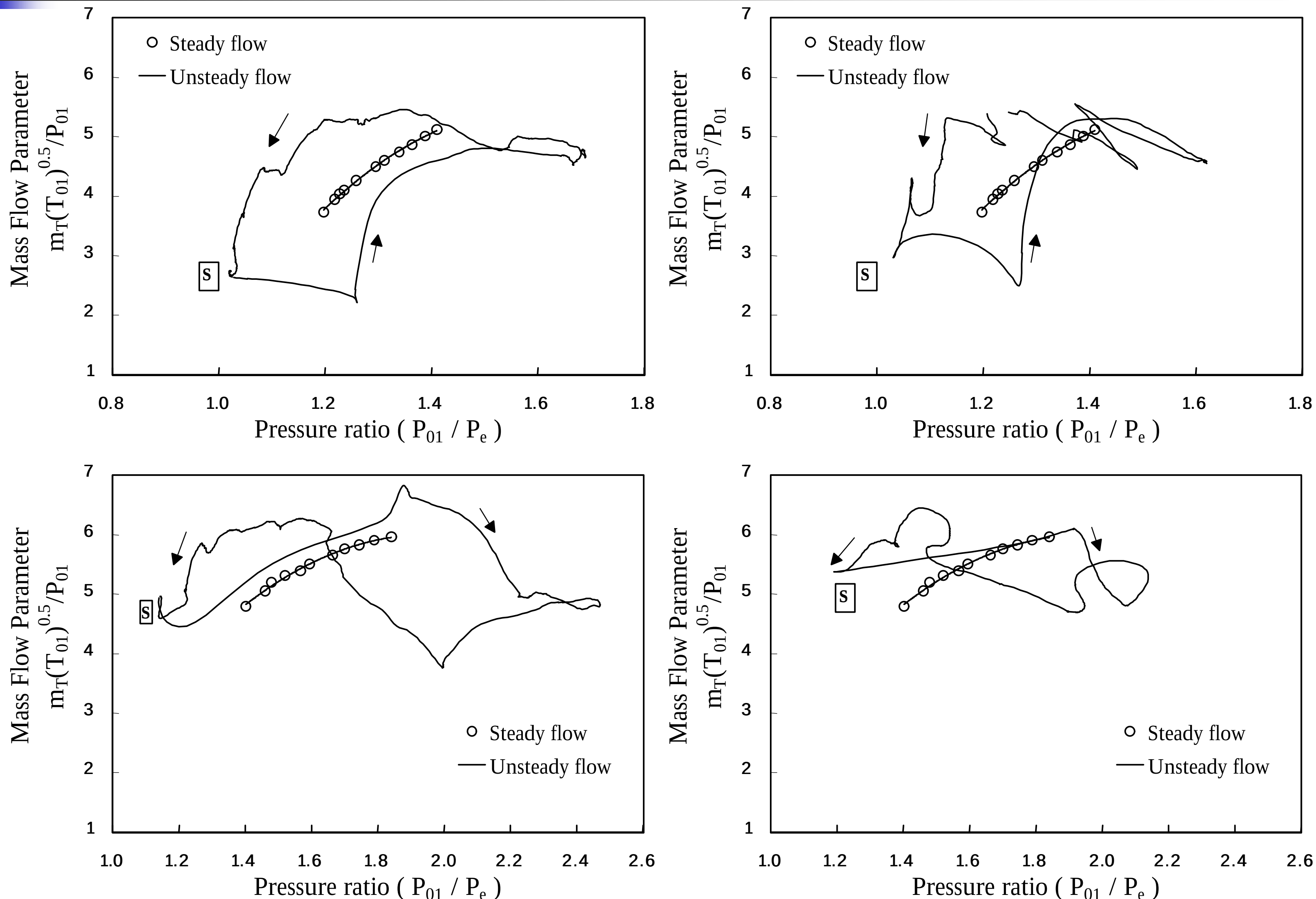


70%

Instantaneous swallowing capacity

50%

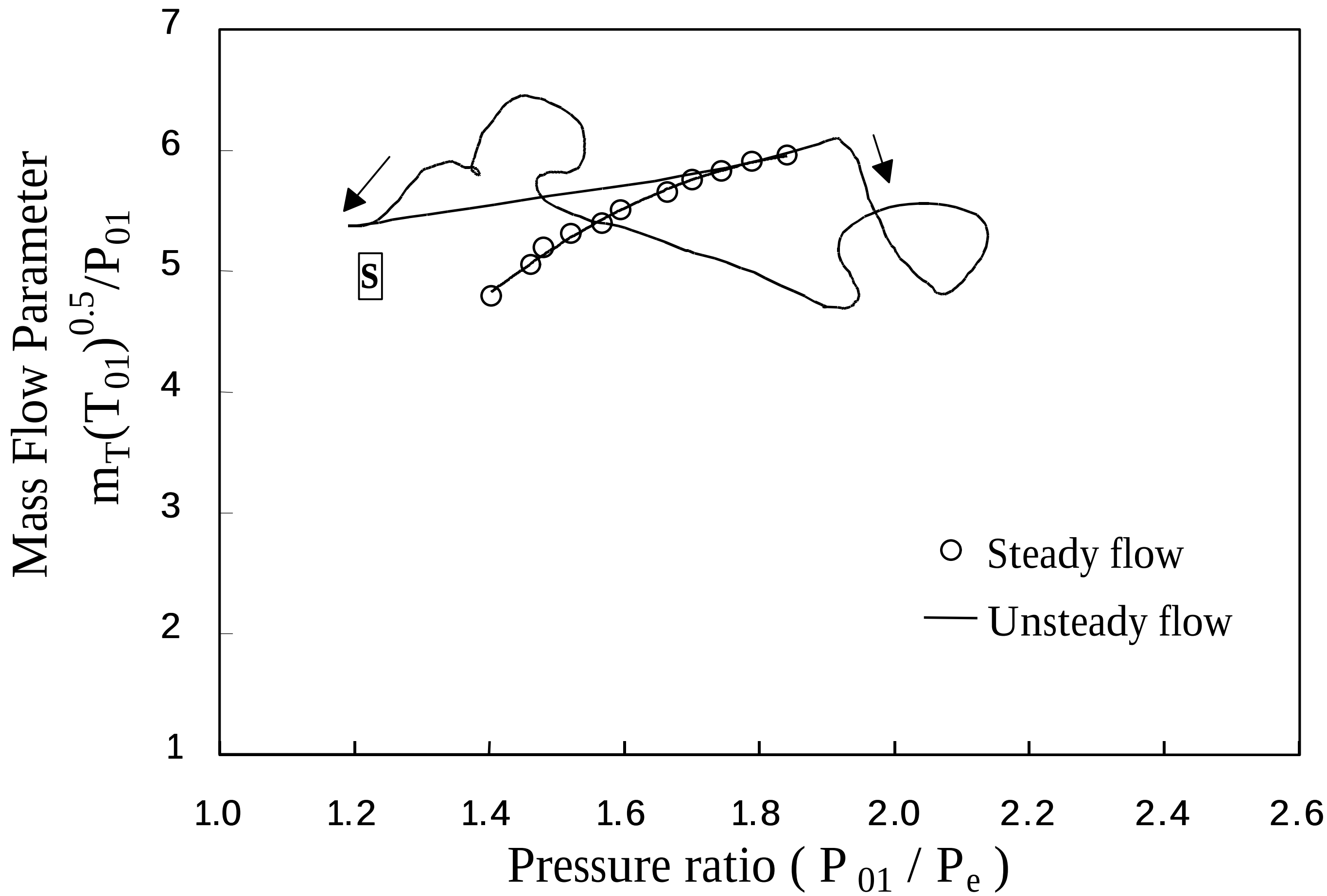
70%



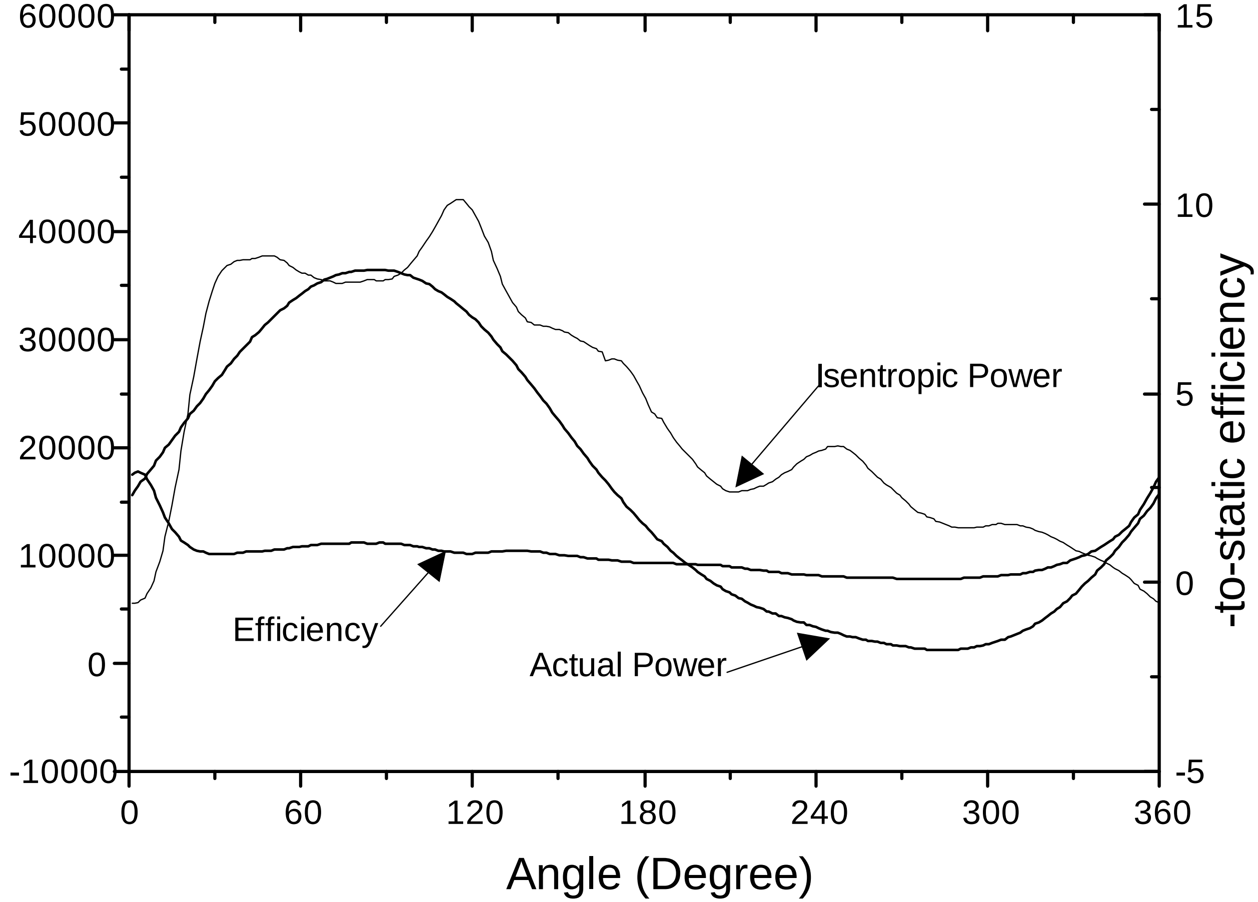
40 Hz

60 Hz

70% speed and 60 Hz



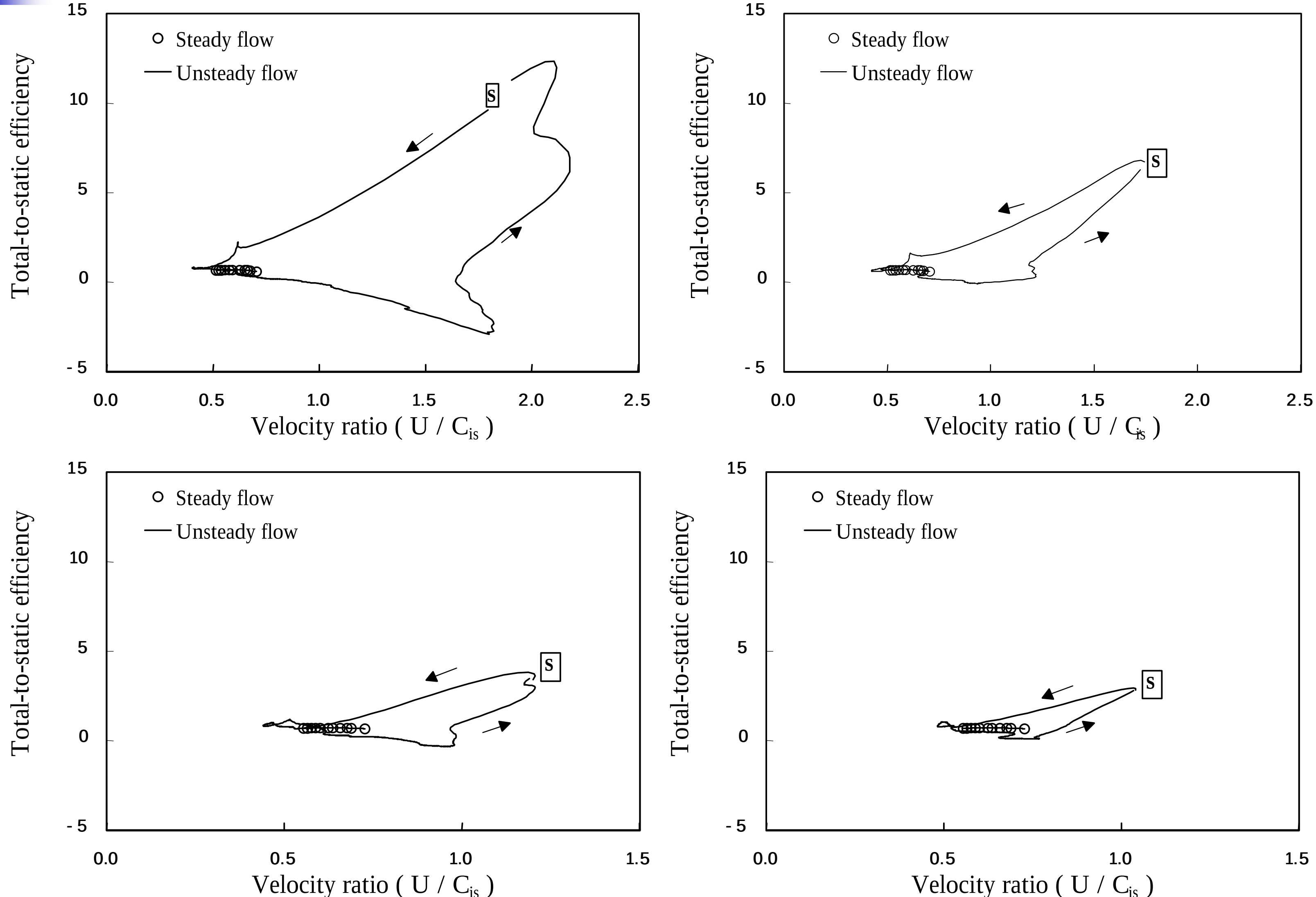
Instantaneous turbine power 70% and 40 Hz



Instantaneous efficiency

50%

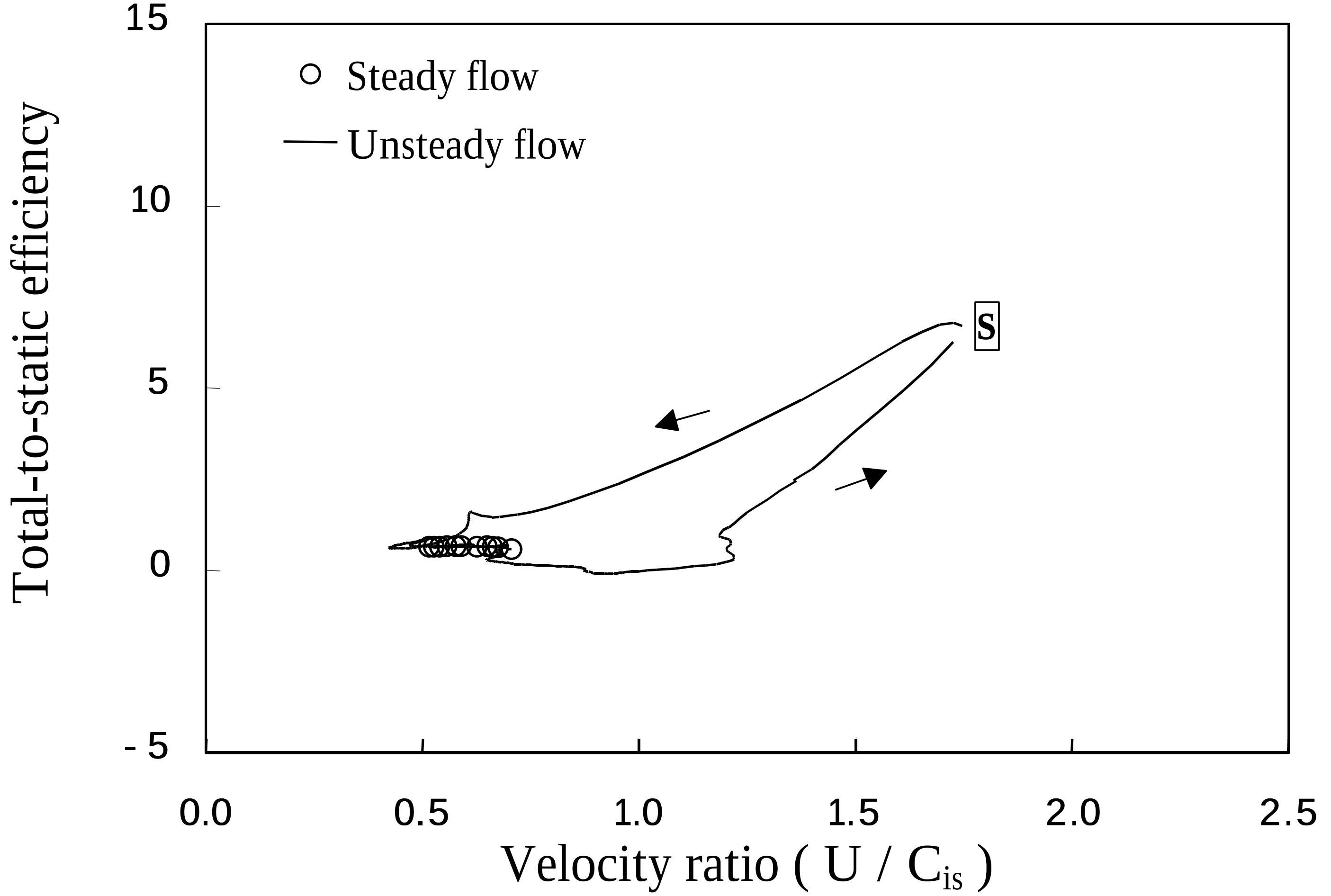
70%



40 Hz

60 Hz

Instantaneous efficiency 50% and 60 Hz



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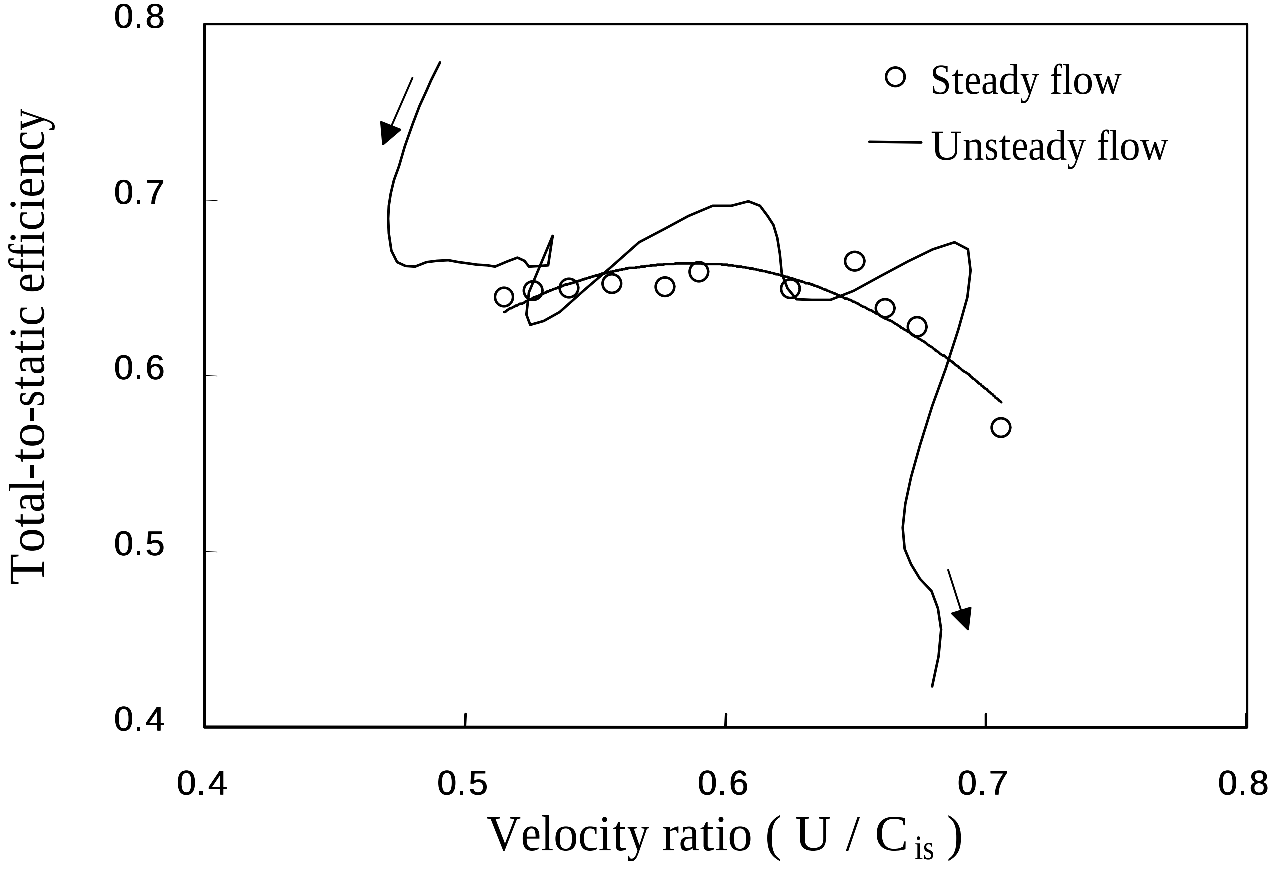
Instantaneous efficiency
50% and 60 Hz



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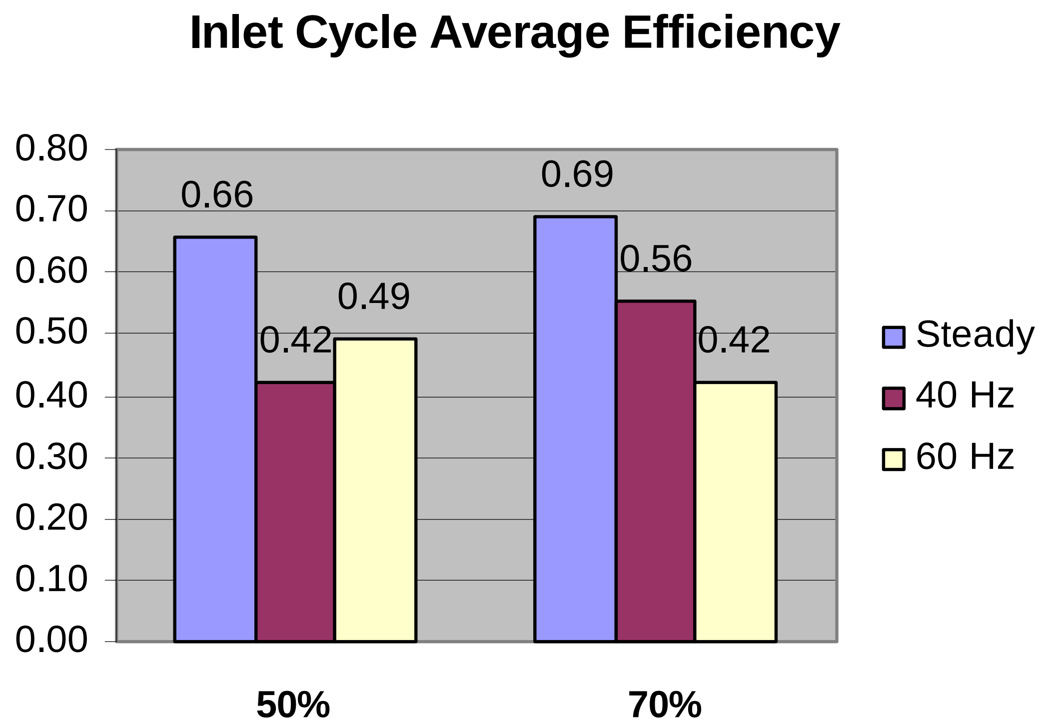
Steady and cycle-mass-averaged total-to-static efficiency

$$\left(m_{t-s}\right)_{cycle-average} = \frac{\int \left(\dot{W}_T\right)_{inst} dt}{\int \dot{W}_{isentropic} dt}$$

- Independent of shift
- Measure of the energy use



Unsteady velocity measurements

Laser Doppler velocimetry.

Inlet.

Exit.

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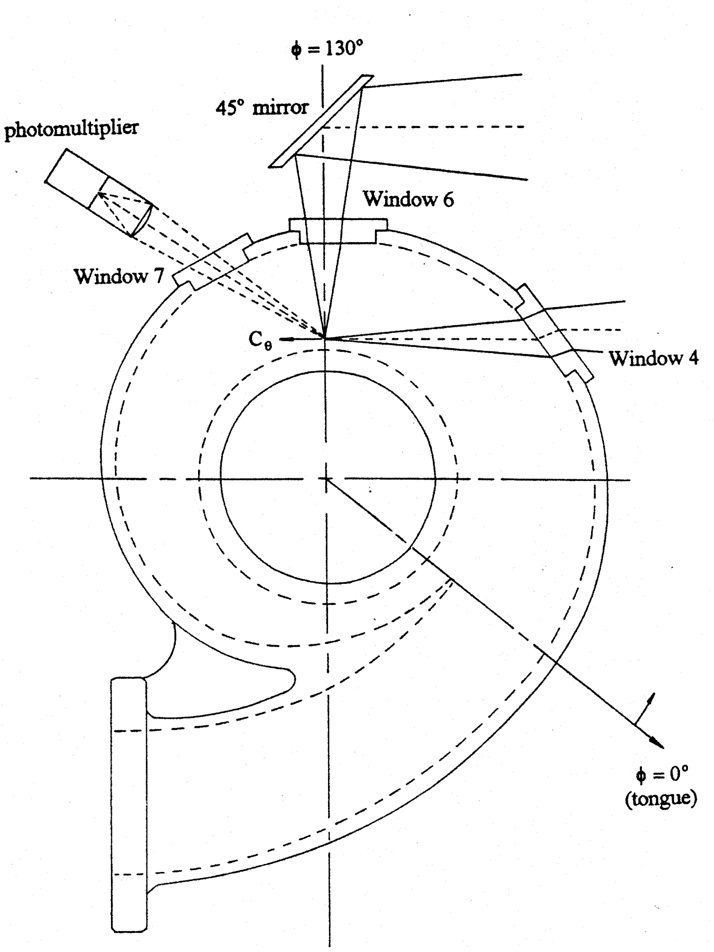
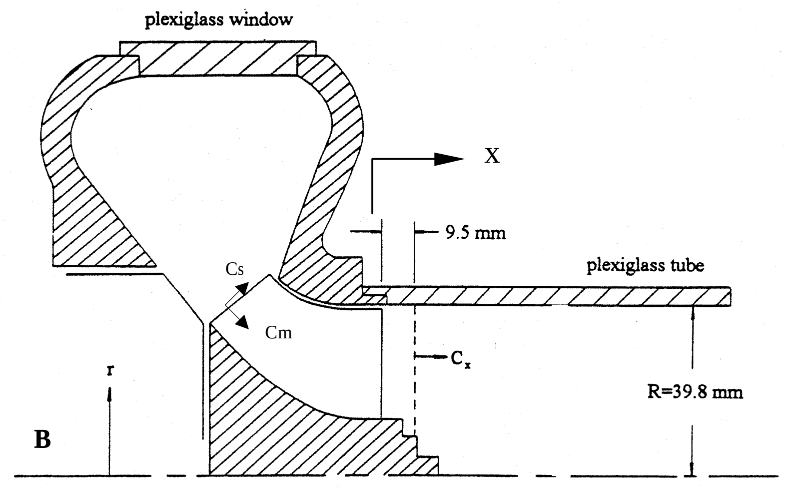
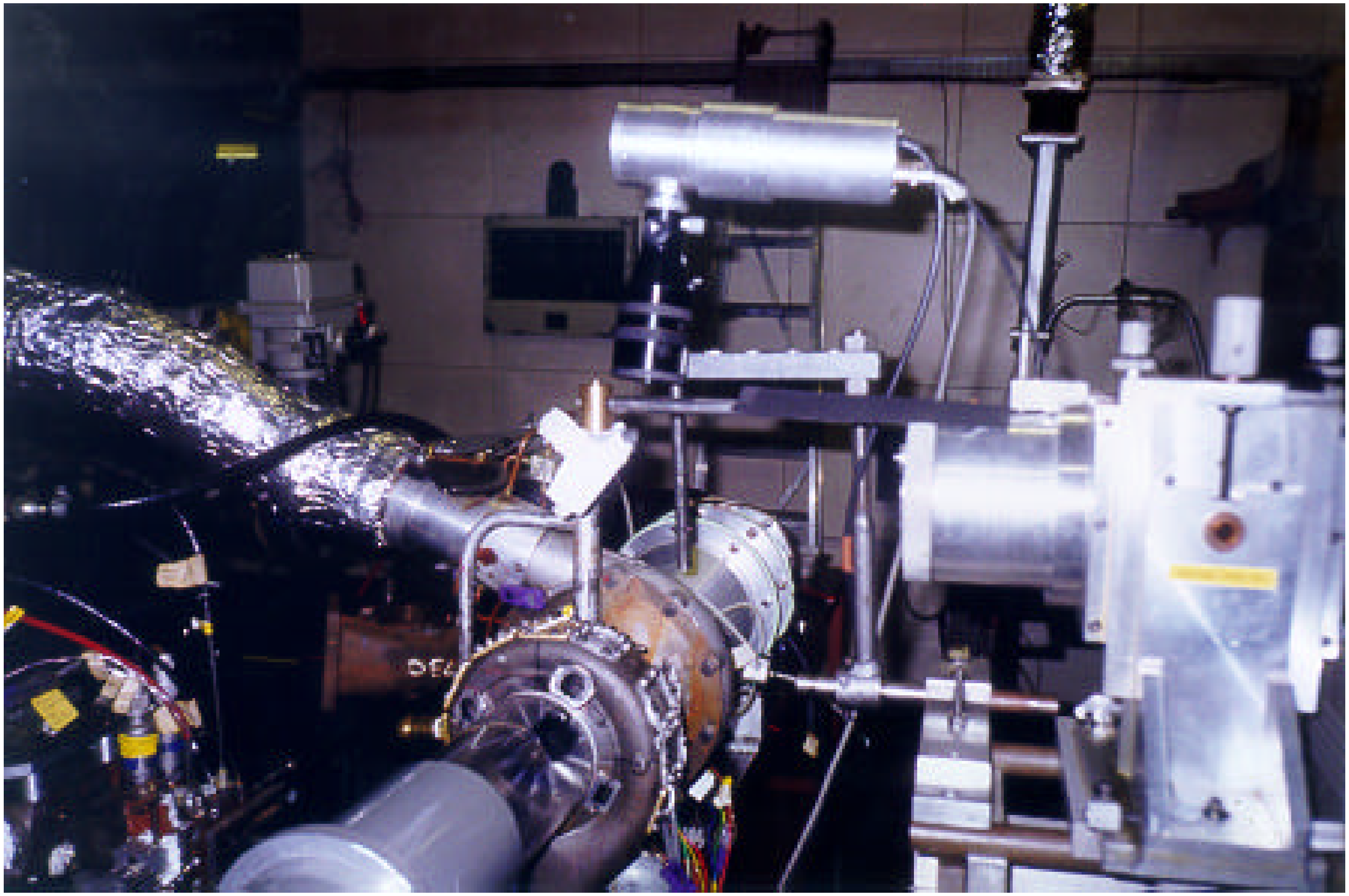
LDV measurement locations





Experimental apparatus



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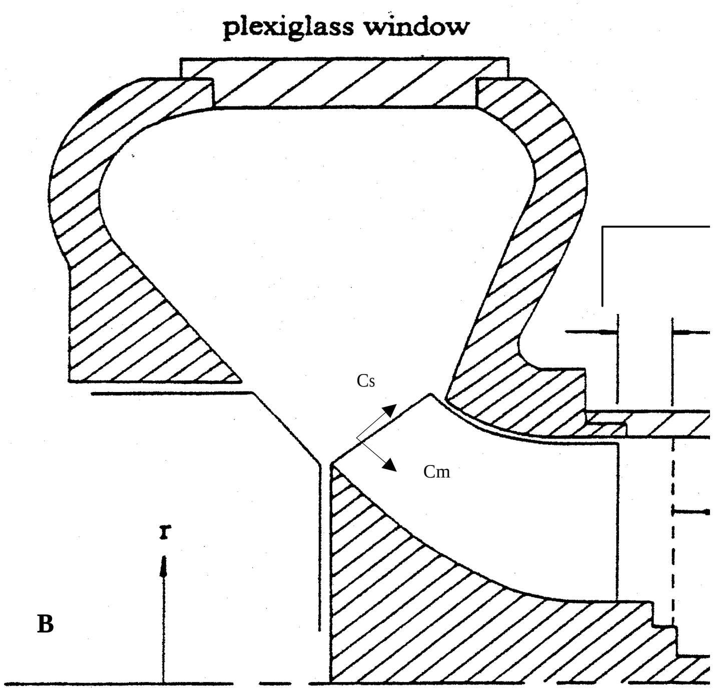
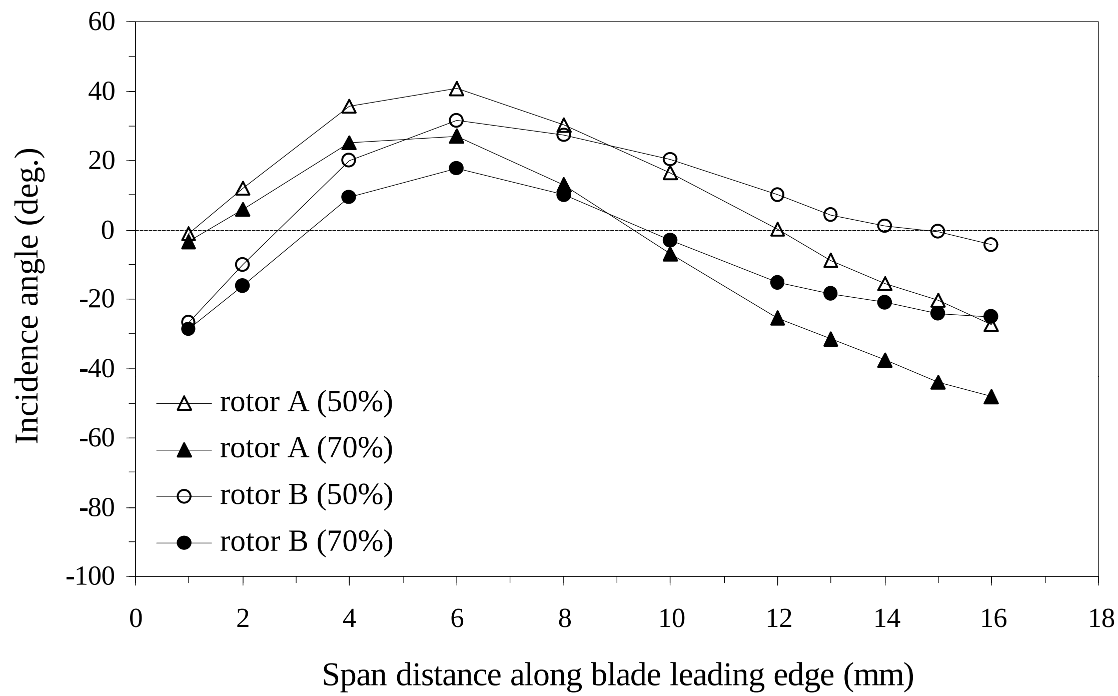
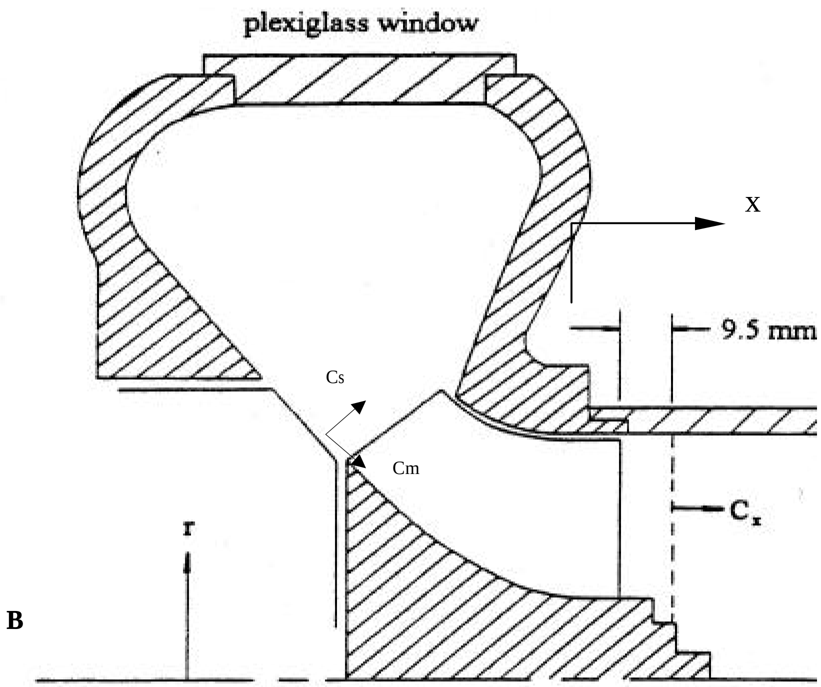
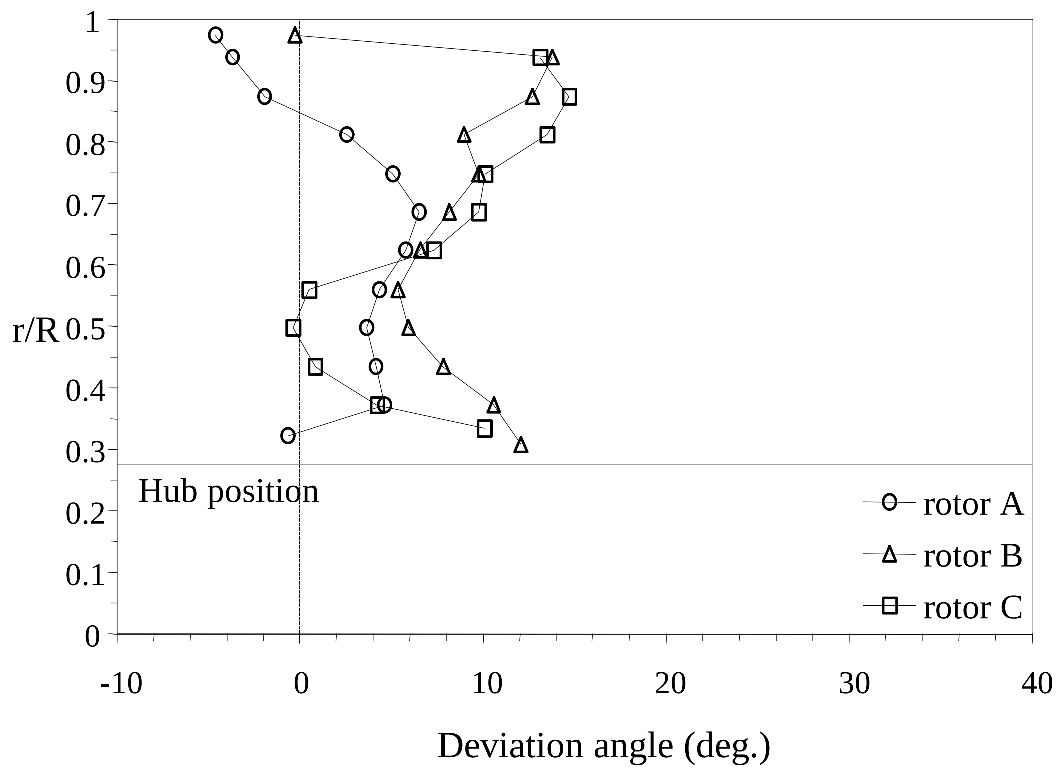
Inlet velocity measurements 40^0



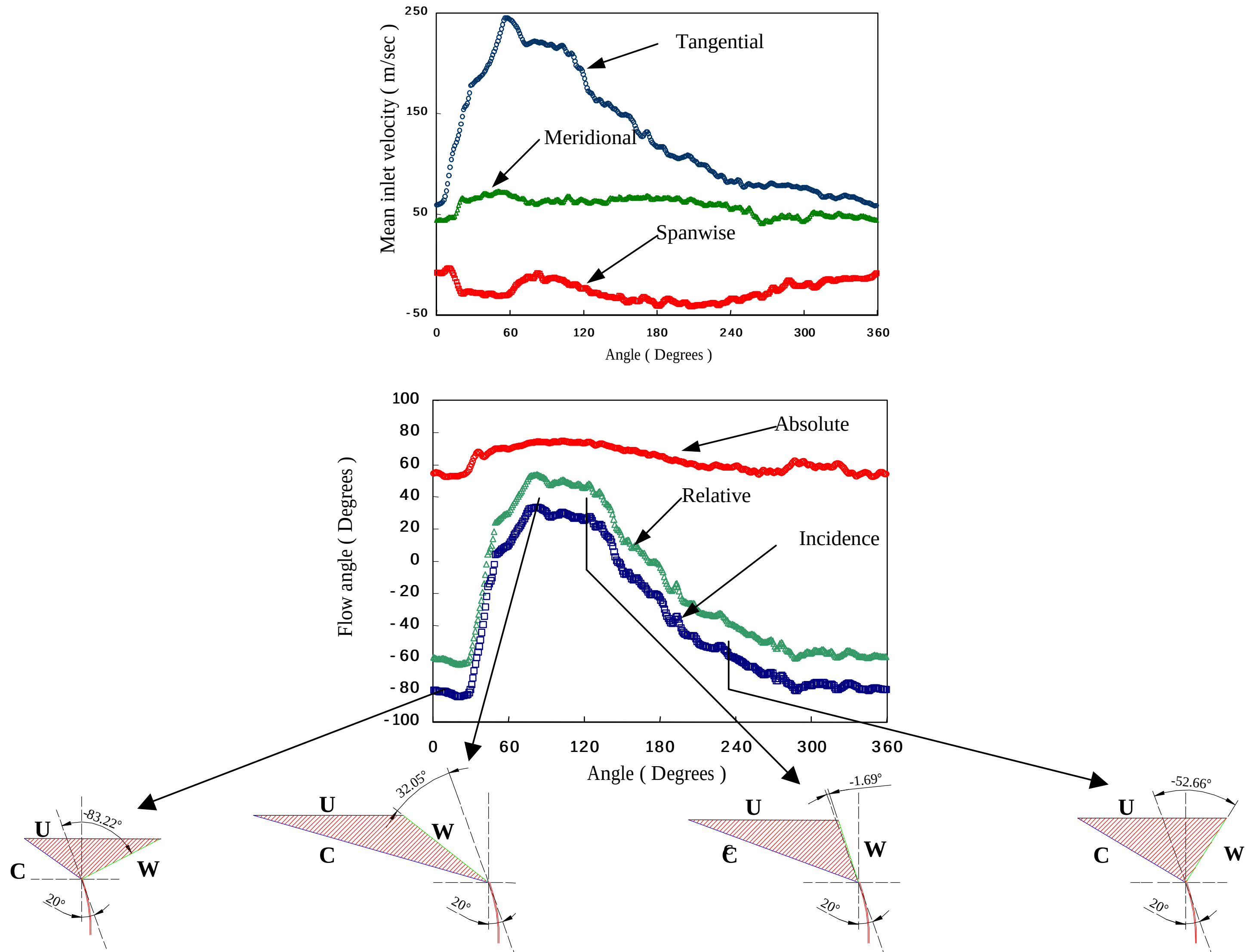


Exit deviation angle

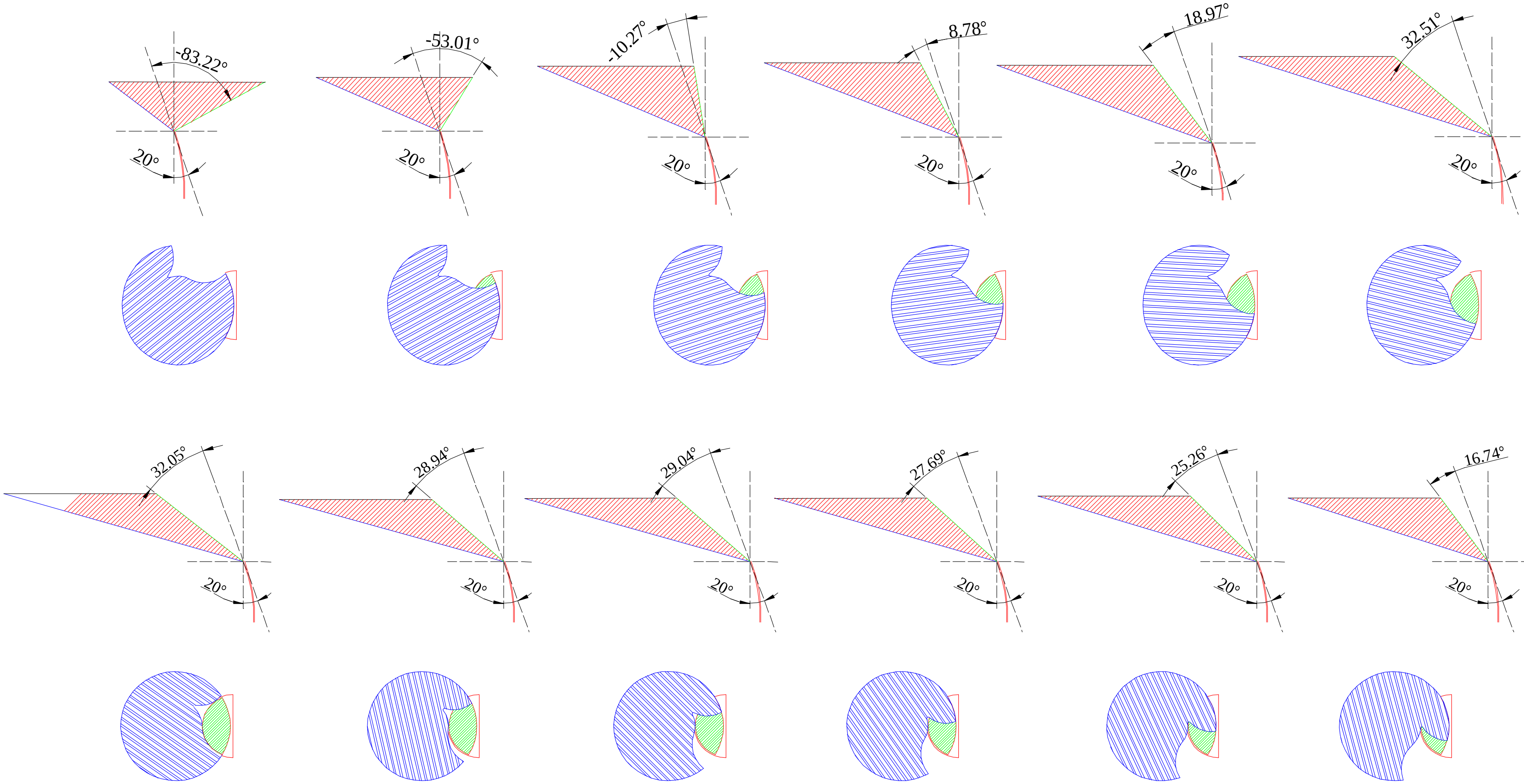




Inlet unsteady velocity



Inlet velocity triangles I



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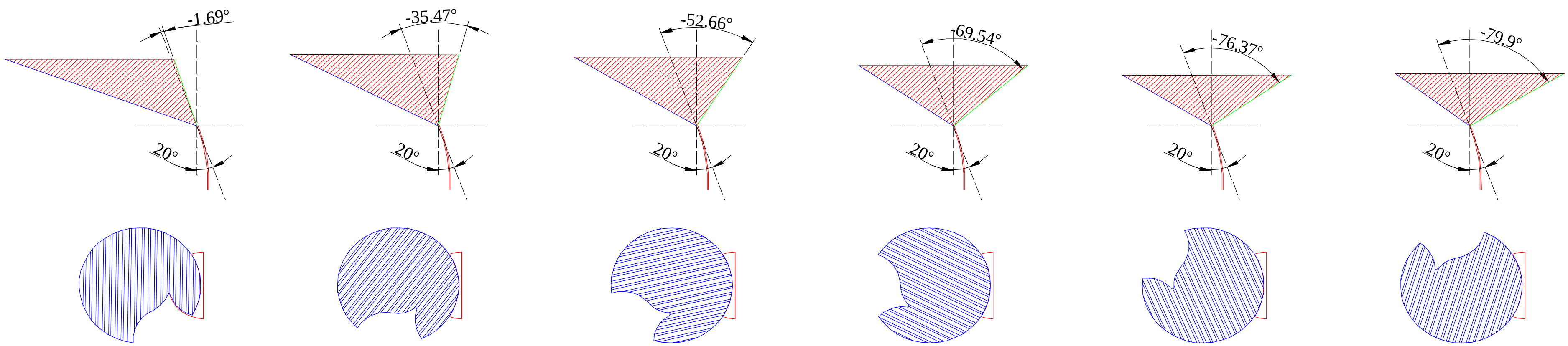
Inlet velocity triangles II



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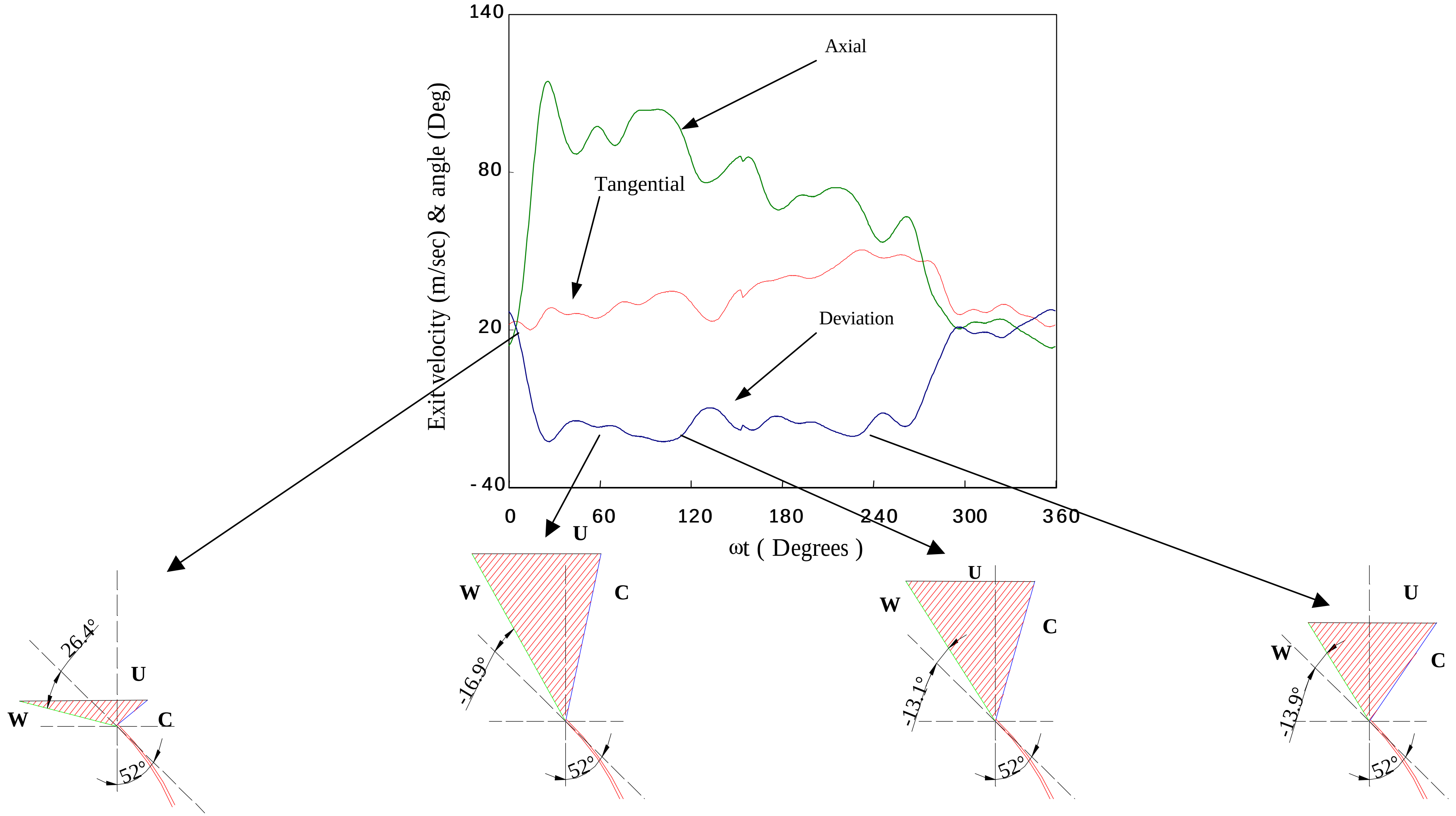
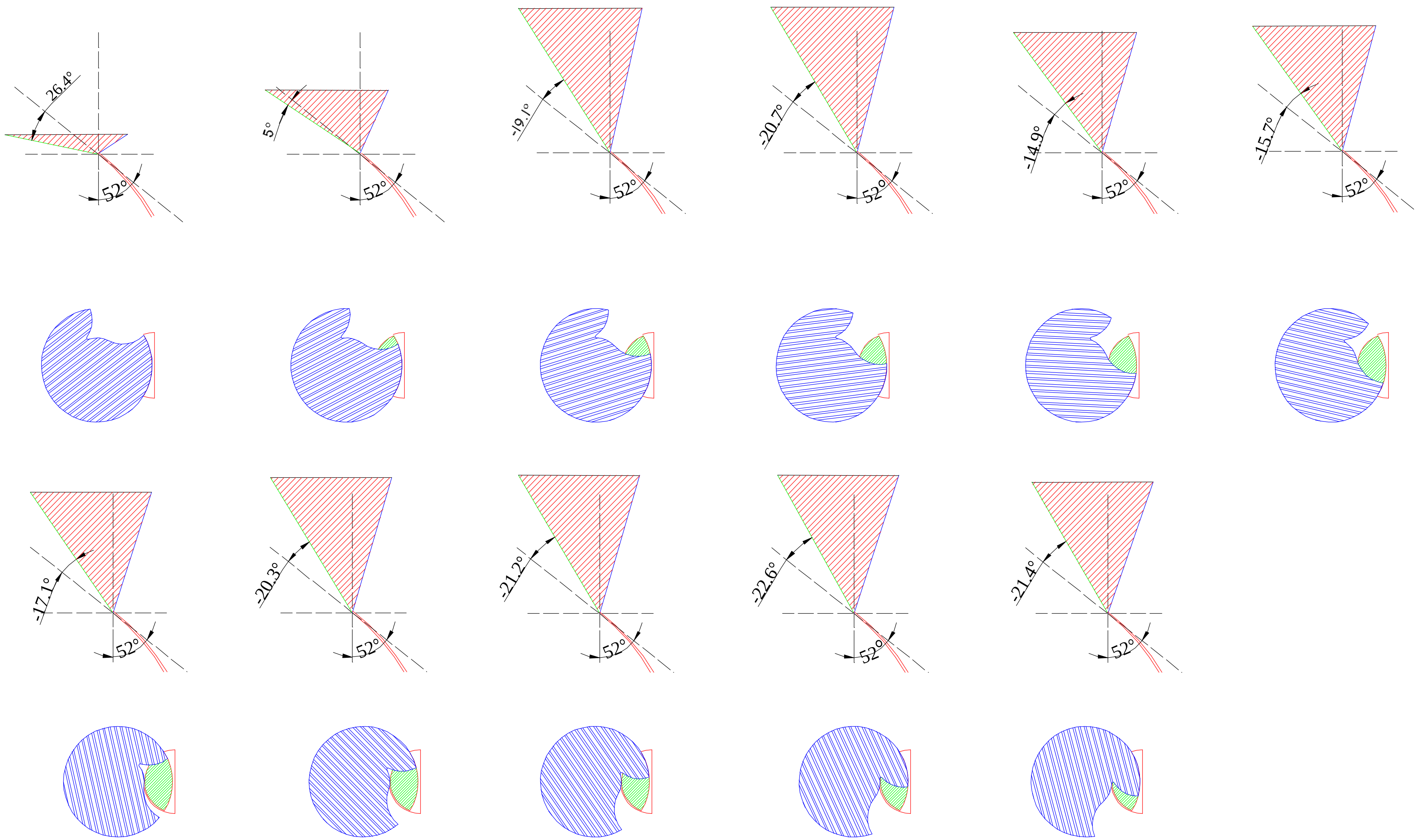
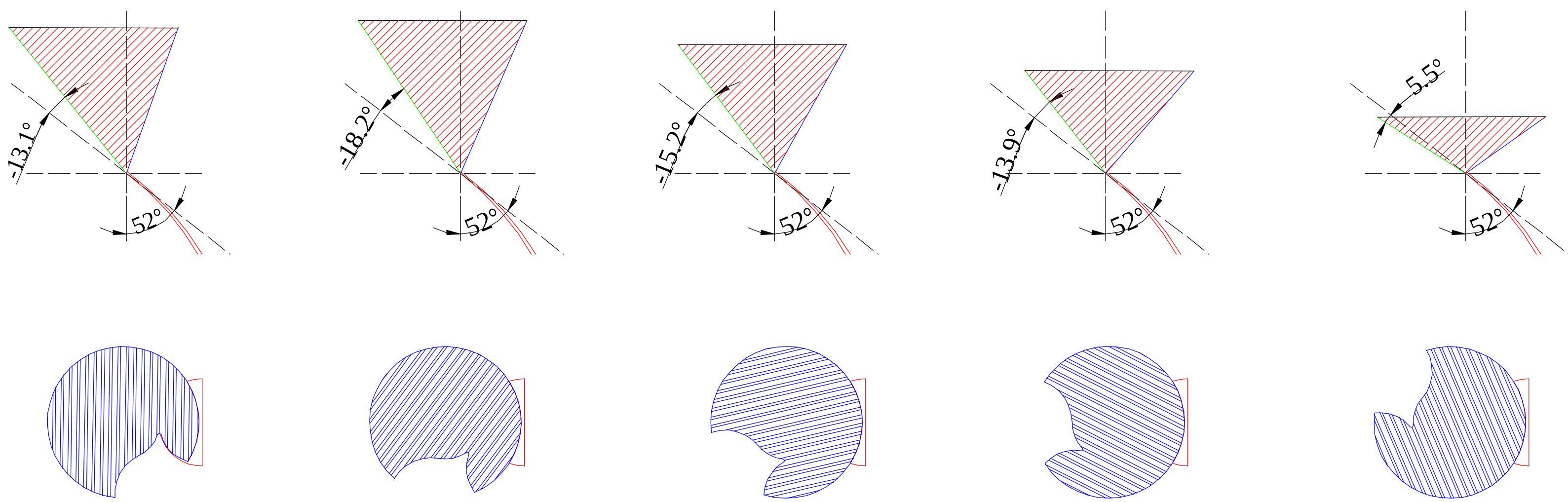
Exit unsteady velocity



Exit velocity triangles I



Exit velocity triangles II



Final remarks

- Mixed flow turbine applications, better use of exhaust energy. Other applications.
- Unsteady efficiency.
- Quasi-steady approach not valid for the turbocharger analysis.
- Inlet conditions very different from the design intent, how to do a better job?
- Velocity triangles.

THE EFFECT OF TURBULENCE LENGTH SCALE ON LOW PRESSURE TURBINE BLADE HEAT TRANSFER

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Unpredicted losses during high altitude operation have been observed in low pressure gas turbine stages. These losses have been attributed to separation on the suction surface of the turbine blades. To gain insight into boundary layer transition and separation for these low Reynolds number conditions, the heat transfer distribution on a Langston turbine blade shape was measured in a linear cascade wind tunnel for turbulence levels of 0.8% and 10% and Reynolds numbers of 40k to 80k. Turbulence levels of 10% were generated using three passive biplanar lattice grids with square-bar widths of 1.27 cm, 2.54 cm, and 6.03 cm to investigate the effect of turbulence length scale. The heat transfer was measured using a uniform heat flux liquid crystal technique. As turbulence levels increased, stagnation heat transfer increased and the location of the suction-side boundary layer transition moved upstream toward the blade leading edge. For this turbine blade shape the transition location did not depend on turbulence length scale, the location is more dependent on pressure distribution, Reynolds number and turbulence intensity. For the 10% turbulence cases, the smaller length scales had a larger affect on heat transfer at the stagnation point. A laser tuft method was used to differentiate between boundary layer transition and separation on the suction surface of the blade. Separation was observed for all of the low turbulence (clean tunnel) cases while transition was observed for all of the 10% turbulence cases. Separation and transition locations corresponded to local minimums in heat transfer. Reattachment points did not correspond to local maximums in heat transfer, but instead, the heat transfer coefficient continued to rise downstream of the reattachment point. For the clean tunnel cases, streamwise streaks of varying heat transfer were recorded on the concave pressure side of the turbine blade. These streaks are characteristic of Görtler vortices. For the 10% turbulence cases, these streaks were not present. The results presented in this paper show that turbulence length scale, in addition to intensity have an important contribution to turbine blade aerodynamics and are important to CFD modelers who seek to predict boundary layer behavior in support of turbine blade design optimization efforts.

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THE EFFECT OF TURBULENCE LENGTH SCALE ON LPT BLADE HEAT TRANSFER

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Minnowbrook III, 20-23 Aug 00

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Overview

- Objectives
- Experimental Approach
- Heat Transfer Results
- Laser Thermal Tufts
- Summary

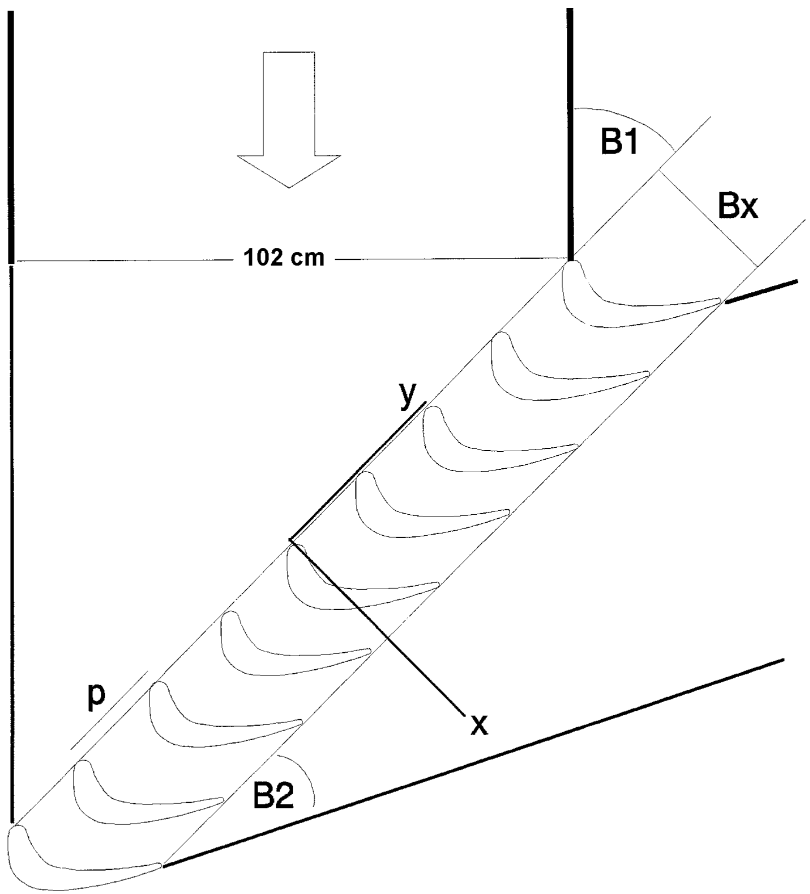
Effects of “length scale” on:

- Stagnation point heat transfer
- Pressure side heat transfer
- Suction side heat transfer
- Separation and/or transition location

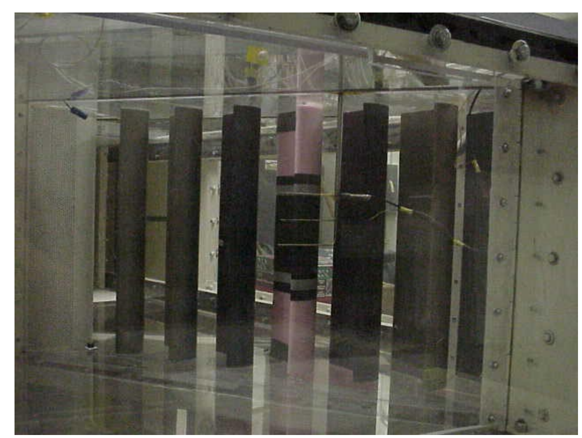
Reynolds Number for Suction Surface Flows

This Study (inlet velocity, axial chord)	**Other workers** (exit velocity, suction surface distance)
40k	109k
80k	219k

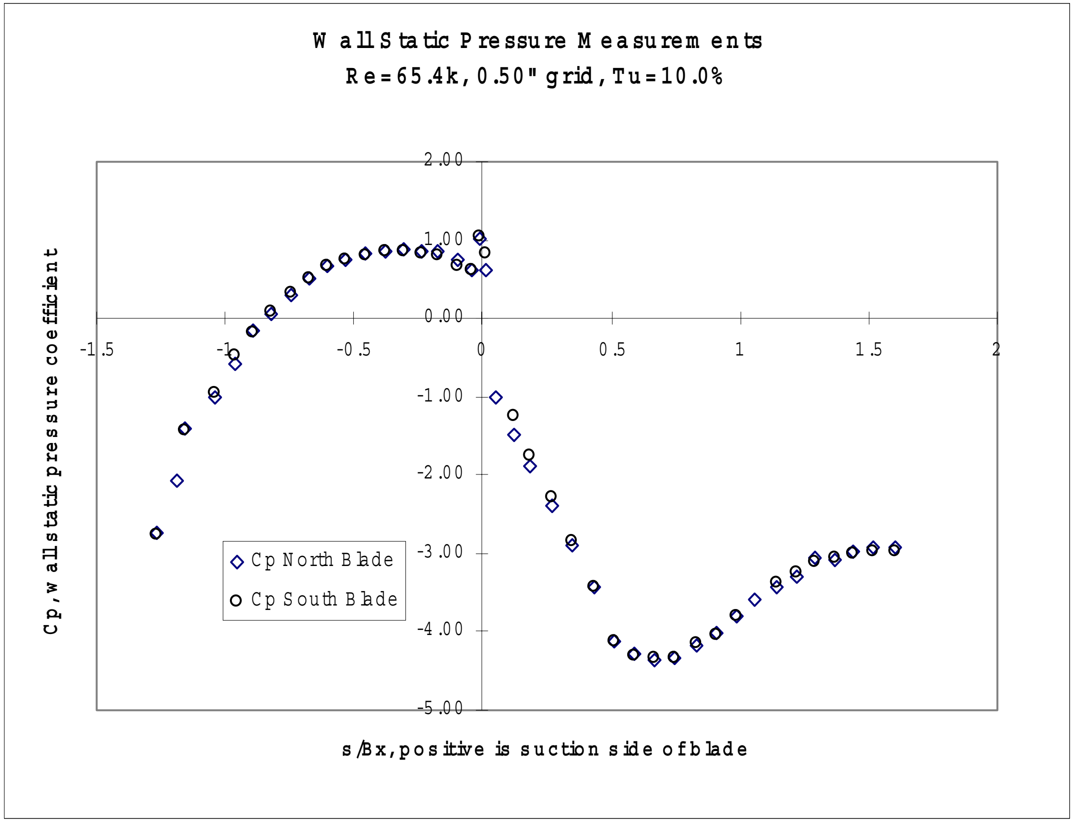
Linear Cascade – Langston Blade Shape

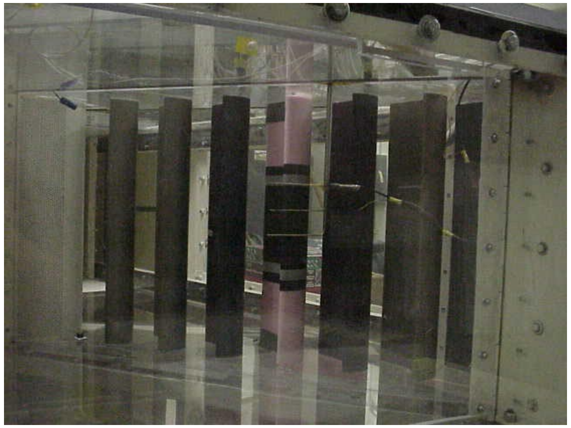


Aspect ratio = 3.86
Pitch/axial chord = .95
Air inlet angle = 46 deg
Air exit angle = 26 deg

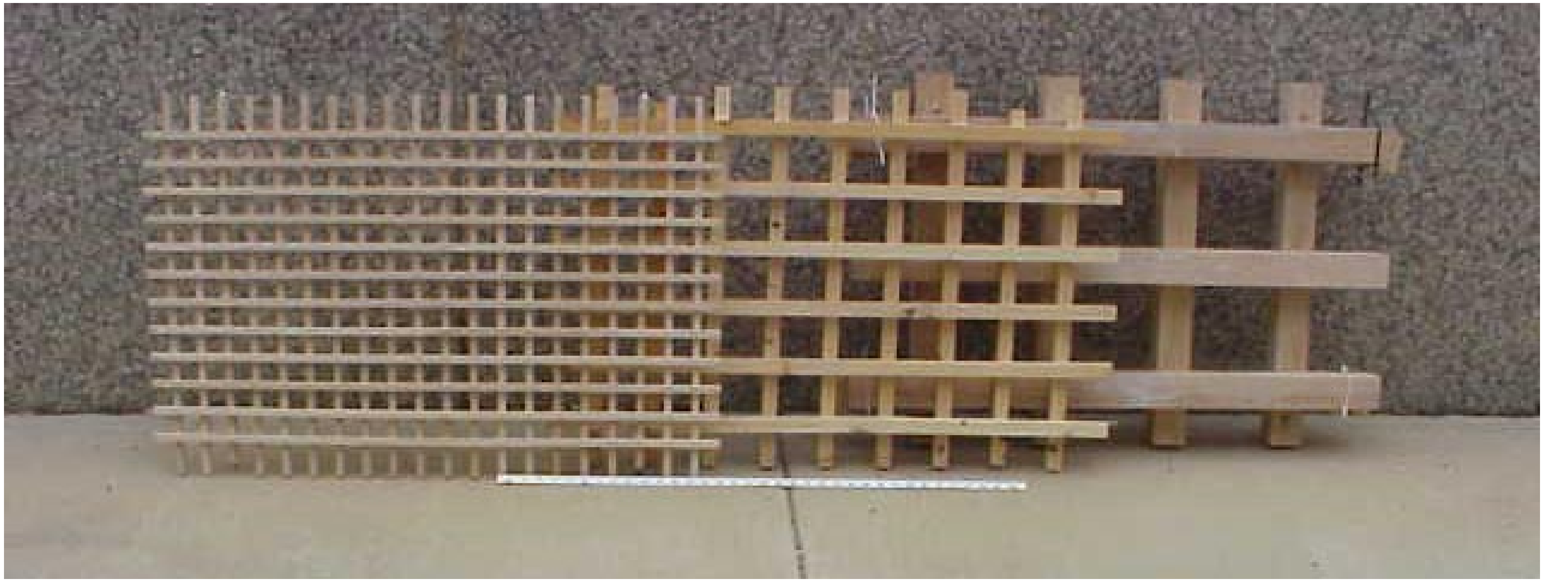


Wall Static Pressure Distribution



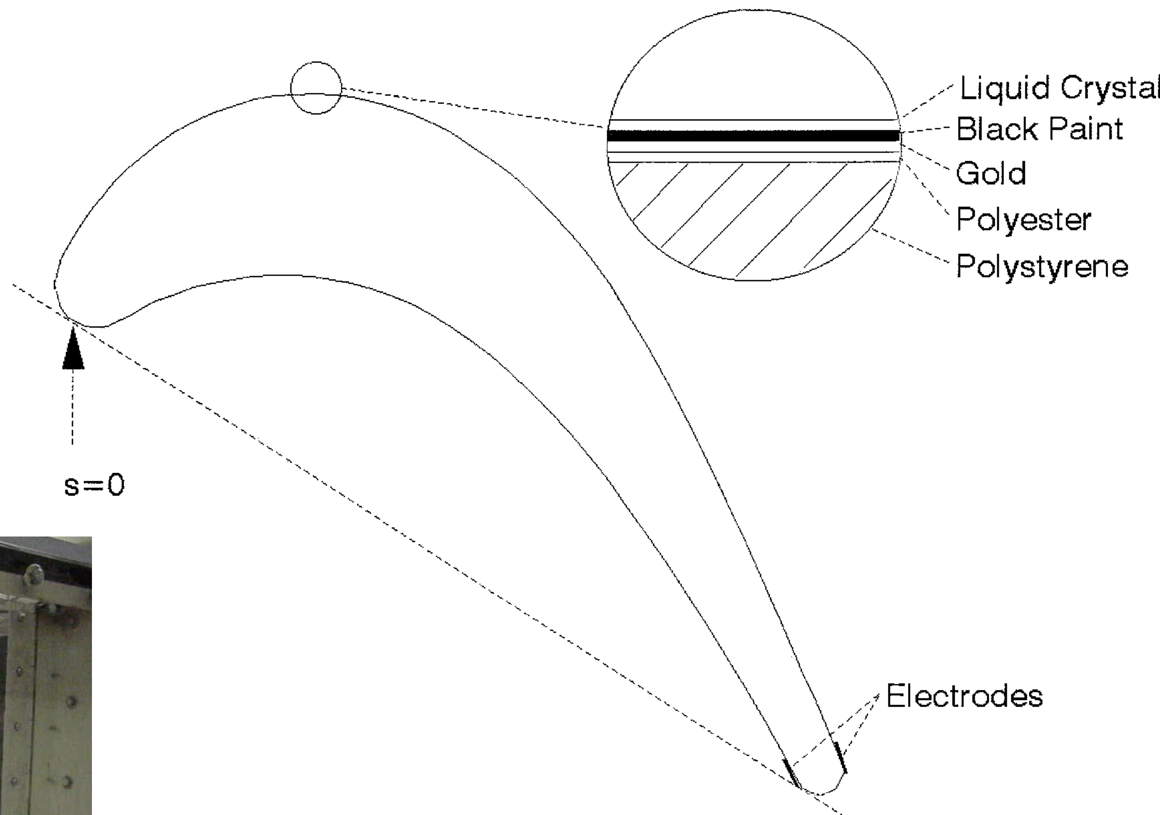


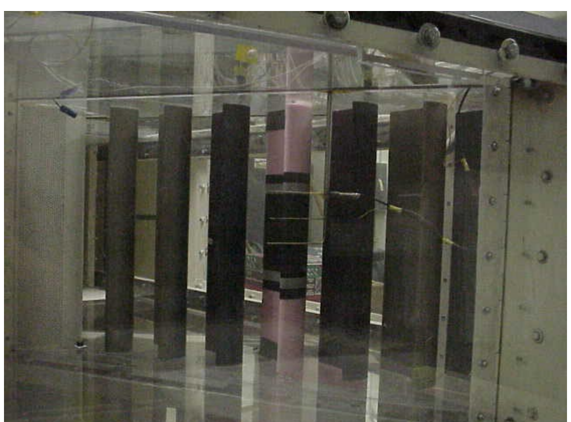
Grid Generated Turbulence



b= 1.27cm	2.54cm	6.03cm
M/b=4	4	4

Uniform Heat Flux Method





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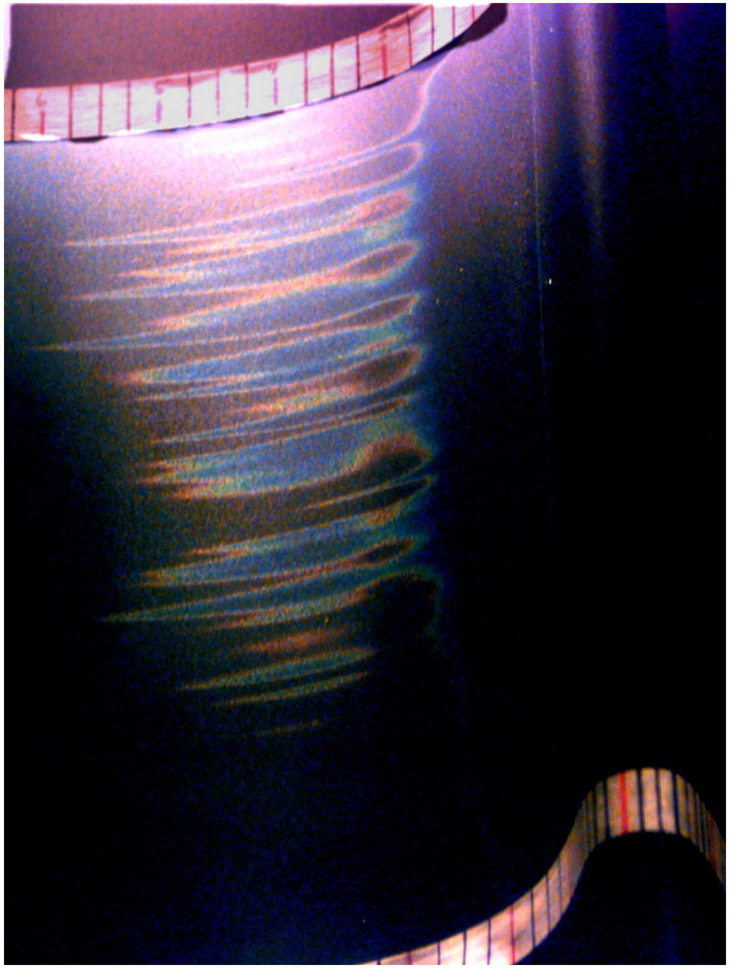
Pressure Surface Heat Transfer



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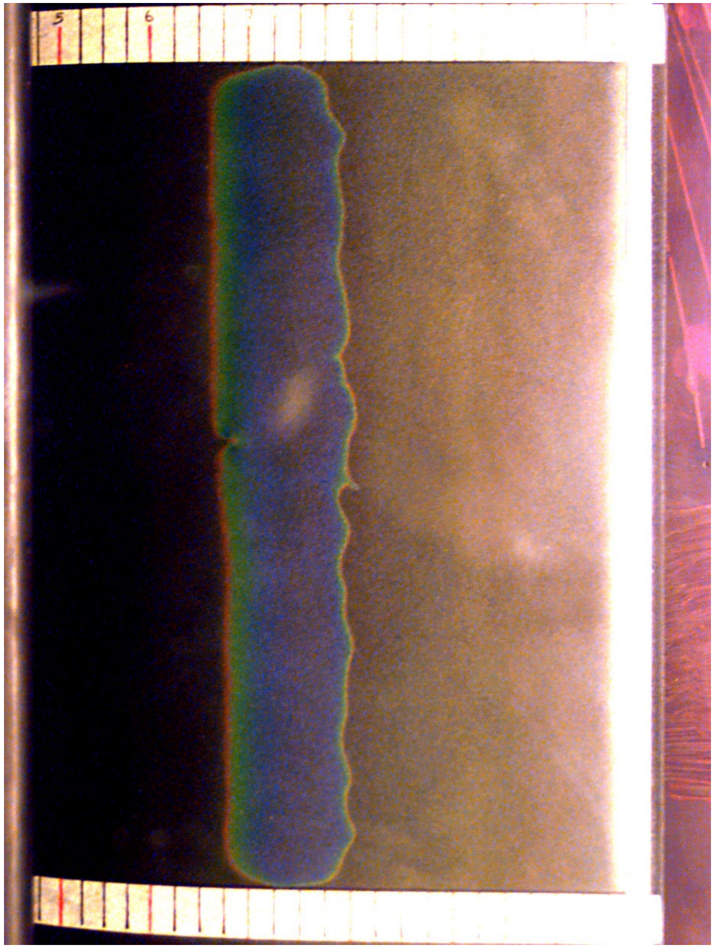
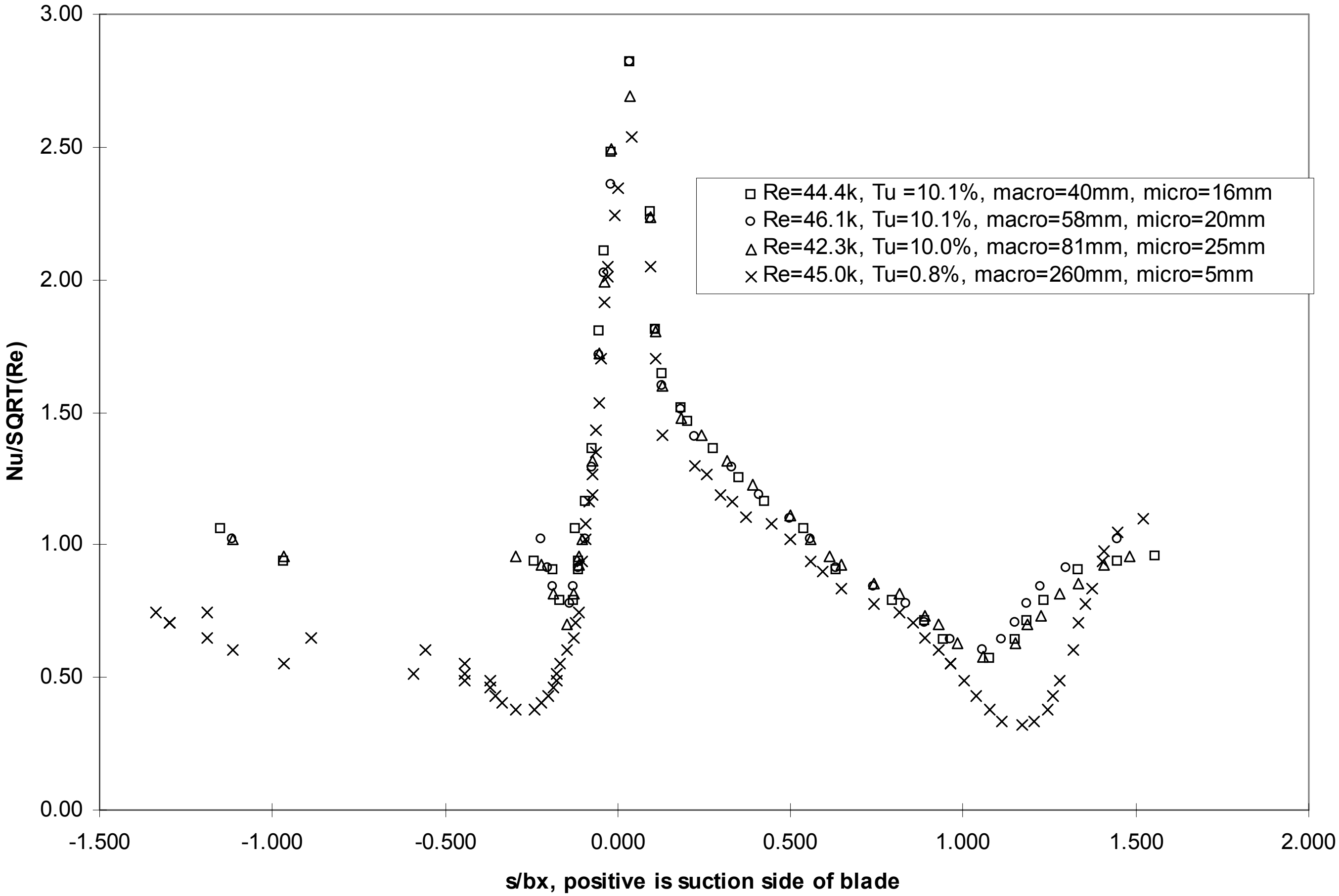
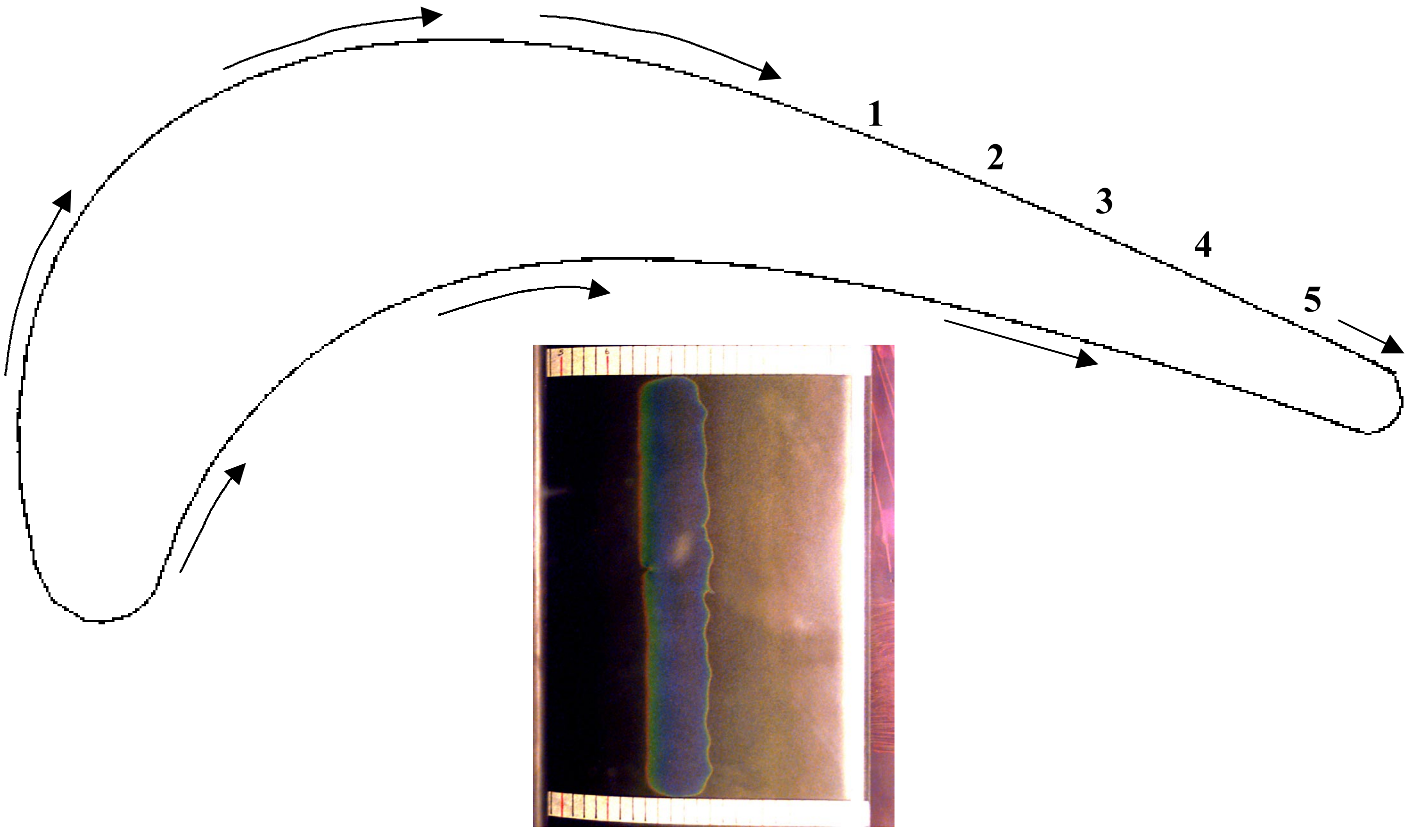
Suction Surface Heat Transfer



Heat Transfer – Low Re



Separation or Transition?



Laser Thermal Tuft Method

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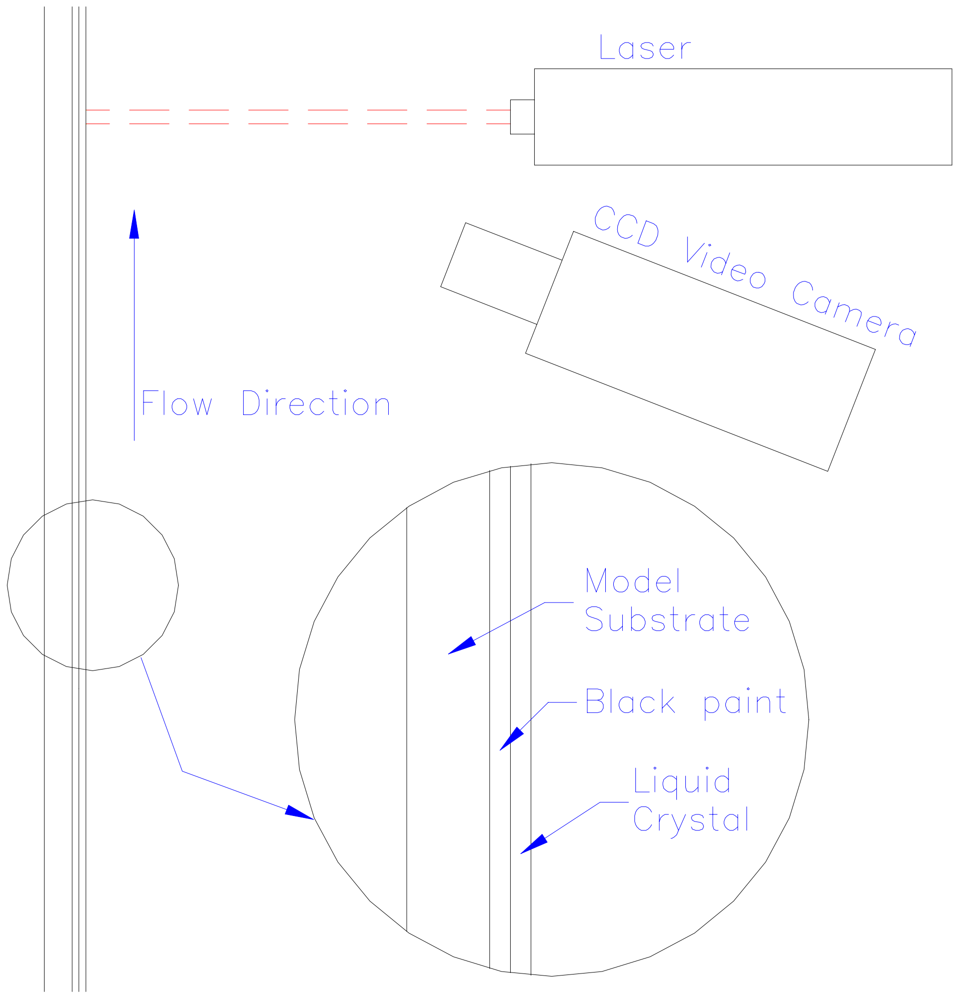

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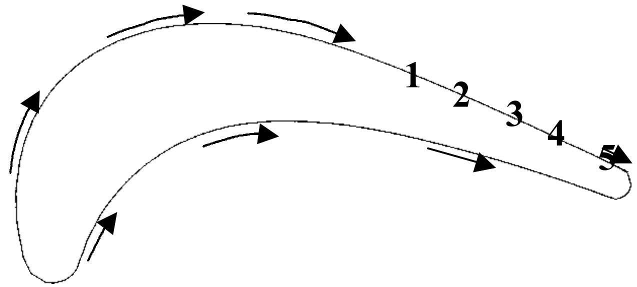
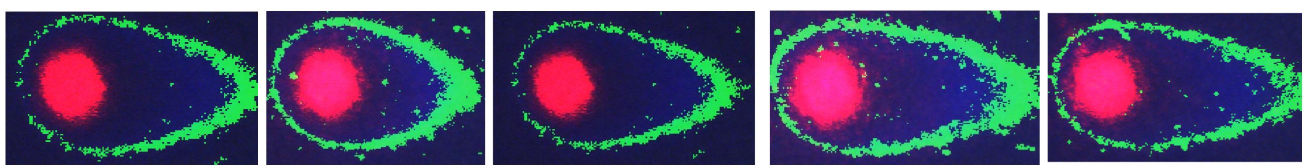
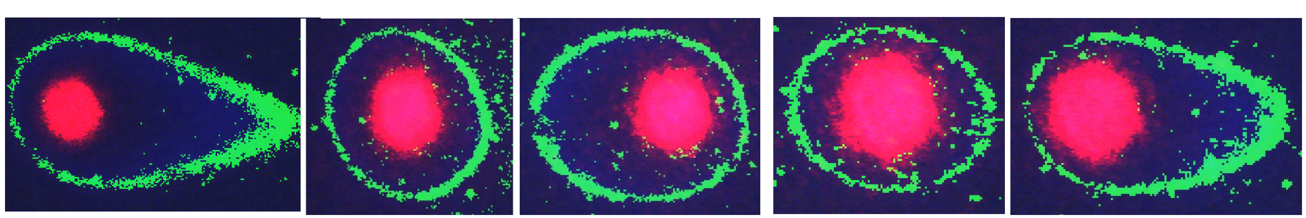
Laser Thermal Tuft Results



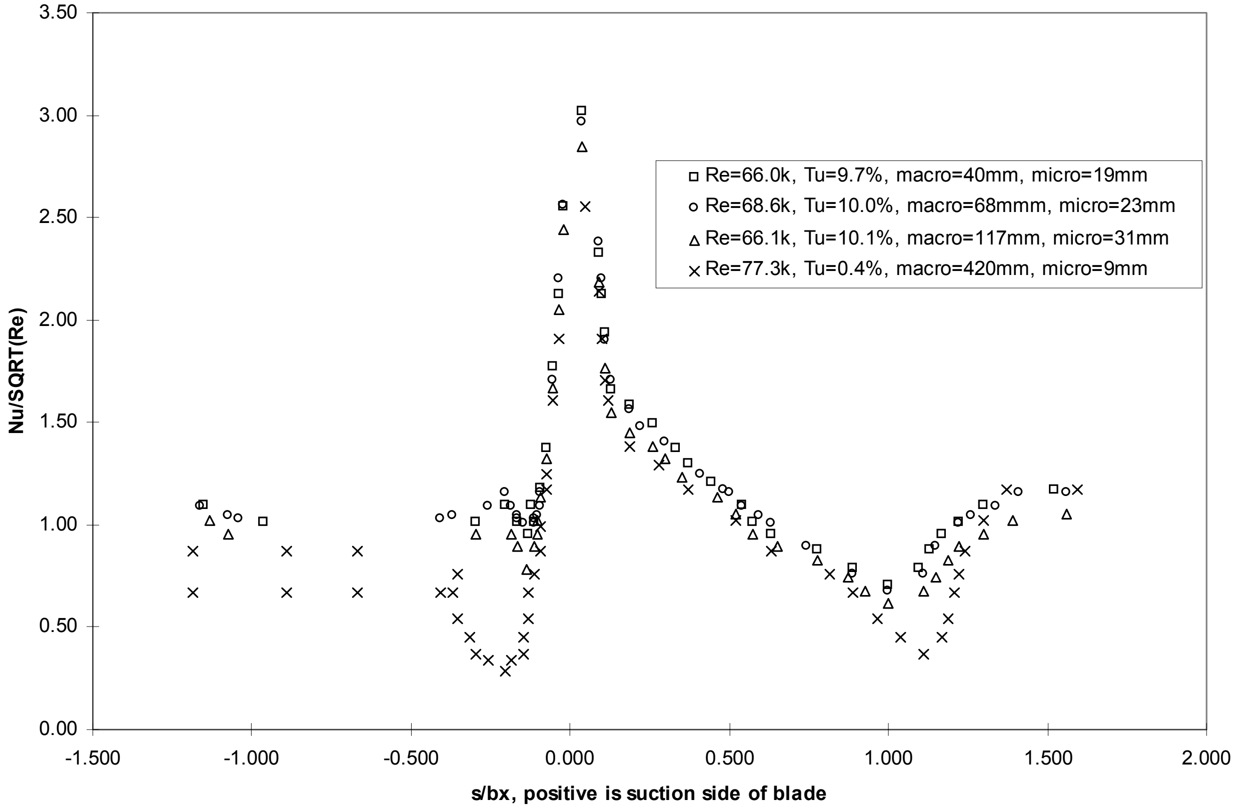


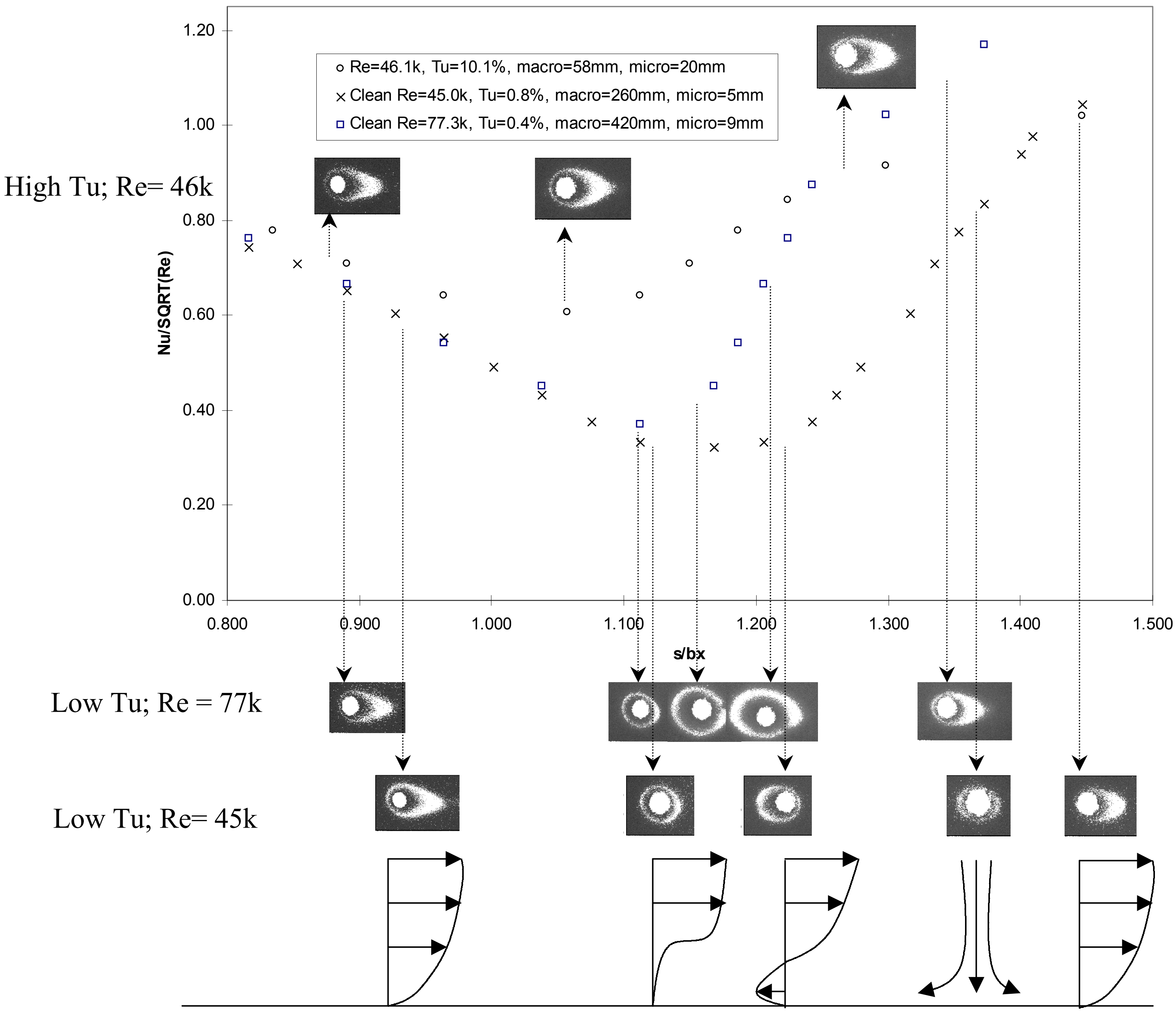
Freestream Turbulence ~ 10%



Freestream Turbulence ~ 0.8%

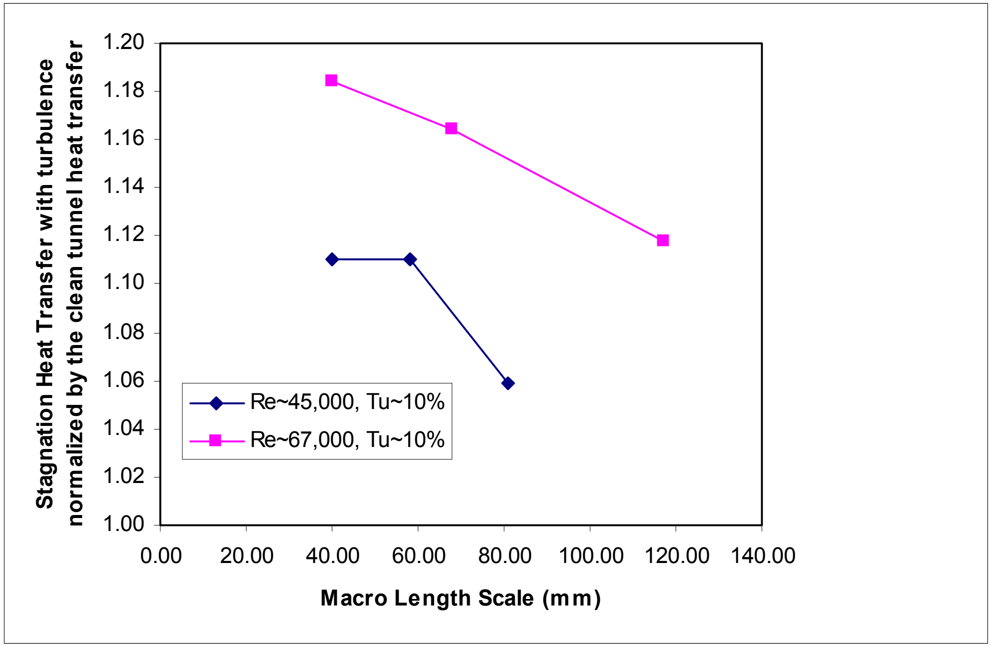
Heat Transfer – Higher Re



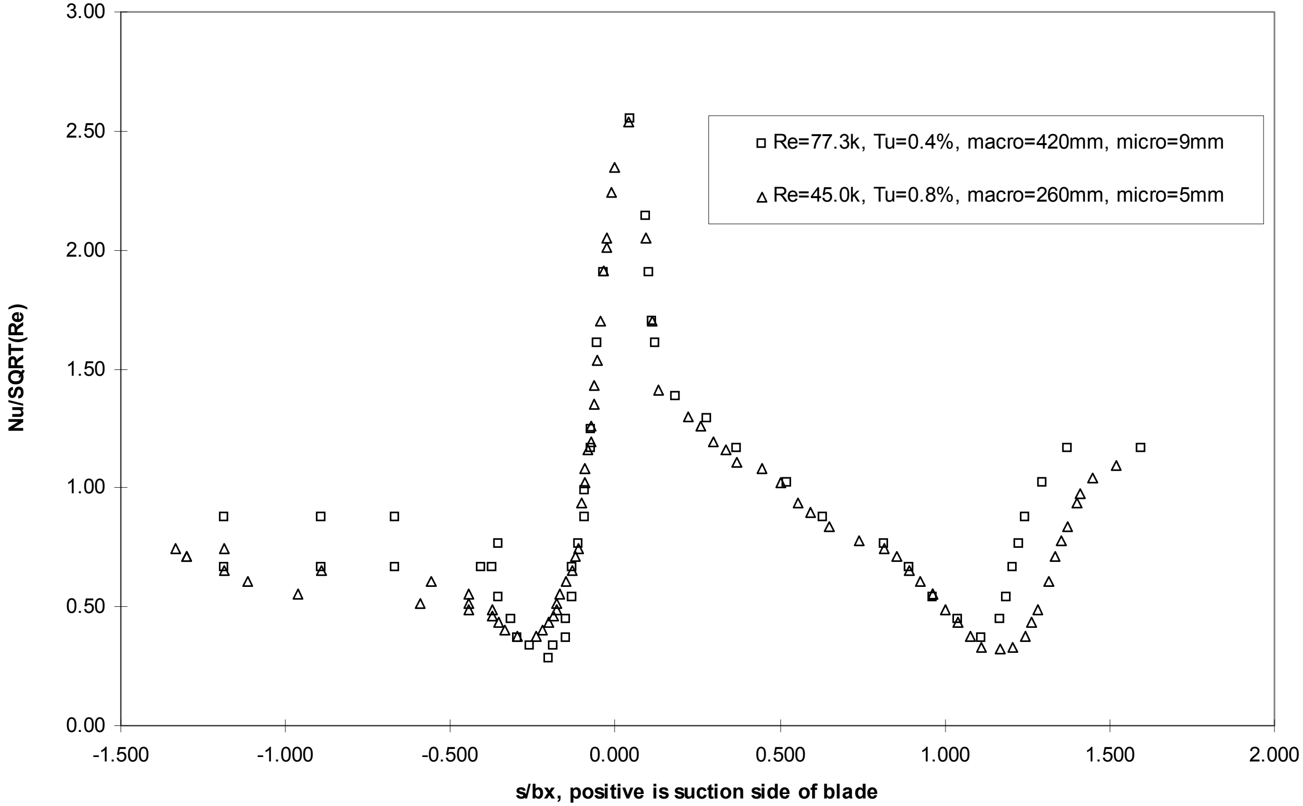


High Tu; Re= 46k
Low Tu; Re = 77k
Low Tu; Re= 45k
Re=46.1k, Tu=10.1%, macro=58mm, micro=20mm
Clean Re=45.0k, Tu=0.8%, macro=260mm, micro=5mm
Clean Re=77.3k, Tu=0.4%, macro=420mm, micro=9mm
Nu/SQRT(Re)
s/bx
0.00
0.20
0.40
0.60
0.80
1.00
1.20
0.800
0.900
1.000
1.100
1.200
1.300
1.400
1.500

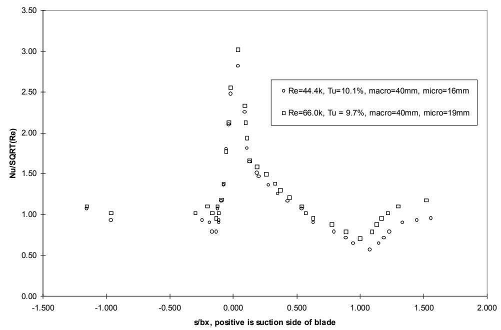
Stagnation Point Heat Transfer

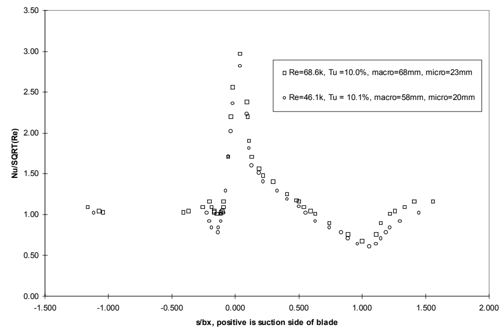


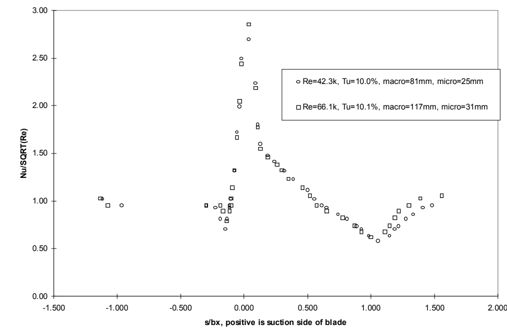
Effect of Re – Without Grid



Effect of Re – Tu = 10%







Small grid
b= 1.27 cm

Medium grid
b= 2.54 cm

Large grid
b=6.07 cm

Minnowbrook III, 20-23 Aug 00

Summary

- For constant Tu, the smallest length scale boosted heat transfer
    - Noticeably at the stagnation point
    - Not at all in the laminar region
    - Mildly in the transition region
    - Not at all in the fully turbulent region
- Low turbulence cases
    - Laminar separation at both Reynolds numbers
    - Görtler vortices on the pressure surface
- High turbulence cases
    - Transition without separation
    - Eliminated Görtler vortices
- Increasing the Reynolds Number
    - Reduced the size of the separation bubble for low Tu cases
    - Moved transition further upstream for high Tu cases

ESTIMATING TRANSITION LOCATION IN THE PRESENCE OF ROUGHNESS AND FREE-STREAM DISTURBANCES

J.D. Crouch and L.L. Ng
Boeing Commercial Airplanes
Aeroacoustics and Fluid Mechanics
Seattle, WA

Receptivity analysis is used in conjunction with linear stability theory to estimate the location of transition for various model-surface finishes and free-stream-disturbance environments. Tollmien-Schlichting instabilities and cross-flow instabilities are considered in the context of swept-wing transition, in low to moderate free-stream-disturbance environments. Receptivity studies include acoustic and vortical free-stream perturbations, surface roughness, and nonuniformities in surface suction.

With simplifying assumptions about the receptivity, a variable n-factor method has been formulated for transition due to cross-flow instabilities. Transition is correlated with the stationary cross-flow vortices for turbulence levels characteristic of flight. At higher turbulence levels, the transition is correlated with traveling cross-flow instabilities. In both cases, the n-factors vary with the surface-roughness level, consistent with a simplified model of non-localized receptivity at the instability neutral points.

ESTIMATING TRANSITION LOCATION IN THE PRESENCE OF ROUGHNESS AND FREE-STREAM DISTURBANCES

J. D. CROUCH
L.L. NG

BOEING COMMERCIAL AIRPLANES

"LINEAR AMPLITUDE METHODS"

- ⇒ ACCOUNT FOR ROUGHNESS/SUCTION VARIATION & FREE-STREAM DISTURBANCES

- → FOR CFD APPLICATIONS

- → SUPPORT WIND-TUNNEL TESTING

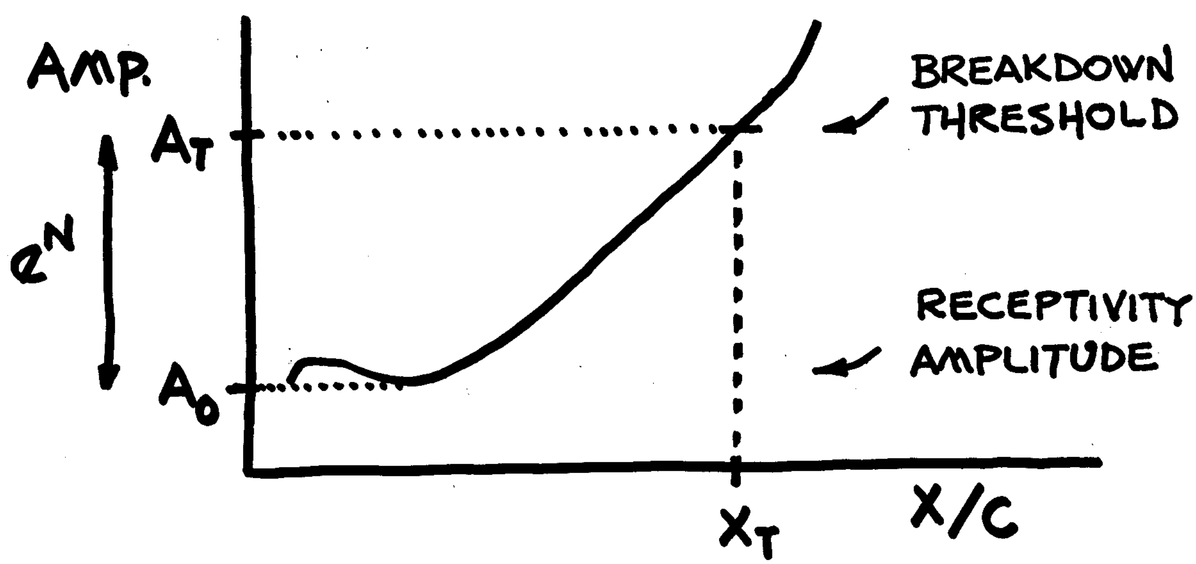
- → FOR AIRPLANES

  MECHANISMS - TS WAVES
  - CROSS-FLOW INSTABILITY

  ENVIRONMENT - FLIGHT
  - WIND TUNNEL

* MACK (1977) TS WAVES & Tu

TRANSITION PREDICTION
(LINEAR AMPLITUDE METHODS)



$$A(x;\beta,\omega) = \underline{A}(x_0;\beta,\omega)\, e^{N(x_0,x;\beta,\omega)}$$

$$\max_{\beta,\omega}\left[A(x_T;\beta,\omega)\right] = \underline{A_T}$$

β = SPANWISE WAVENUMBER

ω = FREQUENCY

RECEPTIVITY

⇒ ESTIMATE $A(\underline{x_0}; \beta, \omega)$

<u>STEADY MODES</u> (CROSSFLOW VORTICES)

✓ DIRECT EXCITATION FROM SURFACE

<u>UNSTEADY MODES</u> (TS WAVES, TRAVELING C-F)

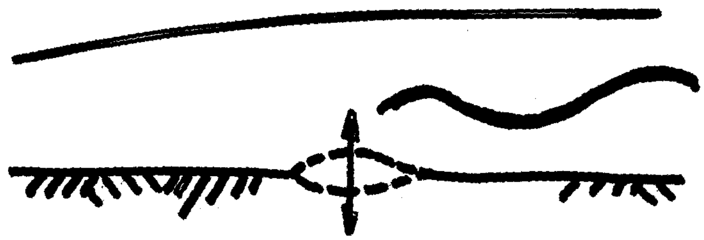
~ DIRECT EXCITATION FROM SURFACE

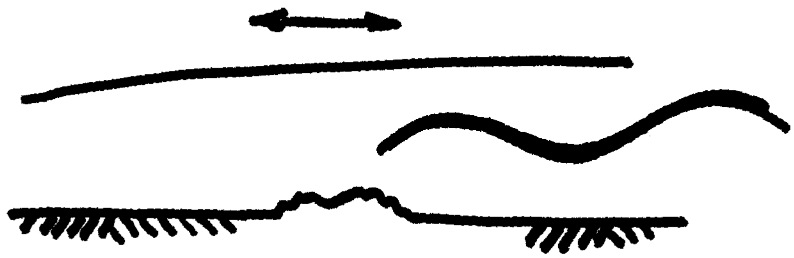
✓ COUPLING BETWEEN SURFACE & FREE-STREAM DISTURBANCES

✗ DIRECT EXCITATION FROM FREE-STREAM DISTURBANCES

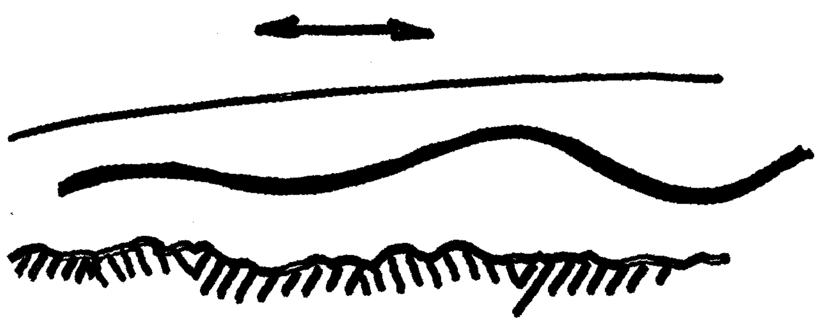
RECEPTIVITY MECHANISMS

LOCALIZED





NONLOCALIZED



TS wave receptivity

	Acoustic ε	Vortical ε
Localized Gaussian hump δ	(1) $\varepsilon\ \delta$	(.05) $\varepsilon\ \delta$
Non-localized wavy wall δ	(18) $\varepsilon\ \delta$	(.5) $\varepsilon\ \delta$
Non-localized idealized roughness $\delta_1\ \delta_2$	(67) $\varepsilon\ \delta_1\ \delta_2$	

Cross-flow instability receptivity

	Steady roughness ε	Unsteady acoustic ε roughness δ
Localized	(1) δ	(36) ε δ
Non-localized	(~5) δ	

Table I

Transition amplitudes for TS-wave transition

Reference	Criterion	A_{TS}
Klebanoff *et al.* (1962)	rapid rise in u'	2-3%
Cornelius (1985)	drop in H	4%
Spalart (1993)	0.1 drop in H	2-4%
Kosorygin (1996)	rise in C_f	2-3%

$A_{TS} \sim 3\%$

Table II

Transition amplitudes for CF-instability transition

Reference	Criterion	A_{CF}
Spalart (1993)	0.1 drop in H	3-4%
Malik *et al.* (1994)	rise in C_f	5-6%
Reibert *et al.* (1996)	rise in C_f †	3-8%
Reibert *et al.* (1996)	rapid rise in u'	O(70%)

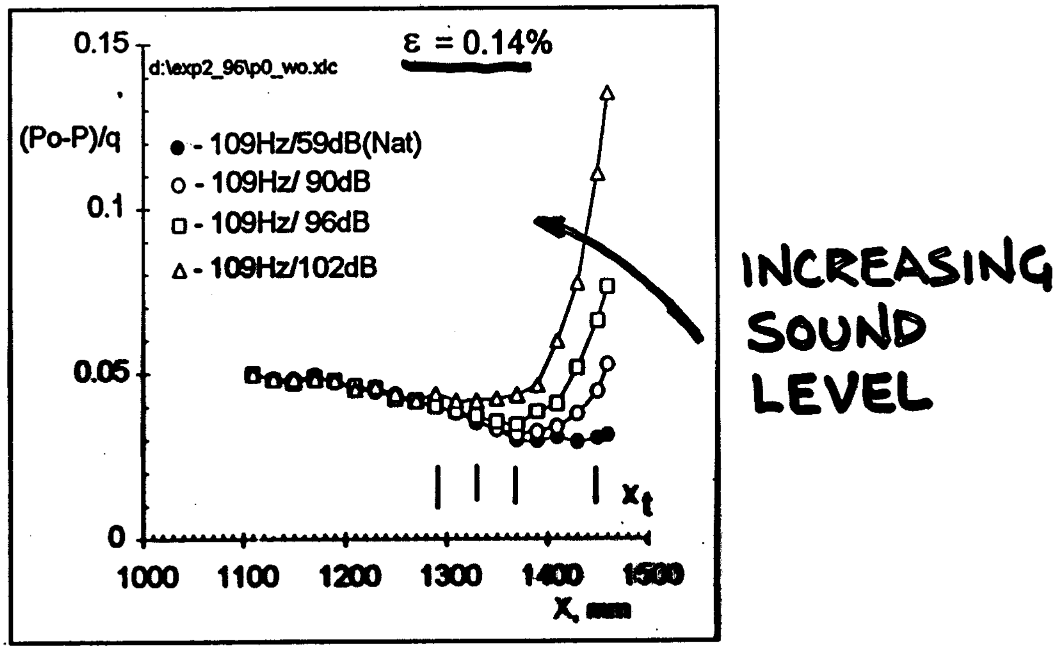
† estimated.

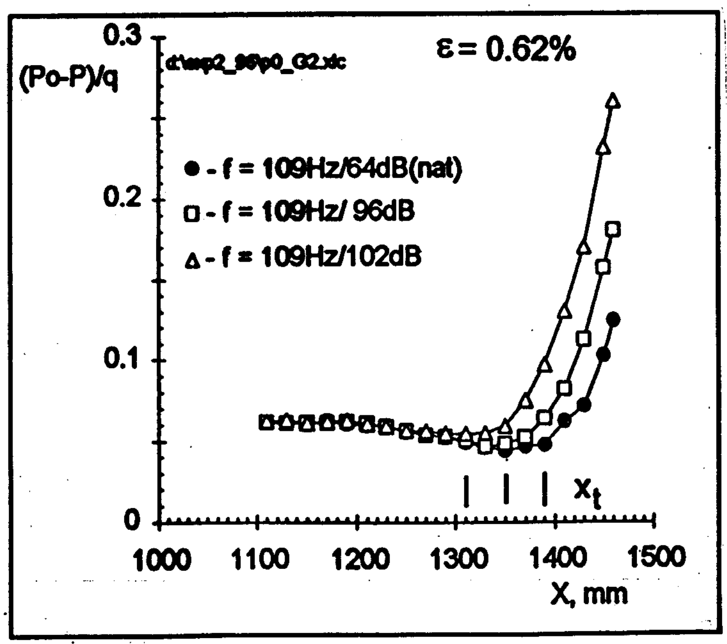
RISE IN C_f : $A_{CF} \sim 5\%$

→ RISE IN u' : DEPENDS ON SPECTRUM

EFFECTS OF NOISE & TURBULENCE ON TRANSITION

(KOSORYGIN EXPERIMENTS), ITAM



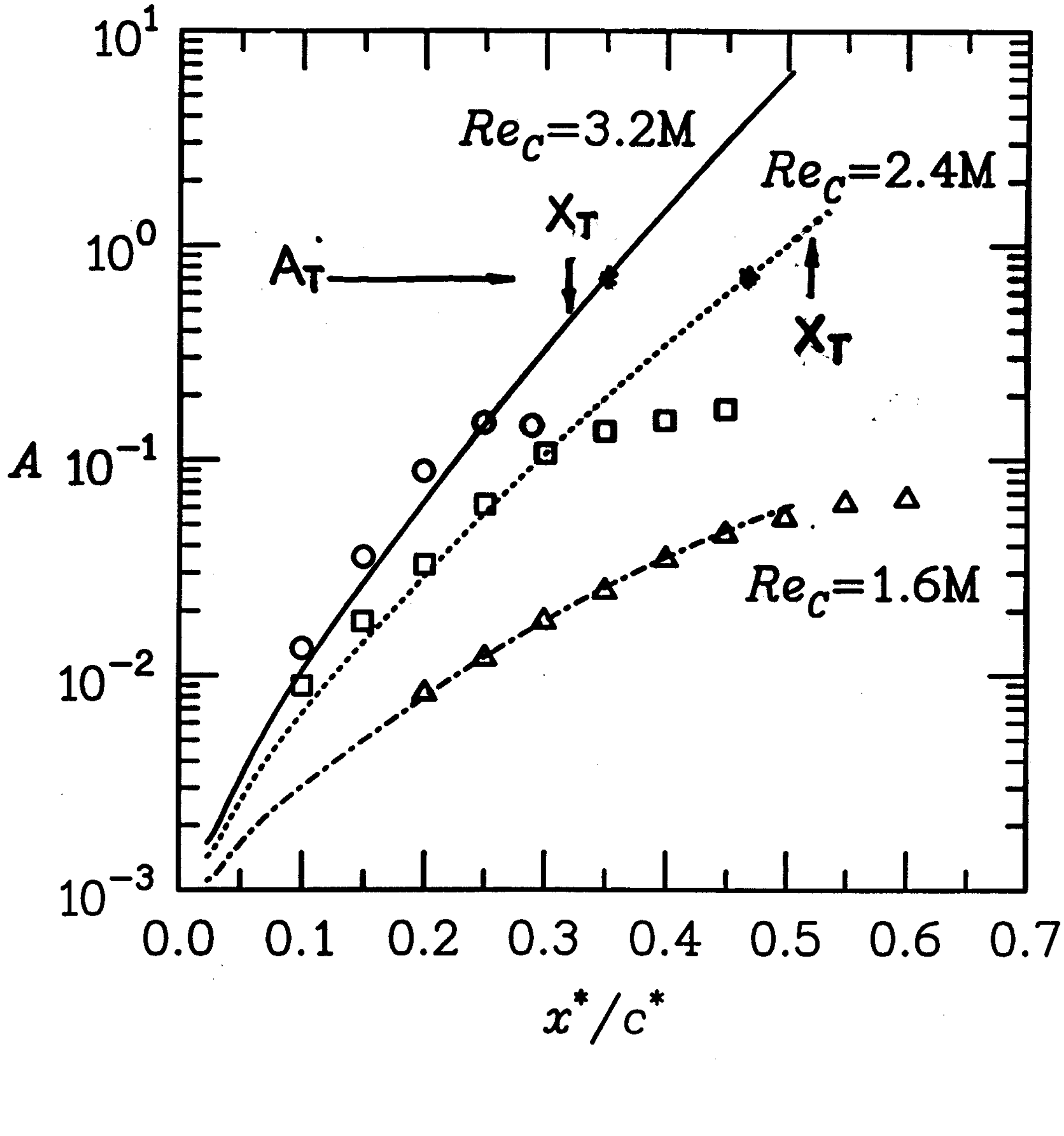


STATIONARY CROSS-FLOW INSTABILITY

→ ROUGHNESS-INDUCED TRANSITION

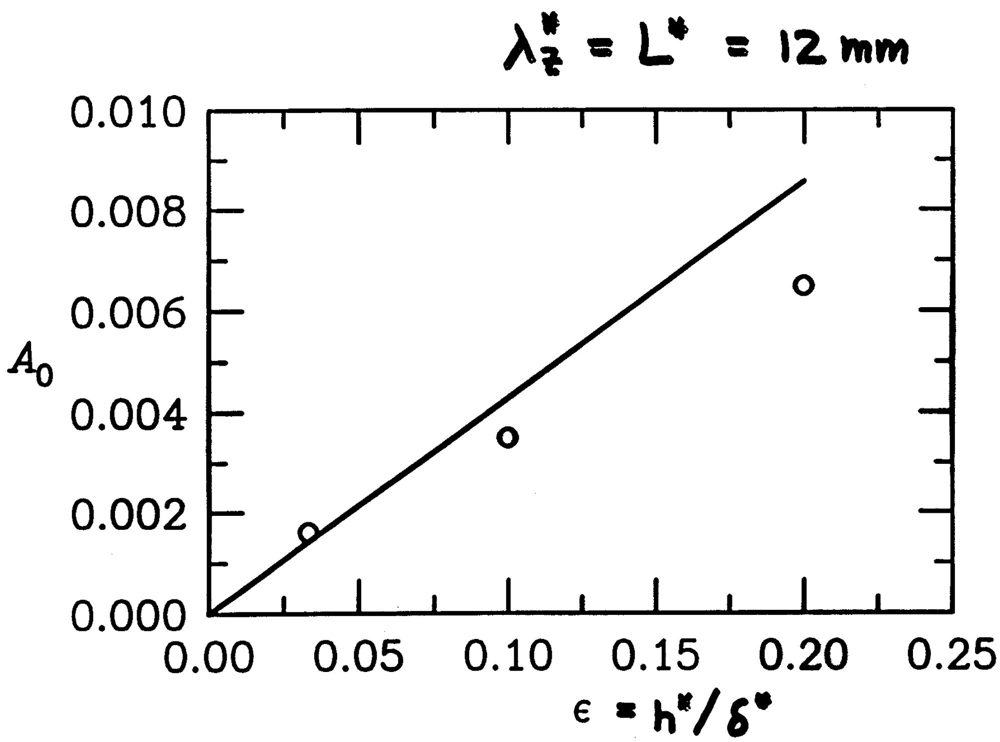
EXP. : REIBERT ET AL. (1996)

VARIATION W/ REYNOLDS NUMBER



RECEPTIVITY AMPLITUDE
VARIATION W/ ROUGHNESS HEIGHT

EXP. REIBERT ET AL. (1996)



EFFECTS ON TRANSITION:

- LIN. AMP. OVERPREDICTS h^* EFFECT
- β SPECTRUM IMPORTANT
- LIN. AMP. NOT VIABLE FOR 'SINGLE β' EXCITATION

VARIABLE N-FACTOR METHOD

- DISTRIBUTED RECEPTIVITY
- UNIFORM SOURCE SPECTRUM

$$\delta = h_{rms} / \delta^{*} \quad @ \quad x_I$$

- INITIAL AMPLITUDE AT NEUTRAL POINT, x_I

$$A(x_I ; \beta, \omega) = \delta \, C$$

- STATIONARY C-F VORTICES

$$N_{SCF} = \max_{\beta} \left[N(x_I, x_T ; \beta, 0) \right]$$

$$= \ln \left(\frac{A_{SCF}}{\delta \, C_{SCF}} \right)$$

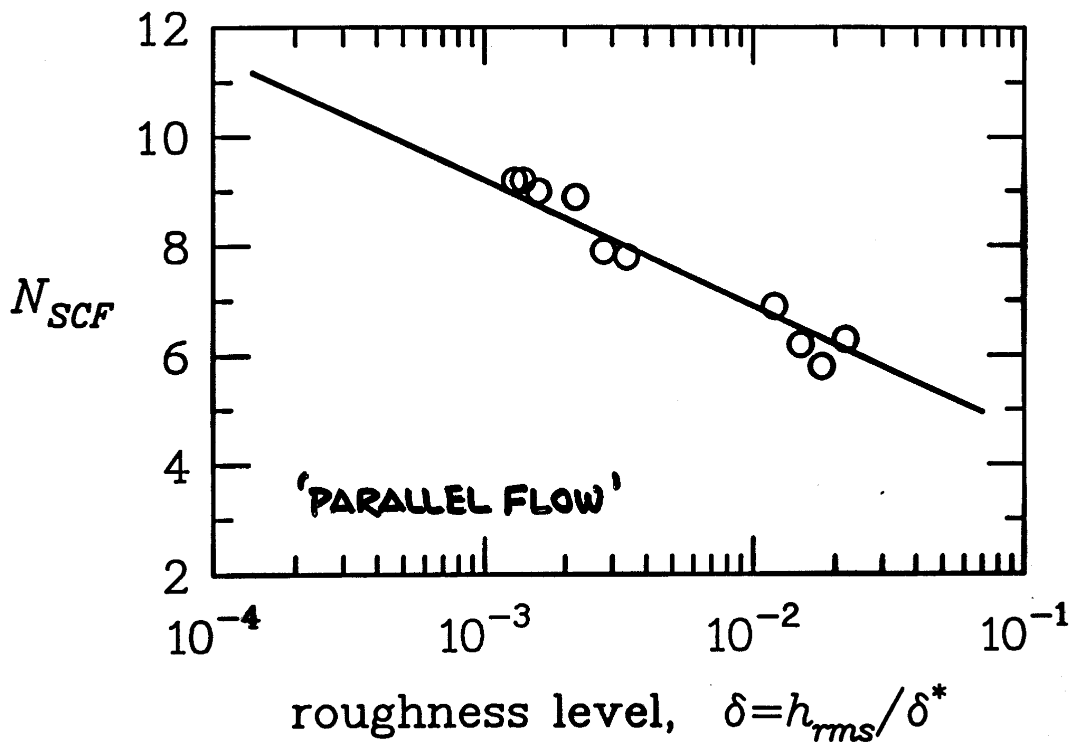
$$N_{SCF} = N_{SCFO} - \ln(\delta)$$

VARIABLE N-FACTOR

STATIONARY C-F VORTICES ($Tu \approx .02\%$)

$$N_{SCF} = 2.3 - \ln(h_{rms}/\delta^*)$$

EXPERIMENT: RADEZTSKY ET AL (1993)

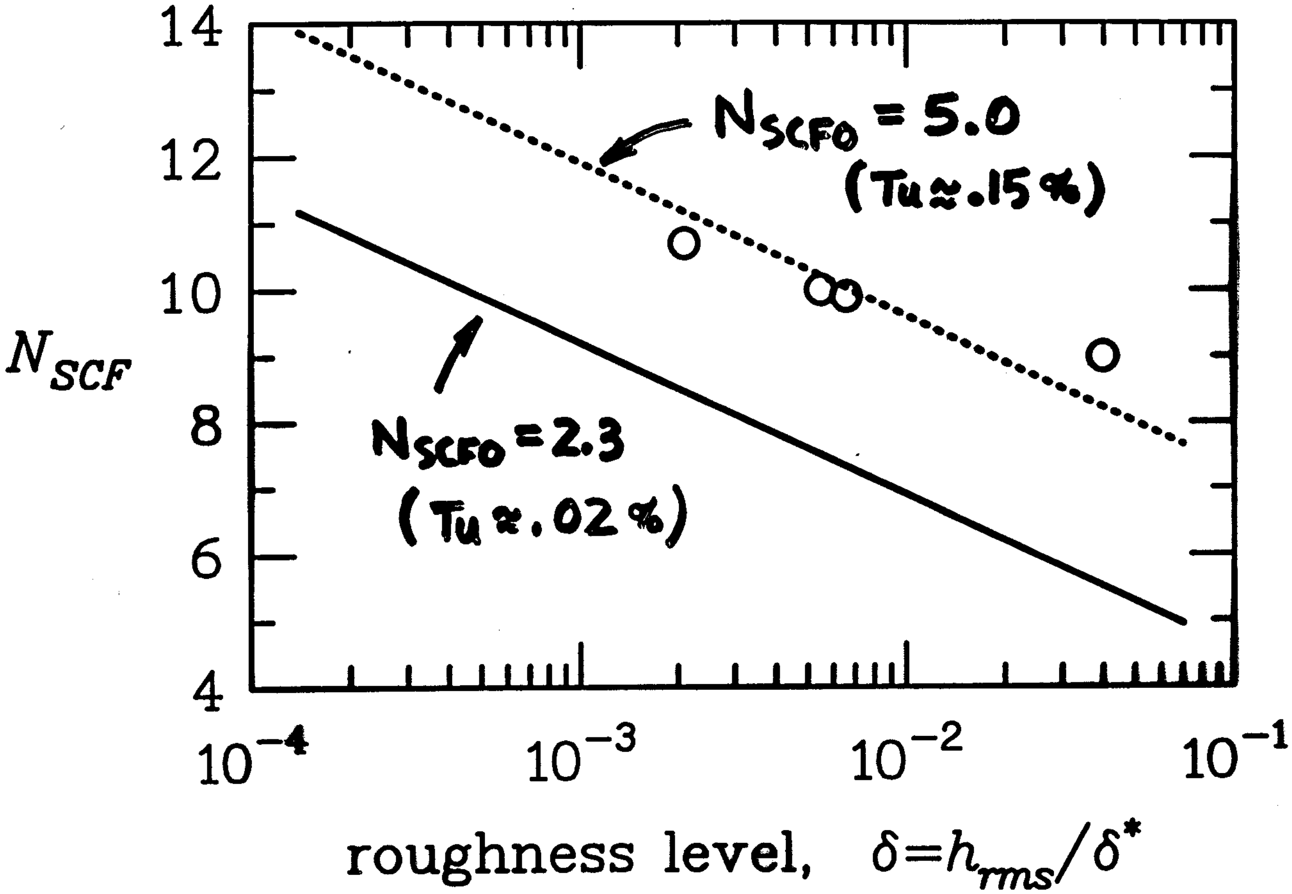


CROUCH & NG (2000), AIAA J.

VARIABLE N-FACTOR
STATIONARY C-F VORTICES

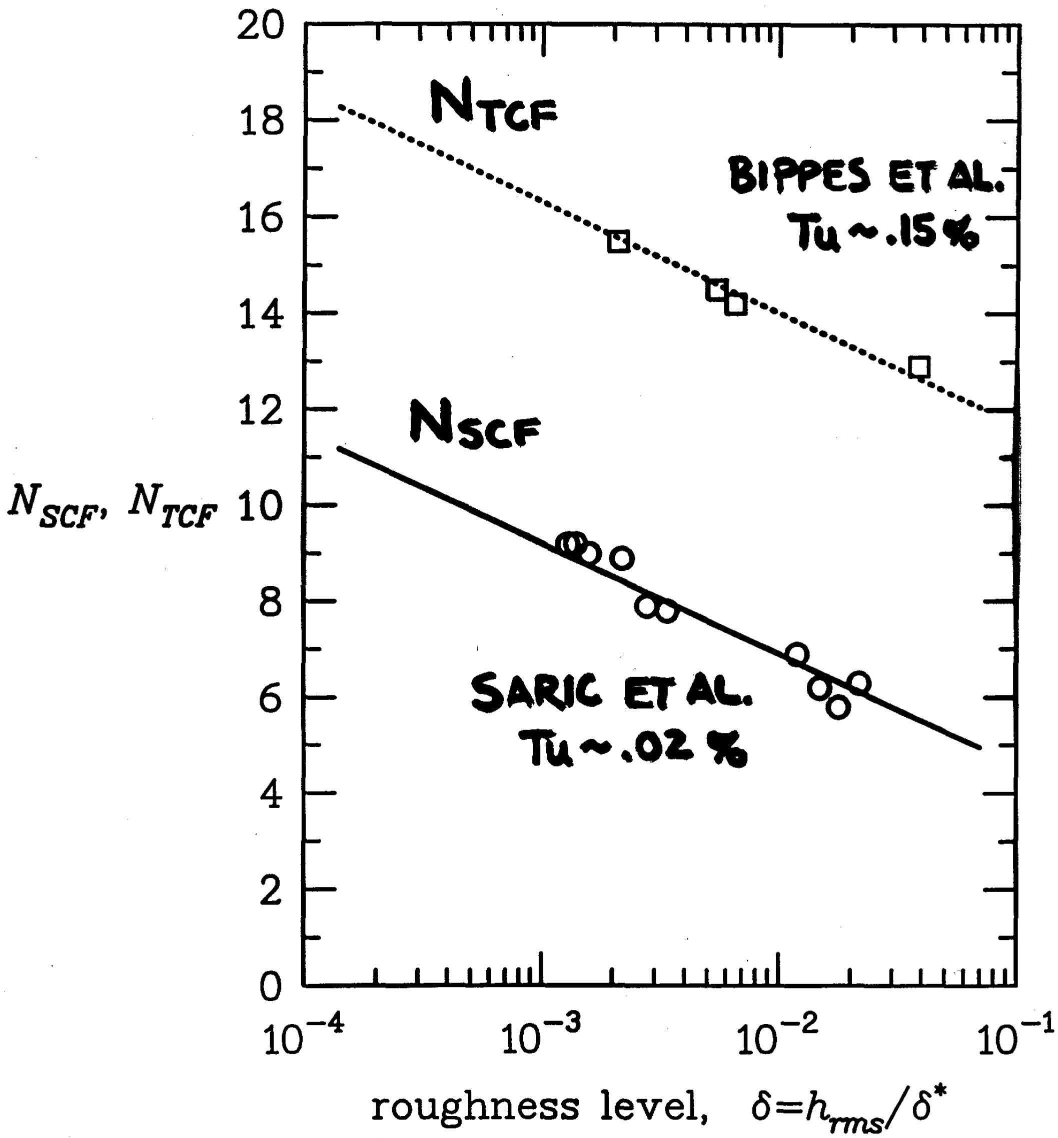
$$N_{SCF} = N_{SCFO} - \ln(h_{rms}/\delta^*)$$

EXPERIMENT: DEYHLE & BIPPES (1996)



CROUCH & NG (2000), AIAA J.

VARIABLE N-FACTOR
STATIONARY & TRAVELLING C-F

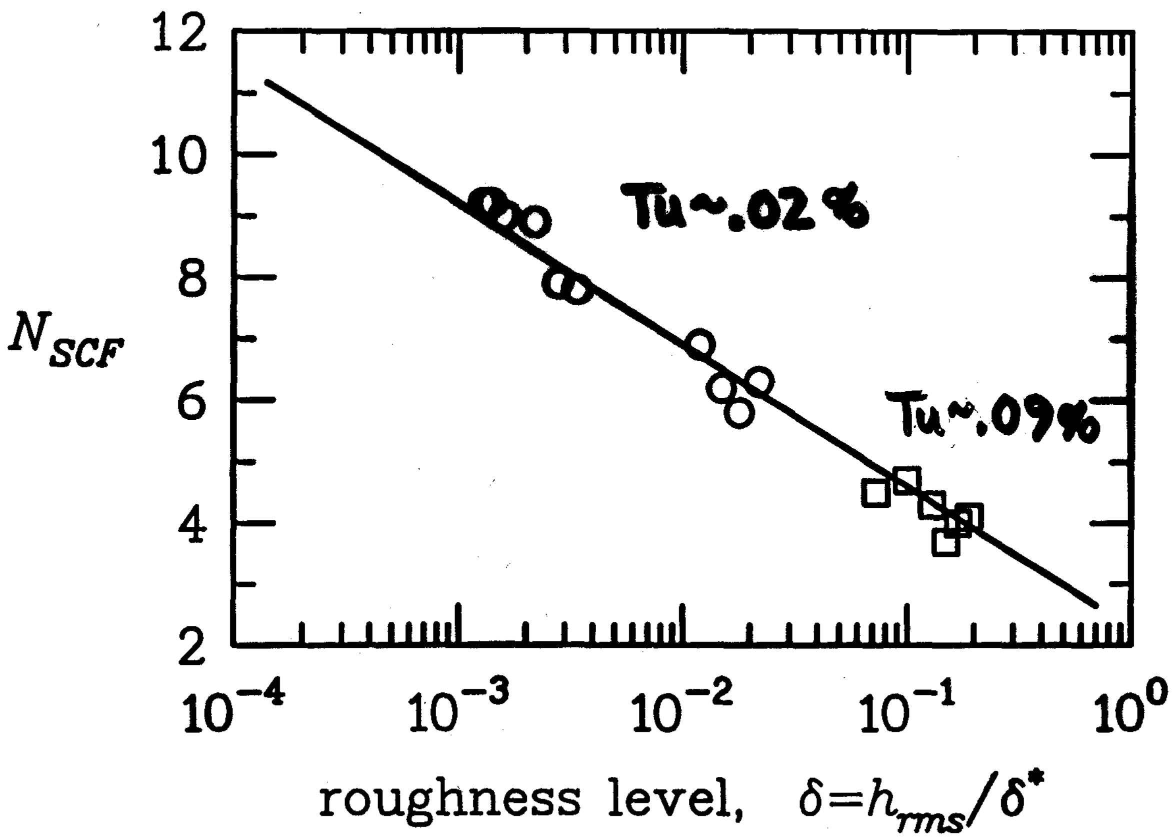


VARIABLE N-FACTOR

STATIONARY C-F

○ SARIC ET AL.

□ KACHANOV ET AL.



CONCLUSIONS

- LINEAR AMPLITUDE METHODS OFFER IMPROVED PHYSICS AT SMALL Δ COSTS COMPARED TO e^N
- RECEPTIVITY ANALYSIS PROVIDES INITIAL AMP.S FOR PRACTICAL FLOWS
- LINEAR AMPLITUDE METHOD
  ⇒ VARIABLE N-FACTOR METHOD
- VARIABLE N-FACTORS IN GOOD AGREEMENT W/ EXPERIMENTS

EFFECT OF A ROUGHNESS ELEMENT ON DEVELOPMENT OF THE VISCOUS LAYER FOR A TURBULENT BOUNDARY LAYER

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In many technical applications, laminar boundary layers are induced, by roughnesses, to undergo transition to a turbulent flow at lower Reynolds numbers than the natural flow transition. The present studies were undertaken to extend the knowledge of the spatial and temporal structure of the transition process induced by a single square roughness element. Particular emphasis was placed on the evolution of the viscous layer since it usually dominates the convective resistance to heat transfer (and momentum transfer) to/from a surface. The aim is to reach a better understanding of the fluid physics structure which evolves in a transition process induced by roughnesses, especially in the near-wall region. The results should also be valuable for benchmarking Direct Numerical Simulations of transition enhanced by the presence of roughness elements.

To measure the wall-normal component close to the surface, two-component laser Doppler anemometry (LDA) was used with the INEEL Matched-Index-of-Refraction (MIR) flow system. With hot-wire and hot-film X- or slant-probes to deduce Reynolds shear stresses, the sensor volume required has a dimension of the order of a millimeter perpendicular to the surface plus the additional space necessary for the support prongs. With LDA, an effective sensor diameter of about 60 µm or less can be achieved so measurements can be obtained to y = 30 µm before "intersecting" the surface. However, the wall can interfere with the laser beams of an LDA system, especially when systems for two- and three-component measurements are employed. One way to eliminate these problems is to use a liquid possessing a refractive index that is matched to that of the wall material. The INEEL MIR flow system provides a basic test facility to study boundary layer transition in detail. The length of the test section is about 2.4 m and it has a cross section of about 0.61 m x 0.61 m, compared to other MIR facilities which have characteristic dimensions of a few centimeters.

Measurements of flat plate boundary layers were carried out with three different roughness heights k and three different freestream velocities, resulting in the following ranges of parameters:

$$k^+ = 5.9 \text{ to } 22;\ 6 \times 10^4 < Re_{x,k} < 1.5 \times 10^5;\ Re_\Theta < 560;\ 2.5 < (x - x_k)/k < 580$$

The LDA system yielded data to a distance as near to the wall as $y^+ = 0.1$ and less. Thus, it was possible to estimate the local apparent wall shear stress accurately from the measured gradient $\partial U/\partial y$. Most of the data were acquired with a two-component LDA operating in the forward scattering mode, thereby permitting simultaneous streamwise and normal velocity component measurements and calculation of their higher-order moments to be performed. The distributions of the nondimensional profiles u^+ and y^+ will be presented as well as development of the fluctuating turbulent components $(u')^+$ and $(v')^+$ and of the Reynolds shear stress in the viscous layer.

In addition to presentation of the results of this recent experiment, plans will be discussed for a comparable upcoming study using the INEEL MIR system. For the DoD-EPSCoR/AFOSR program, Prof. Ralph S. Budwig of the University of Idaho will measure the fluid physics of turbulent and transitional flow over roughnesses characteristic of realistic surfaces of turbomachinery blades. Idealized surface models will be developed from the WPAFB database in collaboration with AF technical representatives.

Effect of a Roughness Element on Development of the Viscous Layer for a Turbulent Boundary Layer

S. Becker*, *K. G. Condie, C. M. Stoots, and D. M. McEligot

Topics

- ***Introduction/previous work***
- ***The unique INEEL Matched-Index-of-Refraction flow system***
- ***Viscous layer development downstream of a 2-D square rib***
  - ***Apparatus***
  - ***Measurements***
- ***Boundary layer over turbine blades with realistic rough surfaces (U. Idaho)***
- ***Concluding remarks***

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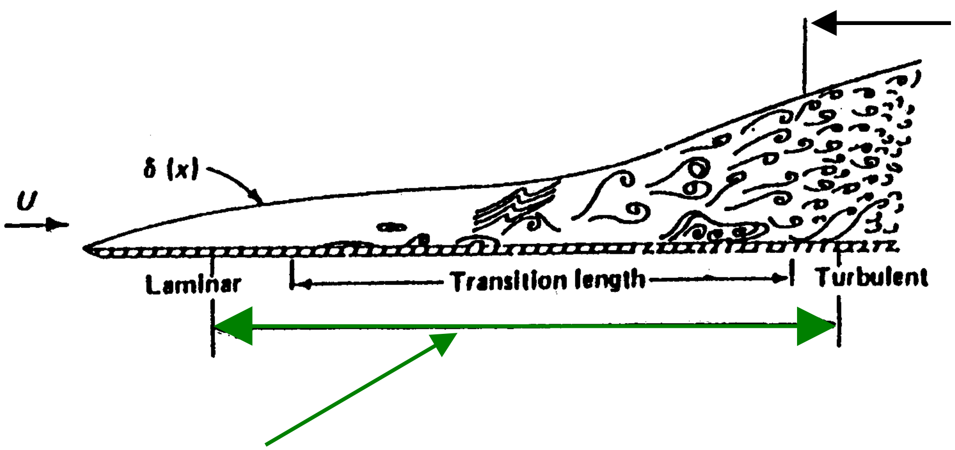
***Question* = How does the turbulent contribution to transport evolve in a transitional boundary layer to enhance heat, mass and/or momentum transfer?**

- ***A measure = Reynolds shear stress*, e.g.,** $(\tau / \rho) = \nu \partial U / \partial y - \overline{uv}$

- ***For f.d. t.b.l., a key uncertainty in __ resistance is in the viscous layer, ~ 5 < y^+ < 30 (also for LES)***

Some previous measurements of transition structure



Developed low-Re t.b.l.

Purtell, Klebanoff & Buckley (1981) "u" y^+ > ~3

Murliss, Tsai & Bradshaw (1981) X-wire y^+ > ~300

Erm & Joubert (1991) X-wire y^+ > ~50

Bypass transition, Suder, O'Brien & Reshotko (1988), "u" y^+ > ~8

Turbine blade, Qui and Simon (1997) "u"

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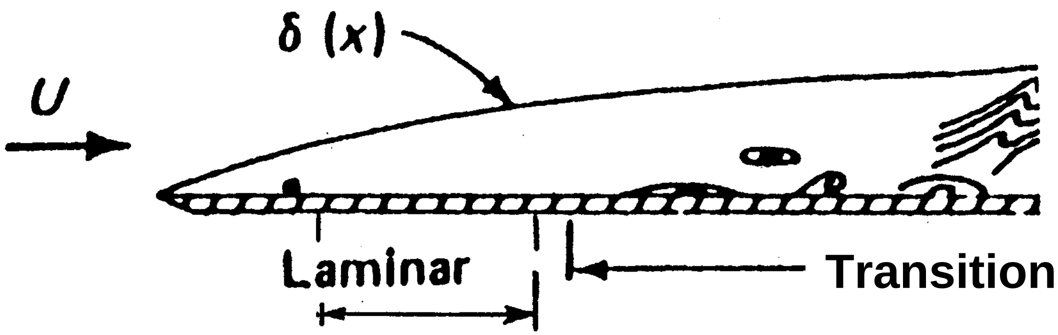
Induced transition

Klebanoff & Tidstrom (1972)

Circular wire, "u"

Emphasis on "recovery zone"

$(x-x_k)/k < 70$ --> laminar



Arnal, Juillen & Olive (1979) - coarse-grain rectangle, "u"

Erm and Joubert (1991) - 3 shapes for trip, downstream profiles affected

Becker, LSTM (1997) - square, "u"

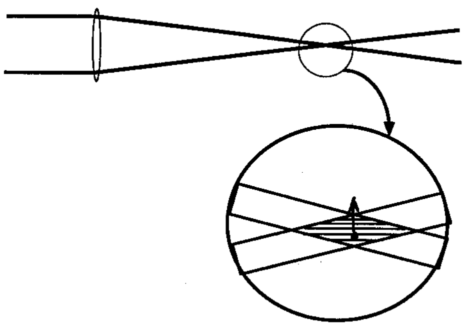
None of these experiments had instrumentation and spatial resolution to deduce v and uv accurately in the viscous layer

Some needs

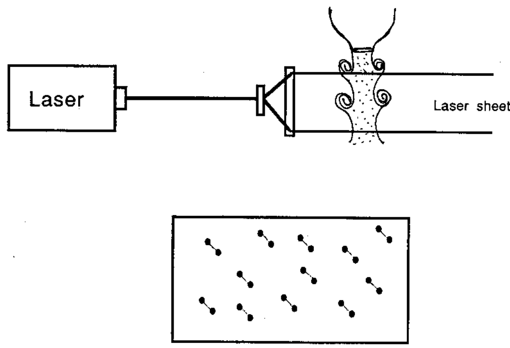
- ***Separate u and v (from "u") --> v --> uv***
- ***Evolution of turbulent transport in the viscous layer***
- ***Benchmark data for DNS, LES, and other CFD***

Benefit of Refractive-Index Matching

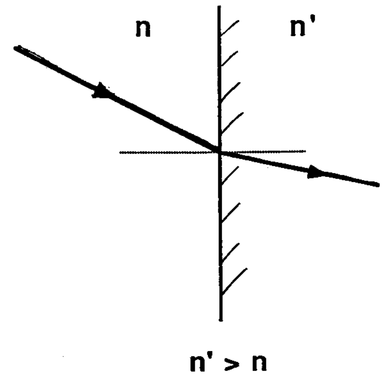
Laser Doppler Velocimetry



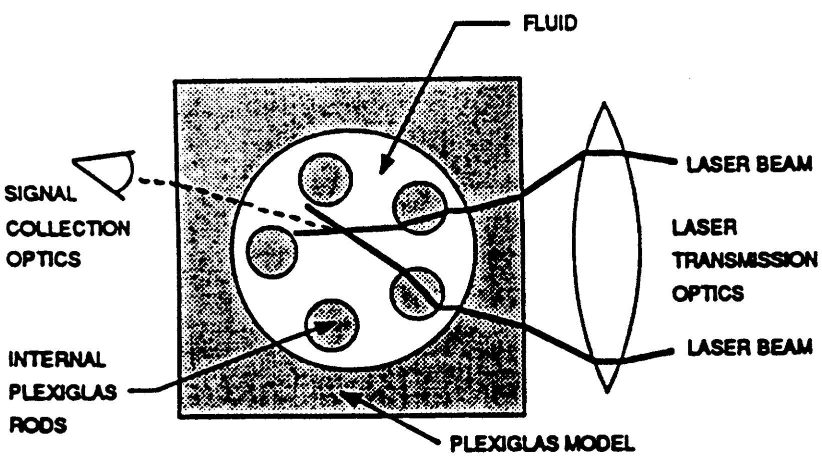
Particle Image Velocimetry



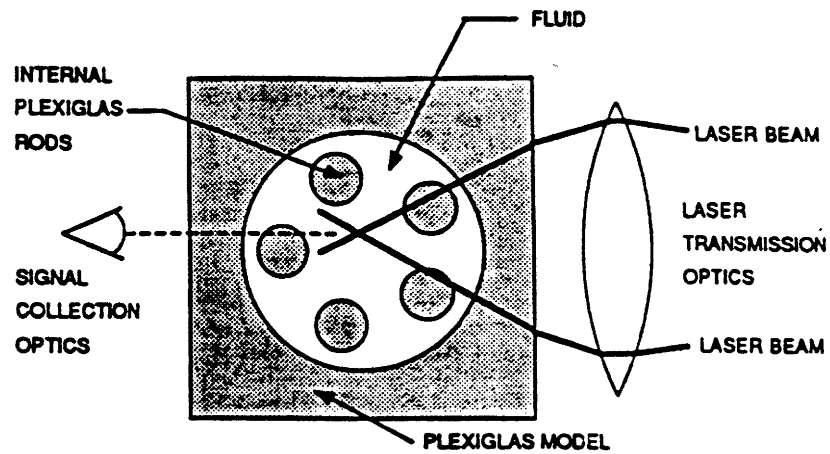
Bragg's Law



Refractive index not matched



Refractive index matched



From Thompson, Bouchery and Lowney [1995]

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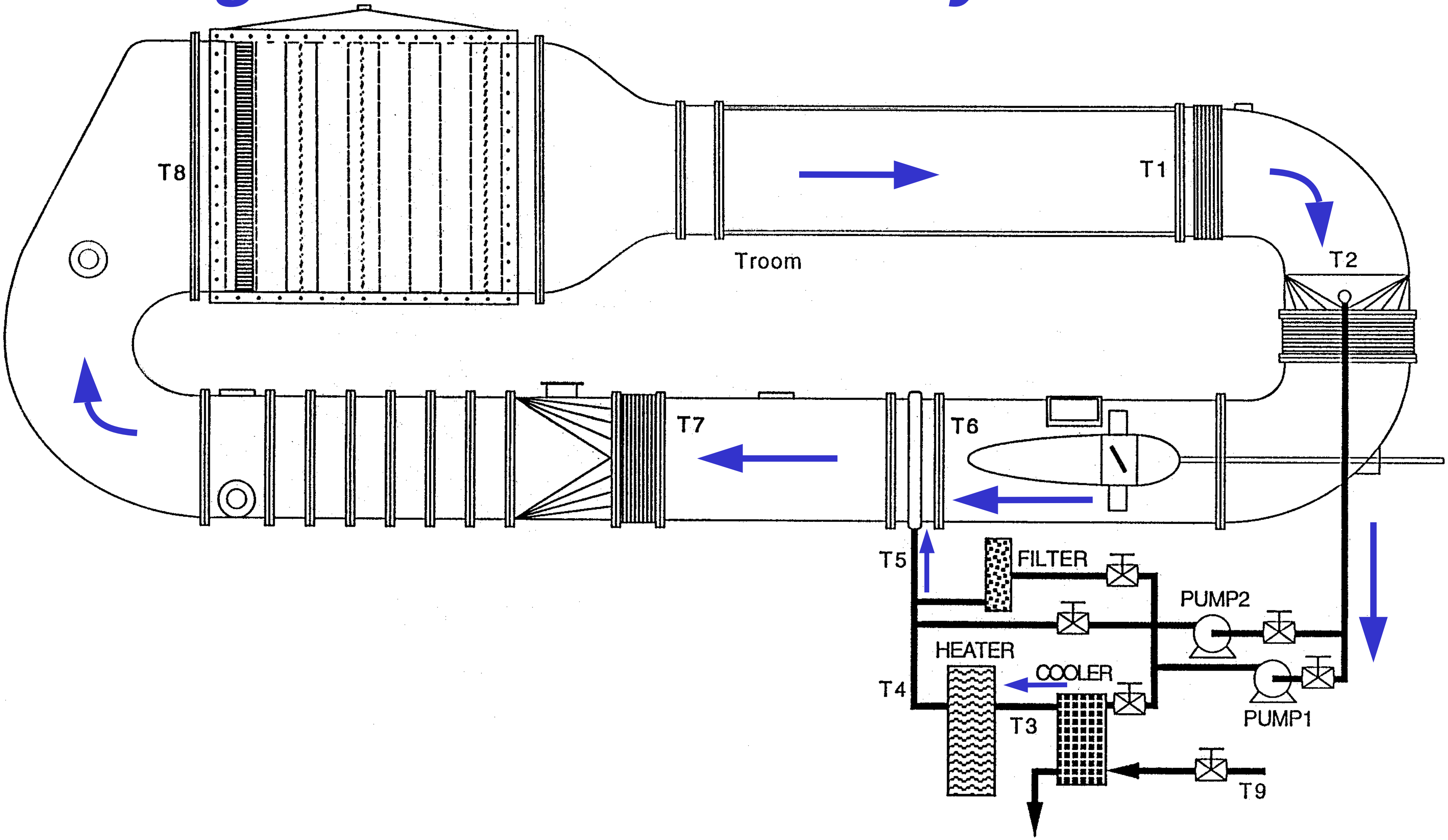
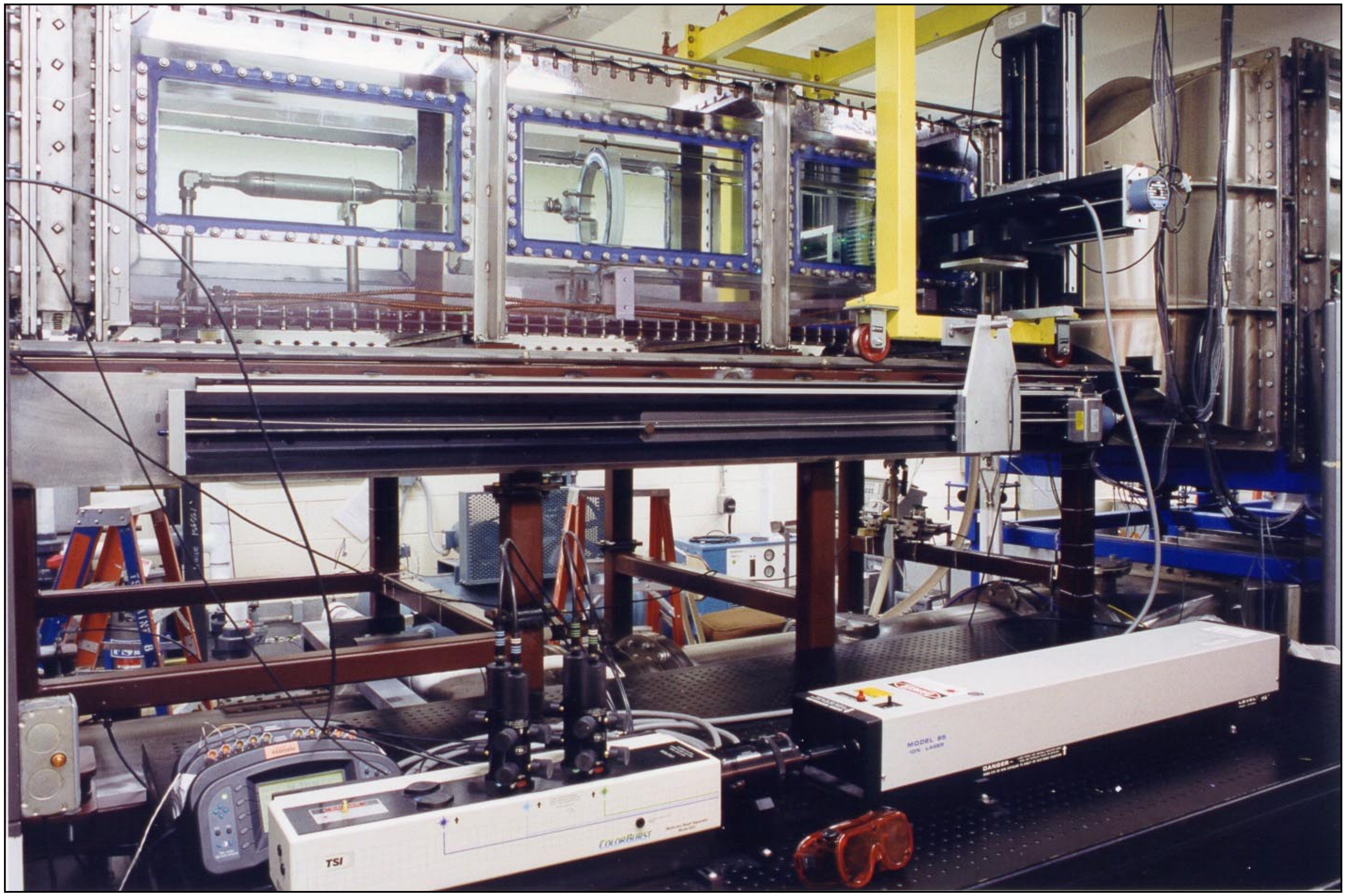
The large INEEL MIR flow system



MIR Test Section



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Advantages of INEEL MIR flow system

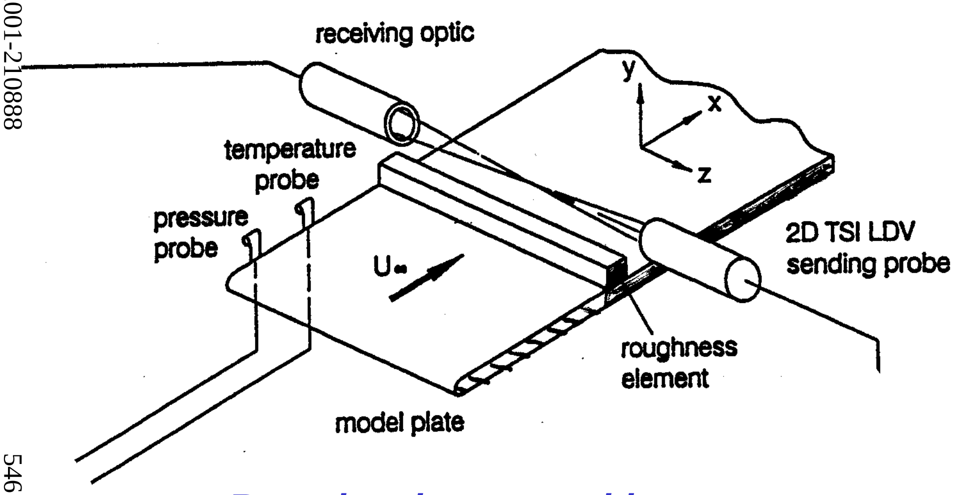
- *Optical measuring techniques for internal and external geometries do not disturb the flow* - *LDV, PTV and MPT*
- *Refractive-index matching avoids optical distortion (and related problems)*
- *Can measure v and its products (uv) to y = "0"*
- *Low velocity --> Re′ < 2 x 10^5 1/m --> large size*

  ----> Good spatial resolution
- *Large size + low velocity)t^+ = tV/L --> t = t^+ L/V*

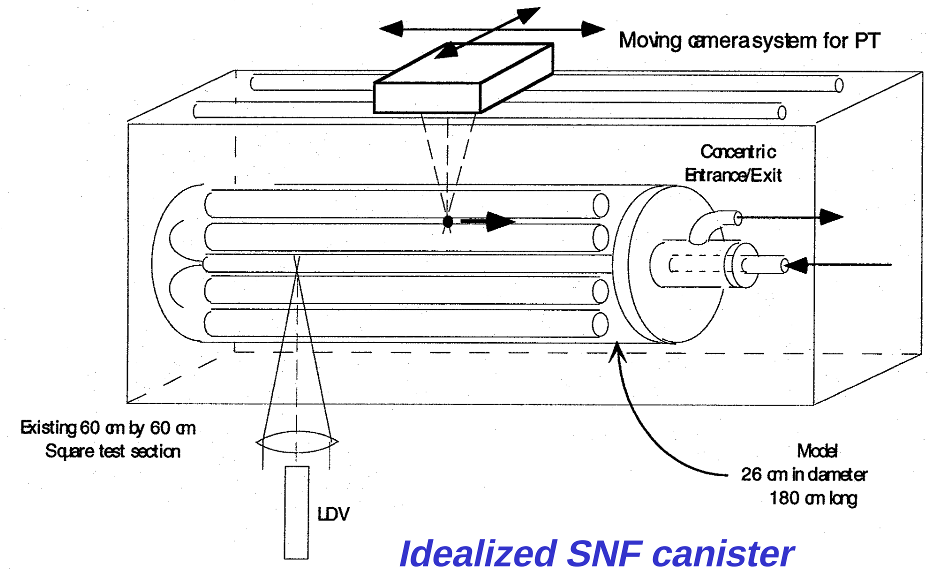
  ----> Good temporal resolution
- *Refractive-index matching + forward scattering --> reduction of noise in near-wall data ----> good signal-to-noise ratio*

  ----> Benchmark data

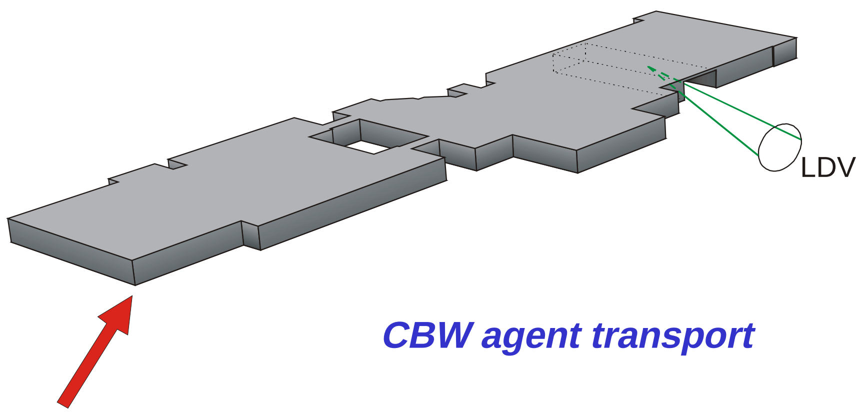
Recent and current experiments



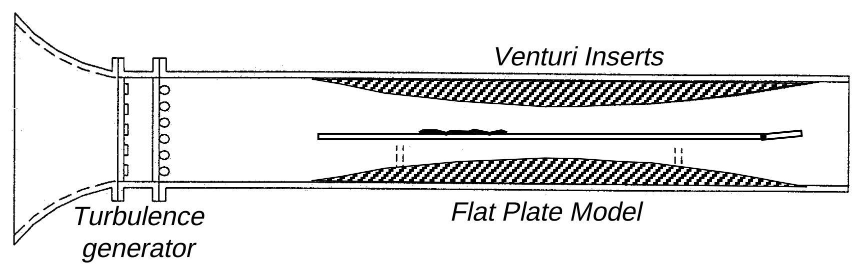
Boundary layer transition



Idealized SNF canister



CBW agent transport



Realistic rough surfaces in turbomachinery

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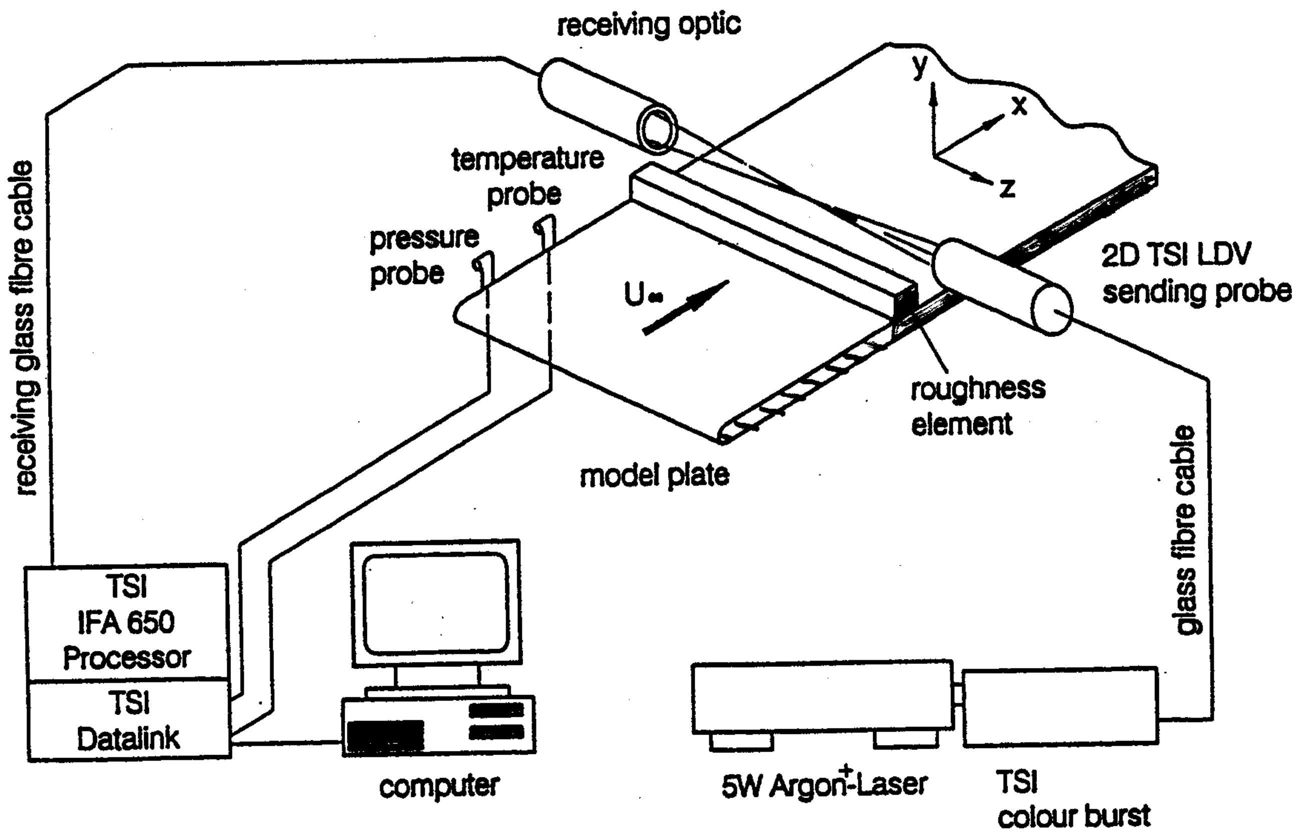
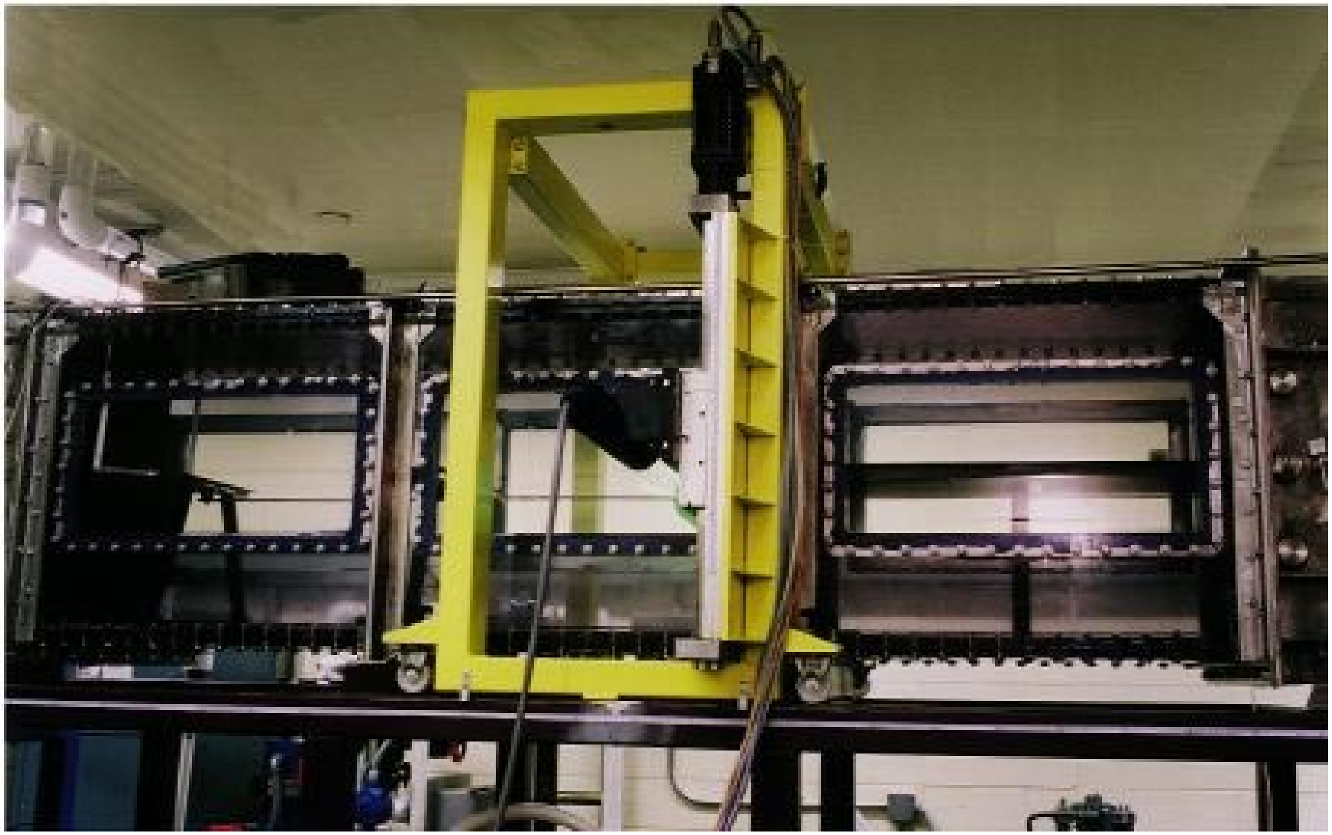
Experiment on viscous layer development downstream of a 2-D square rib



MIR test section with BLT model installed



Flow is right to left

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Present experiment

Objective = Examine the structure of the transition process induced by a square rib, in terms of u', v', and uv.

Measurements

$u(t)$ and $v(t)$ by LDV, $d^+ < 0.4$

Rib and plate downstream transparent, refractive indices matched

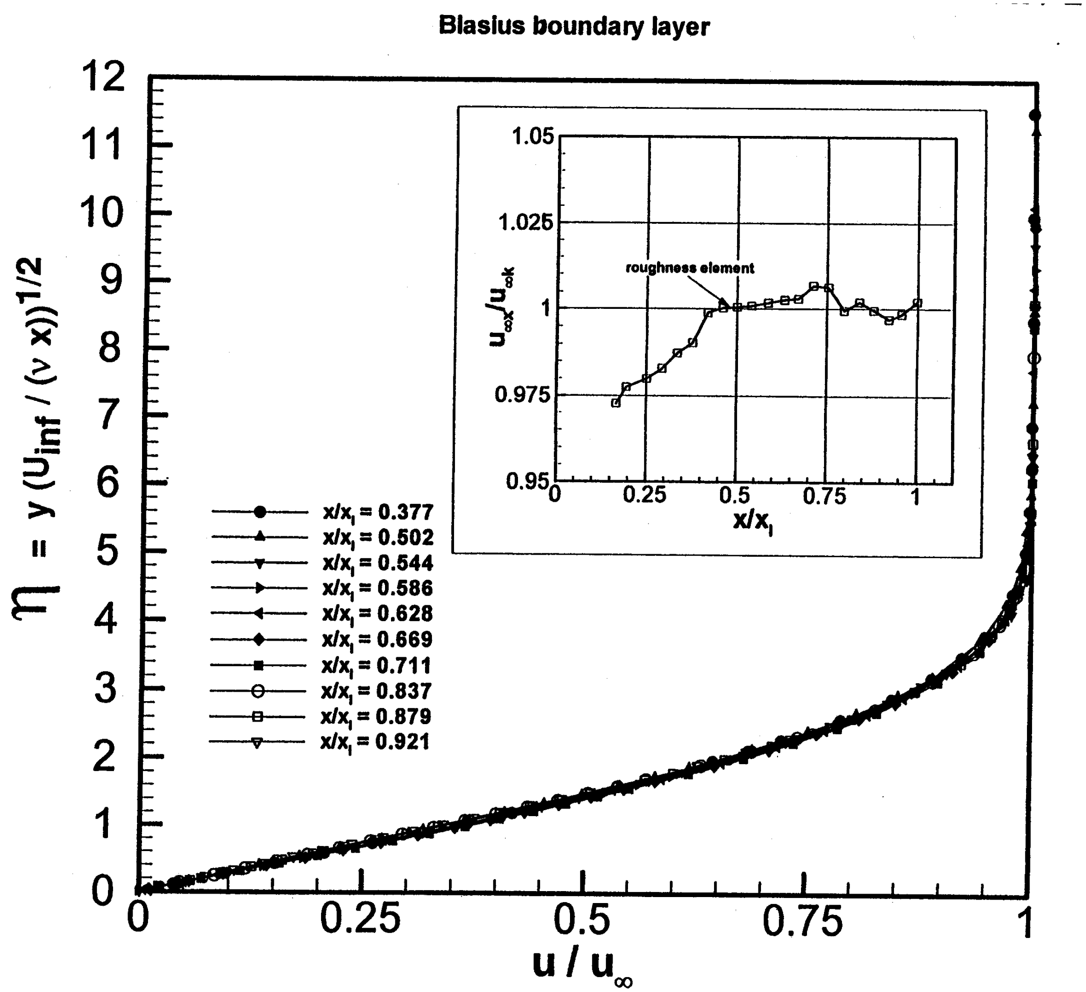
$k = 0, 2, 4, 6$ mm, $0.75 < U_\infty < 1.75$ m/s, oil

$\rightarrow$ $k^+ \approx 5.9$ to 22, $6 \times 10^4 < Re_{x,k} < 1.5 \times 10^5$, $Re_\theta < 560$

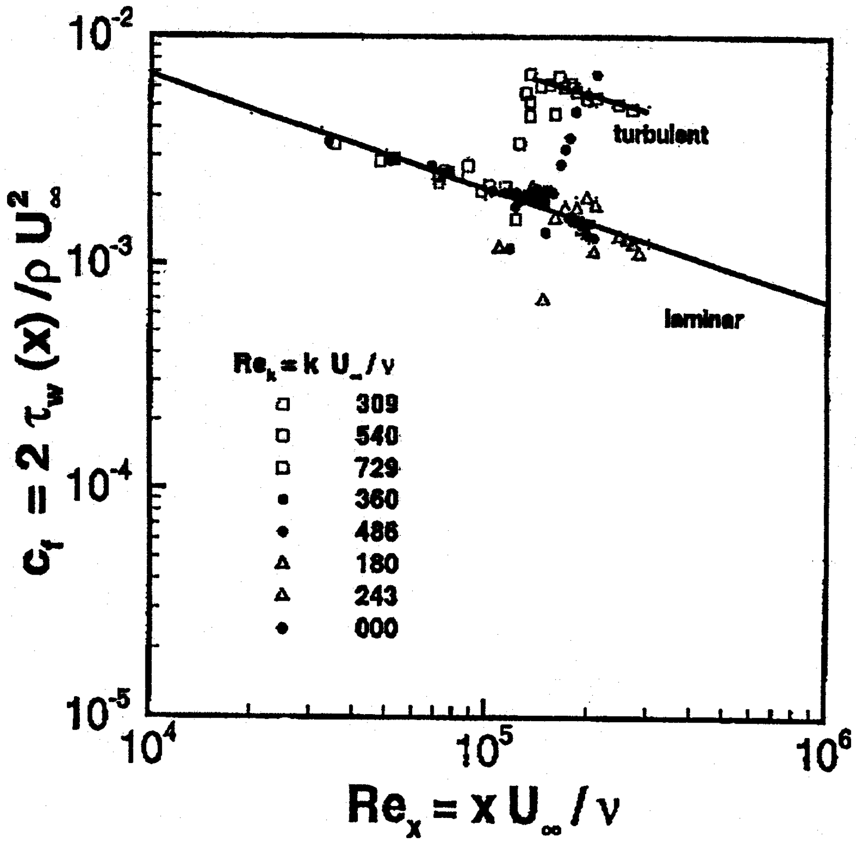
$y^+ > 0.5$, $2.5 < (x - x_k)/k < 580$

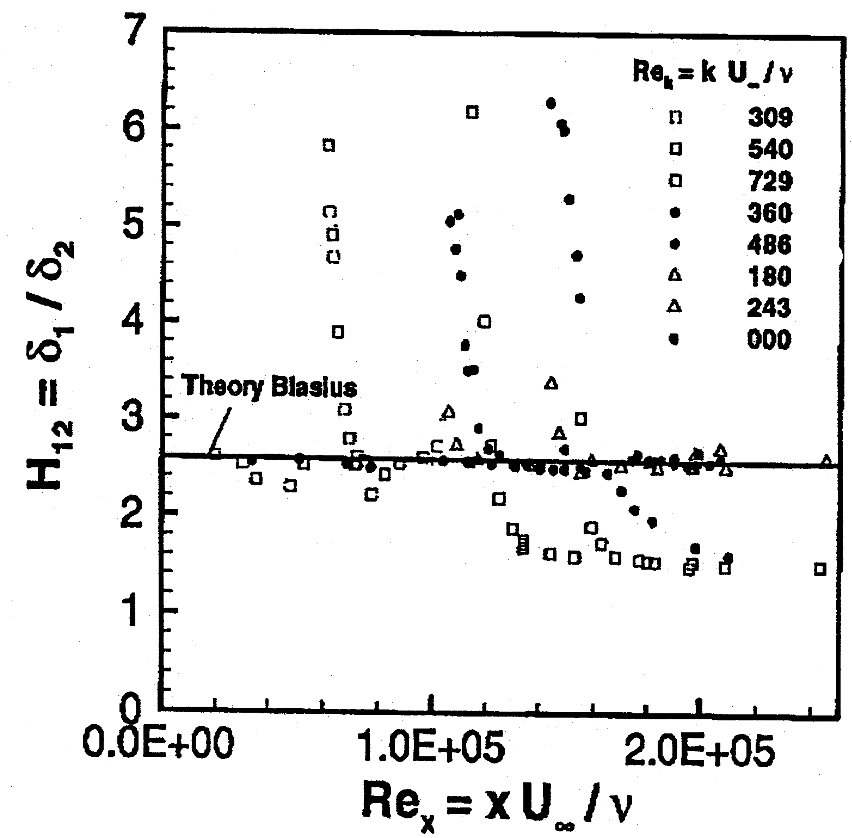
Time series and mean profiles, 7 runs with rib

Smooth wall *0.37 < x/L < 0.93*



Wall shear stress and shape factor





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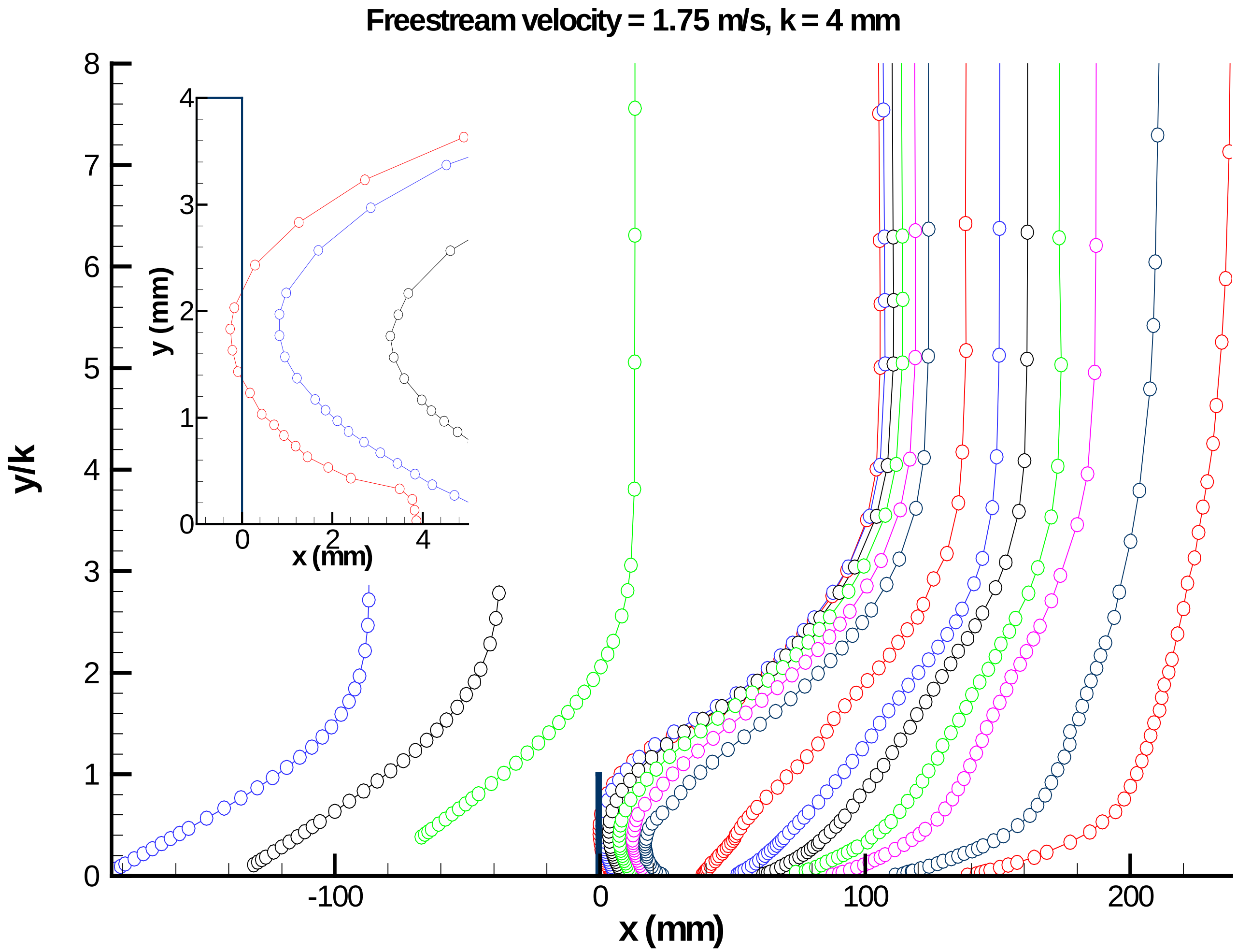
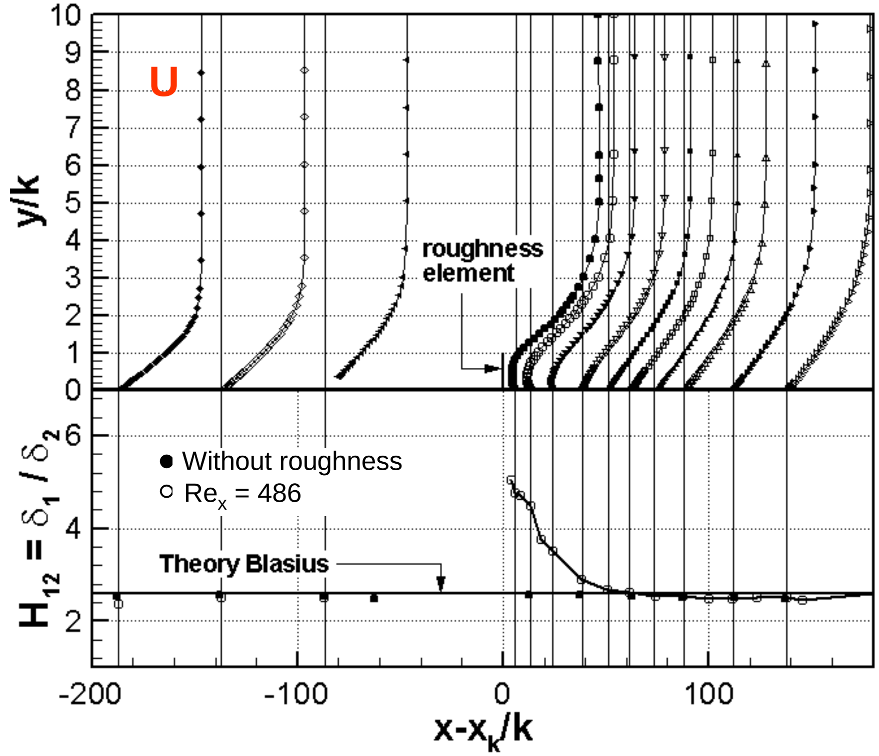
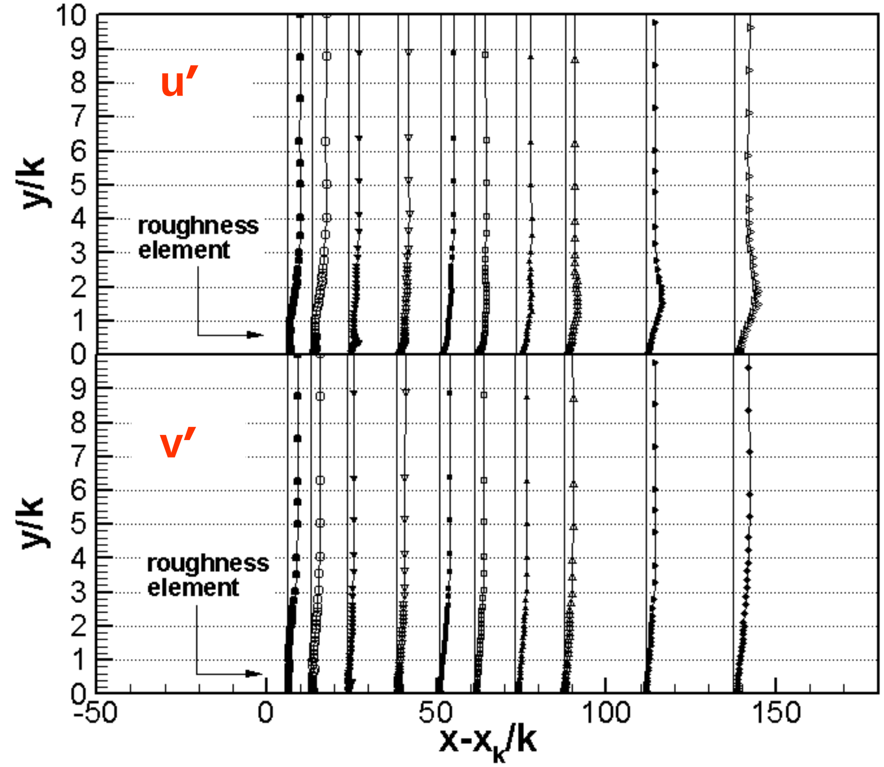
Experimental Results - Mean streamwise velocity, U

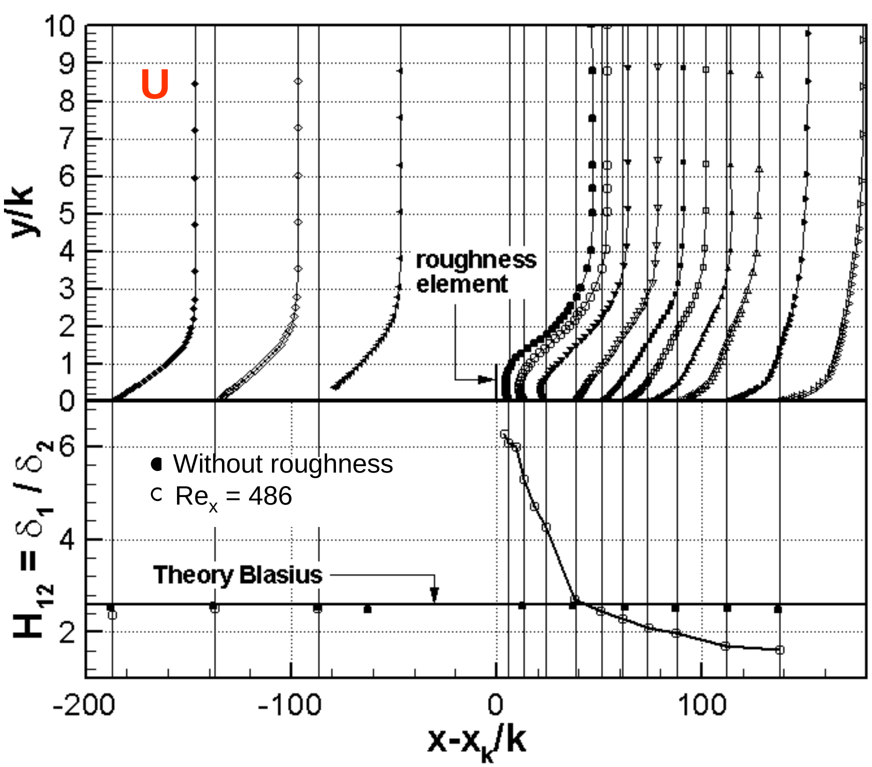


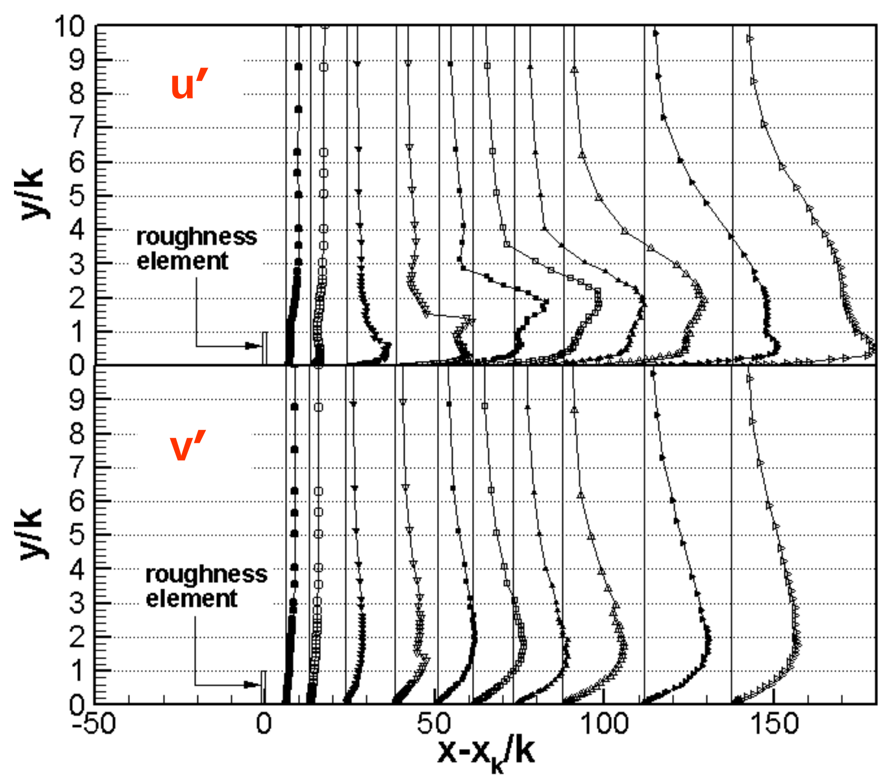
$k^+ \approx 11.6$, $Re_{x,k} \approx 1x10^5$, recovers to laminar flow





$k^+ \approx 14.9$, $Re_{x,k} \approx 1.4x10^5$, undergoes transition to turbulent flow

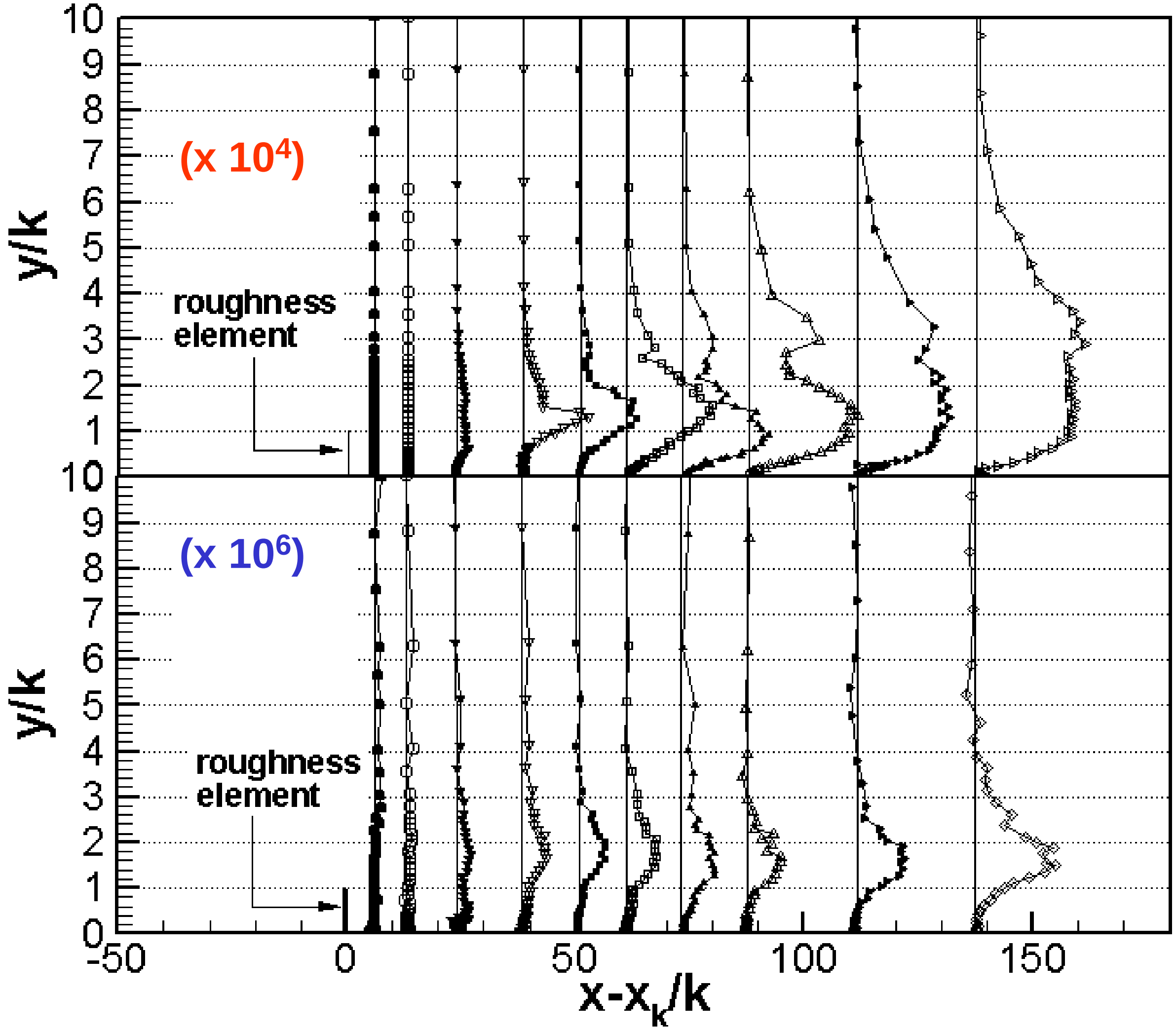




Evolution of Reynolds shear stress, $-\overline{uv}/U_\infty^2$

$k^+ \approx 14.9$
Transition

$k^+ \approx 11.6$
"Laminar Recovery"



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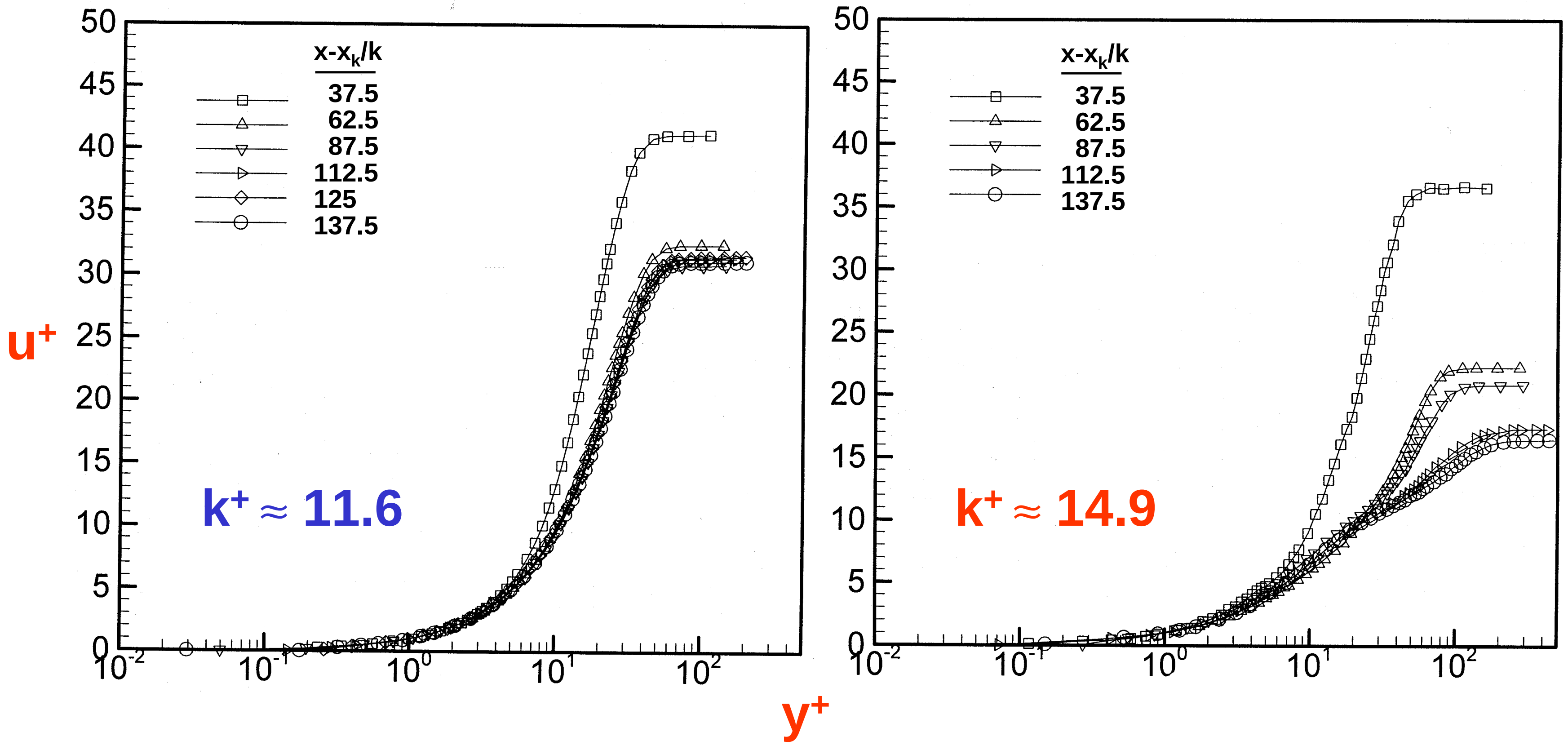
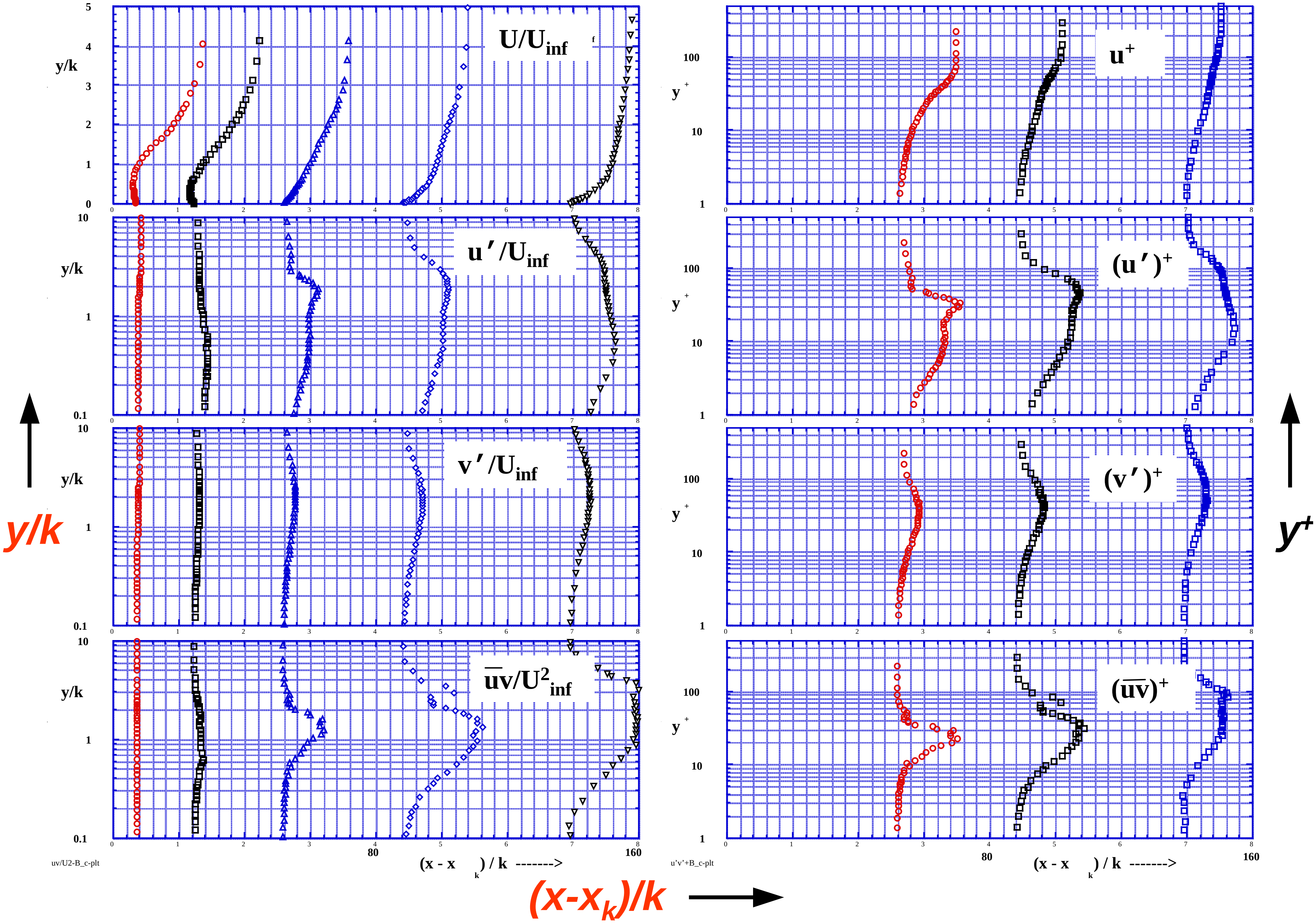
Mean velocity profiles, $u^+\{y^+\}$

Laminar recovery | *Transition to turbulent*



Development of mean quantities downstream of 2-D rib (k = 4 mm, k+ ≈ 14.9)



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The Boundary Layer Over Turbine Blade Models With Realistic Rough Surfaces

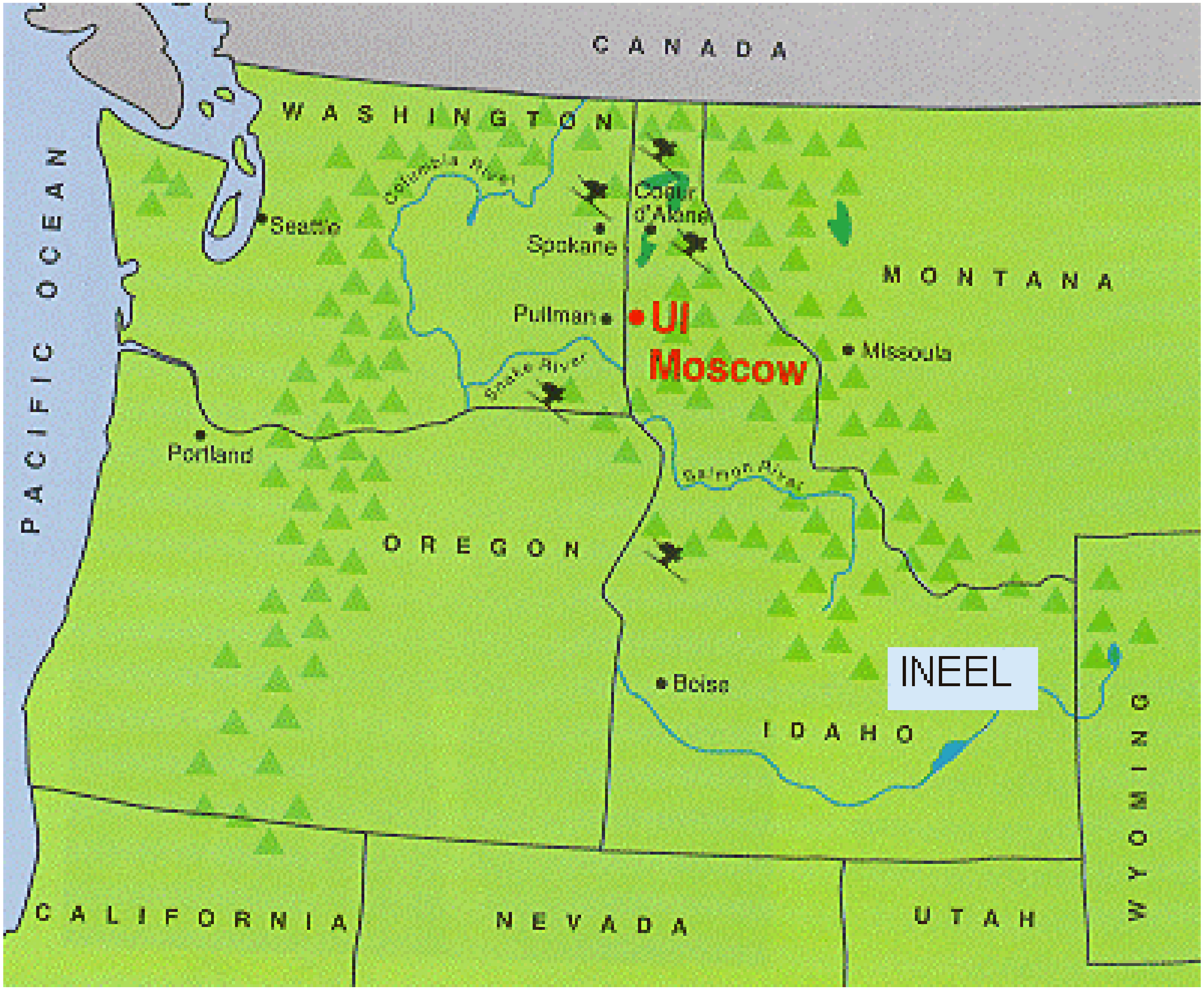
Ralph S. Budwig, Hugh M.McIlroy Jr., and William J. Dalling, University of Idaho (UI)

Keith G. Condie and Donald M. McEligot, INEEL

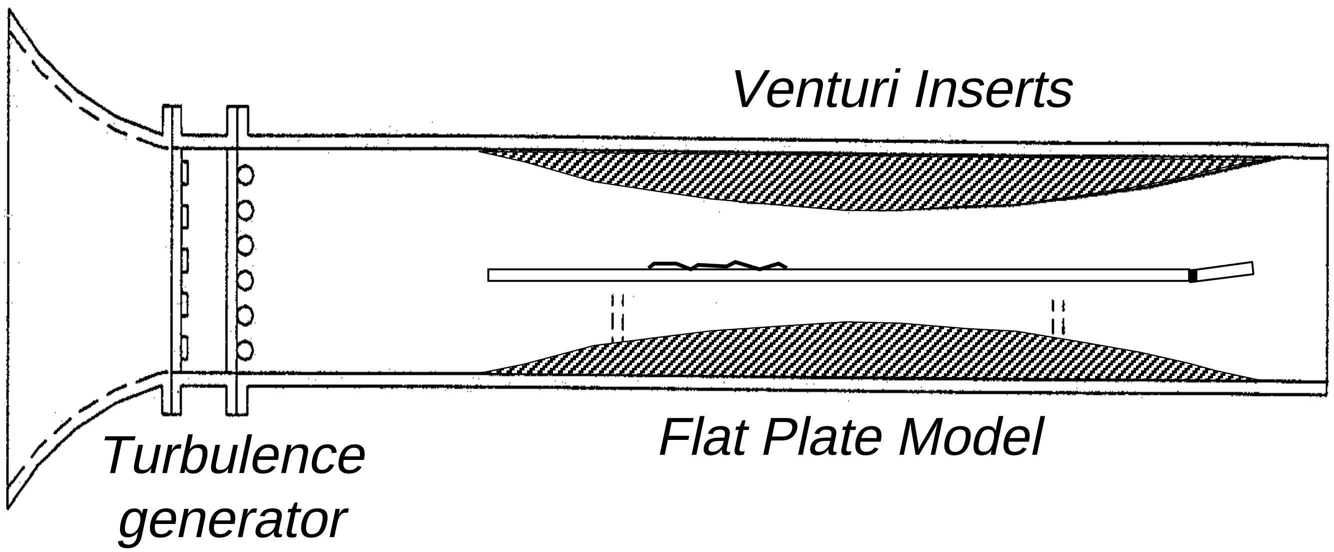
Objectives

Conduct measurements that will reveal the influence of realistic surface roughness on the boundary layer

- *High quality turbulence data in the near wall region*
- *Simulate turbine flow conditions*


CANADA
WASHINGTON
PACIFIC OCEAN
Columbia River
Seattle
Spokane
Coeur d'Alene
Pullman
UI
Moscow
Missoula
MONTANA
Snake River
Portland
Salmon River
OREGON
INEEL
Boise
IDAHO
WYOMING
CALIFORNIA
NEVADA
UTAH

Experiment



Expected parameter range

Re_x	0 to 300,000	Roughness	smooth
Tu	~0.5% and $\mathcal{O}$(10%)		uniformly distributed
dp/dx	favorable		"realistic"
	favorable to adverse		

Concluding remarks

- ***The large MIR system is a versatile, useful tool for examining flows in complicated situations***
- ***New measurements of the development of Reynolds stresses during the transition process were obtained closer to the wall than possible before***
- ***In the transitioning flow, turbulent transport evolves in the inflectional layer downstream of the rib then propagates towards the wall and outward***
- ***The data should be valuable for assessing predictions by CFD codes***
- ***U. Idaho experiment will evaluate effects of idealized roughness characteristic of turbomachinery applications***

A BASIC NOZZLE TEST FACILITY FOR FLUID-STRUCTURE INTERACTION IN TRANSONIC FLOW

T.H. Fransson and O. Bron
Royal Institute of Technology
Chair of Heat and Power Technology
Stockholm, Sweden

ABSTRACT

A prerequisite for aeroelastic stability investigations in turbomachines is the understanding of the aerodynamic forces acting on the blades. In order to obtain precise insight into aeroelastic phenomena associated with oscillating shock waves, fundamental experiment to further understand the behaviour of travelling pressure waves in non-uniform transonic flows at different operating conditions are needed. The emphasis is on the unsteady interaction of upstream propagating acoustic waves with a shock in transonic convergent-divergent nozzles at different inlet boundary layer conditions, and how this interaction can affect the unsteady pressure distribution on the surface. This presentation intends to present the facility in which those experiments are being performed, and give an overview of the intended future modifications and investigations. Different test objects and their instrumentation will be presented as well as the first preliminary results.

NOMENCLATURE

L2F	Laser-Two-Focus Anemometer
LDA	Laser-Doppler-Anemometer
Re	Reynolds number
U_∞	Inlet Velocity in Free Stream
D	Characteristic Dimension of BL
ν	Fluid viscosity

INTRODUCTION

Transonic flows about streamlined bodies are strongly affected, particularly near the shock location, by unsteady excitations. Experimental and computational studies [1,3] have shown that the unsteady pressure distribution along the surface of an airfoil or a cascade blade in unsteady transonic flow exhibits a significant bulge near the shock location. Tijdeman and Seebass [11] reported that the unsteady pressure bulge and its phase variation resulted from non-linear interaction between the mean and unsteady flow. This non-linear interaction causes a shift in the shock location, which produces the observed large bulge in the unsteady pressure.

Studies [5] on choked flutter have shown that, in unsteady transonic flows around a single airfoil, the shock motion, and then the pressure distribution along the surface, can be critical regarding to the self-exciting oscillation of the airfoil. It was also found that the mean flow gradients are of high importance regarding the time response of the unsteady pressure distribution on the airfoil surface. Moreover, numerical computations [4] have shown that the exact location of the transition point could strongly affect the prediction of stall flutter.

Further studies [2] suggested that this sharp rise in the unsteady pressure distribution was due to the near sonic condition, and that the near-sonic velocity acts as a barrier they called *acoustic blockage* preventing acoustic disturbances from propagating upstream in a similar way to the shock in transonic flows. A transonic convergent-divergent nozzle experimentally investigated by Ott et al. [10] was thereafter used as a model to investigate the non-linear acoustic blockage. Analytical and numerical computations [6,7,8,9] were then carried out to analyse and quantify the upstream and downstream propagation of acoustic disturbances in the nozzle.

OBJECTIVES

The objective is here to present the facility which is used to study the unsteady interaction of upstream propagating acoustic waves with a shock in transonic flow, and its intended modifications to add incoming wakes and a fluctuating wall.

TEST FACILITY

Experiments are performed in the nozzle test facility, which was designed to be highly modular so that different test objects, so called "bumps", can be inserted in a 100x120mm square test section. A 1MW compressor provides a maximum mass flow up to 4.7 kg/s at 4 bars and 30°C. A cooling system also allows a temperature range from 30°C to 180°C, and the adjustment of different valves controls the mass flow and the pressure level in the test section. A special design allows the test objects to be raised up in order to cut off the boundary layer to the atmosphere (see fig.1). As a result, different inlet Mach number (from M=0 to 0.8) as well as different Reynolds number (from Re=U.d/ν=54,000 to 22,000,000) can be reached.

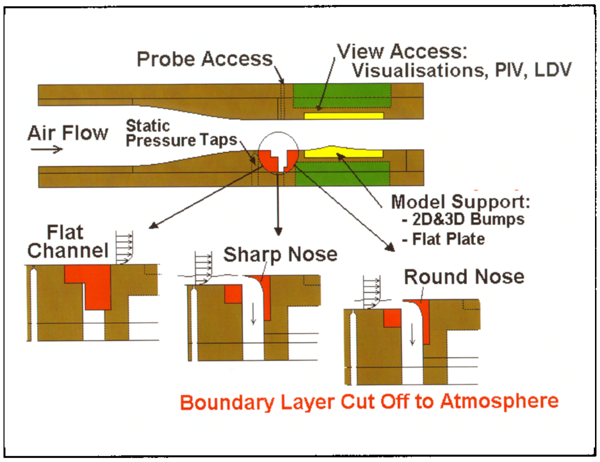


Figure 1: Schema of the nozzle test facility

FIRST TEST OBJECTS AND INSTRUMENTATION

A first test object consists of a long two-dimensional (2D) bump which can slide through the width of the test section. This bump is equipped with one row of 80 hot film sensors, and three staggered rows of 50 pressure taps each. Thus, a complete mapping of the steady and unsteady pressure distribution over the channel width is possible, as well as the determination of the boundary layer state on the bump.
A second test object consists of a three-dimensional (3D) bump which was numerically designed to create different local accelerations of the flow through the width of the test section. The design parameters were the length and the thickness of the bump , as well as the throat line position. As a result, the shock wave is slightly bent instead of being perpendicular to the main flow direction. This special shape of the nozzle will allow to study the influence of the mean flow gradients on the shock motion. Among four models available for instrumentation, one is instrumented with 350 pressure taps (fig.2).

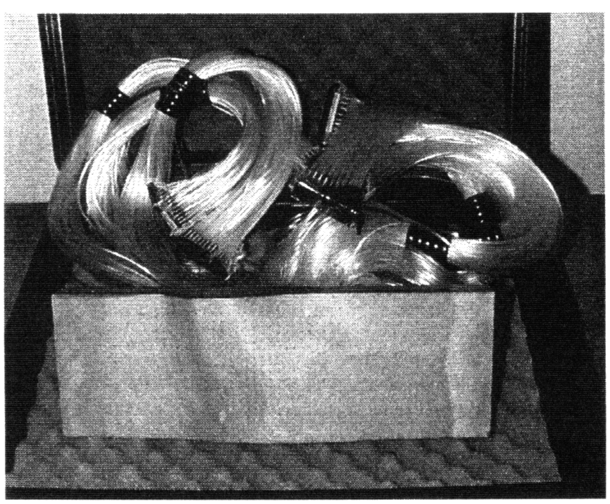


Figure 2: Instrumented 3D bump

Regarding unsteady measurements, a rotating ellipse placed downstream of the test section is used as a pressure wave generator with frequency up to 600 Hz. As a result, pressure perturbations propagate upstream at a speed which is function of the local flow velocity, and interact with the shock wave. Unsteady pressure measurements are performed using standard Kulite transducers instrumented on the same test objects as for steady state measurements.

MEASURING TECHNIQUES

Pressure measurements will be performed using a 200-channel 'steady state' pressure data acquisition system from PSI (up to 300Hz on each channel, and ±0.05% full scale accuracy), and a 32-channels transient system (up to 20kHz sampling). The boundary layer behaviour is investigated with surface mounted hot films, hot wire traverses, LDA measurements and surface oil visualisations. A conventional Schlieren system is used to monitor the shock motion in the 2D nozzle using a high speed camera (up to 8000 pic/s). A state-of-the-art three dimensional Laser-Two-Focus Anemometer (3D-L2F) will been employed to measure the 3D mean velocity vector and the turbulence intensity at the inlet boundary as well as at different stations in the test section. PIV measurements are also foreseen in the future.

ACKNOWLEDGEMENT

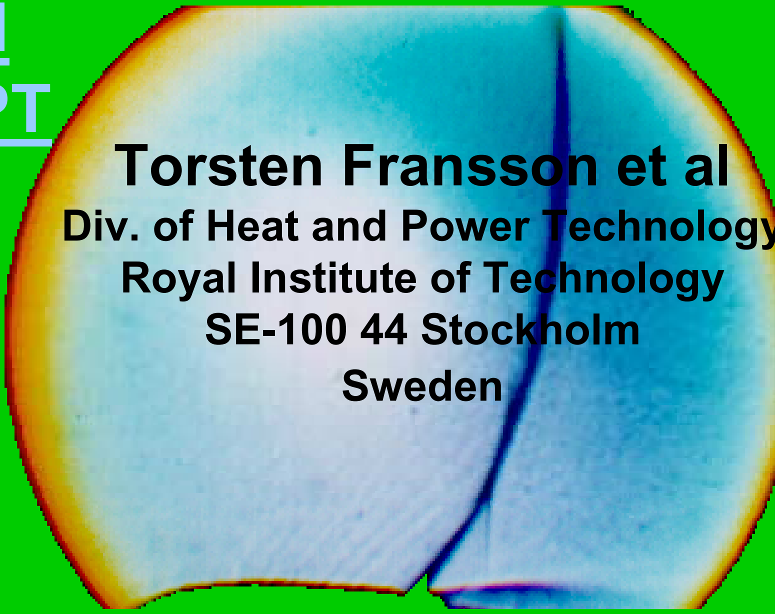
The authors wish to thank STEM (project 6303) for their financial support.

New Test Facilities For Fluid-Structure Interaction in High Sub- & Transonic Flow

Acknowledgement
Background from aeromechanical perspective
Objectives
3D Bump flow with oscillating back pressure
- Results

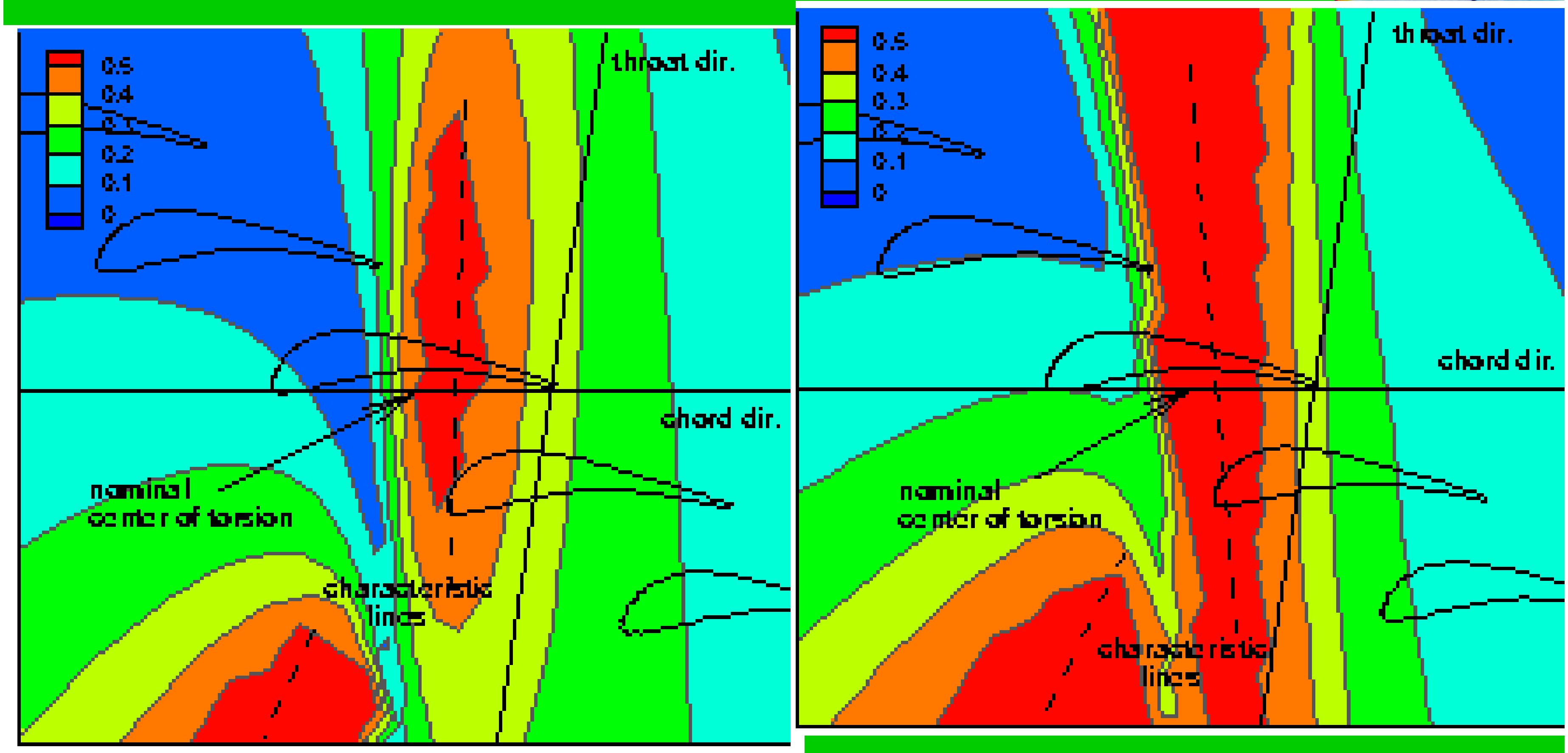
3D Bump flow with vibrating wall
Annular sector with full-scale HPT
- Results

Vibrating LPT-blade
Future extensions
Conclusions



Torsten Fransson et al
Div. of Heat and Power Technology
Royal Institute of Technology
SE-100 44 Stockholm
Sweden

Critical Red. Freq. Vs Modeshape/1



STCF4: M2=0.9 & 1.19

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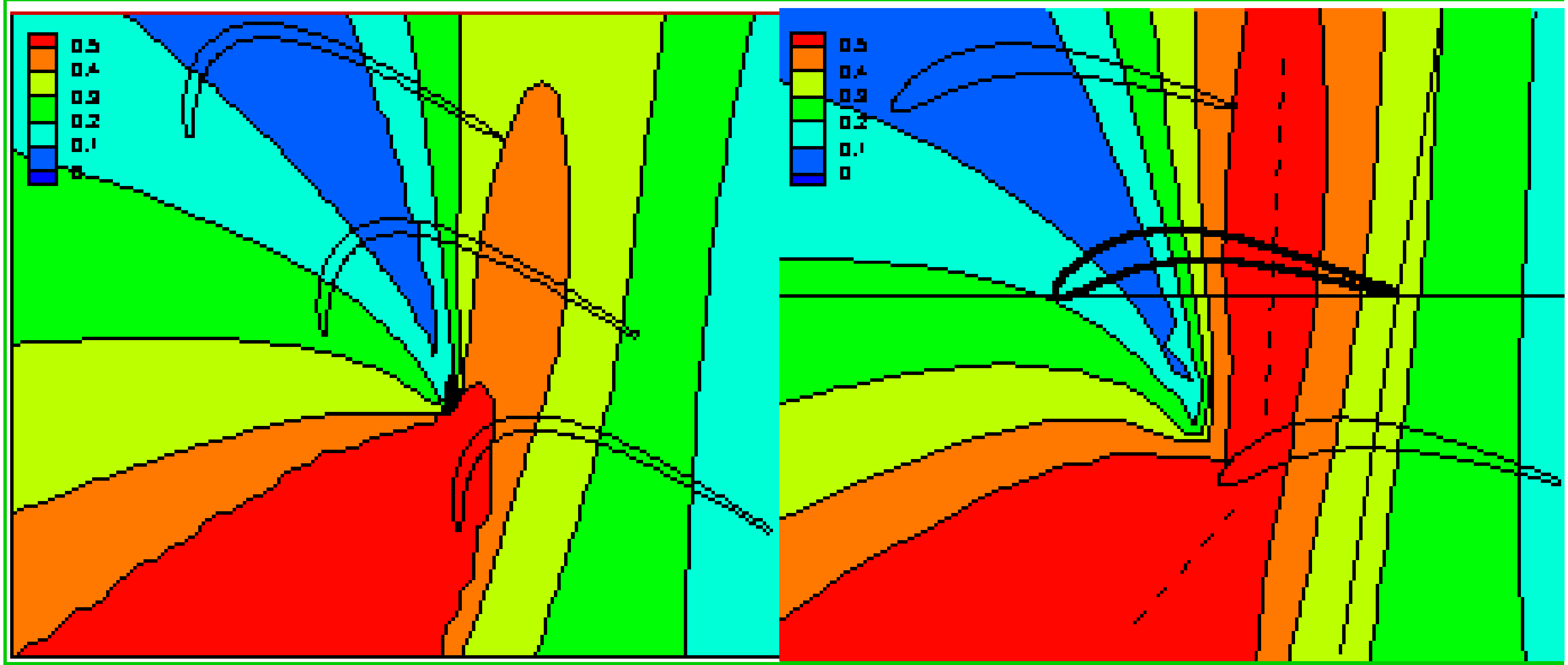
Critical Red. Freq. Vs Modeshape /2



LPT: M2=0.74

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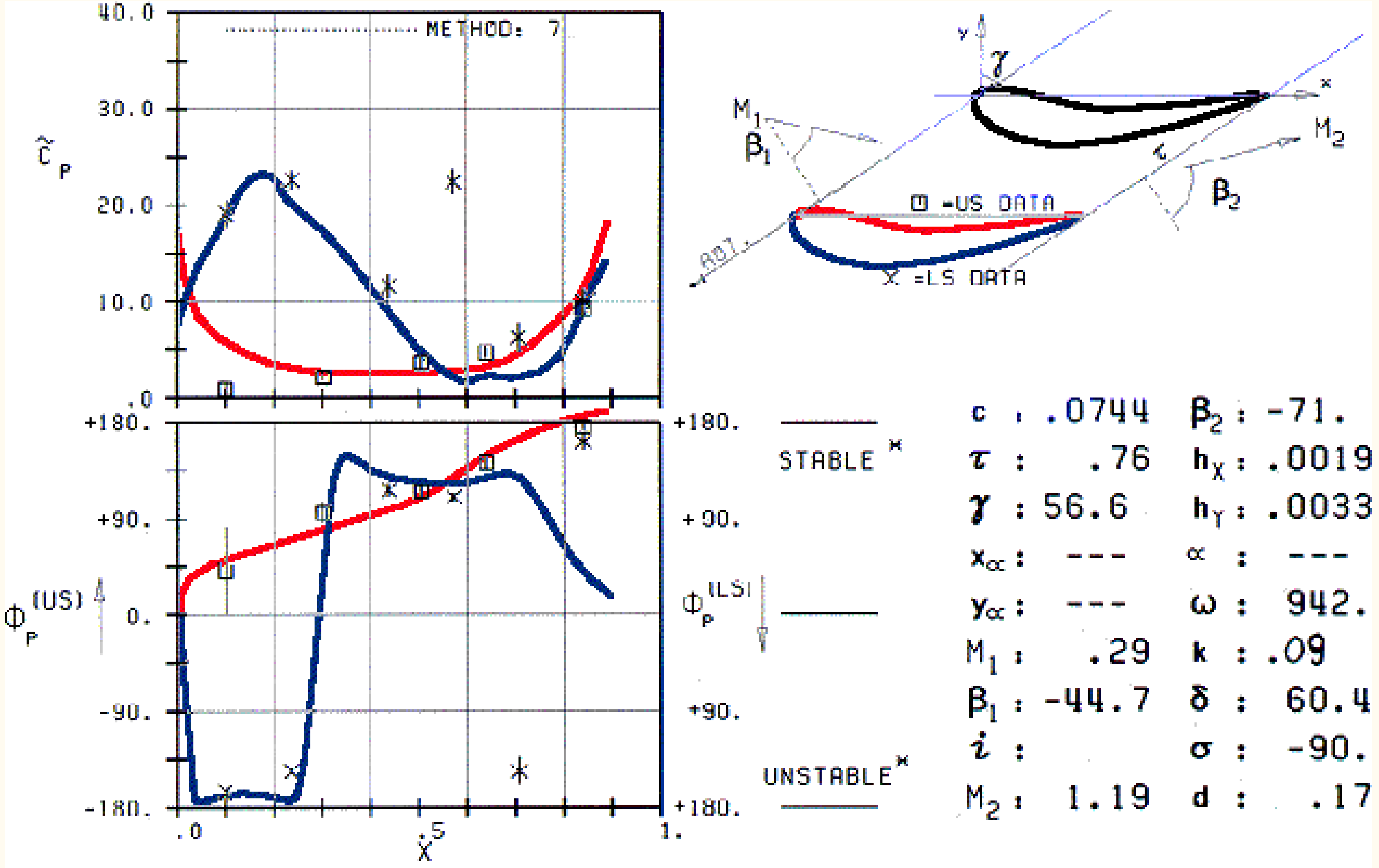
Unsteady cp and phase vs chord

S5B2C3p7: amplitude and phase



Magnitude and phase lead of unsteady blade surface pressure coefficient

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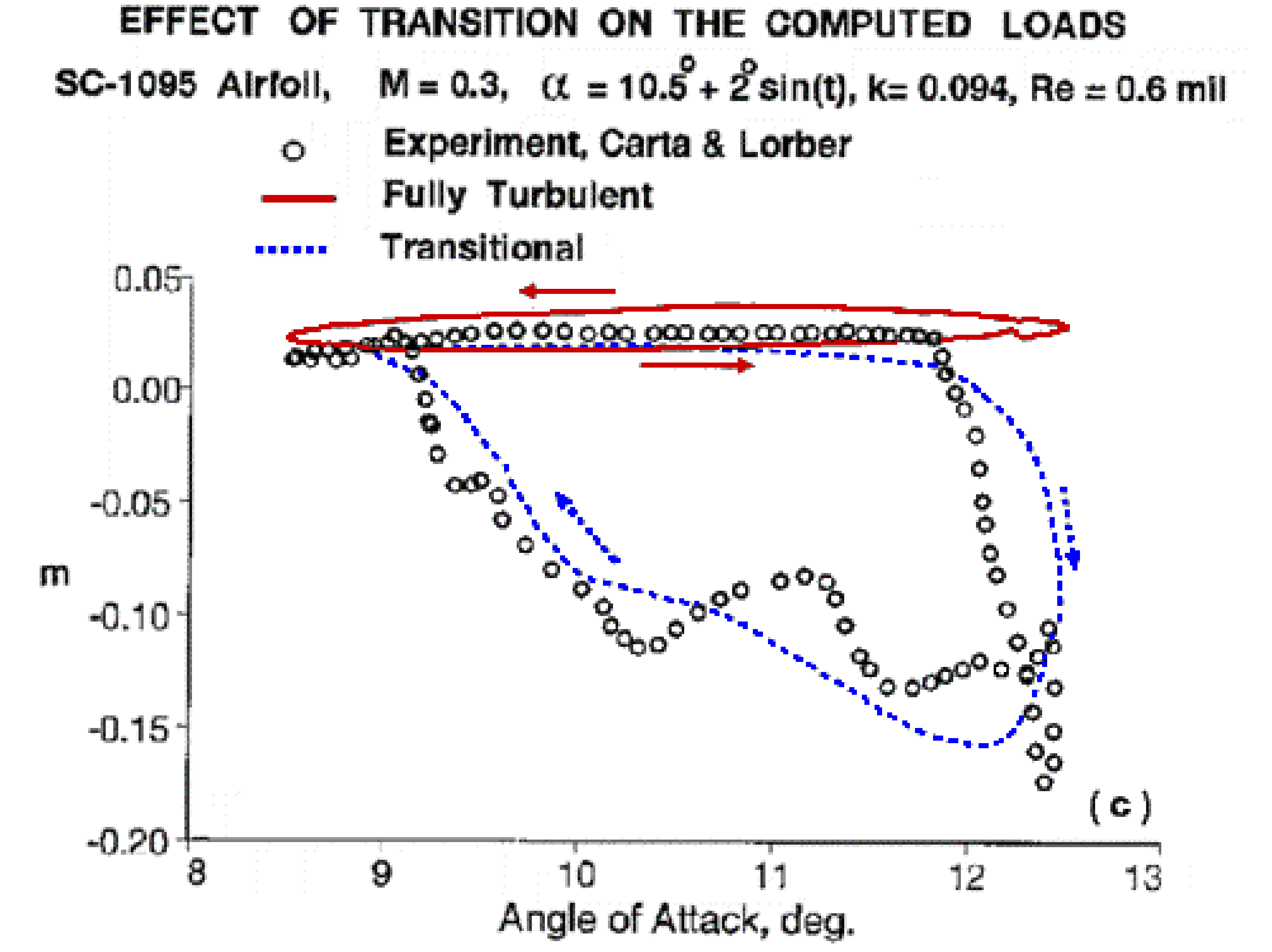
Infl. of Transition on Aeromech. Response?



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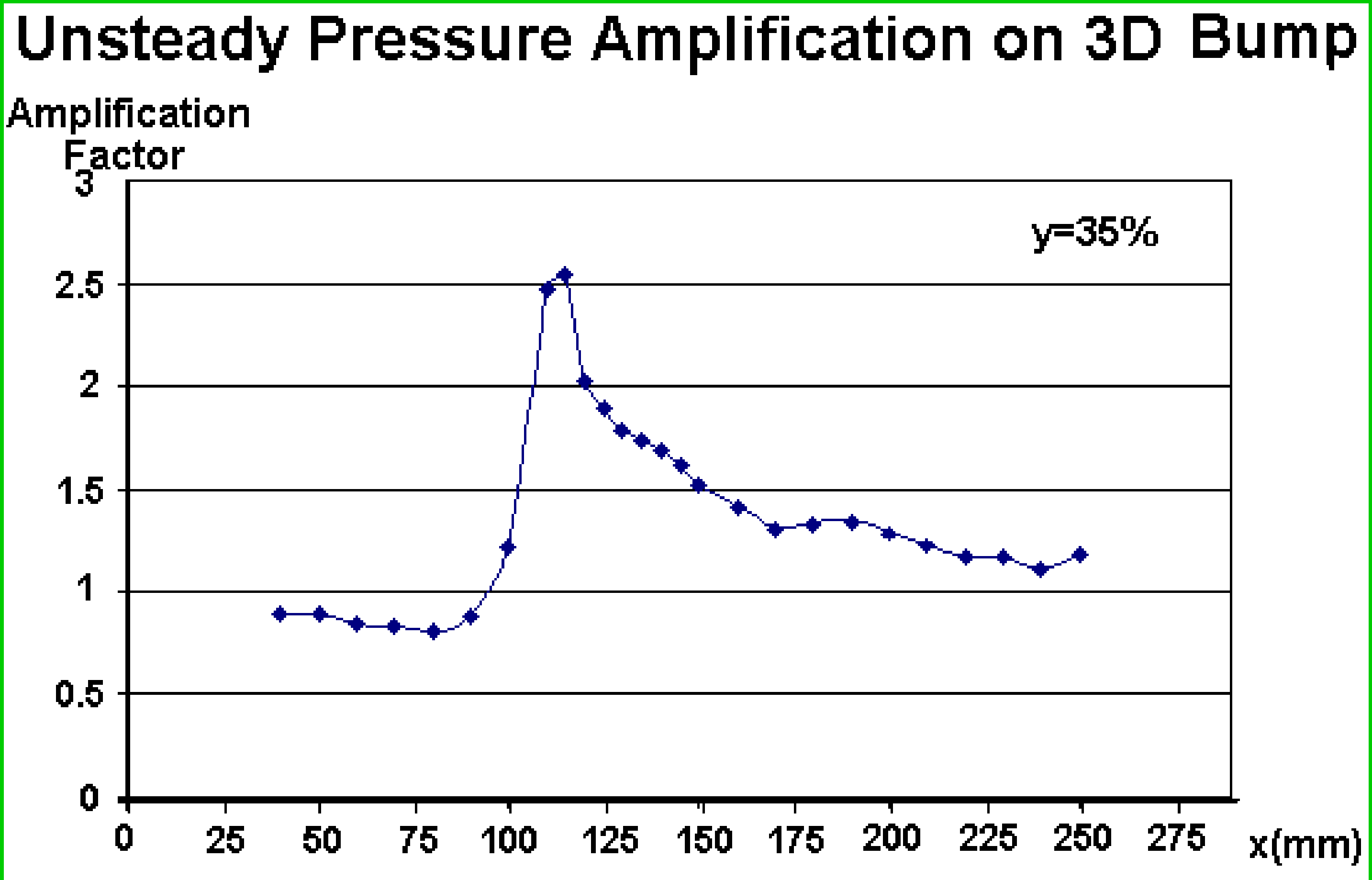
Acoustic Blockage



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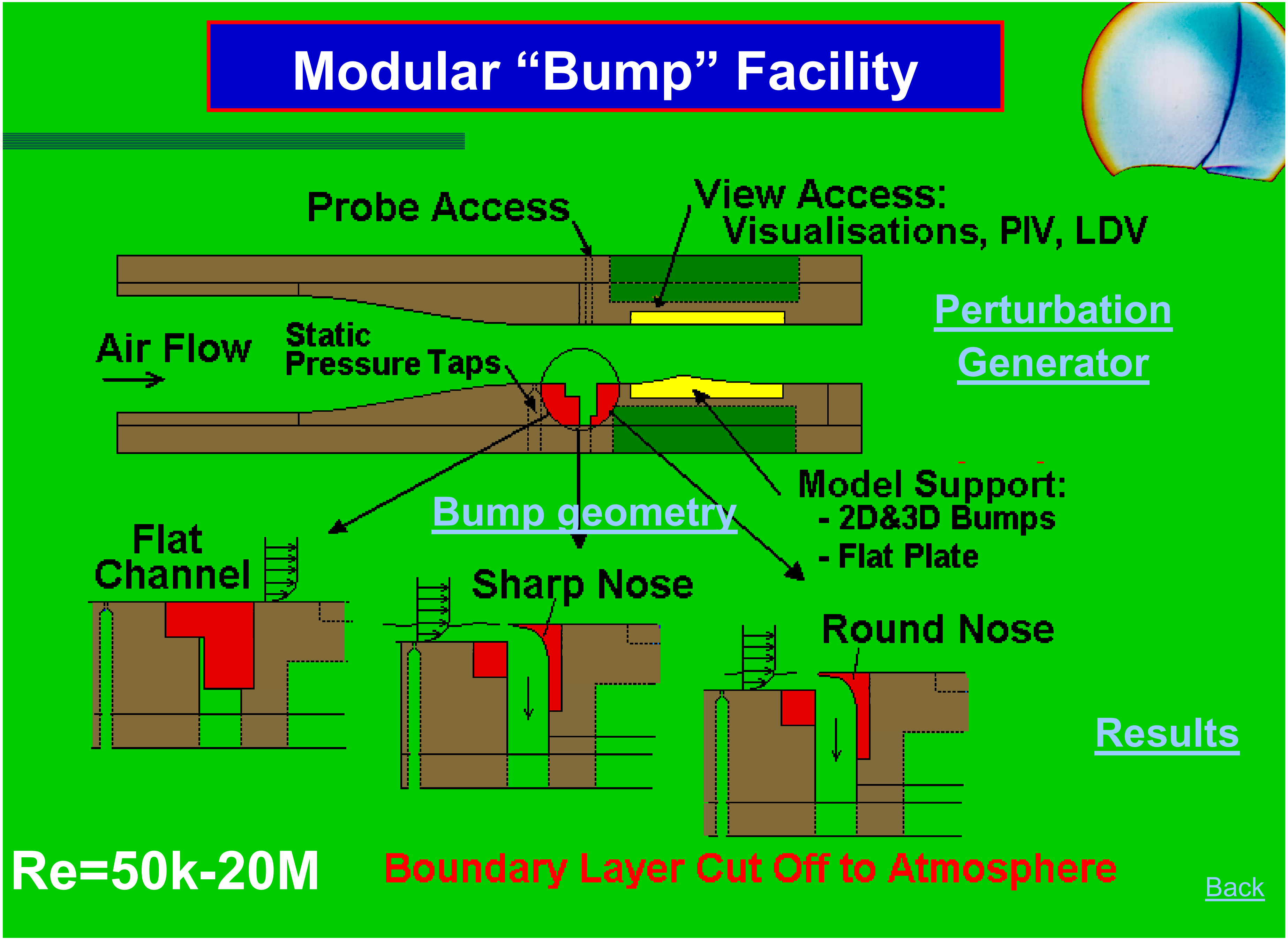
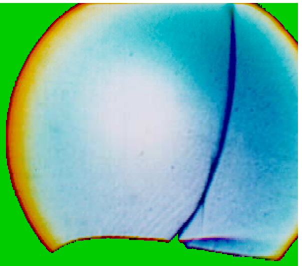
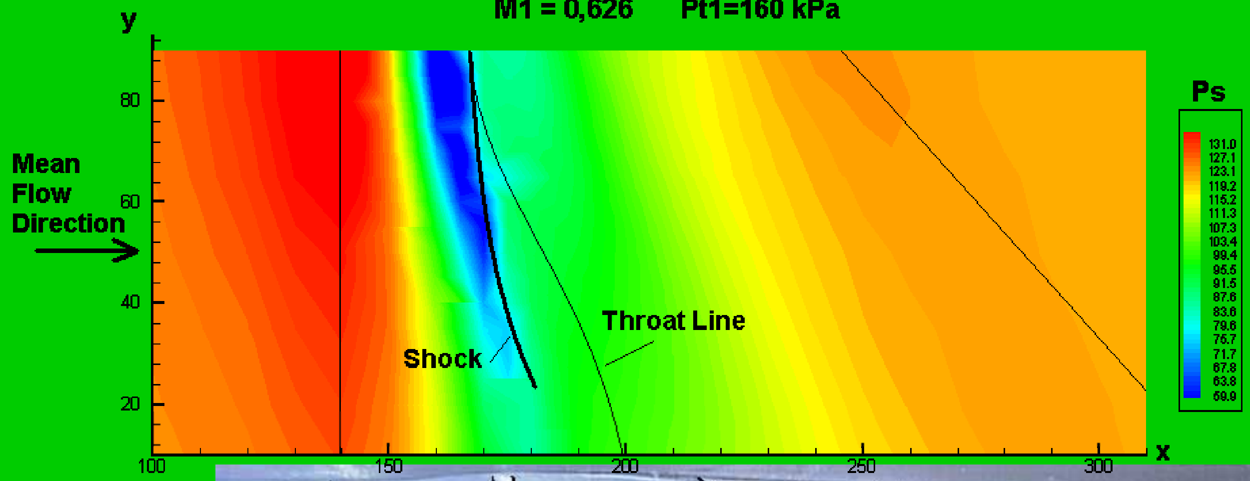

Modular "Bump" Facility
Probe Access
View Access:
Visualisations, PIV, LDV
Perturbation
Generator
Air Flow
Static
Pressure Taps
Model Support:
- 2D&3D Bumps
- Flat Plate
Bump geometry
Flat
Channel
Sharp Nose
Round Nose
Results
Re=50k-20M
Boundary Layer Cut Off to Atmosphere
Back

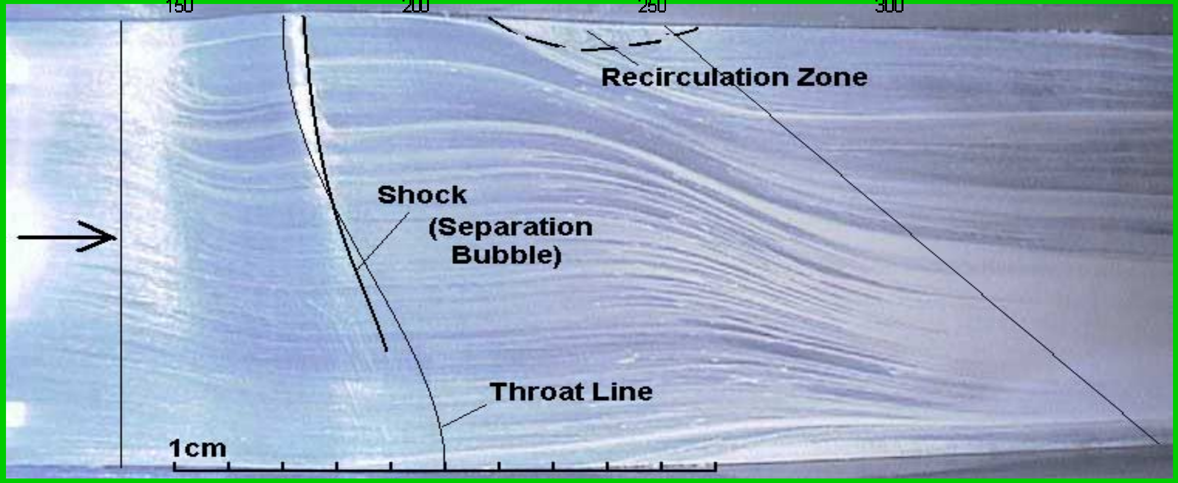
Results



Static Pressure on 3D bump

M1 = 0,626   Pt1=160 kPa





Unsteady global

Oil Visualization

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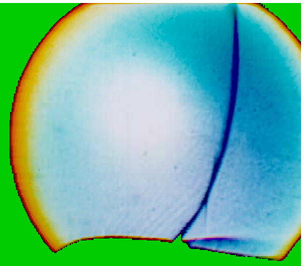
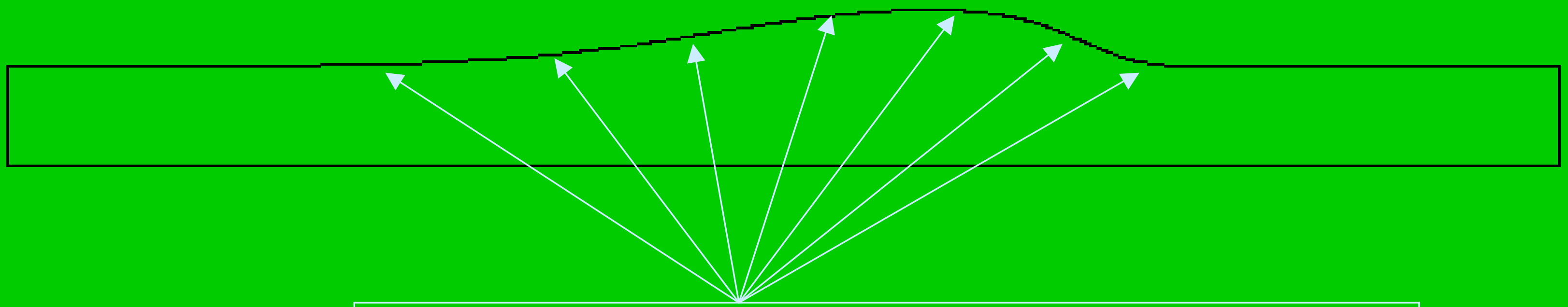
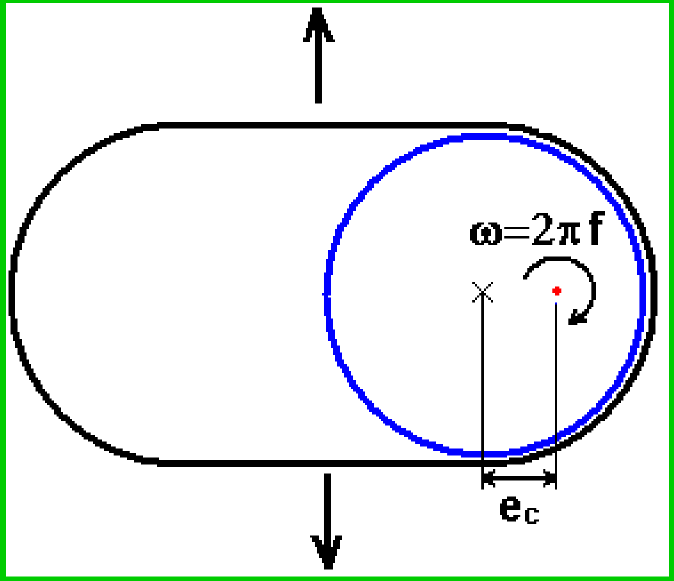
Fluid-Structure “Bump” Facility





Discreet Locations for Actuators



- Bump material: Rubber
- Eccentric rotating rods
- Independent frequency, amplitude, phase

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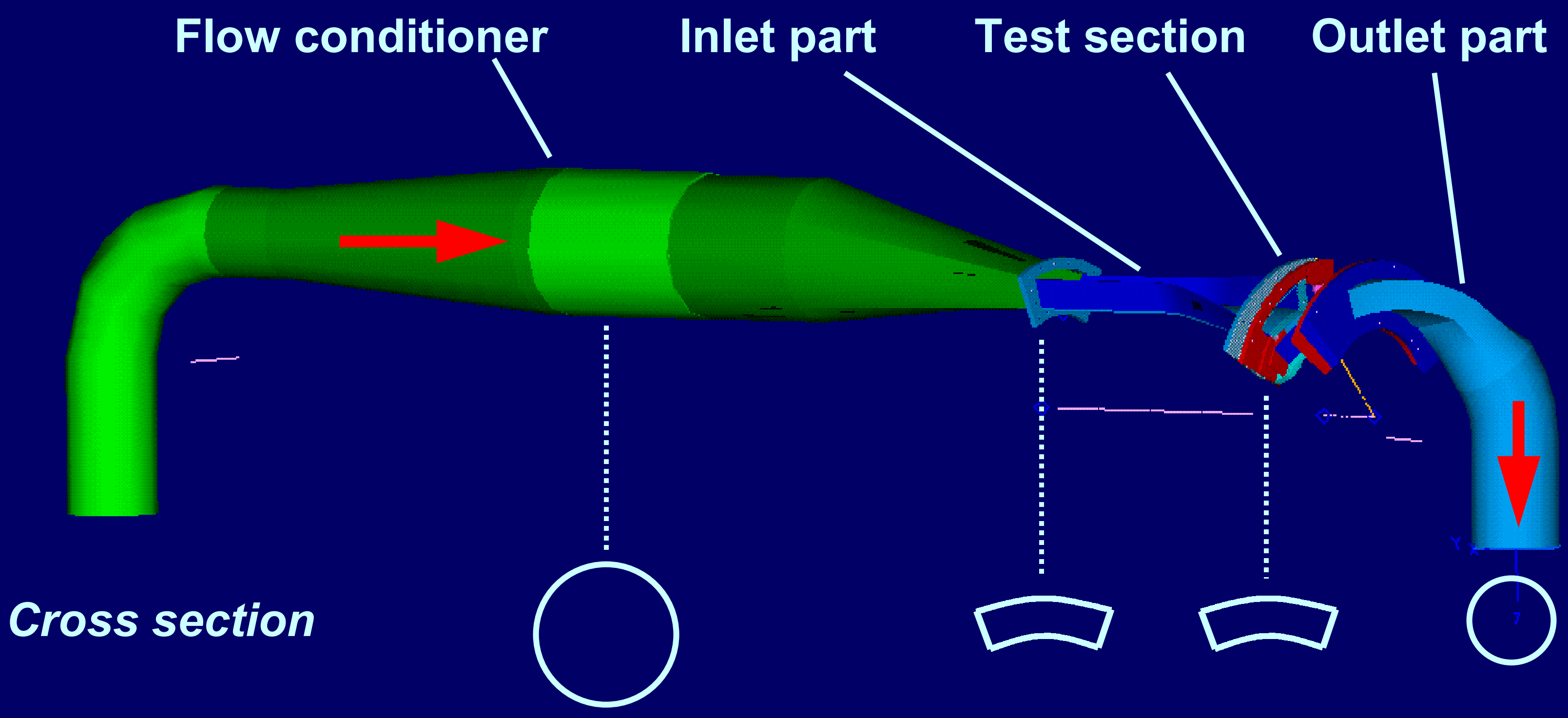
Annular Turbine Cascade Facility



Steady Results

Back

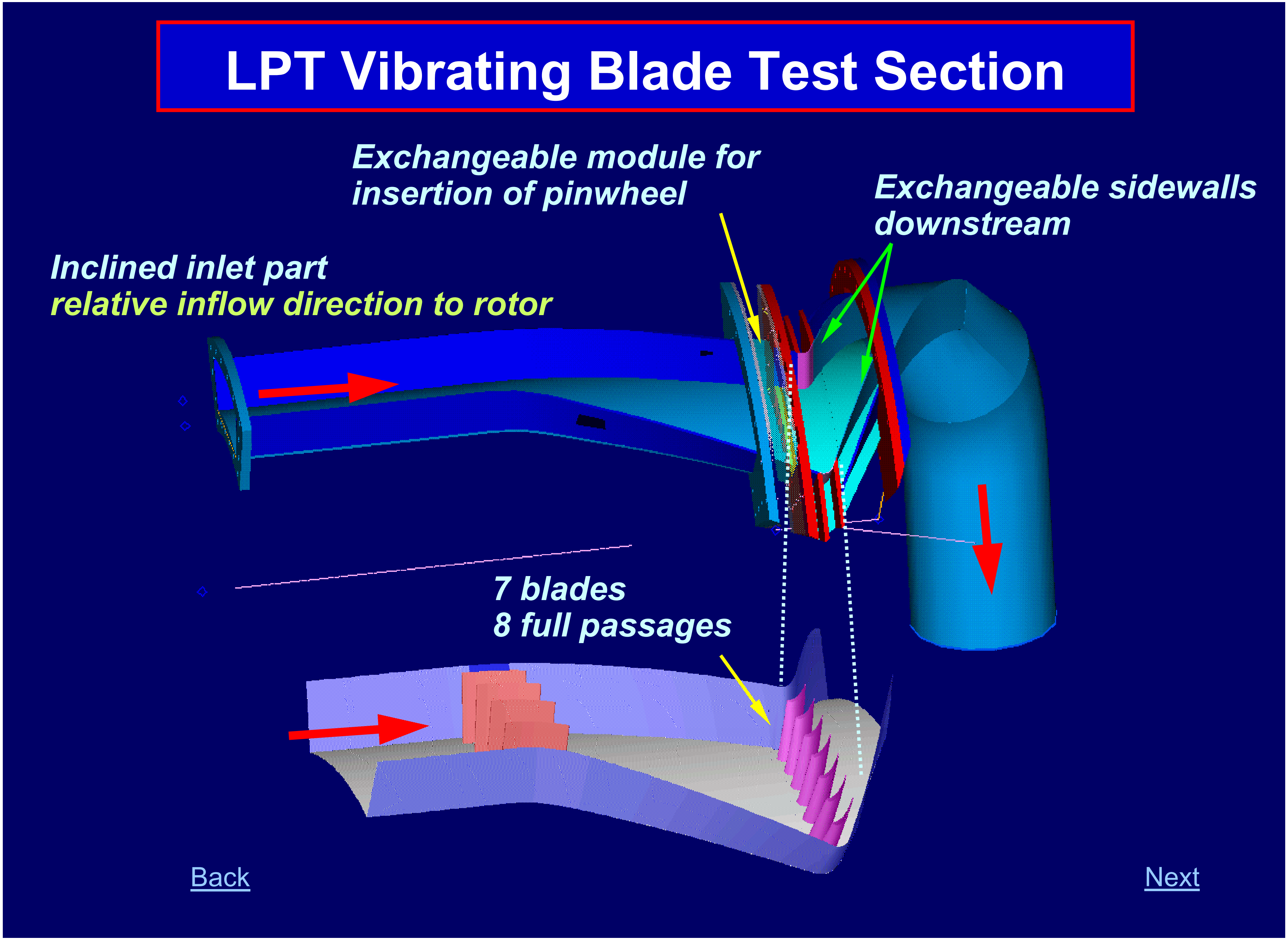
1st Vane HPT 40 MW Industrial Gas Turbine: Full Scale

- Identical M1, M2, Re as in machine
- Identical facility exists as "hot"

Steady-state results

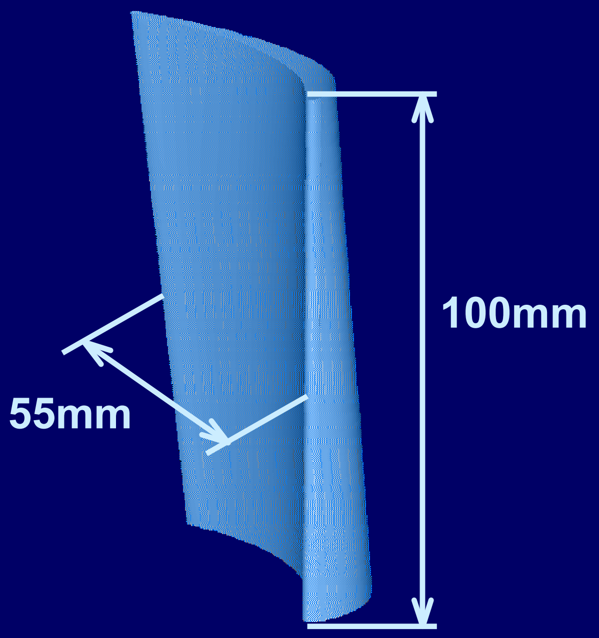
- Tip M_{iso} distribution
- Hub M_{iso} distribution
- Tip end wall Miso distribution
- Profile Miso distribution

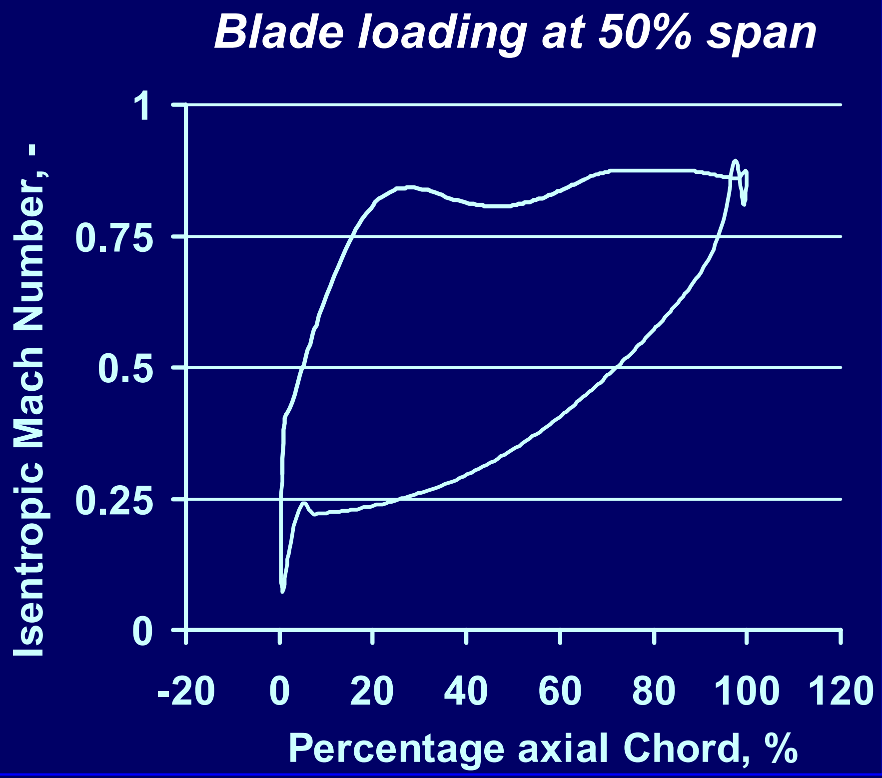
Back


LPT Vibrating Blade Test Section
Exchangeable module for insertion of pinwheel
Exchangeable sidewalls downstream
Inclined inlet part
relative inflow direction to rotor
7 blades
8 full passages
Back
Next

Test Object

- Low pressure turbine rotor blade profile





M_{in} … M_{out} : 0.32 … 0.82

Re (c_{ax}) : 370'000

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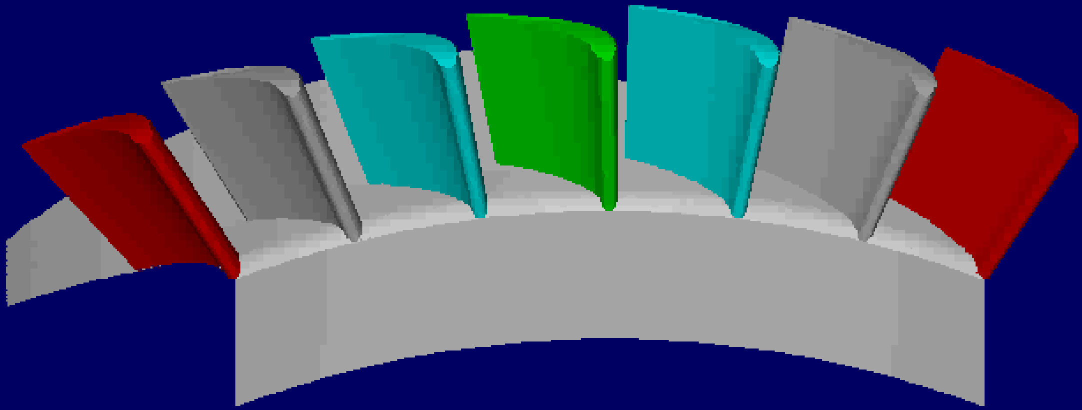
Controlled Blade Oscillation

1st Bending Mode

Osc. Mech.



Amplitude : 0...10deg

Frequency : 0...500Hz

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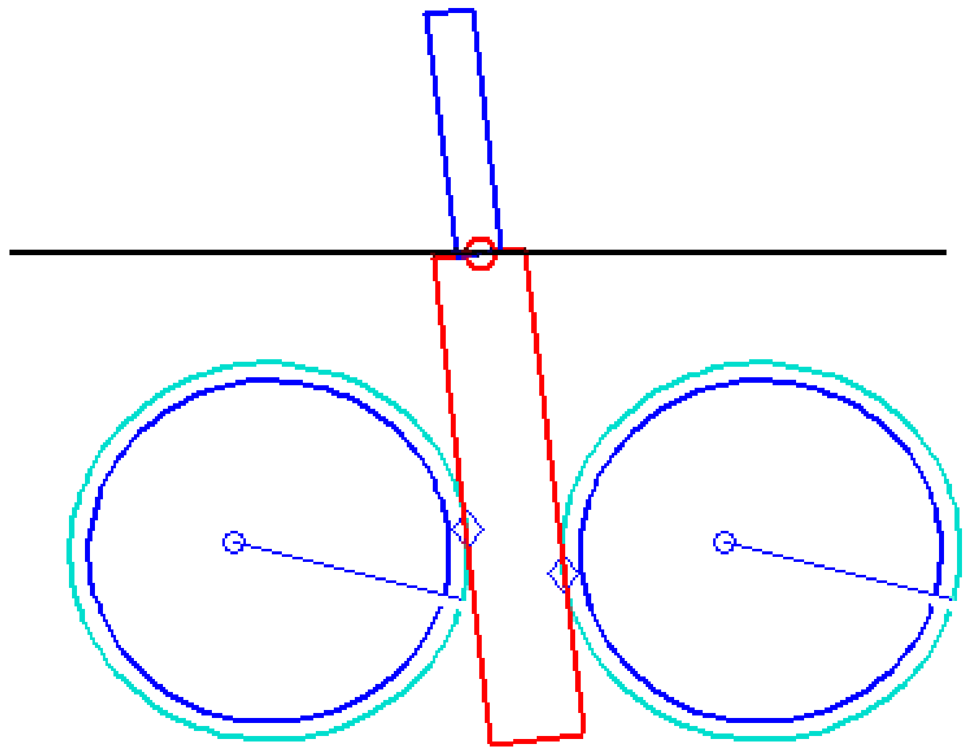
Oscillation Mechanism



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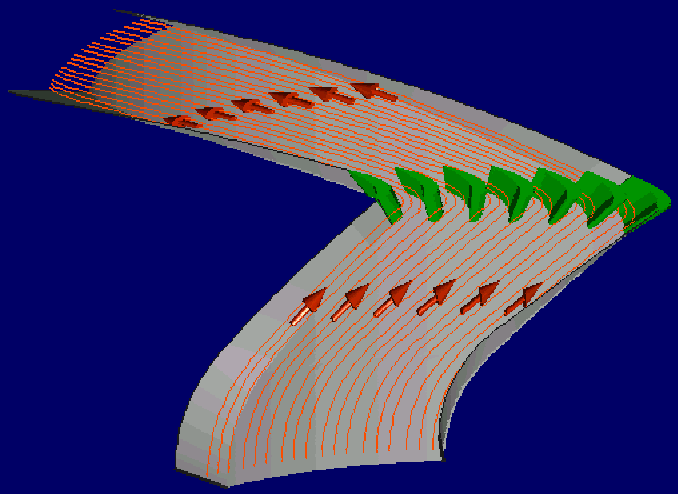
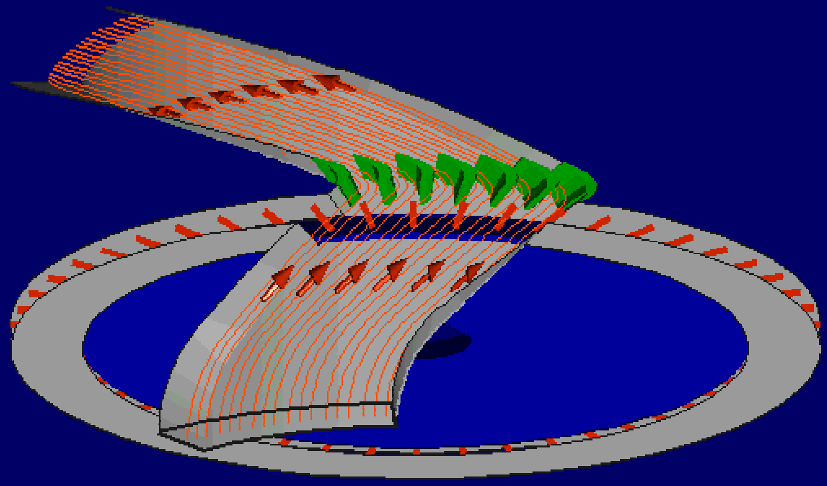
Future Extensions of Sector and Bump Facilities

- Rotating pinwheel upstream
  - simulation of stator wakes



Present design



Future extension

- Same wheel for bump facility

Back

The End

- The first unsteady experiments failed
- New test facilities
  - for high subsonic and transonic flows
  - "high" reduced frequencies related to blade vibrations
  - physical understanding
  - extended data bases
  - code validation in high-speed flows
- Steady state periodicity in sector facility looks good
- Autumn:
  - Hot film, then film cooling on HPT vane
  - Unsteady measurements on 2D/3D bumps
- Spring: Oscillating bump & LPT flutter

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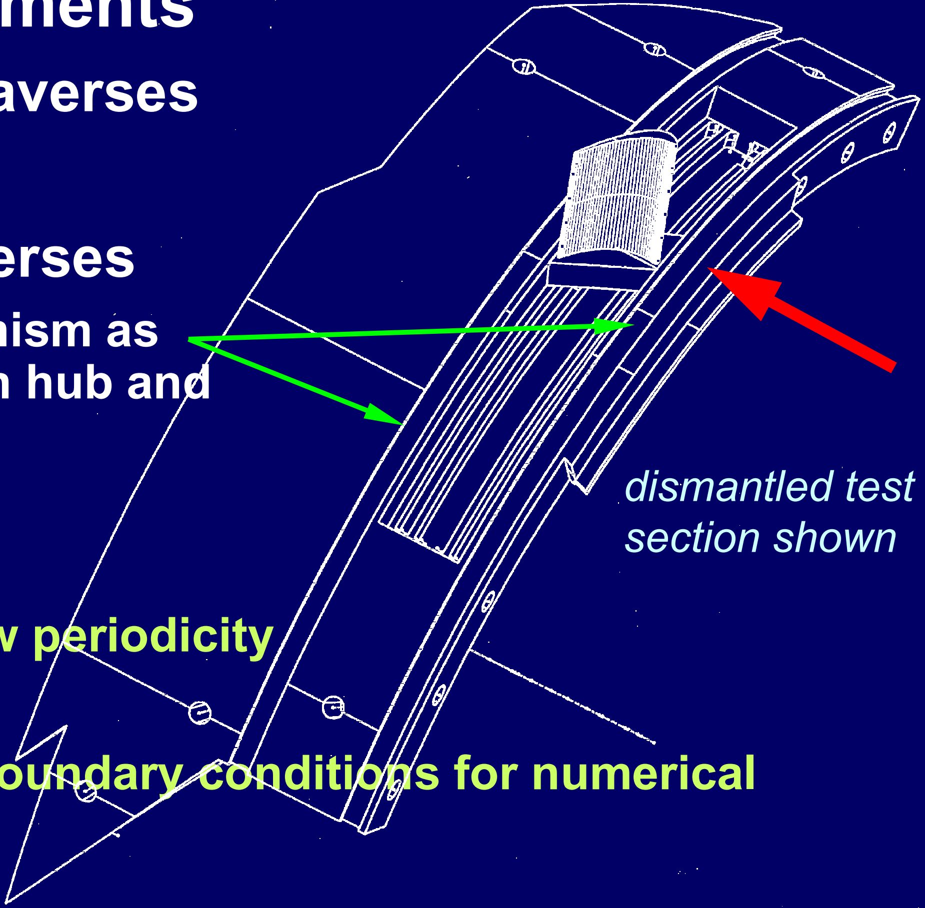
Cascade Specifications

- **Flow conditions**
  - → M_{in} … M_{out} : 0.32 … 0.82
  - → Re (c_{ax}) : 370’000
- **Blade Oscillation**
  - – controlled 1st bending mode
  - – can be inserted at different positions
  - – oscillation mechanism of mechanical type
- **Boundary layer treatment**
  - – cutoff upstream at hub and shroud possible

Cascade Instrumentation - Steady

- **Pressure measurements**
  - **multihole probe traverses**
  - **wall pressure traverses**
    - **traversing mechanism as slider integrated in hub and shroud**



→ **assessment of flow periodicity**

→ **determination of boundary conditions for numerical simulations**

Cascade Instrumentation - Unsteady

- Pressure measurements
  - KULITE fast response pressure sensors
  - wall pressure
    - → traversing mechanism as slider integrated in hub and shroud
  - blade surface pressure
    - → oscillating blade
    - → one steady blade

- Optical measurements
  - transparent window in shroud
    - → flow visualization, shock triggering

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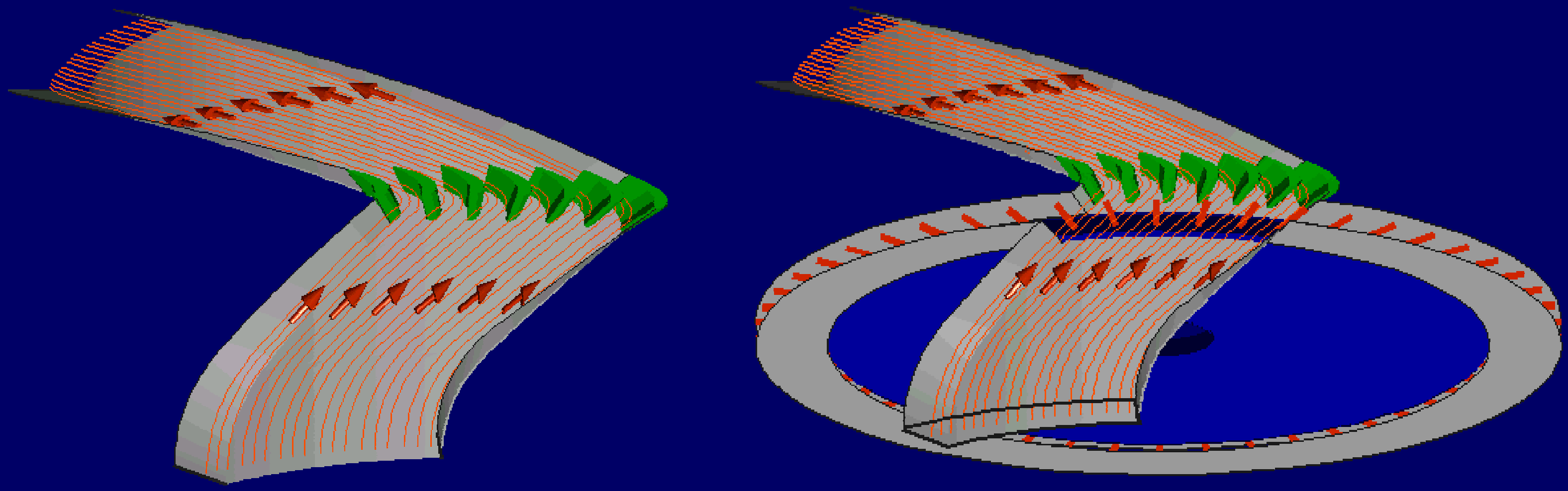
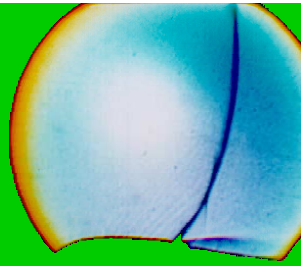
Future Extensions of Sector Facility

- Rotating pinwheel upstream
  - simulation of stator wakes



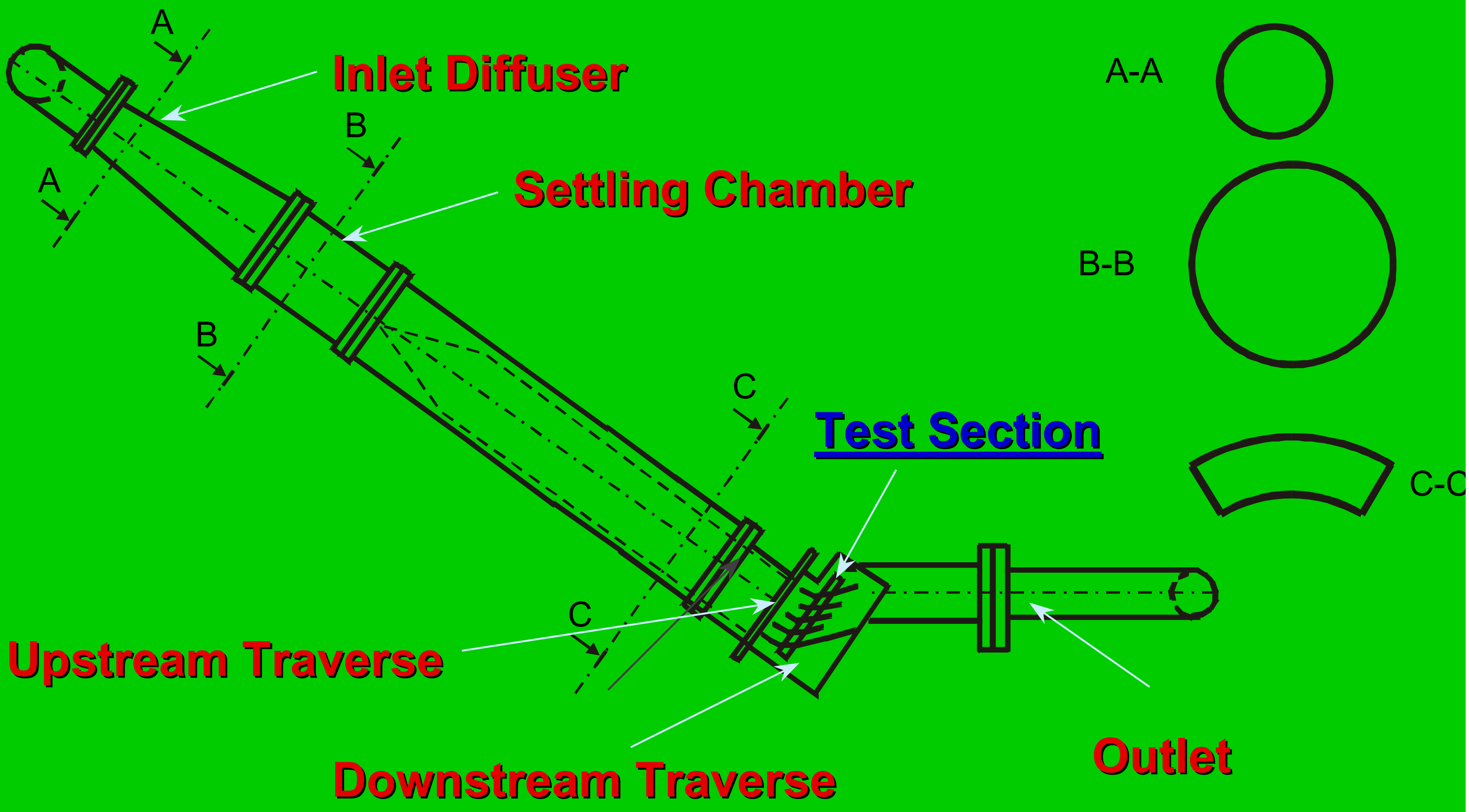
Present design *Future extension*

Possible Further Extensions



- Installation of flexible bump to obtain **flow/structure interactions**
- **Simulation of Wake Passage to investigate unsteady Transition**
- **Steady flow gradients study** using different 2D/3D bump
- **Upstream pressure pertubations** induced by upstream rotating rod
- **2D downstream pressure perturbations** to simulate rotor/stator interaction
- **Active/passive control** to act on forced response

Annular Turbine Cascade Sector Facility



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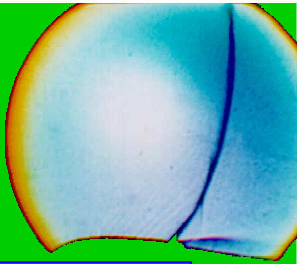
Conclusion Annular Sector

- An annular sector cascade test facility has been designed and gone into service.
- Homogenous inlet flow conditions with a periodic flow field through flow passage -1 and +1 could be obtained
- The periodicity of the flow field has been confirmed with the isentropic Mach number distribution on NGV -1, 0 and 1.

Acknowledgements



- The presentation covers mainly three new exp./num. projects on Swedish national level

- Funding by:
  - Swedish Gas Turbine Center
  - Swedish Energy Agency
- Collaboration with:
  - Department of Mechanics, KTH
  - Department of Physics, KTH
  - Division of Thermo & Fluid Dynamics, CTH
  - Division of Fluid Dynamics, LTH
  - Only exp. part performed at KTH/HPT discussed

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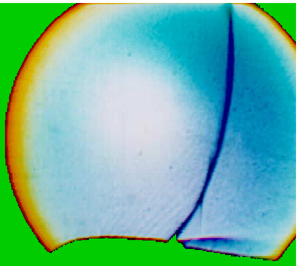
Objectives



- Establish a better understanding of fundamental steady/unsteady flow interactions by determining the
  - importance of the “acoustic blockage” in 2/3D transonic flow
  - non-linear shock/boundary layer interaction in unsteady flows at different transitions
  - Study wave propagation in a 3D cascade environment
- Creation of high quality experimental data bases

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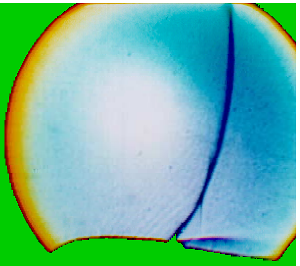
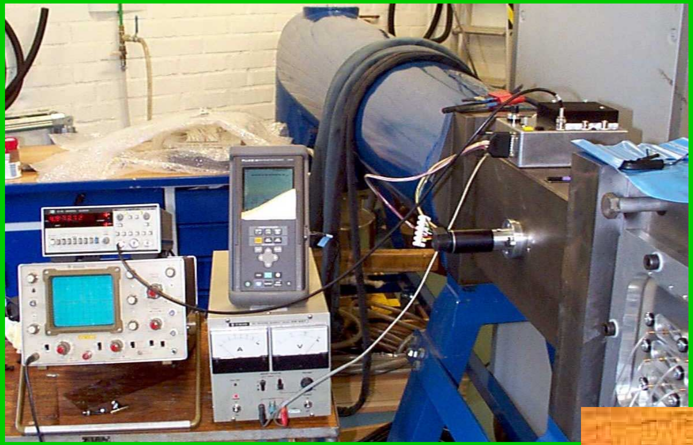
Perturbation Generator



- Downstream Rotating Rod
  - Different Shapes for Different Amplitudes
  - Perturbation Frequency Up to 650Hz
  - TTL Output Signal for Measurements Trigger



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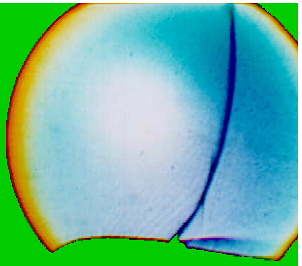
Bump Geometry



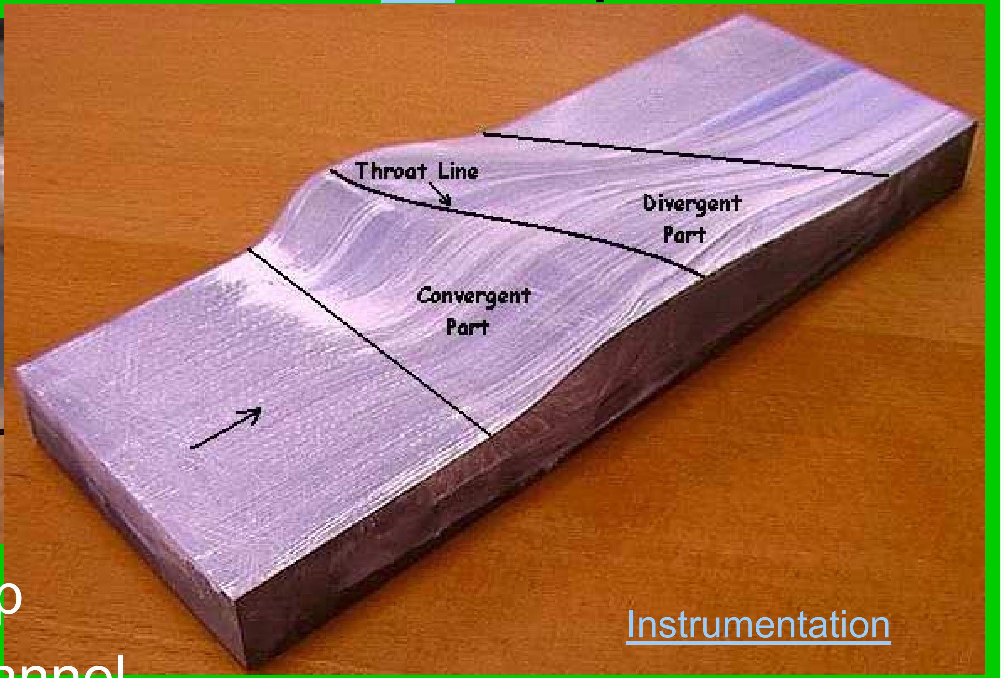
2D Sliding bump

Same Cross Section as 3D bump

Sliding through Wind Tunnel Channel

2D Shock Configuration

3D bump



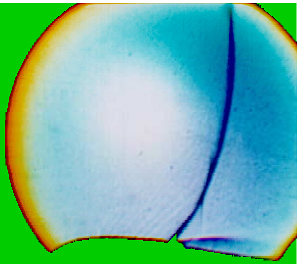
Instrumentation

Increasing length and thickness across channel width

Varying Mean Flow Gradients

Bent Shock Configuration

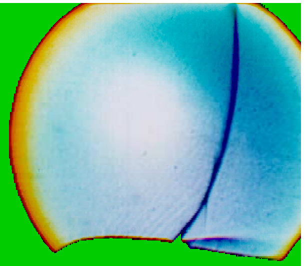
Instrumentation 3D Bump

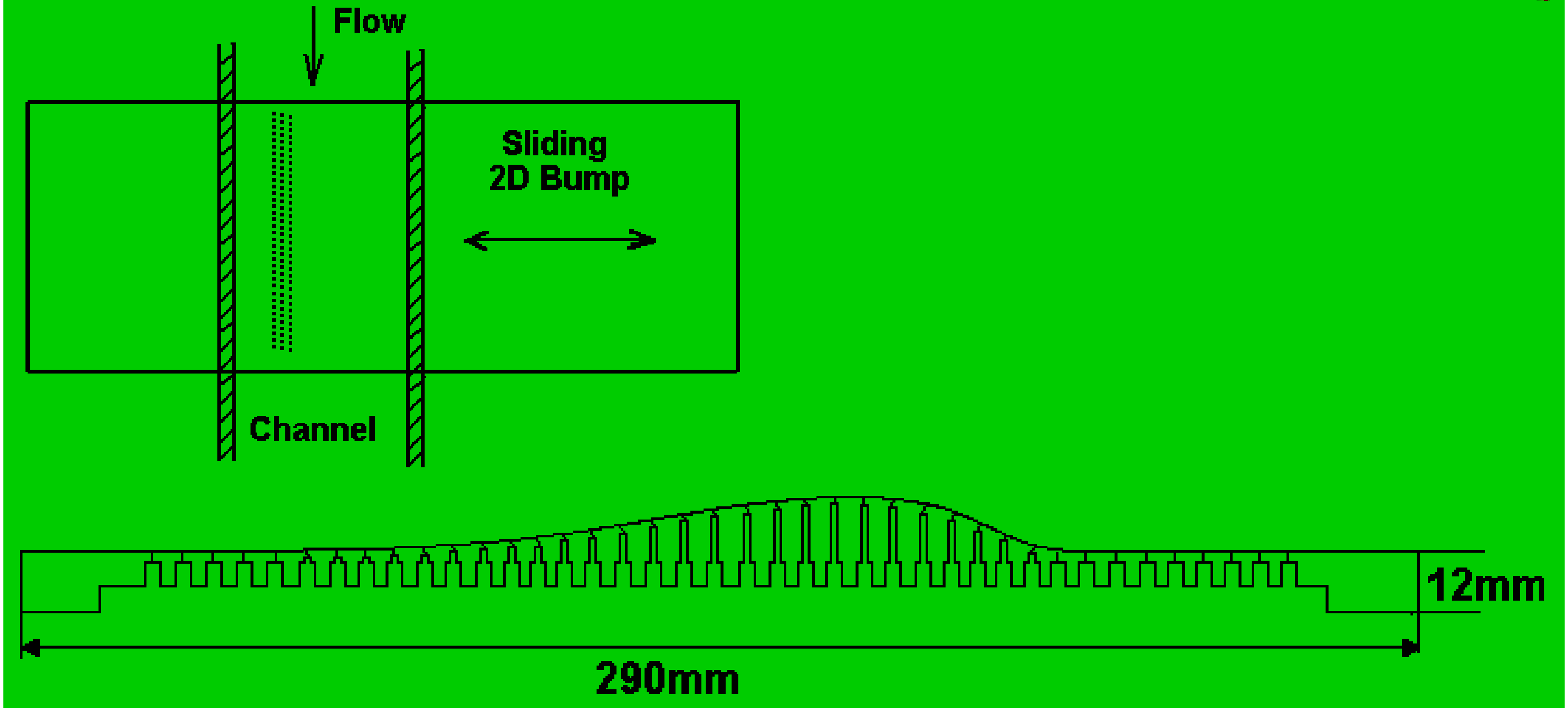


- 350 Pressure Taps
- 32 exchangeable Kulite Transducers
- Hot films in 1-2 lines

Back

2D Bump





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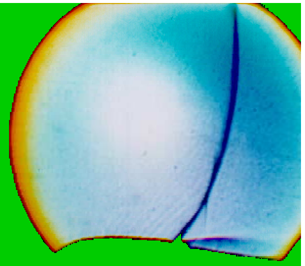
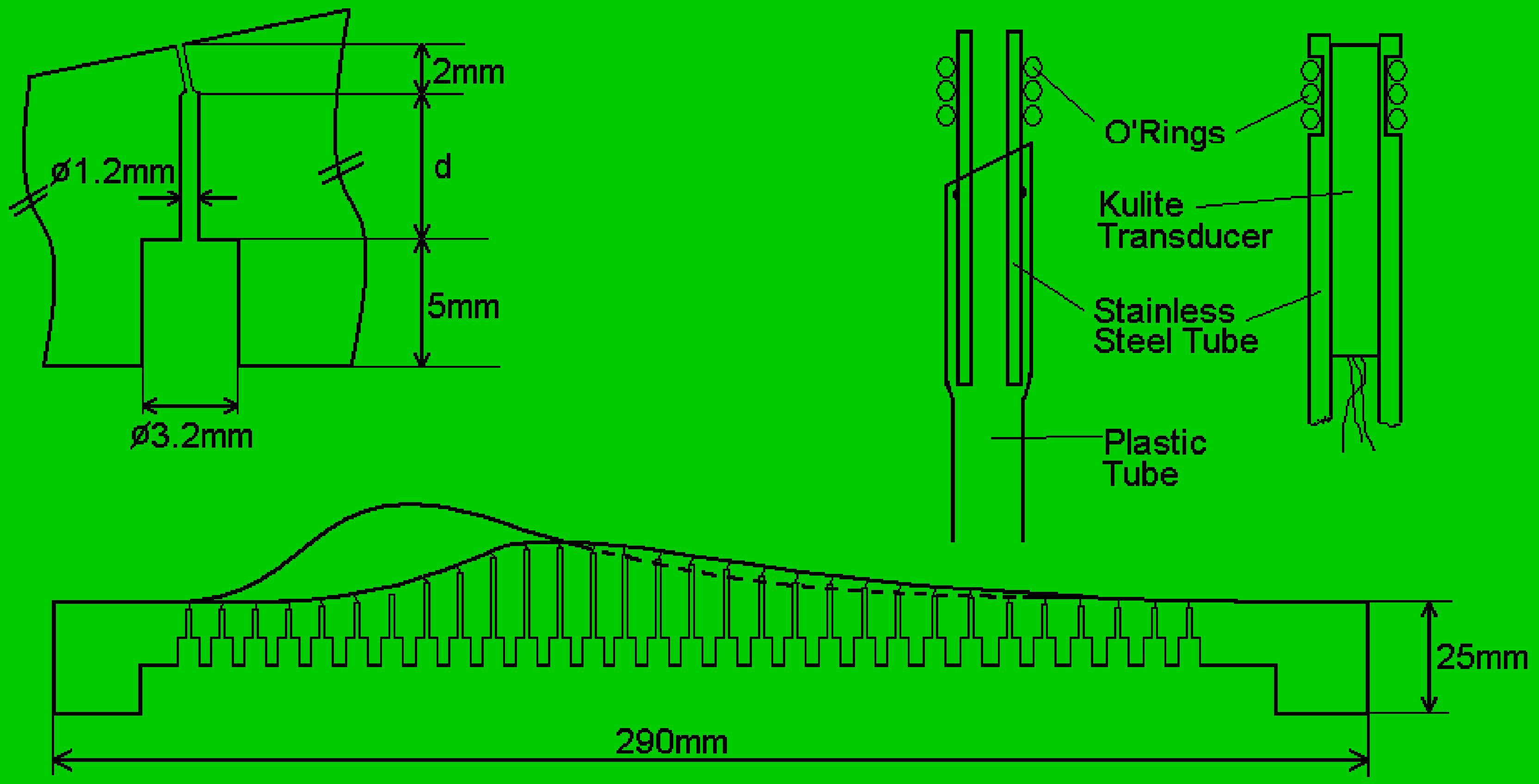
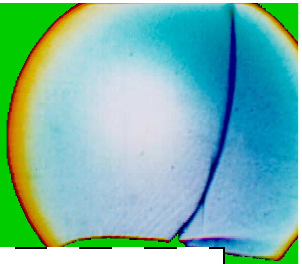
3D Bump

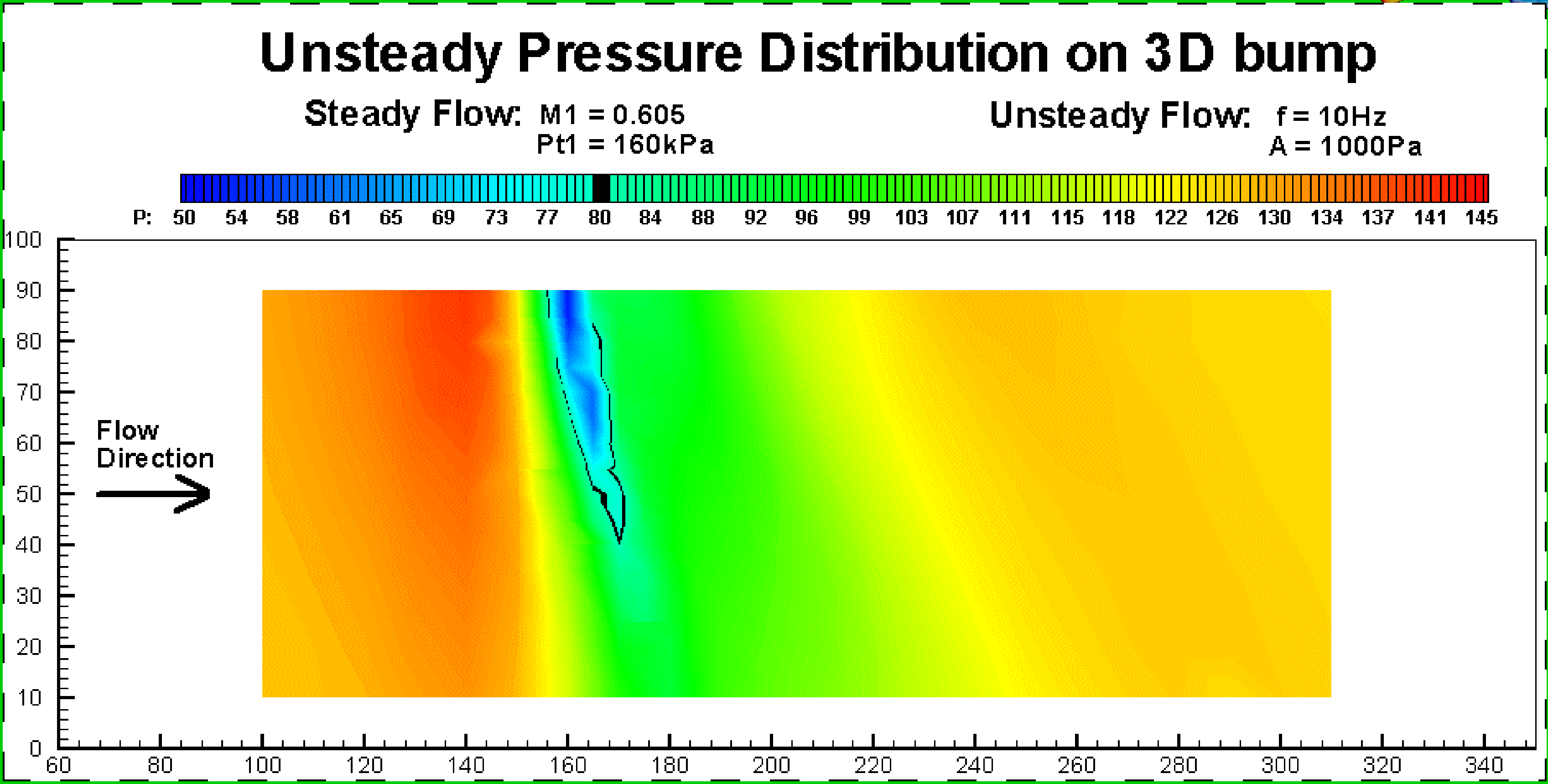



2mm
ø1.2mm
d
5mm
ø3.2mm
O'Rings
Kulite Transducer
Stainless Steel Tube
Plastic Tube
25mm
290mm

Back

Unsteady Results





Unsteady perturbation

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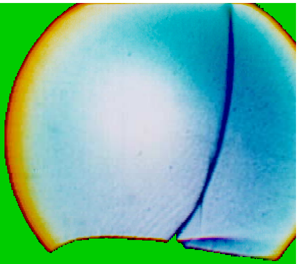
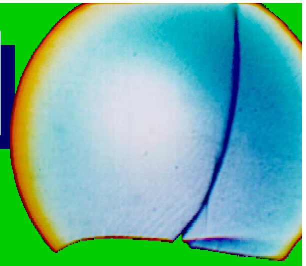


Measurement Techniques / Air Source

- Present & planned measurement techniques:
  - 200 channel “steady” pressure system
  - 32 channel 20 kHz unsteady pressure
  - 3D L2F
  - PIV
  - 16 channel hot film
  - Hot wire
  - Conventional schlieren
  - (Development of high response pressure sensitive paint)
- Air source:
  - Continuous run 1MW compressor
  - 4.7 kg/sec at 1 bar & 30 C

Pressure Measurement Systems



- PSI 8400 system
  - highly parallel and modular data acquisition system
  - ADC Up to 50,000 channels/sec
  - Different Pressure Range Scanners (7kPa, 35kPa, and 100kPa relative to atmosphere)
  - 208 Channels with 0.05% full scale accuracy

- **Kayser Threde K8000**
  - **Real Time Data Storage System (3.2 Msamples/sec)**
  - **32 Independent channels with:**
    - → **100kHz bandwidth differential input**
    - → **programmable input voltage (5 to 5,000mV)**
    - → **programmable calibration and offset correction**
    - → **12 Bit A-D Converter with 1Msamp/s per channel**
    - → **48dB/Octave low pass filter with Fc**

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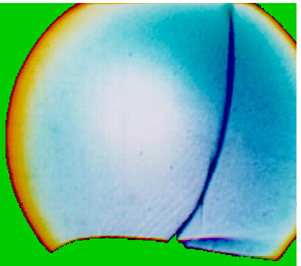
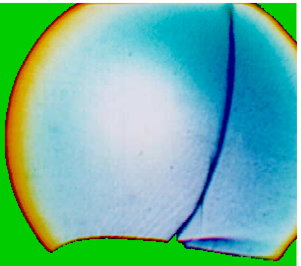
Background



- Large influence of unsteady flow effects in turbomachinery flow
- Large importance of transition location prediction for performance
- Lack of understanding of fundamental unsteady flow phenomena
  - How do 3D effects and transition influence the aeroelastic performance

Method of Attack



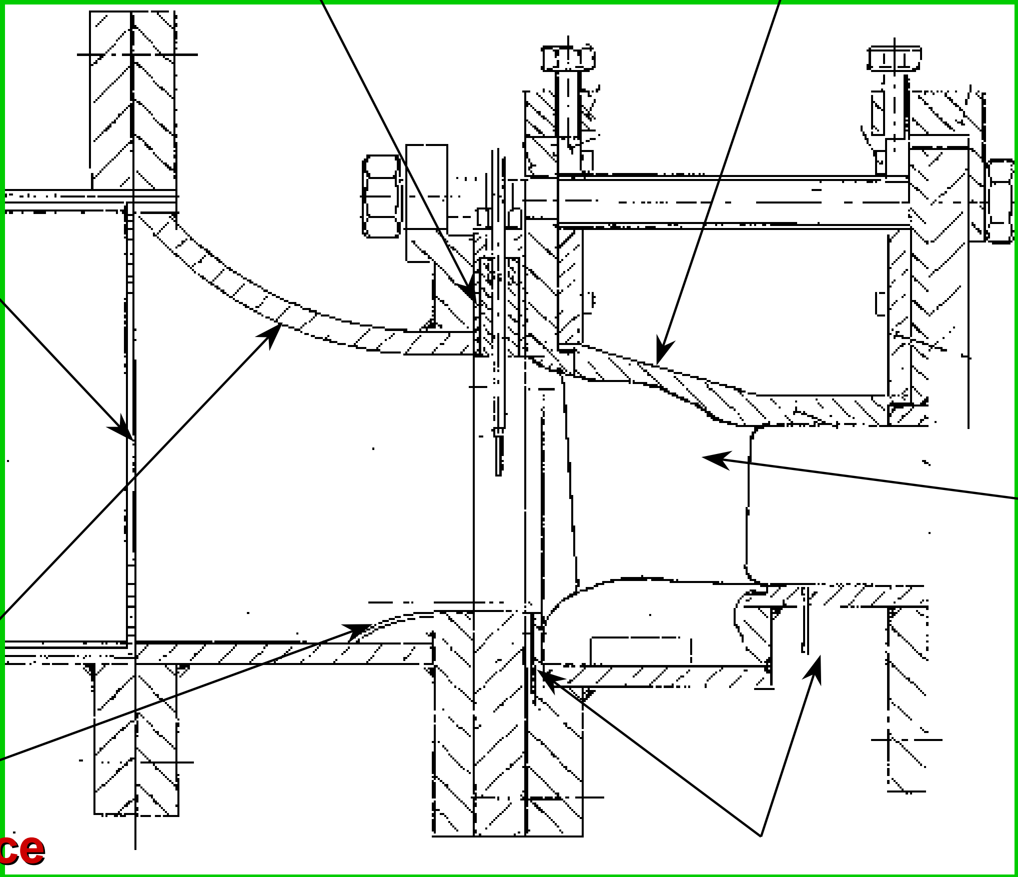
- Design of two highly modular test facilities
  - Transonic wind tunnel with unsteady “bump flow”
  - Annular turbine cascade sector facility with vibrating blade
- Design of Tests Objects
  - 2D & 3D “bumps” with downstream perturbations
  - 5 LPT blades in a sector with the middle oscillating
- Detailed steady/unsteady measurements
  - inlet and outlet conditions
  - boundary layers
  - wave propagation
- Planned extensions
  - rotating upstream rods in both facilities
  - oscillating “bump”

Planned Extensions

- Installation of flexible bump to obtain flow/structure interactions
- Simulation of wake passage to investigate unsteady Transition
- Steady flow gradients study using different 2D/3D bump
- Upstream pressure pertubations induced by upstream rotating rod
- Active/passive control to act on forced response

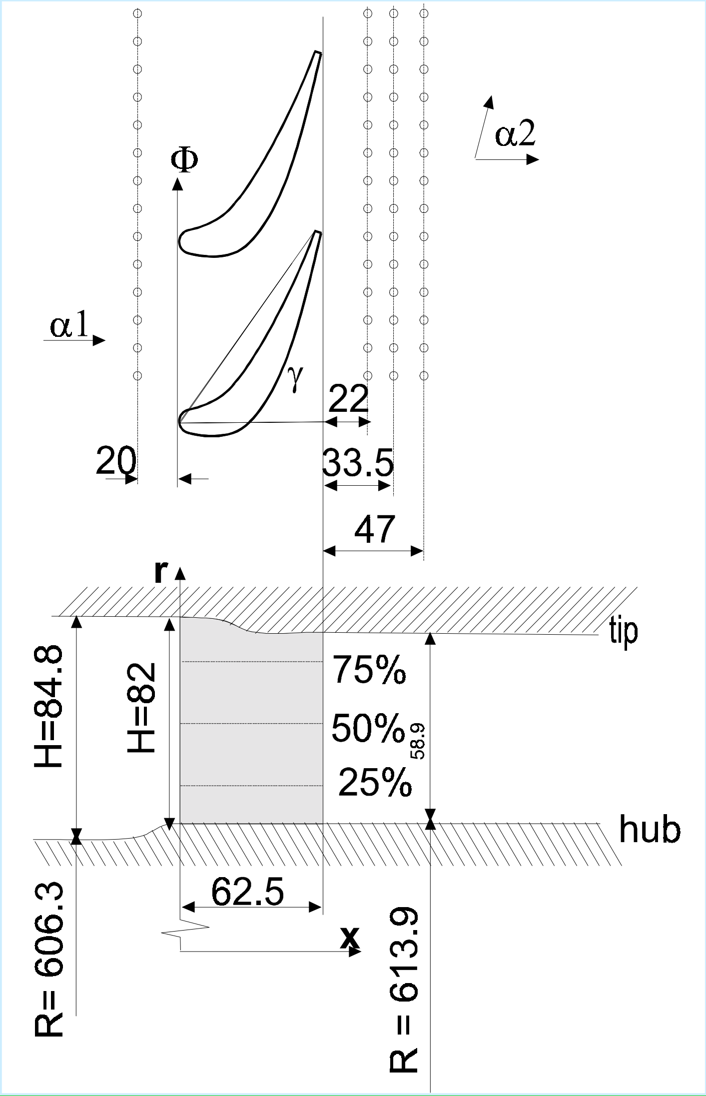
Test Section

BACK

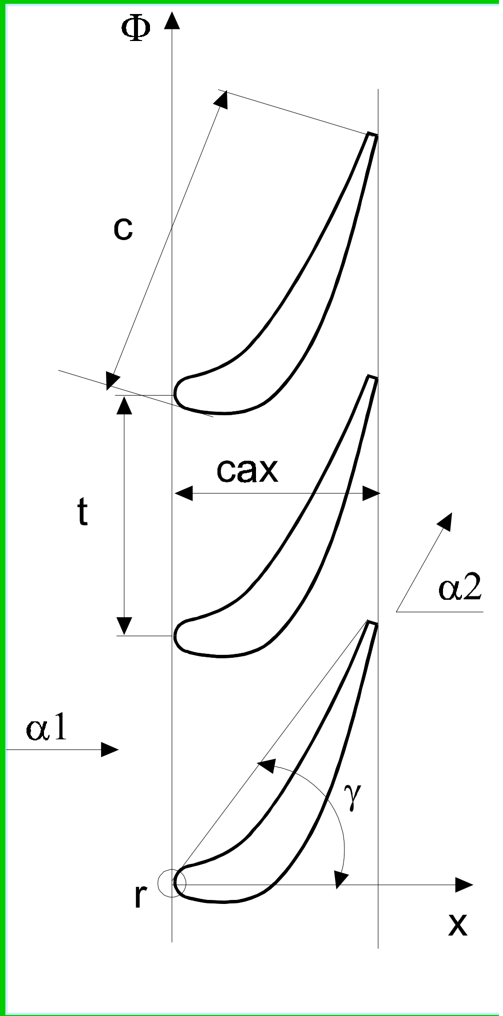


Cascade Geometry & Instrumentation

BACK

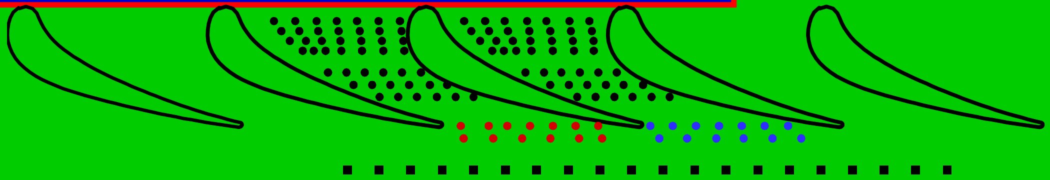


No. of blades	6
axial chord	65.7 mm
chord	110.4 mm
M_1	0.1
M_{2iso}	0.9
α_2	74.9^0
t	7.2^0

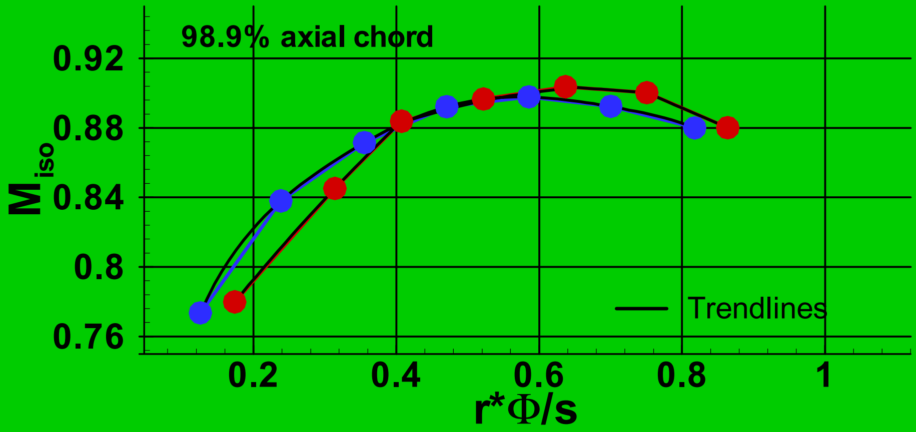


Tip M_{iso} Distribution

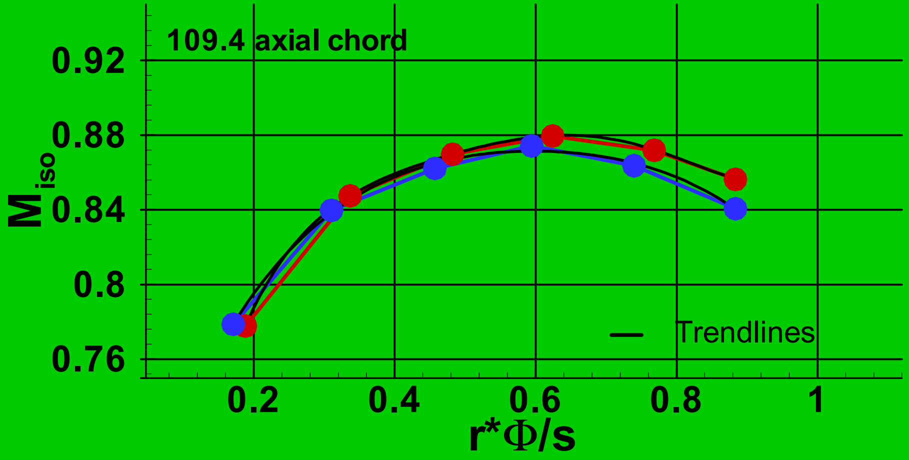
BACK



Tip M_{iso} distribution 98.9% of c_{ax}



Tip M_{iso} distribution 109.4% of c_{ax}



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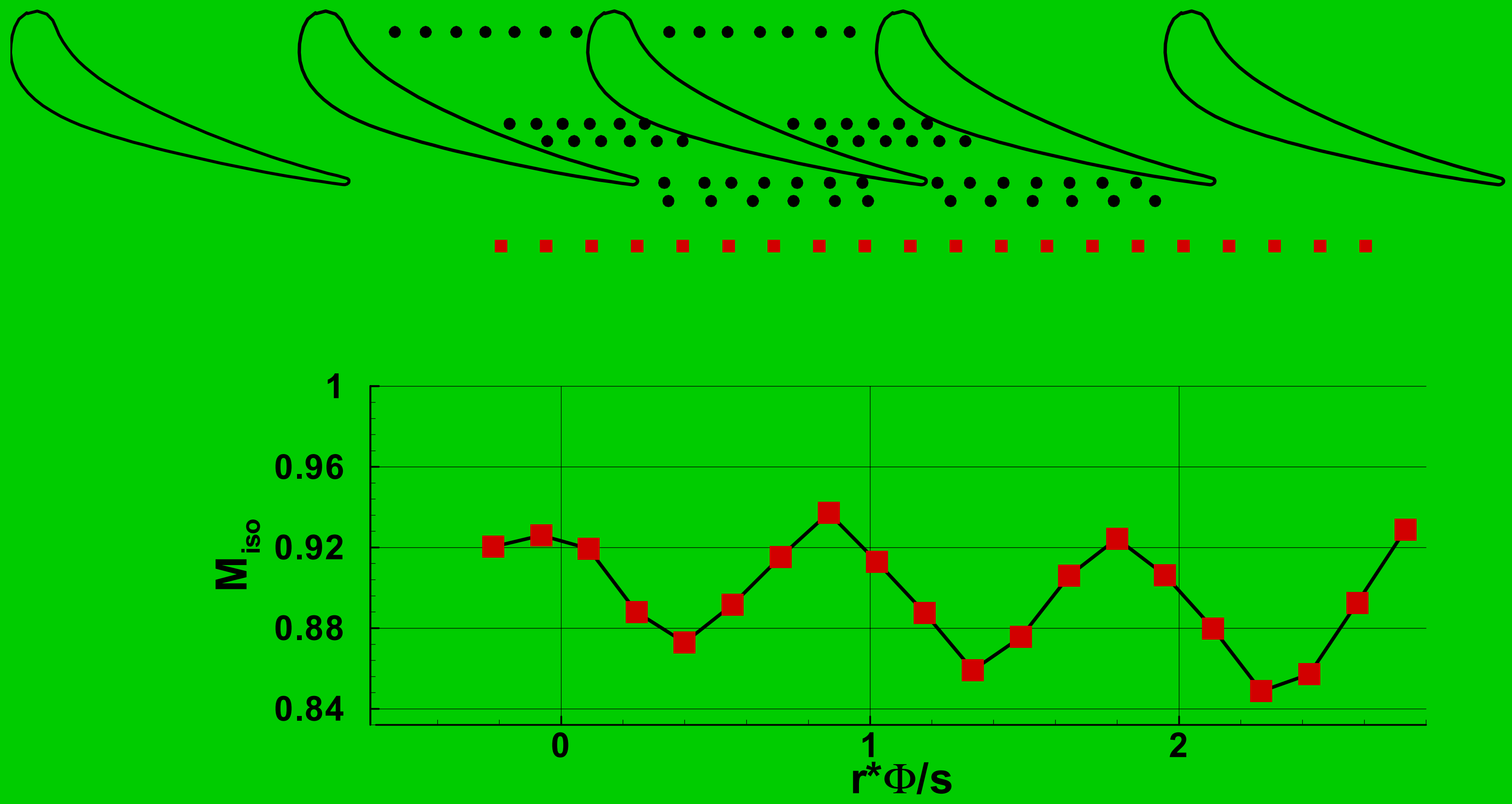
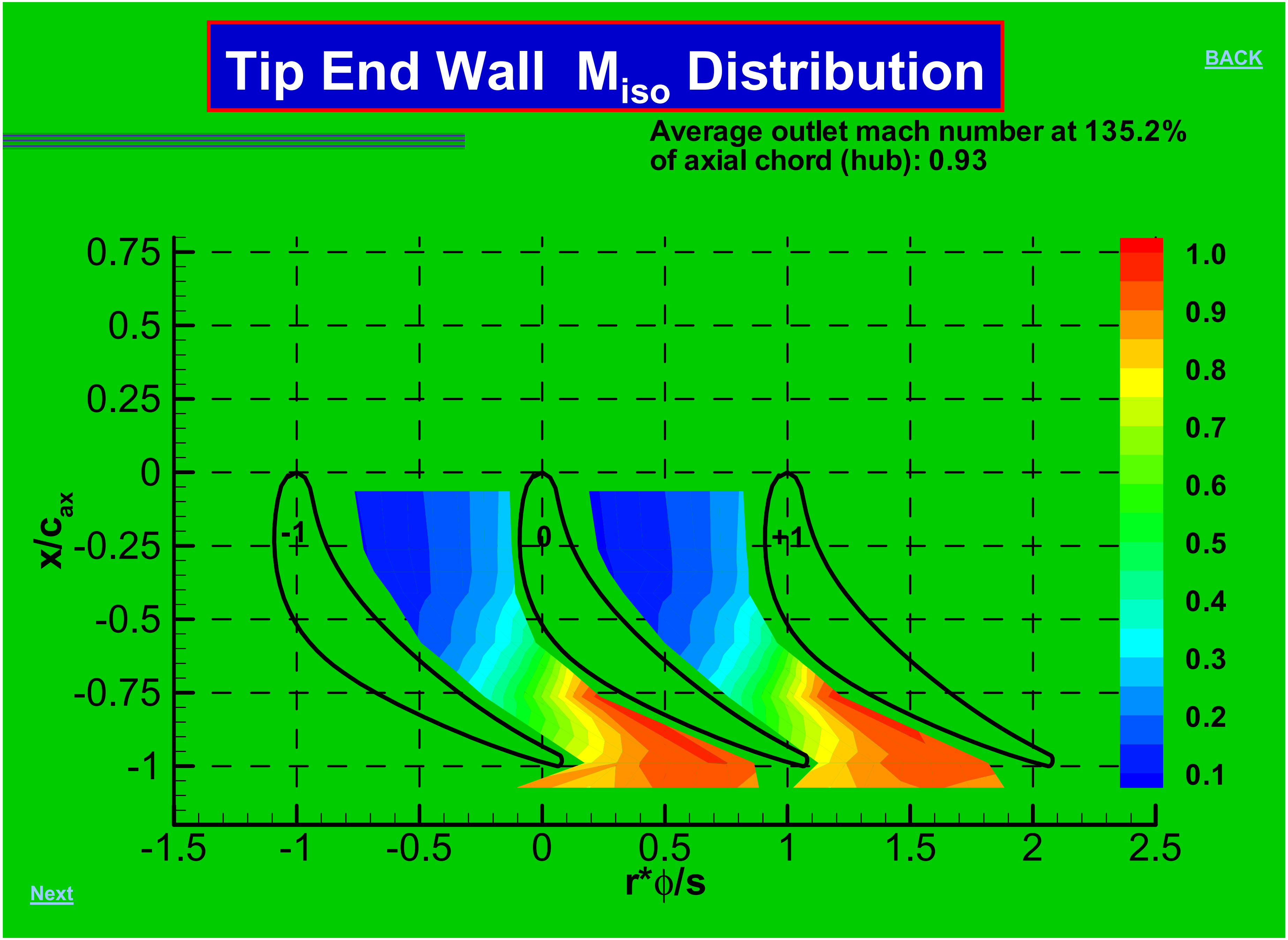
Hub M_{iso} Distribution

BACK



Hub M_{iso} distribution 135.2% of c_{ax}

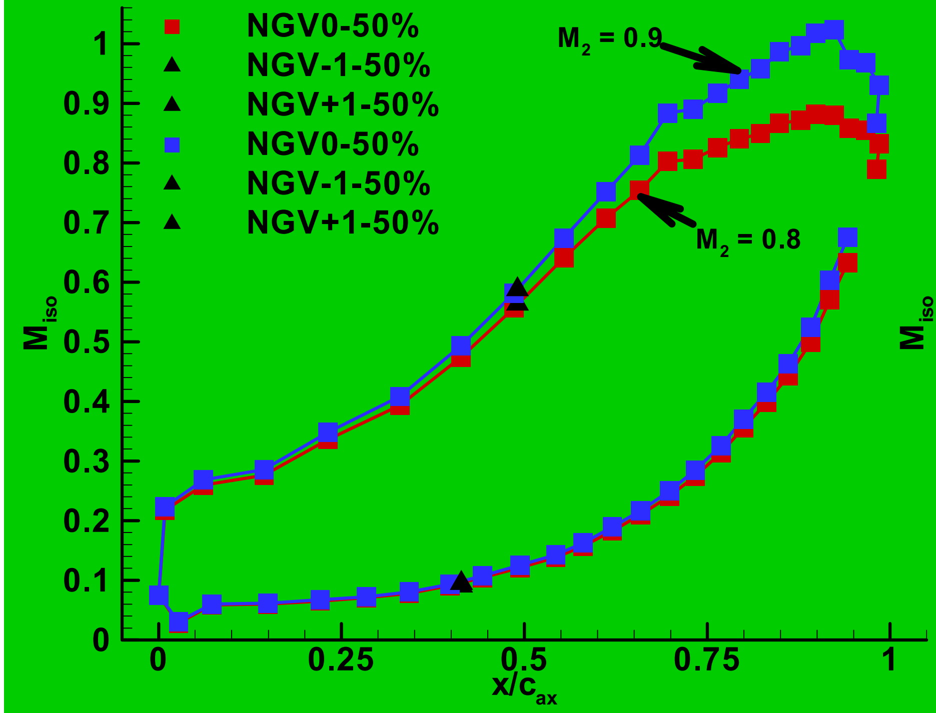
Next



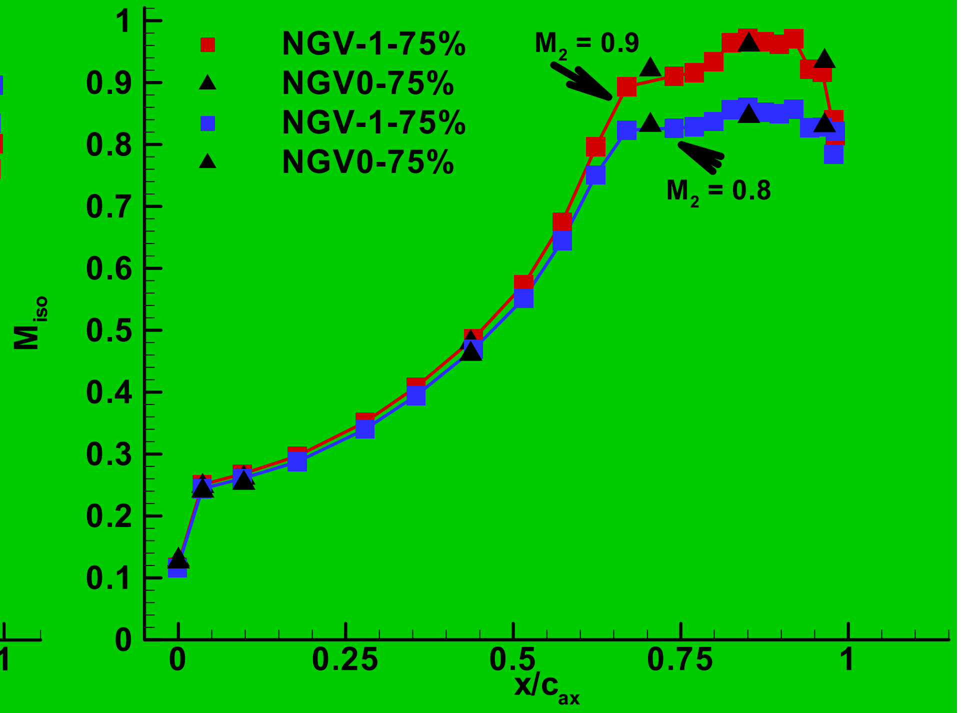
Tip End Wall M_{iso} Distribution
BACK
Average outlet mach number at 135.2% of axial chord (hub): 0.93
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
x/c_{ax}
-1
0
+1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
r*φ/s
Next

Profile M_{iso} Distribution

BACK

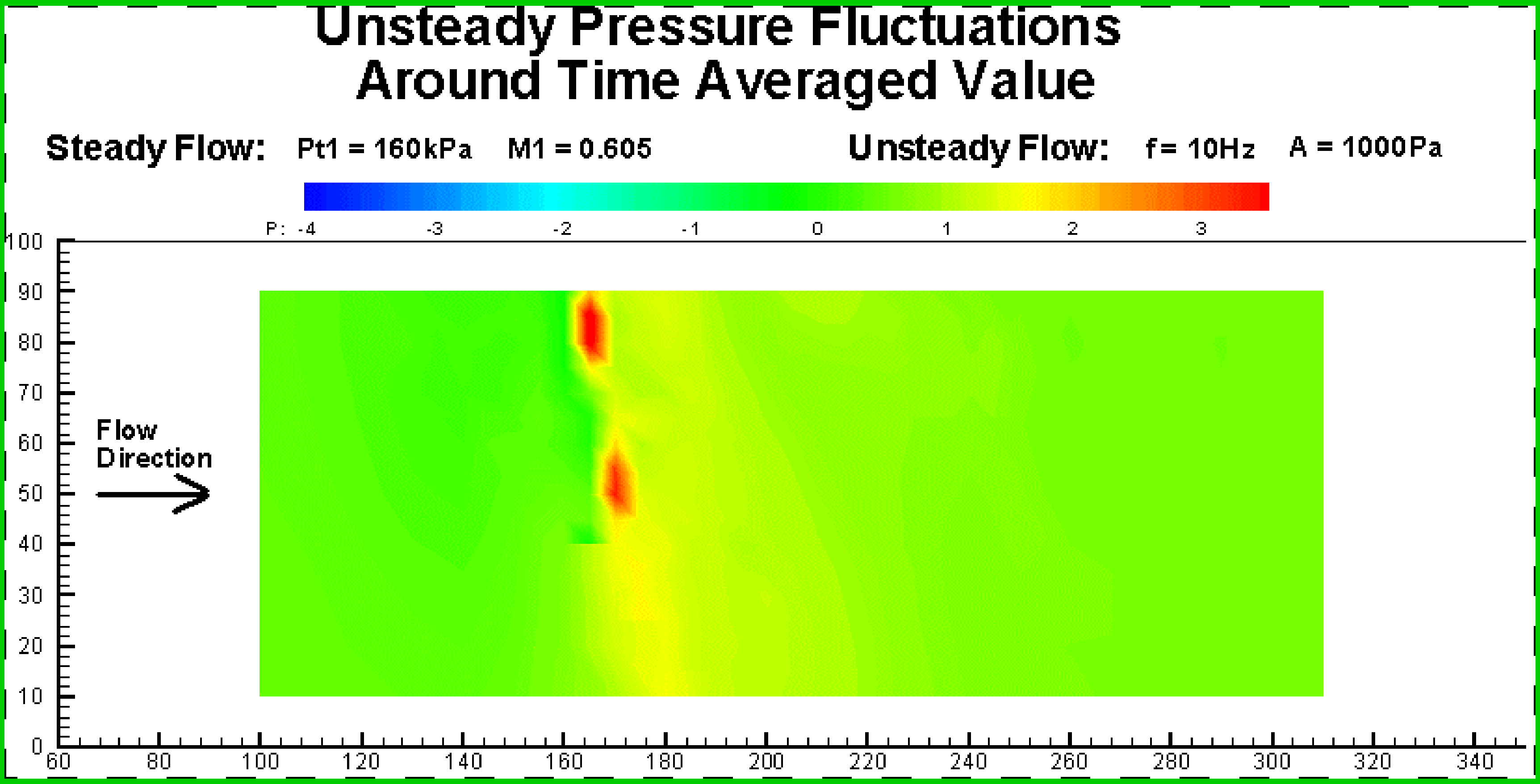


Profile M_{iso} distribution 50% span



Profile M_{iso} distribution 75% span

Unsteady Perturbation



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FINAL PLENARY SESSION TRANSCRIPT

J. Paul Gostelow
University of Leicester
Leicester, U.K.

Breakout Sessions Reports and Discussions

Okiishi: We've got four hard working groups that have been spending some time together talking about various ideas and we are going to hear their reports now. About ten minutes each. To gain some perspective, this workshop is about transition in flow and turbomachines and is a vehicle for using this knowledge. So as each of the groups comes up to report we need to keep in mind these two things. We are talking about boundary layer transition, impacts of the transition and what impacts transition. And particularly on transition that occurs in turbomachines. So let's try to keep our eyes on those two drivers. We have a by-pass group. That is going to be reported on by Greg Walker and then we have a group that concerned itself with flow separation details and George Huang is going to report for that group. Then we have a group that looked at the whole gas turbine engine and tried to address the question of what are the disturbances that would impact transition in some way. Finally we have a calming group. So, Greg, start talking.

By Pass Transition

Walker: We had fourteen people participating in the by-pass transition group and we led off on that subject. It was agreed that the definition and concepts of by-pass transition had changed over time since the term by-pass was first coined by Morkovin. Morkovin's original idea was "that phenomenon which by-passes known transition modes". There was no universal agreement on what the current definition should be but some suggestions or comments on what attributes it might have are, firstly: the original definition of Morkovin as "that which by-passes all known theories". Secondly, and this was a major attribute, "that process which is non-linear from the beginning and shows no evidence of linear amplification". As a corollary of that we might say "any process which gives earlier transition than would be predicted by the e^n method". It was agreed that free-stream turbulence was not a good basis on which to define by-pass transition as laminar flow was observed up to 30% of free stream turbulence under some circumstances and certainly our observations indicate it does not necessarily follow that a high level of free stream turbulence implies that we will have by-pass transition. Another factor to take into account in by-pass transition is that the shape of the turbulent spots may be quite different from those of the classical arrowhead shaped spots that are observed under zero pressure gradient natural transition conditions and this may be due to the surrounding flow being unstable if the by-pass mechanisms cause the breakdown to occur earlier. There was some disagreement on whether we should classify transition under a mean flow distortion as by-pass. Some thought we should, others thought that this was merely an example of changing the receptivity of the flow. I think the general conclusion is that because of this diversity of opinion that we should be careful to define the term by-pass whenever we are using it and one of our members, to be rather provocative, asked the question "Do we need to use the term by-pass anyway"?

Getting on to natural transition, this is complementary to by-pass transition and it was suggested here that it might be better to use the term “canonical transition”; that is something that follows a known route for this process. Natural transition can include situations where the disturbance environment is altered by design and perhaps it would be better to use the term controlled transition for this sort of case because there will always be forcing of the disturbances in the boundary layer by the natural environment in any case. It was agreed that transition resulting from point disturbances which led to three-dimensional wave packets showing an initial stage of linear amplification should probably be classified as natural transition and as a result of that it would appear that we are correct in classifying the observations from Hughes’ experiments of wave activity in decelerating flow transition, on our compressor blades, as characterising natural transition. The final topic we touched on briefly was sub-transitions and it was agreed that these were characterised by relatively abrupt changes in the intermittency distribution within the transition zone, which caused it to differ from the standard intermittency distribution of Dhawan and Narasimha. It was agreed that the situation of transition followed by re-laminarisation followed by re-transition did not really fall into a class of sub-transitions. Someone suggested that it would be useful to see whether there were new spots being formed at a sub-transition, although it seems rather unlikely because sub-transitions normally occur fairly well into the transition zone, where the ability to form new spots is restricted by the increasing proportion of turbulent flow. It was agreed that the most probable explanation for sub-transitions in spatially varying flow where we have a rapidly varying pressure gradient along the surface is most probably due to changes in the rate of growth of turbulent spots. These are particularly pronounced where we change from an accelerating flow to a decelerating flow within the transition zone and that is the situation that is prevalently found on the suction surface of low-pressure turbine blades. That concludes my report.

<u>Okiishi:</u> Good report Greg. You’ve earned your group some discussion time. Would the group stand so that we can identify you. Any comments or questions?

<u>Clark:</u> Having been in that group I don’t remember us agreeing that it was most likely not the increasing rate of spot generation. I remember arguments being made but I don’t remember us reaching a consensus. So I disagree with the conclusion that was drawn.

<u>Okiishi:</u> So you would call that an unresolved question.

<u>Walker:</u> I mentioned two possibilities there. One possibility was the number of new spots generated through the transition zone varying. The other was the changing rate of growth of spots through the transition zone. I thought there was a majority opinion that the latter effect was likely to predominate.

<u>Corke:</u> I think the situation that we had in mind that might create new spots was when a shock impinged on a transition zone. Because of the severe adverse pressure gradient in that case it was not clear that new spots would not be formed.

<u>Walker:</u> I would certainly agree with that.

<u>Okiishi:</u> This is good. We are getting some pertinent information from this group.

Simon: Under that definition is by-pass transition reserved for only attached flow transition? It is not applicable to transition of a shear layer over a separation bubble?

Walker: I don't know that I would have separated flow transition as a separate class. I would say that you either have natural or by-pass transition and that can cover either attached or separated flow. That's my personal view.

Povinelli: I wonder about Roddam's term sub-transitions, because I get the impression that what you are describing might be called the actual transition that occurs when there may have been some other type of transition beginning and this other one came along and dominated and caused the final transition. So sub-transition sounds like an inappropriate way of describing it. I have the feeling there must be a better term.

Narasimha: I certainly can propose one. The only reason I called it sub-transition was that it occurs within the transition zone. There is this main transition from laminar to turbulent flow going on. Within that zone there is some kind of change that takes place.

Clark: It seems that we identify the sub-transition from a change in slope of an $F(\gamma)$. What can cause that change in slope is either N, σ or U_{inf}. So if we define the sub-transition to find an identification of it by that change in slope I don't think we can judge *a priori* that it was simply sigma that changed.

Narasimha: I think that is correct. That is why I would like to make a distinction. This is a personal view. I would like to make a distinction between sub-transitions and the reasons for sub-transitions. As I said a minute ago, the sub-transition is noticeable as a relatively abrupt change. But of course within the transition zone the only reason for adding the word sub is that there are other transition processes going on already. I think they are right. In principle you can't tell. I don't think there is enough experimental data yet to tell whether it is caused by the number of spots being made or by the propagation characteristics. This is something you have to settle by more work.

Okiishi: What is your group's intention with regard to recording this.

Walker: We could write this up and include it in the proceedings of the meeting.

Gostelow: What will happen is that the words being recorded there will find themselves transcribed in writing as in the previous conference and find themselves in the proceedings, pretty well verbatim, unless you decide otherwise.

Flow Separation

Okiishi: Let's move on to the next group, which is the flow separation group. George Huang will report for that group. Let's have that group stand up so that we can see who was in it.

Huang: The group you see met twice. John joined us in the second meeting. In the first meeting we all agreed on everything. After John arrived we disagreed again. After about ten minutes we all agreed again. We started the meeting talking about prediction, 2D prediction. Some questions were raised whether 2D prediction is valid.

We believe that separation is easily categorised into 2D, but that reattachment is a 3D phenomenon. So we think that we should look at 3D instabilities before we go onto a prediction method. We think that perhaps we should gain better understanding about the stability of the bubble. That would help us in predictions. We talked about instabilities not only in terms of a bubble's shear layer instability, we also have to look into the global instability. We believe that there is some kind of global instability inside the bubble that would give rise to a feedback mechanism with a Strouhal number of about one. And we believe it is important that we should look into that as well. We also touched upon the point that the Roberts correlation that many people use is actually from 1975; it's really out of date. Maybe we should come up with a better correlation. We should look into that direction as well. We also say that "When we classify the bubble is there only one type of bubble or should we classify different types of bubble, such as long bubble, short bubble" and we want to look at the instability of the different types of bubble. Look at their similarities, look at the differences. Perhaps that will help us in understanding the separation phenomena. And we think that in terms of prediction the leading edge short bubble is probably easier to predict. The long bubble is probably most susceptible to global instability; perhaps this is more difficult to understand and also to predict.

We also talked about "Maybe we should design an experiment, because reattachment is more of a 3D phenomenon it is harder to predict and the separation is easier, perhaps we should devise an experiment which would have a fixed bubble and then we can prescribe some free stream turbulence and look at how the reattachment is influenced by the free stream". Can we devise an experiment, one that was talked about was the backward-facing step. But another member of the group said "We have seen so many backward facing step experiments - we don't need another one". But perhaps we can look into some kind of turbomachinery-related problem because probably we can identify a problem that will give us more insight into these phenomena.

One member in the group is more from a modelling background. He wanted to see an experiment that had transition taking place just before separation. Also another set of experiments should see the transition take place more on top of the bubble; we need more experiments of those type. One is to look at by-pass transition, the other to look more at shear flow transition.

We talked about the length scale and had a lot of debate about that. We wanted to know what is the length scale in bubbles. We agree that both the length scale and the turbulence level are important but we wanted to know what length scale we should define. Perhaps we should classify the length scale: identify all the possible length scales that are important, such as the turbulent length scale, the bubble length scale and perhaps document them. When we talk about documentation we asked what results do we need from experiments. We came up with a conclusion you may not agree with. We think of all experimental data the raw data is the one that everyone has to store. Because one day you might want to go back to the data and look in a different way at the data. We spent a lot of time discussing the best way to store the data. ASCII or some other form? Perhaps we should put it into a format that is accessible to all members in the group.

One more thing before we end. One member raised the issue "Now you talk a lot about stability, bubbles etc. How does that help us in modeling? Are we missing something? Do we have a problem bridging the two. The modeler and the person doing the stability analysis. How do we bridge the two?" That is the question at which time was up.

I said we need all experimental data. We need time domain, frequency domain, everything to be documented - everywhere.

Fransson: Coming from outside this community I think it would be very useful to us to know what I should look at in detail for your kind of problems. It would be very useful to have a list of priorities with what would you like to see measured, how would you like to see it measured, if possible, and with what priority.

Huang: I think that is a good point. The way we approached this discussion is that we adopted a top down approach, not a bottom up approach. The experimentalists tell me "I am measuring this, I am measuring that, I have this much information. I have to think about how to digest the information on instabilities etc. for the model". Perhaps next time we should do it in a different way - we should ask the modelers to pose the question to the experimentalists: What do they need?

Okiishi: They need to understand the phenomenon first.

Huang: As well. Both ways.

Fransson: From my perspective it would be very useful if a conclusion from this today would be a list of information that you would like to have in order to model your problem. I know what I need in order to model my problem but I do not know what you would need in order for us to connect. If you could give me a list of priorities that would be perfect and we will try to give you that information. And probably I will also learn something from that at the next meeting.

Okiishi: Other questions or suggestions?

Smith: There have been countless experiments in the past on separating flows and also computations.

Gostelow: Have there been any good experiments on separation?

Smith: I am the last person to ask about that. There were some experiments done in Scandinavia by a PhD student in the late 90's that were reported in a meeting two years ago. He was talking about transition ahead of separation and beyond.

Theofilis: I want to answer in an abstract way. Maybe what is on the board is the answer. It is not about repeating the experiment. It's about doing the experiment for different things and conditions.

Herbert: We may take down a copy of Mark Morkovin's list of preferences.

Okiishi: How succinct is the list? A couple of pages?

Hodson: It could be appended to a CD.

Walker: I think what Torsten is suggesting for the aeromechanical problem is something new. These are observations from a separating flow on an oscillating surface. Not only is the flow oscillating but also the boundary surface is moving so I think it important that the motion of the bounding surface should be accurately prescribed as well if we are going to interpret the data properly.

Fransson: That I know how to do, so I could easily give that information. That is fairly easy from my perspective.

Industry: I think there are some tests that need to be redone. Particularly if you try to apply the models that are developed in comparison against experimental data where not enough information is taken, such as special information about turbulence intensities, things of that nature. Some of these need to be redone.

Okiishi: Do you have any experiments planned for your rig, Don? Separation bubbles, detailed measurements?

McEligot: Not specifically. We don't have any funding for doing anything like that. We do have the flow over a building model and there will certainly be recirculation zones behind that, the flow will be separated but it is not a turbine blade.

Turbulent Spots and Calmed Region

Okiishi: Let's move on to spots and the calmed regions that go along with the spots. What do you call them Paul?

Gostelow: Blobs. I'm trying to think of a less drastic name.

Johnson: No - blobs it is. We started out with three people and expanded to eight. The objective was to define what we really mean about the spot or the calmed region and to talk a bit about the characteristics of these regions. We also decided after my presentation that spots should be red and calmed regions should be blue.

The definition we came up with was that a spot was a distinct region inside which the flow has turbulent boundary layer characteristics. We tried to qualify the characteristics but decided that included everything, such as profiles, Reynolds stresses, everything that you can measure within that. We had some problems with the region. We started out with bounded region, confined region, so we were uncertain about that.

A spot usually propagates. We debated whether the word usually should be within that and decided that it should.

Regarding the characteristics, we thought that once fluid has entered the spot it cannot leave the spot. There are, of course, spots that do not meet the classical Emmons spot model. We have seen that very much at this meeting. We tried to cover that in the following two statements:

An embryo or early spot will exhibit some form of structure.

Also we have the sub critical spots which are induced by some other disturbance, free stream turbulence or wake-passing. These have these rather odd shapes and also grow at these rather lower rates so they basically have rather different dynamics. It is suggested that maybe these sub critical spots are most relevant in turbomachinery.

So after the spots we switch to the calmed region. Definition: Again we felt that the calmed region always has to be associated with some form of turbulent region, such as a turbulent spot, strip or blob, as defined by Paul Gostelow. Or a wave packet, so you can have a calmed region behind a wave packet as well. And it will always have a fuller profile than a laminar boundary layer. The profile within the calmed region relaxes from that fuller (more stable) profile back towards the laminar profile. That is supported both by the types of models that use unsteadiness and viscous diffusion and also by numerical flow visualisation which supports that.

As far as the fluid is concerned all the fluid enters the spot by its trailing edge. So there is no fluid that passes from the spot into the calmed region. We seemed fairly convinced that that was the case. So the calmed region, it has often been said, results through a rapid relaminarization. We are saying that that is definitely not the case. That the calmed region is not formed by relaminarization of the spot fluid.

<u>Okiishi:</u> Let's have some questions, comments and suggestions.

<u>Hodson:</u> The blue stuff looks identical to what it did three years ago. Is that correct?

<u>Ramesh:</u> Well, the calmed region hasn't changed.

<u>Hodson:</u> I'm glad I didn't join the group then. On your red stuff, I think you said fluid never leaves spots. We did an experiment five or six years ago where we had a flow transitioning before it flowed over a porous surface, which had suction below it. The intermittency dropped as you went over the surface. I never worked out whether the spots were getting smaller or we were relaminarizing. If the spots were getting smaller, which is what I suspect was happening, then, in a sense, fluid is leaving the spots

<u>Hourmouziadis:</u> If you suck the flow from the spots what do you expect?

<u>Okiishi:</u> You'd accept that exception, right?

<u>Hodson:</u> I wonder if there is anything in that.

<u>Gostelow:</u> You are not supposed to do that though.

<u>Durbin:</u> The spot is a wave packet and in general the wave doesn't move at the same speed as the fluid.

<u>Herbert:</u> You can get diffusion out of the packet.

<u>Seifert:</u> I think we are smiling because there is a famous experiment by Gad el Hak and others. They generated a spot with a puff of coloured fluid. They generated the spot and they never saw the colour leaving the spot. A spot is wavy, of course, it is a shear flow disturbance. But the convection speed is such that in general particles entering it will not leave it. Perhaps a coincidence or perhaps not but I think it is a fact.

<u>Hourmouziadis:</u> Simply the kinematics would suggest that. The thing cannot convect as fast as the rest of the fluid does. So there are two alternatives. It is either a solid blob moving through the fluid or there is some fluid coming in and getting out. The phenomenon is moving slower than the rest of the flow.

<u>Jones:</u> This is why our definition is so valuable.

<u>Walker:</u> The surrounding fluid actually rides under and over the spot. So the spot actually appears to the rest of the flow like a perturbation in displacement thickness. You can actually pick the spot going past by looking at the perturbations in the free stream velocity. So fluid does not have to go into the spot. It can go around it. It looks like a solid body. It stays with the spot and moves with it, then more gets accumulated into it and the surrounding fluid is also moving around it and over it.

<u>Narasimha:</u> I believe that in a well-developed spot, of the kind that Gad el Hak and others have studied. It is true that the fluid that goes into a spot does not get out in general. However I would hesitate a great deal to make that a defining characteristic of a spot. Because, as we have discussed during this meeting, there are all kinds of different spots. The initial spot, the sub critical spot, blobs and so on. There is no doubt in my mind that there are varieties of situations in which a fluid, when it becomes turbulent, can get out and leave that turbulence. Of that I've no doubt. Why - because we know of a variety of situations in which we know that, at least locally, fluid is getting out as well as getting in. Getting in at one place and getting out at another place. So I feel that it should not be made a defining characteristic of a spot because if you did so then of course you are constraining a spot to be an extremely specific entity. You can always take the view that if in fact fluid gets out of a spot you could make it a part of the definition. So I feel that it is good to use the word spot (or blob) as any island of turbulence. That island may grow, that island may shrink, it can do a variety of things. I think we should try and see in every situation what it does. There may be situations where the island shrinks, as Howard was saying, and fluid does get out. So I don't think we should say that we then not call it a spot.

<u>Smith:</u> I don't think you can make that the definition of a spot. This is a property for which the added word usual applies.

<u>Narasimha:</u> If you say "usual" or if you say "fully developed spot" I agree.

<u>Jones:</u> That is what was intended. Other spots we called sub-critical or something else and we didn't attribute that property to those other spots. Only to the fully developed Emmons-type spot.

Okiishi: So, once again in view of Mount Emmons we have had a very good discussion on spots. Now on to the final group for discussion of the engine disturbance environment.

Engine Disturbance Environment

Murawski: What is the engine disturbance environment? What do we know about the combustor? Let's ride through the turbine!
[Displayed charts:]

Looking at the turbine exit and into the IGV (Inlet Guide Vanes)

Turbulence Intensity, Length Scale, Total Temperature, Temperature and Velocity Profile, Low Velocity, Low Ma (0.1), Possible Hot Streaks, Possible Chunks of Carbon, Turbulence Decay Rate.

In the IGV

Leading Edge Showerhead Cooling, High Turning Curvature, Stable Secondary Flow, 1.1 – 1.2 exit Ma, Surface Film Cooling, Surface-to-Freestream Temperature Difference, Surface Roughness (TBC Spallation), Shocks, Reflected Shocks, Potential Downstream Rotor Interaction, Hot Streaks, Film Cooling Freestream Mixing.

Out of the IGV and into the First Stage HPT Rotor

Wakes, Shocks, Huge Secondary Flows, Unsteady Purge Leakage Flows, Reflected Shocks, Trailing Edge Cooling, Hot Streaks.

In the First Stage HPT Rotor

(In the IGV) + (Out of IGV) + (Tip Leakage, Film Cooling, Aero-Elasticity of the Blades, Centrifugal Force Effecting Film Cooling Outlet 1.3 Ma)

ENGINE OPTIONS

A

Inter-Turbine Duct
Endwall Separation
Shock Reflection
No Film Cooling TBC
Struts (Secondary Flow)
Auxiliary Cooling

IGV LPT
Low Aspect Ratio
Thick Inlet B.L.
Service Nozzle Guide Vanes
Wakes

B

Vaneless LPT Rotor
Shocks from HPT
Low Reynolds Numbers

Outlet Guide Vane
Similar to LPT with Lower Pressures & Lower Re

LPT Rotor
Rotation
Tip Leakage
Purge Flows
Lower Pressures and Lower Re

We may group these disturbances into the following categories:

NON-ROTATING – NATURAL DISTURBANCE
(Always in turbomachinery)

- Pressure Gradients, Axial Velocity, Ma Gradients:
- Curvature:
- Temperature Difference ($T_w – T_{freestream}$)
- Shocks:
- Reflected Shocks:
- Secondary Flows:
- Endwall Separation:
- Aspect Ratio:
- Turbulence Transition / Separation:

NON-ROTATING – DESIGNED DISTURBANCE
(Choice by design)

- Film Cooling:
- Surface Roughness:
- Hot Streaks:
- Purge Leakage Flows:
- Struts (wakes, profile loss, secondary flows):

ROTATING – DESIGNED DISTURBANCE
(Choice by design)

- Tip Clearance:
- Aero-Elasticity:
- Centrifugal Force Effects on Film Cooling:
- Wakes:

The important question is what should happen next?
Each of these quantities is considered by the designer and we need to determine what the designers need for input. Something quantitative out of these issues that were mentioned. That quantitative information is to ask the designer exactly what they put into their models. What we should do is to take each of those disturbance effects that we listed and discuss how each of these disturbances affects boundary layer transition in about two to five sentences only. Then quantify each of the impacts on transition, with references, in one to two sentences. So for each of these issues listed we should succinctly, in about 7-10 sentences per issue, wrap up the question.

There was then a discussion towards the end that had to deal with measuring actual engine conditions in an engine and making that data available for wide use. This was seen as a lacking thing that would help drive transition research.

Okiishi: Thank you Chris. You have made a useful summary of a lot of diverse comments that were hard to reach as consensus on. Anyone from the group wish to add a comment or two?

Hodson: I have a brief comment. Your last statement about "something needs to be measured". The same statement was made at the end of Minnowbrook II, and I suspect Minnowbrook I. Nothing is happening. What is going to make it happen this time?

Murawski: I don't have two million dollars.

Okiishi: What you say is true. There is going to need to be some activity following this meeting. Or it will be just buried in the end. Or it will come to the same conclusion as last time.

Gostelow: What happened to the compressor guys, did they just go to sleep? External influences: - birds, hailstones, dust, volcanic ash - more important things - inlet distortion most important.

Okiishi: Paul, we just didn't get that far.

Anon.: Getting back to Howard's comment. If you really want this to happen you need to have more than just a long laundry list. You need to prioritise the list. What exactly do you need measured, and in what priority, and what's the payoff? That's how you start developing advocacy to do it. I'm afraid that if what comes out of here is a general statement, like "we need better measurements of that whole turbine operating environment" it's a motherhood statement that doesn't help. But if you can put together the right motivation, and the priorities in which you want them, I think you can start picking off bits and pieces.

Okiishi: I think it's a point well taken and I think some of the engine companies have already asked those questions and they've got the shortened lists and are going after what they need but this is highly proprietary. So the trick is how do you get this from smaller engine companies and companies that don't have the workforce to pursue these things. And that would be a very tricky thing to do. How do you ask them and how do you get things done?

Narasimha: I think Howard is completely right. This is something we have discussed at the previous two meetings. I actually have read our account of the previous two meetings. What I found was that for Pratt and Whitney, Om Sharma offered a rig that he has for making measurements of the disturbance environment; provided there were people who would work on it he was willing to loan his equipment at no cost. Provided there was money to support the students who would carry out that work. I hope we can make that happen.

Ashpis: We want results from a real engine, not a rig. The turbulence environment may be significantly different.

Narasimha: I don't know exactly what he was offering. I thought it was some schedules in a turbine. Not a real turbine - I don't know how realistic it was.

Anon.: What realistic turbine do you have at Glenn Research Centre?

Ashpis: Following the Minnowbrook II recommendation I looked at what can be done in-house at Glenn. We have at Glenn several combustor facilities and we could measure at the exit of various combustors. However, the real constraint is lack of proper high temperature instrumentation, high frequency response instrumentation that can give us velocities, scales and spectra. We also have a warm turbine rig equipped with can combustors where the temperature is lower, but still beyond instrumentation capabilities. There was an attempt several years ago to measure turbulence in that rig with a hot-wire, but results were inconclusive. Development of special purpose instrumentation is the real challenge; the turbulence measurements will easily follow. Glenn is now funding a project lead by Oldfield at Oxford. The idea is to circumvent the temperature constraint by quickly passing a probe through the hot gas and collecting the data at high speed. This project is in progress, and some experiments were recently completed at a Glenn in a cold freestream turbulence research facility. Another probe to consider is the infinite-tube pressure probe that was originally invented at NASA and developed further at UTRC. This probe was described by Om at the last Minnowbrook. It can measure high frequency pressure fluctuations, but there are still many practical problems with that probe that are being worked on at UTRC. And it is still limited to pressure fluctuations while velocities are of most interest.

As to tests in real engines, I have tried hard to promote the project at NASA and at a couple of joint planning meetings with Wright Lab. I quoted the recommendation made by the international forum of Minnowbrook II. Unfortunately nobody thought it is of high priority. One obstacle is that NASA responds to needs of industry, and industry doesn't put this project on their high priority list. The current fiscal situation at NASA makes it impractical to fund a two million dollar project, particularly if the strongest expression of interest from industry and other government labs is lacking. So it is not that there has not been any effort in this area. But we need to be realistic about what can be done.

Hourmouziadis: There are always two ways of looking at such problems. There are ways of trying to get everything in the best way, in the way that we want to have it. Like getting the disturbances at the exit of a nozzle guide vane, with all turbulence parameters, spectral content and everything. But the other way is trying to do the best with what is available or even measurable in such a situation. The second way is the only way that has been used up until now. Progress was based on what could be done. Why don't we try to do that?

Hodson: For example, do you need to do the full hot turbine to begin with?

Hourmouziadis: Right. We start with a rig. Rear stages have got all the disturbances of the front stage in them.

Okiishi: I think that's partly what you were alluding to, right Tom? You'd got to the designer ask, so that it needs someone to ask that.

Beutner: Part of that is putting a cost to it. It is not just the importance. The key link is addressing high temperature instrumentation, we'll get there slowly. If the cold rig gives you enough of the answer to make a significant advancement and it is cheap, that's where you start.

Gostelow: Compressors are basically cold rigs.

Ashpis: Besides the question if the turbulence environment in rigs represents the turbulence in a real engine, there is a question if cold facilities could be adequate. There is a paper, by Oldfield if I correctly recall, that concludes that turbulence characteristics like scales are unaffected by the temperature, which may enable tests in a cold facility, but this conclusion has been questioned and it is not clear if it is generally correct. Therefore it is not yet clear if information from cold rigs is applicable to hot flows. There are many experiments where the turbulence environment characteristics are not being documented properly. Often it is given only in one point, there are insufficient surveys, and the spectrum is not measured. That is where we have to start, to thoroughly measure the environment in experiments. In many historical experiments this has not been done. It is well known in the history of wind tunnel experiments that a misguided the concept of Unit Reynolds Number was developed, and the reason was the tunnel disturbance environment was ignored.

Anon.: One trend that may not be obvious. It wasn't to me until fairly recently, while working with Pratt and Whitney, is that probably the least sensitive part of the engine, where most of the work is being done now, is not the main gas path, it is all the secondary flow passages. Attachment, separation, transition when it is rotating is very complex and significantly more challenging than the main gas path to predict these things. If you think the main gas path looks scary you should look at the secondary flow passages.

Okiishi: Quite an art - that's a good comment. I think we need to pay attention to what you have just said, it is significant.

Clark: We need to shift funding money to secondary flow passages.

Narasimha: We have discussed these issues several times. Maybe for once we should start at the other end of the problem. What is the data that we would know how to use if we got it? For example in the list that was made the number of parameters was just enormous. Such a large number of parameters you really need to know to characterise the environment. I am quite sure that that large number is correct. But suppose all that information were there. What would we do with it? I think maybe we should start asking that question. What is the information that we are actually in a position to use? In the old days we just thought that free stream turbulence intensity was enough, maybe people would say length scale, now they would say spectrum. But if you are going to see how many chunks of carbon there are, what you are going to do with the hot streaks. What are we going to do with that information?

Okiishi: O.K. Fair comment. One more question? We've been at this for over an hour. It is probably time to declare a minor victory and go and do something else.

Povinelli: By the time we meet again for Minnowbrook Bill Reynolds' twenty million dollar program is going to have solved all these problems.

Durbin: Bill Reynolds' will never solve them, you tell him.

Povinelli: Isn't that what the DoE program was for?

Okiishi: We should all sign up at Stanford? Is that the idea? O.K. well, I think this has been an energetic discussion and that we have accomplished what we set out to do with the working groups.

WORKSHOP SUMMARY SESSION TRANSCRIPT

Roddam Narasimha
Jawaharalal Nehru Centre for Advanced Scientific Research
Bangalore, India

Gostelow: After the first two Minnowbrooks we were very fortunate to have Roddam Narasimha to sum up the meeting and I think we would probably all agree that he gave us some focus, some targets, some objectives, some challenges at those two meetings. I think that has been an important part of the process in keeping things moving and so we had no hesitation whatsoever in inviting Roddam to do the same thing again. He had hesitation in accepting that invitation; he thought he was becoming over-exposed to the media here. I can understand his concerns and his modesty but we assured him we very much wanted him to do the same thing again. So without saying any more I'll say "Roddam, over to you, we look forward to your summing-up".

Narasimha: Well, thank you very much for asking me again. As you said I was beginning to wonder whether I should do the same thing again or not. But on the other hand I found that it is useful to myself to sit back and see what actually happened at this meeting and how it compares with what we had said in earlier meetings in the series. I think it would be fair to say that at this meeting I have had less time to collect my thoughts than at the previous meetings. We have not had sufficient time to discuss every issue that came up. So you may find that my summary is a little biased. Maybe there are things that I have forgotten. But I hope that if I write something up I could make a slightly more complete account. So at the present stage this is a personal reaction to what you have heard in the last two or three days. I see that somebody has already done part of my job on the board - is that you, Paul [Gostelow]?

Gostelow: Greg Heitland – from industry!

Narasimha: Very good – I think that will complement very nicely what I might say here.

So let's start with the topic of turbulent **spots** - which has always been a concern at these meetings, and very rightly I think. Let me begin with a historical note. The spot that appeared in Emmons' first paper on the subject was a sort of kidney-shaped blob; the shape of what we now call the Emmons spot is actually the result of the work of Schubauer and Klebanoff, who made all these nice measurements in a boundary layer in a big tunnel – one of the first quiet tunnels in the world. Now the thing about the Schubauer-Klebanoff spot –and I want to keep coming to this question again and again – is that the associated experiments were made at relatively high Reynolds numbers: we must remember that external aerodynamicists are preoccupied with high Reynolds numbers. No tunnel Reynolds number is high enough for them: I'm sure Jeff [Crouch] would agree. You get data at wind tunnel Reynolds numbers but that is not flight. Internal aerodynamicists on the other hand do not have this preoccupation about high Reynolds numbers. They are working at low and rather awkward Reynolds numbers, so the fact that they do not always find the Schubauer-Klebanoff spot is not really, from one point of view, such a big surprise. Now during this meeting various questions have been asked, sometimes in the working groups and sometimes in this hall; and some have been radical; e.g. "Do spots occur naturally at all?" Well, I think the answer to that is "Yes", although it was not so categorically given at the time it was asked. In conversations with Greg Walker we recalled what Knapp and others observed with smoke flow pictures taken in a little tunnel. It showed spots similar to the ones we now associate with Emmons and Schubauer. I think that in Terry Jones' data there are also spots that look very similar to the Schubauer-Klebanoff type. I'm sure that in that long smoke tunnel that Mac Head had in Cambridge there were also spots. However it is clear that spots can come in different shapes and sizes, especially when they are not fully developed, which as I said is a pre-occupation of external aerodynamicists. *Sub-critical Emmons spots* (as we may call them) do occur, and can behave in unusual ways, and I think we have had evidence of that in this meeting. If your Reynolds numbers are around the stability limit the spot can either be damped or amplified and this can make for funny shapes.

Now I want to make a brief aside here, and use my privilege as the man who is doing the summing up, by showing you some results on boundary layer stability characteristics that not everybody here may be familiar with. Now it is well known that the laminar boundary layer on a flat plate is unstable, and the stability loop was calculated long ago by Tollmein and by many other people later on. But the non-parallel theories that have been developed in the last fifteen years or so tell us that there is no such thing as a unique stability loop. The stability loop varies with height in the boundary layer because it is non-parallel; or rather you don't have a *loop* – you have a stability *surface*. What is the shape of that surface? Now I hadn't seen a picture of that surface so I have one here for you (Fig. 2). You can think of this red area here as the normal stability loop that you see. The coordinate into the paper is the distance normal to the surface. So the red is near the surface, the blue is somewhere in-between and the green is near the edge. You can see that the stability surface has a very funny shape. You have valleys and ridges here and a near discontinuity here. So it is possible that the disturbance will amplify at some heights in the boundary layer and damp out at others. In the middle is a slice of that stability surface which is crazy; here is what it looks like (Fig. 3). This slice is located roughly where you saw the blue in the previous slide. You can see that it has funny kinks and folds and so on. I show all this only to highlight the fact that disturbances in the boundary layer will not just amplify all across the boundary layer at some specific station: they will amplify at some heights and damp at others till the Reynolds numbers get sufficiently high. So it should not be a surprise that there can be sub-critical spots which are strange in some ways.

Furthermore, we can have distorted spots, we can have sleeves, and spots may be expected to do crazy things in 3-D flows. They can be "blobs" as Paul Gostelow calls them. And the propagation parameters can vary significantly.

Now in Minnowbrook I there was a lot of talk about spot-hunting. Terry Jones and Howard Hodson announced a hunt, but nothing else was said at the last meeting about it so I thought the project had been abandoned. I am very happy to see I was wrong; from the pictures that Terry Jones produced it is nice to see that some of the things we discussed years ago are now actually beginning to happen. So I would like to congratulate the hunters for what they are bringing in, in particular the first measurements of the number of spots per meter per second. It is also nice to see that the measurements are in the right ballpark, so the scaling arguments we have been using without the benefit of direct measurements can't be too bad.

Hodson talked about moving breakdown zones or lines and Frank Smith had very suggestive results from his simple 'half-minute' calculations of inviscid theory. I think it is very important to look at such theories. I was taken by the way that the spots broke up and the way that they showed sudden changes in an adverse pressure gradient. It is quite possible that these are related to the observations that we make in experiments on spots, and to the *sub-transitions* I talked about.

Now **By-Pass Transition**. This is one of the things we have discussed at this meeting. This was always in the background in the previous two meetings as well. And in fact once again I was very happy listening to what was said about the subject at this meeting because a lot of it could be traced to the earlier meetings: I recall the many arguments we had earlier (against the prevailing view), asking why T-S mechanisms must automatically be assumed *not* to operate at high free stream turbulence levels. Jim Kendall was here at Minnowbrook I, with some very interesting results, and so was Morkovin. And we had talked about the role that might be played by T-S mechanisms, operating as transfer functions, filters etc. on a noisy forcing. I think Walker's results at this meeting have shown that there is actually a great deal to all those ideas we discussed. And so I would say that Tollmein has in fact been hiding in the high free stream turbulence level transition that we commonly encounter in turbomachines. There was a lot of discussion about whether we should continue to use the word by-pass, or whether its definition should be changed from the ones currently in use, based exclusively on the values of turbulence intensity. Greg Walker reported on that last night on behalf of his working group. I believe it might still be very convenient to reserve the word 'by-pass' for some mechanism that is non-linear almost from the very beginning, so to speak. For example the disturbances may be so large that the mean flow is affected. In such cases the route followed would be obviously not canonical, and there maybe more significant dynamical changes than in those situations where the high free stream turbulence acts only as a mask.

All of that leads us back to stability, and it is interesting that stability ideas still play such a strong role in terms of giving us insights. We talked about pressure gradients – I'll come back to sub-transitions later. We talked about sub- or super-critical spots. Theophilis' work on global instabilities, the 3D flows that Crouch talked about, Smith's work on spots: all of these show that, unlikely as it may sound, linear stability theory is still teaching us a lot of things. I think that this is fortunate from one point of view, and is actually something that should be pursued a great deal more.

Direct Numerical Simulation (DNS). We talked a little bit about DNS at the first meeting, and then at the last meeting we said, "the time has come to undertake a major project on Direct Numerical Simulation". At this meeting, on Monday, there was much scepticism about what DNS could do, and even the suggestion that maybe we shouldn't bother about it. I'm glad that that discussion was undermined completely by the presentation made by Paul Durbin; and even by the great insights obtained from linear DNS work of the kind that Johnson and Theofilis described. I feel that this meeting has already demonstrated that insights from DNS are going to be valuable. For example we had very interesting results presented for a control volume, and I don't think that all the measurements and calculations that have been made earlier had given us that kind of insight. We can argue about what is actually happening there, that is not my point; but DNS has certainly put new thoughts in our minds.

What is the purpose of computing? There was one view here, circulating in this meeting, that it is basically providing reliable numbers. But I remember that many of us who grew up in the early days of computing used to read a pioneering book by Paul Hamming that carried an inscription on the first page saying "The purpose of computing is insight, not numbers". That, of course, people would not agree with now; I would say that we should modify it to say "The purpose of computing is both insight and numbers". Numbers for design from DNS may not happen right now, it may never happen. There is too much numerical information in DNS. But certainly in terms of providing insight I think that DNS is going to be exceptional; we have seen the first evidence of that at this meeting. And in any case it is going to happen, I believe, whether funding agencies support it generously or not. So what we should do, in my view, is not to debate whether DNS should be done or not; the question rather is what are the most interesting things to do.

Separation bubbles. Here once again, going over the earlier Minnowbrooks, I think over the last seven years quite a lot has happened. I remember that when I came for the first meeting separation bubbles hadn't been studied for decades after the early work done on wings: we were all talking about what had been done in the 1960s! But now I see that the situation is changing. At the last meeting we had some discussion of the different types of bubbles, when they occur, and so on. At this meeting we had several contributions to understanding the temporal/spatial structure of different types of bubbles; for example interesting data from laser thermal tufts was presented on reattachment. However the thought was going round in my mind about why people were not discussing the *probabilities* of reverse or forward flow in separating and reattaching flows: we know that separation is intermittent, and we need a separation intermittency distribution. In other separated flows both Roger Simpson and Kida in Japan have made detailed maps of probability distributions, for example in flow past backward-facing steps. We know how these probabilities vary as you go downstream. It is not as if there is a unique reattachment point - there isn't one, and the results that were shown by Theophilis are an indication of what actually happens. On global instabilities I must recall what appears in the lovely pictures in the book by Prandtl and Tietjens - there are all these lumps, and it might be that these lumps we have seen and known about for such a long time might indeed be global instability: this is an interesting thought to pursue.

Sub-transitions. There was a lot of discussion here on sub-transitions, including whether that is the right word to use or not and about what is going on. But, as the culprit responsible for introducing this word, I should say that what I have had in mind was that it was something which happened relatively rapidly within the transition zone, making it appear anomalous in some way compared to the canonical high Re transition zone on a flat plate. For example a sub-transition could result from something which happens to the spot after it has been created, because of pressure gradient, Reynolds number, surface geometry, etc. So it is like a sub-plot in this drama of the transition from laminar to turbulent flow. What is happening can be either geometric or dynamic; and spot propagation parameters can change a great deal. They are functions of Reynolds number and of the age of the spot. Once again there is evidence for this in earlier work. Here are some measurements that were made in Bangalore by Rao, nearly 35 years ago. This is the speed of propagation of the spot plotted versus Reynolds number (Fig. 4). What you see here is the spot propagation velocity at the front and the rear of the spot. Values are like 0.85 to 0.9 and 0.5 as the Reynolds number increases, but as the Reynolds number decreases the differences are much smaller, that is to say the growth rates are much smaller. That was actually for a sleeve on an axisymmetric body. We should have curves like that for different kinds of spot. So I think that that can be very important for turbomachinery flows because they are often not fully developed. If subtransition occurs early in the zone fresh breakdowns may occur, and workers from Pratt and Whitney have been arguing that if there are shocks in the flow they may trigger fresh breakdowns. I think that is a possibility to be kept in mind, although if sub-transition occurs later in the transition zone I have difficulty in imagining that further breakdowns can occur in a nearly turbulent boundary layer. One of the things it would be interesting to do, now that these **spot hunting** techniques are beginning to be under control, is to see what happens in sub-transitional flows and also what happens in highly three-dimensional flows.

Engine Disturbance Environment. This is also an issue which has been discussed several times here but it seems to me that this is one area in which there has been virtually no progress. If I'm wrong I would like to be corrected by somebody here. But we've discussed this subject again and again and I doubt whether we know any more about it than we did seven years ago. Every time we keep making recommendations that this should happen, but it doesn't happen. So I come to the conclusion that most people wish that someone else would do it. Now it is going to be a major project and may cost millions of dollars; where are the money and the men to do it? As I mentioned yesterday evening, Om Sharma made an offer last time but as far as I can see it has not been taken up. Much more thinking on the subject is needed. Maybe we need money from both NASA and AFOSR within a business format. I think we need to define more precisely what our priorities should be. In particular we have to decide what we will *do* with the data. Suppose that by some magic some angel came along and gave us all the funding and the people, and that we eventually get loads of data. What difference would that make? I'm not quite sure that we know exactly what to do with that data. So perhaps we should spend a little more effort trying to find out what it is in the disturbance environment that we need to know. Some hard-headed thinking is required here, and some new strategy. I don't know whether the organisers would like to keep that issue open. We can do that but my fear is that next time around, unless some change in thinking takes place, we will still be asking how come we don't know anything more on the subject than we did ten years ago.

Well. There have been a lot of other interesting developments here: e.g. Klebanoff modes, with various numbers now on those modes from Tom Corke, regarding whether they grow in x and whether the magnitudes change. There has been a lot of work on unsteady transitions and wake passing: Hodson, Durbin, Simon have presented new results. Paul Gostelow had some. John had weighted Strouhal numbers to describe what goes on in such flows. Some work on control of transition was reported by Seifert. Work on models was reported by Dorney, Steelant, Dick, George Huang and others. So there has been a fair amount of that kind of work as well.

Let me just make this final **summary** of what has happened in this meeting so that we can see where we are.

I see that spots continue to occupy our attention. During this meeting and the last one, we are beginning to paint a good portrait of the calmed region. But attention at this meeting has been shifting to young, sub-critical spots and the numbers on spot formation rates that experiments are now beginning to give us. Modelling is still getting attention; last time we discussed early work on unsteady modelling, wake passing transition etc. On Klebanoff modes there was some discussion at the first meeting; there was not as much last time but perhaps now we can quote some numbers. I think on by-pass the scenery is changing, as far as I am concerned in the right direction, so I expect there will be some more insight when we meet next time. Stability continues to be giving us new insights still. On DNS, I personally think the goals that we began setting last time are now on the way to being achieved or even surpassed, although I expect that there will be some differences of view here, and maybe there will be some comments during the discussion. On separation bubbles it seems to me that we have made considerable progress since Minnowbrook II, but on the disturbance environment we have done little.

That would be my summary, a very personal one I'm afraid.

Where do we go from here? What next?

I expect to see more results in coming years on spot identification and spot-hunting, especially in sub-transitional or otherwise anomalous flows, and 3D flows. The time has now come to shift attention to more strongly 3D flows. It is not that everything about 2D flows is understood, but that the big picture is settling down as far as 2D flows are concerned. But 3D flows can give us many surprises so that is one of the things we should spend more time on. I have already said a great deal about DNS, I believe that it is going to happen. I hope that people like Thorwald Herbert will find the patrons they are looking for. Sub-critical spots, blobs, in 3D flows maybe: I think we can expect more of that. We should understand high free-stream turbulence *non-bypass* routes. Perhaps, with the altered perspective on what by-pass may be, we will have a different kind of picture of high disturbance transition routes. I think that we will continue to get insights from stability theory; I will not be surprised if we discover that, just as Mr Tollmein has been hiding on the suction surface of a turbine blade, Mr Goertler will be hiding on the pressure surface: surely we should actually look for those waves. If they are there in turbulent flows I don't see why they are not there in transitional flows, being hidden because of the high free stream turbulence.

I hope that at the next meeting we shall look at these problems, transition in high pressure turbines, on short stubby blades, in 3D flows and so on. These are messier flows, than the nearly 2D flows that low-pressure turbines experience, but I do think there might be many fascinating things may happen there!

So the number one area that I think we should emphasise may be 3D flows, perhaps with DNS. That's a very personal view, and I thank you for asking me to share them with you.

Gostelow: We now have a few minutes for discussion and any questions. For anyone to attack Roddam or describe any ideas you might have. We'll cut it off pretty quickly but if you have questions feel free to go ahead and ask them

Hourmouziadis: It is not a question. I was wondering if we should not use DNS as a simple numerical experimental tool. For example we should pick out very simple flows, like flat plate with pressure rises, and have a look at the spots and calming zones and try to understand how this materialises. At present we still have the most detailed results from Paul's experimental work. I think we should put that together to understand how this thing works.

Durbin: I have work in that area that has been funded; as soon as I find a student I'll be working on that and I think you are absolutely right. It is an experimental tool and can generate data just like a laboratory experiment. It is a mistake to think of it as a design tool but it is correct to think of it as an experimental tool.

Narasimha: I just want to go back to a suggestion that was made last time, that we should in fact pick certain well-defined situations, do a DNS, dump the data that comes out so that it is available for everybody to analyse. So if somebody has taken the trouble to make a solution for situations that a group can identify, and the data is openly available, then I think a lot of analysis could be done which may be very useful. I think we were generally agreed on that last time but on Monday it seemed that people were not intending to proceed along those lines. I believe that would be a mistake.

McEligot: Last time you were suggesting that we take a particular airfoil shape and do DNS calculations at a Reynolds number of, say, 50,000 based on chord. Paul essentially has done that except I get the impression that he has confused it by putting wakes in front.

Durbin: I've done it both with and without the wakes but it is a lot more interesting with the wakes.

Narasimha: Paul has done more than we set out to do! That's wonderful.

Simon: Can we use Mann Rai's calculation that has already been done? That is a simulation of the Sohn & Reshotko flat-plate experiment. And just go back and do some data mining that we haven't done yet.

Durbin: We've done that T3A case that I didn't show. I don't think Mann Rai had enough resolution as he indicated in his paper: he mentioned that at Minnowbrook II.

Theophilis: Whether it is stability analysis or DNS we should pay more attention to proving ourselves useful to these people, although it is very nice to go all the way with analysis and for me personally it has been very enriching.

Okiishi: I think that for the future I would personally like to see more questions asked about the role of the kinds of instabilities that we talked about at this meeting. What I would call turbomachine instabilities. Stall, surge and these kinds of phenomena. I don't know the answers but I have a feeling that some of the knowledge that we saw displayed here would be useful in helping product designers to avoid those surprises that detract from reliability because you don't expect them and then they happen. Then we have a whole re-engineering program. The other thing I would point out would be what Thorsten brought out which is the aeroelasticity drivers. On the one hand we have the response people who are looking at the blades and what they are doing, but I think there are drivers that may have fundamentally some relationship with knowledge about transition. This is not a criticism but an addition to your list. These are some unknowns in product design that people who've thought about it know more about and can get a handle on.

Gostelow: Can I support what Ted has said and say that I would like to have seen compressor and fan problems added to that list as well as the HP turbine because I think there is possibly more scope there, especially with regard to stability. Greg, tell us about your wall chart.

Heitland: This is our current design cycle in turbine aero. You would find a very similar process in compressor aero design. The engine cycle in the middle is what drives the whole process. The first to feed into that is the 1D code. This is a highly calibrated empirical tool, plus this magical technology adder, which management sees as our CFD tools. Every year for every new design that adder gets bigger and bigger. We go through a fairly standard process of a 2D code which feeds into an airfoil geometry code to design on streamlines. Then we come to do a quasi-3D code for quick iterations on designing the airfoil shape; we iterate back and forth to get airfoil geometry in quasi 3D then we go to our 3D steady viscous code, using the k-ε models, but probably the most popular in our area is Baldwin-Lomax. Then finally as a last check we'll kick out to the multi blade row 3D steady code. But the trick is we don't know what our turbulence intensity is. We don't know what to put into that value. We could maybe guess. Nor the length scale. These determine whether the airfoil separates or not. We can get it to separate depending on the turbulence intensity level we put in. This is a big problem.

Gostelow: Do you want to match Om Sharma's offer last time and provide an engine fully instrumented and bring the results along to Minnowbrook IV? Can we tempt you to that?

Heitland: I don't carry the clout that Om Sharma carries in our company.

Hourmouziadis: The 2D design they are using in the quasi 3D system. That's a Navier-Stokes code?

Heitland: It's the MISES code.

Hourmouziadis: Do they have any laminar flows there? Will it predict transition?

Heitland: It's somewhere in between.

Hourmouziadis: I didn't think there was anything in between.

Heitland: You'd be surprised.

Durbin: If you go to any engine company you'll see exactly the same thing. Exactly the same machinery, exactly the same use of codes, and they are increasingly wanting to rely on CFD and they are increasingly needing models. When they talk about length scale what they actually mean is ε, not correlation length scale, and I think there is an extent to which Roddam maybe actually underplayed the modeling. That was one line "modeling" then go on. But that's really where they need the help. When they support experiments they say "do the experiment that we need to go into the modeling". Maybe there should be a shift to recognising that the product, from the academic level, is at least the basic models and then they tally them to their needs. I think there should be more of that focus. It's like a question you asked "If you had the data what would you do with it?" Or to rephrase that "What data do you need to go into these models?" But the answer is that the question you raised – "If I had the data what would I do with it?" means "How would I put that into a model?"

Narasimha: My point was not to say what should not be done but rather to express the feeling that sometimes when people ask for length scales or something it is not absolutely clear to me that that is what is going to provide the answer. And it may well be that some experiment tells us that that is not what we should ask for – perhaps we should ask for something else. And this has happened again and again so we should always keep that in mind as well. For example, what we heard about by-pass is an excellent instance. In an earlier meeting in this same hall we have heard that up to 2% f.s.t. is one regime, 2-4% is another thing, 4-15% is yet another thing and so on. But in the light of work that has been done in between, and in particular Greg Walker's presentation, we now see that that may not be the way to look at it. The people making models have a very hard task on their hands, and there is always the possibility that we are not asking the right questions. In terms of by-pass, if someone comes and says, "You just give me the free stream turbulence and the length scale and I will do everything else", I am not sure that is enough. We just have to keep that in mind, that is all I am saying.

Gostelow: May I just say that I think this raises the question of whether we have a Minnowbrook IV, and of what the balance is. I think this has always been a balancing act. We work with our sponsors and with you folks whose support we appreciate. We started out very much with the concept of a balance between the fundamental transition community and the turbomachinery community, who hardly ever got together, and we wanted to get half of each of them in this room and bash their heads together, and it worked. The question is whether that's the way to go, or whether we focus on the engine industry, or what? I don't want you to answer that right now but I do want each of you to think about this and get your views in to John or Terry or myself so that if we do have a Minnowbrook IV, and let us know whether you think that is a good idea or not, then we know how to get it just right so that we are serving your interests, and the interests of the people who are supporting us. So let me raise that as a question.

Hodson: Can I pick up on what you have said, and to a certain extent what Paul Durbin has said. I don't think you can actually use the words data and models in the same sentence. Perhaps you didn't mean that, I don't know. But I think it actually hits the nail on the head. What industry wants is, forgive me if I'm putting words in your mouth, quick fast dirty solutions. And that is very different from the sort of stuff we are seeing from the fundamentalists, the true modelers. I think anything else is correlations. We can disguise it and call it what we like but really it is data being used to represent what we think might be happening. And I actually don't see that much convergence. Although Minnowbrook I, II and III have worked in the sense of bringing us together, I don't see much convergence.

Gostelow: Would you like to see more convergence?

Hodson: I think we have to.

Okiishi: Right across the border in Vermont there's a guy who operates a company. Their business is to design turbomachines. The puzzle to me has been the engine companies all have secrets. And they don't want to come to this meeting and reveal what their hands are like, so they are going to be careful by saying what they need in the way of design helps or new models and so forth. If you take a guy like Japikse, who owns Concepts, here he is trying to broaden his expertise as far as what he can do to design turbomachine x, turbomachine y, a wide variety of turbomachines. It would be interesting to bring him to this meeting. Have him maybe keynote it and say "Here is where we are at design-wise, this is what I think we need" and then have him sit here for two or three days and at the end like you, Roddam, say "Now I have some insights, what a gold mine, there is so much knowledge here. I'd like to tap all of you to help me become a more successful designer". He doesn't have secrets in this way, he wants to have that knowledge, and he is not ashamed or afraid to tip his hand a little bit and to say, "We are ignorant here and we don't know how to do this quite." That could be a possible tack to bring this convergence.

Hodson: I think you are being too nice. We've got people from industry here, why not ask them now?

Okiishi: I know, but everybody from industry has to be a little bit cautious.

Hodson: Well they can tell us if they are holding back.

Gostelow: Are you holding back?

Heitland: I'll spill my guts. (Laughter).

Okiishi: We are missing that element - the design chiefs are not here.

Gostelow: O.K. Thank you for that. That has been a good discussion. I want to conclude by thanking Roddam. Roddam got us off to a provocative start on his favourite subject of sub-transitions and really got the ball rolling very well. He has wrapped things up very nicely and again I think set you some interesting challenges and asked you some good questions. So I would like you to join me in thanking Roddam. We have to conclude there. Thank you all for coming and I hope you've enjoyed it.

Narasimha: Before you go I think we should thank the three organizers, John LaGraff, Paul Gostelow and Terry Jones for organizing another splendid meeting in this series.

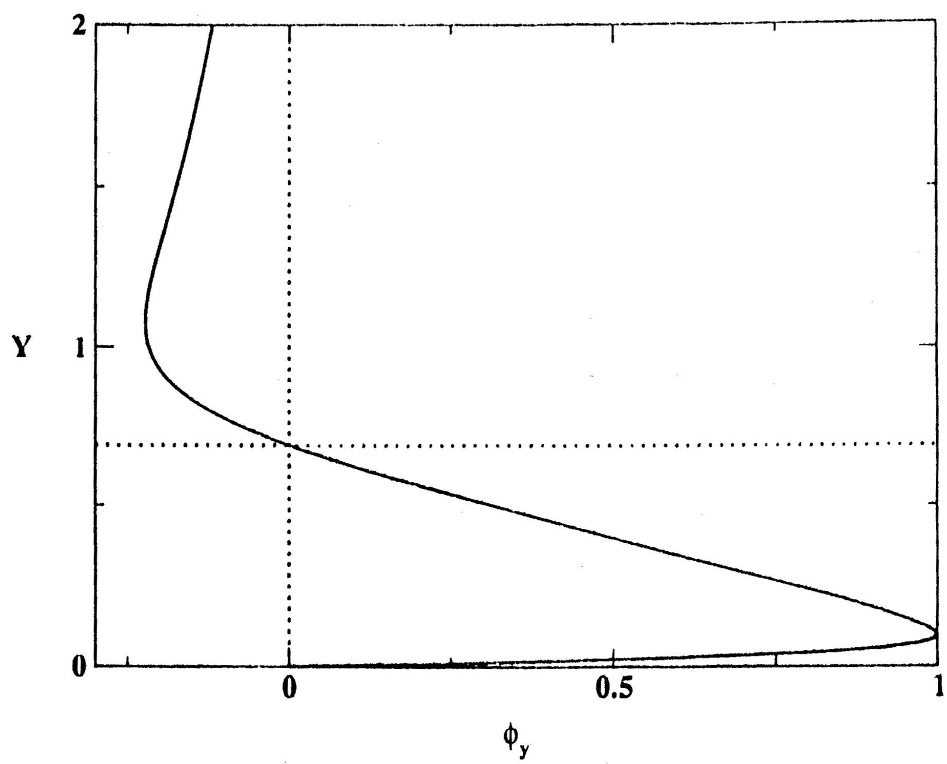

Figure 1. Typical eigenfunction for the Blasius boundary layer, showing the three zeroes respectively at the wall, at infinity, and at an intermediate point.

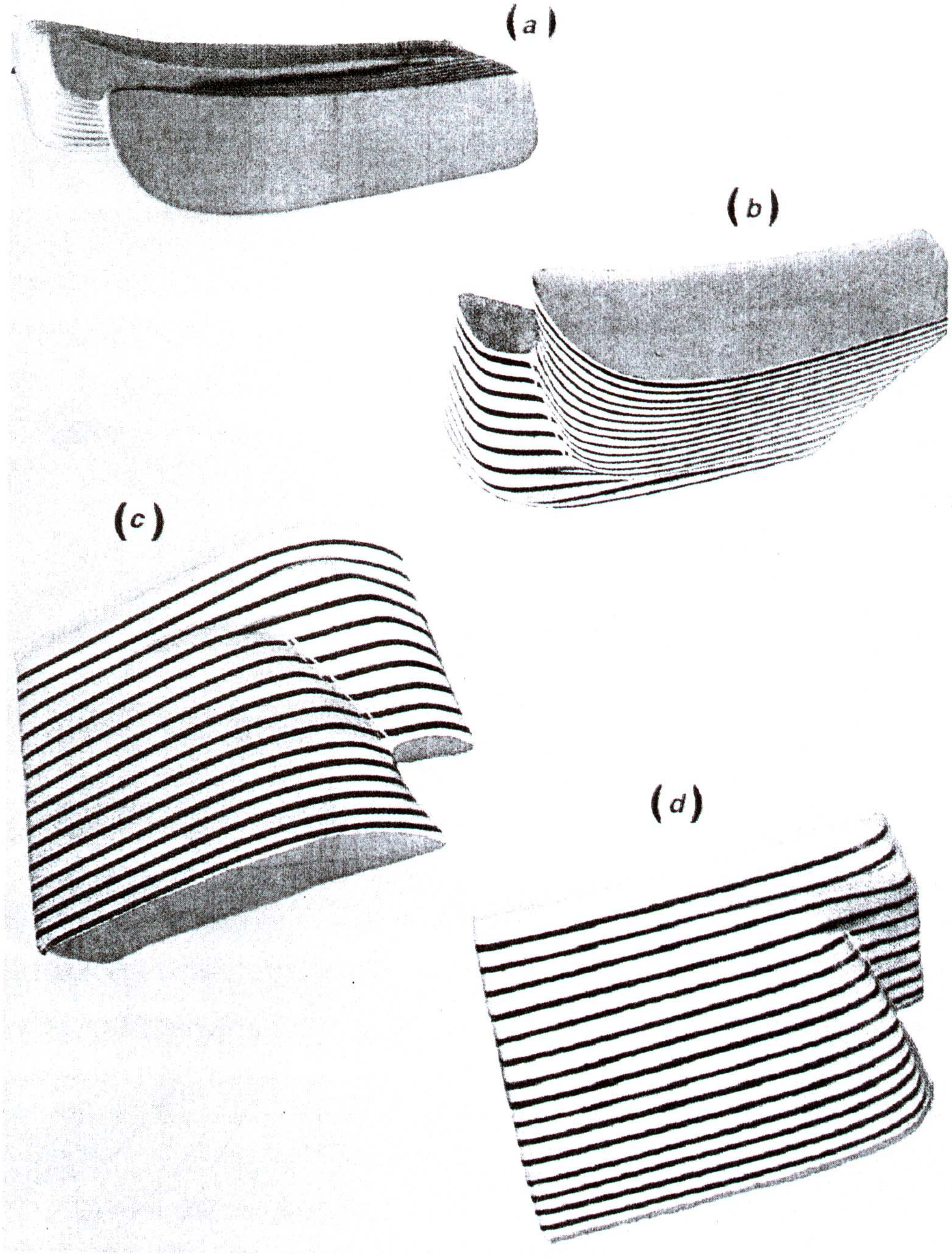

Figure 2. Four views of the stability surface for the Blasius boundary layer, in (y, ω, R) space. The surface is generated by stacking up, along the y-axis, stability loops generated at various values of y. The red surface is close to the wall, the blue surface is near the intermediate zero, and the pink surface is near the top of the eigenfunction shown in Figure 1. (a) View with R to the right, ω towards the top and y into paper. The red region is close to the unstable regime shown in the classical Orr-Sommerfeld stability loop. Note the barely discernible cut-back near the blue loop (shown in greater detail in Figure 3). (b) View from below, showing the lower branches of the stability loop stacked along y. (c) and (d) Other views, chiefly of the lower branches, showing the valley and ridge nature of the topography of the stability surface.

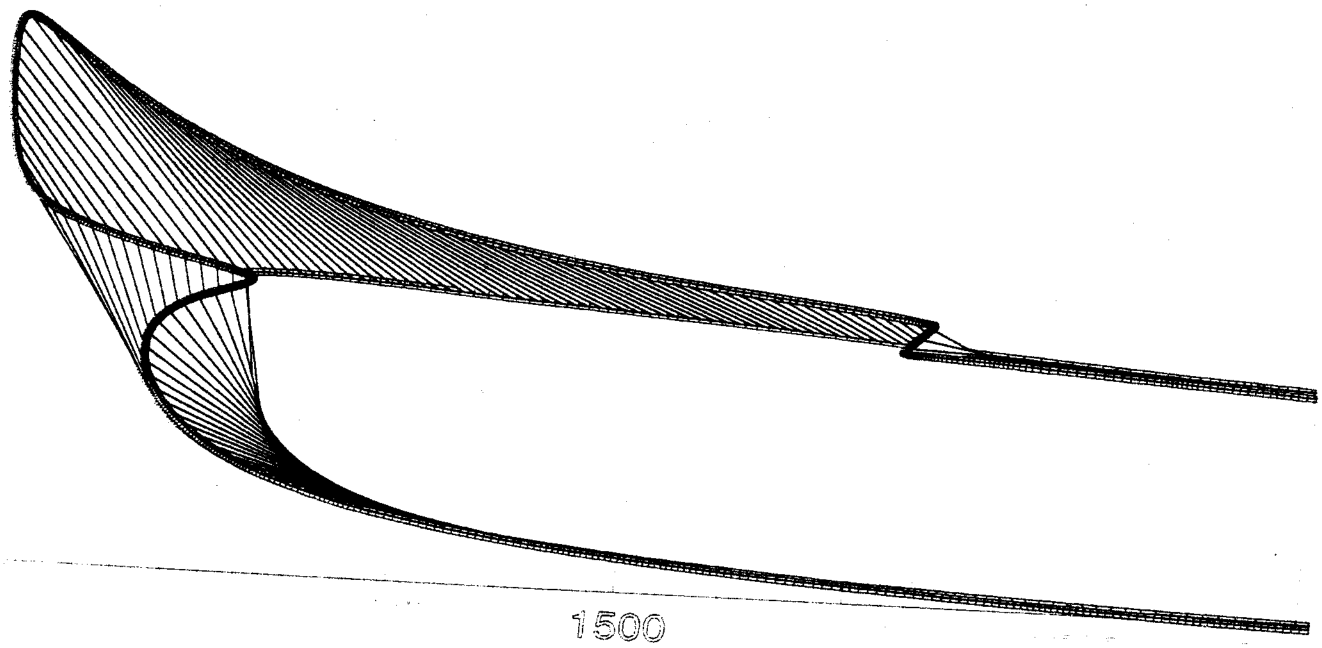

Figure 3. A slice of the stability surface of Figure 2, taken around the blue loop, bounded by y = 0.69, 0.70. The axis shown in R. Note the fold-back on the upper branch.

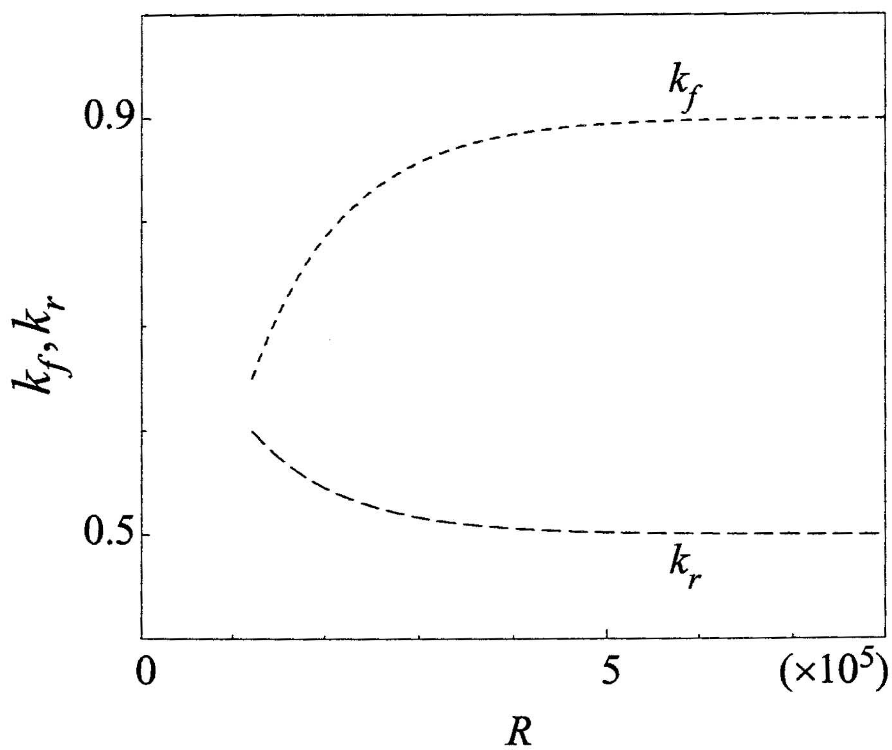

Figure 4. Schematic of variation with Reynolds number of the velocities of the front (k_f) and the base (k_r) of a turbulent spot.

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13. ABSTRACT ***(Maximum 200 words)***
This volume and its accompanying CD-ROM contain materials presented at the Minnowbrook III—2000 Workshop on Boundary Layer Transition and Unsteady Aspects of Turbomachinery Flows held at the Syracuse University Minnowbrook Conference Center, Blue Mountain Lake, New York, August 20–23, 2000. Workshop organizers were John E. LaGraff (Syracuse University), Terry V. Jones (Oxford University), and J. Paul Gostelow (University of Leicester). The workshop followed the theme, venue, and informal format of two earlier workshops: Minnowbrook I (1993) and Minnowbrook II (1997). The workshop was focused on physical understanding the late stage (final breakdown) boundary layer transition, separation, and effects of unsteady wakes with the specific goal of contributing to engineering application of improving design codes for turbomachinery. The workshop participants included academic researchers from the USA and abroad, and representatives from the gas-turbine industry and government laboratories. The physical mechanisms discussed included turbulence disturbance environment in turbomachinery, flow instabilities, bypass and natural transition, turbulent spots and calmed regions, wake interactions with attached and separated boundary layers, turbulence and transition modeling and CFD, and DNS. This volume contains abstracts and copies of the viewgraphs presented, organized according to the workshop sessions. The viewgraphs are included on the CD-ROM only. The workshop summary and the plenary-discussion transcripts clearly highlight the need for continued vigorous research in the technologically important area of transition, separated and unsteady flows in turbomachines.

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