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Scale-resolving simulations of bypass transition in a high-pressure turbine cascade using a spectral-element discontinuous-Galerkin method

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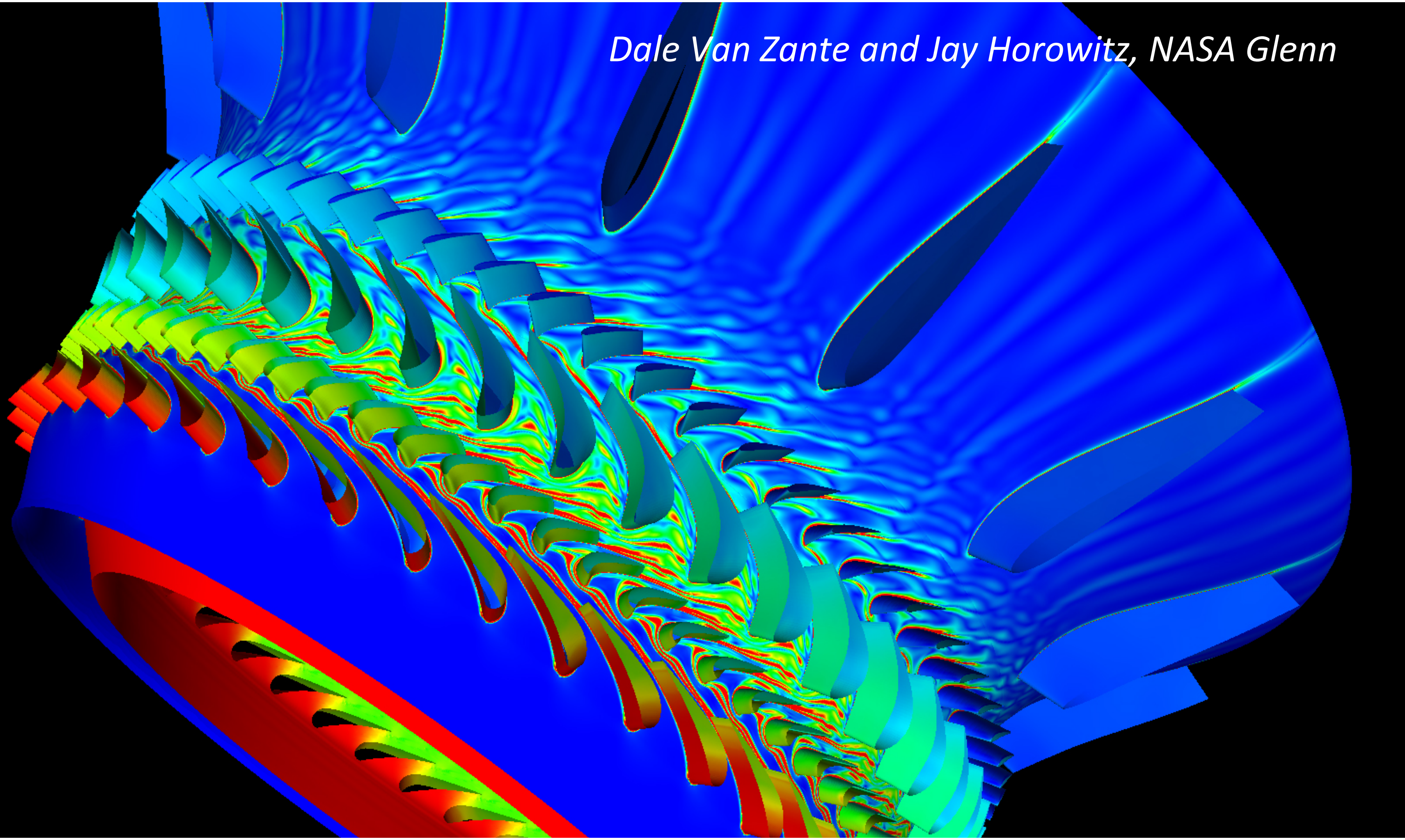
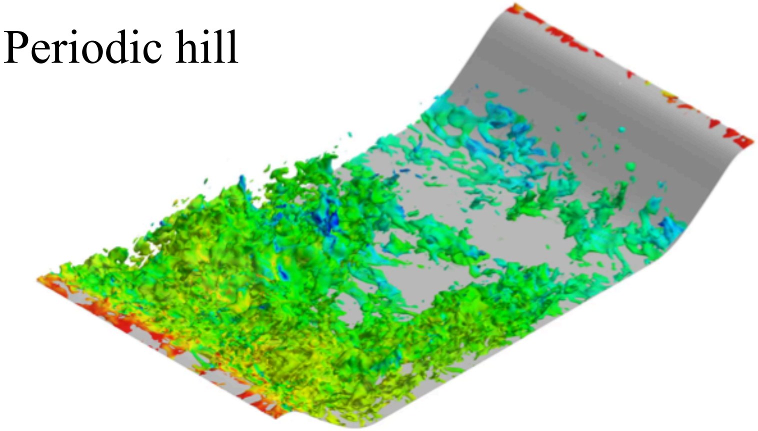
Introduction


Dale Van Zante and Jay Horowitz, NASA Glenn

- Turbomachinery flows are inherently complex (e.g., flow separation, transition, turbulent wake, wake impingement, complex moving geometry) with wide range of scale

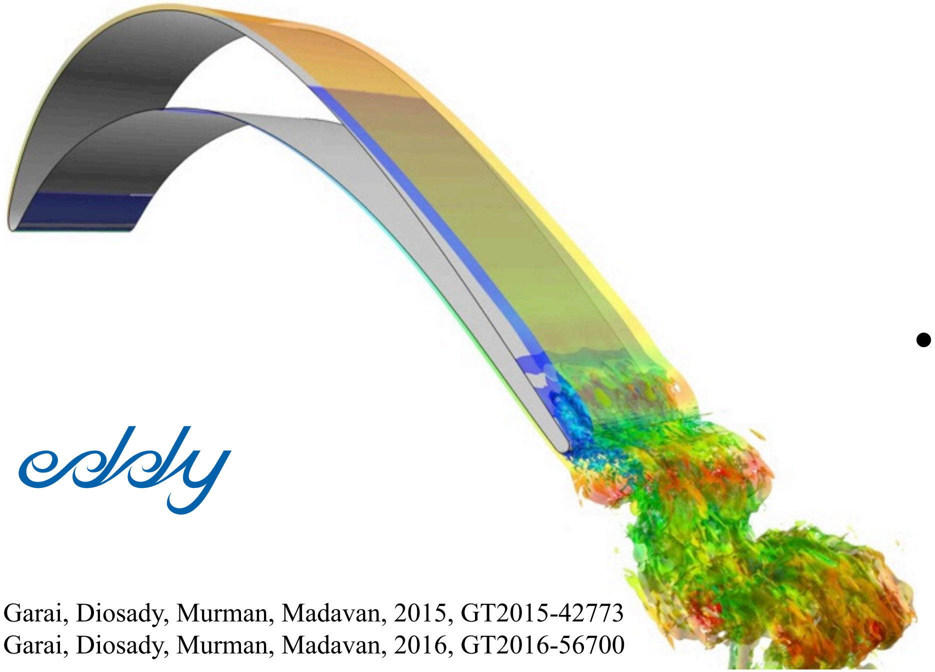
Introduction

Periodic hill



Diosady, Murman 2015, AIAA paper 2014-2784

LPT

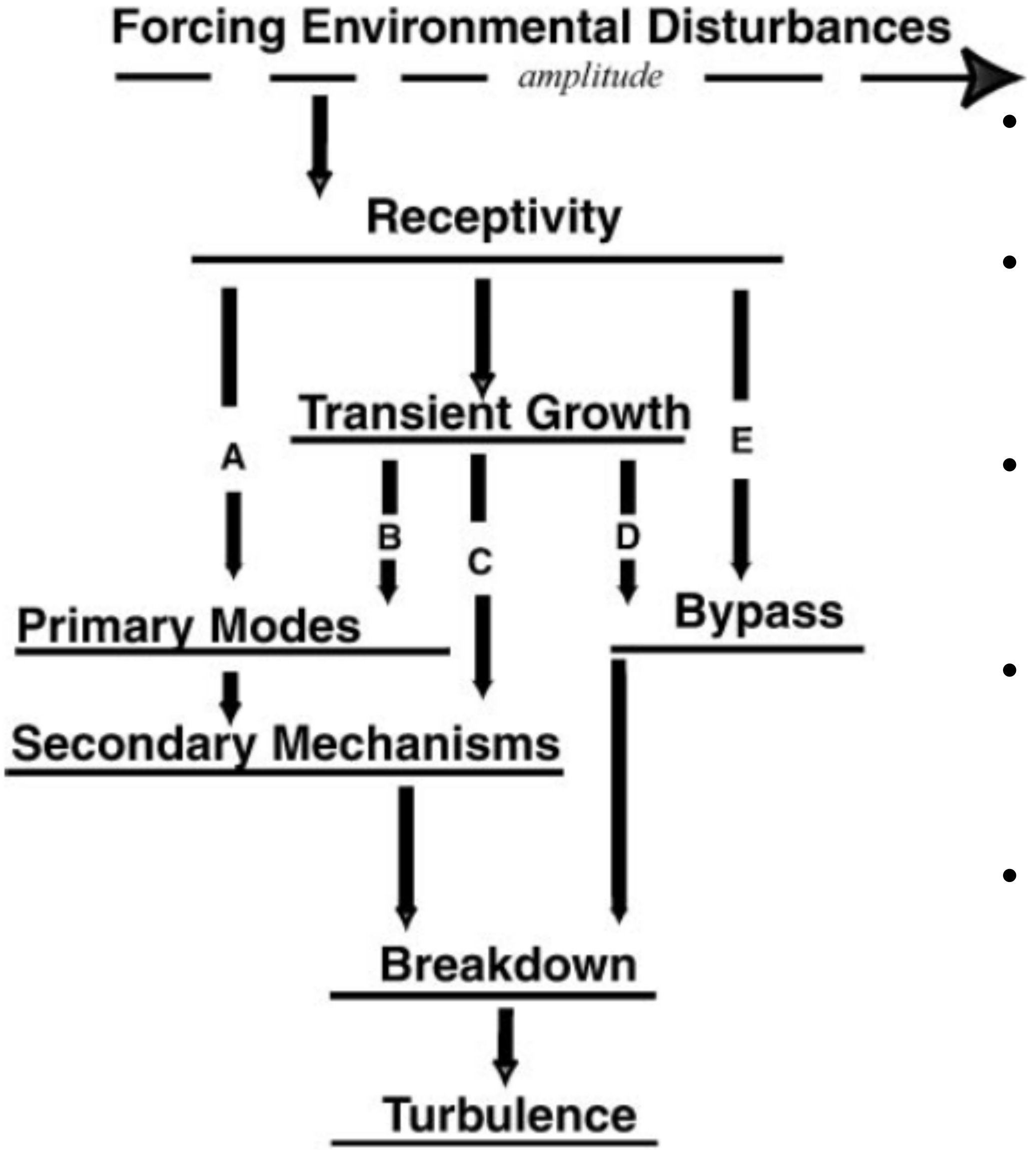


Garai, Diosady, Murman, Madavan, 2015, GT2015-42773
Garai, Diosady, Murman, Madavan, 2016, GT2016-56700

- Develop high-fidelity DNS/LES methods for next-generation computer architectures for turbomachinery analysis (and design)
- Higher-order Discontinuous Galerkin (DG) methods are the subject of considerable research
  - Both space and time treated in a similar fashion
  - Complex geometry handling
  - Robust with respect to unstructured mesh quality
  - Efficient implementation on modern exascale hardware
  - Extends to arbitrary orders of accuracy in space and time
- Code has been used to simulate unsteady separated flows (periodic hill, low pressure turbine blade with and without inflow turbulence etc.)

- Diosady, Murman 2014, AIAA paper 2014-2784
- Diosady, Murman 2015, AIAA paper 2015-0294

Introduction



- High operating Reynolds number for HPT → flow remains attached
- Natural mode of transition (TS waves, K/H type instability) occurs for low inflow turbulence
- Bypass mode of transition (Klebanoff mode, secondary instabilities) occurs for high inflow turbulence
- Leading edge receptivity, flow acceleration, geometry curvature etc. further complicate transition process
- Reliable accurate prediction of transition is needed for thermal load prediction

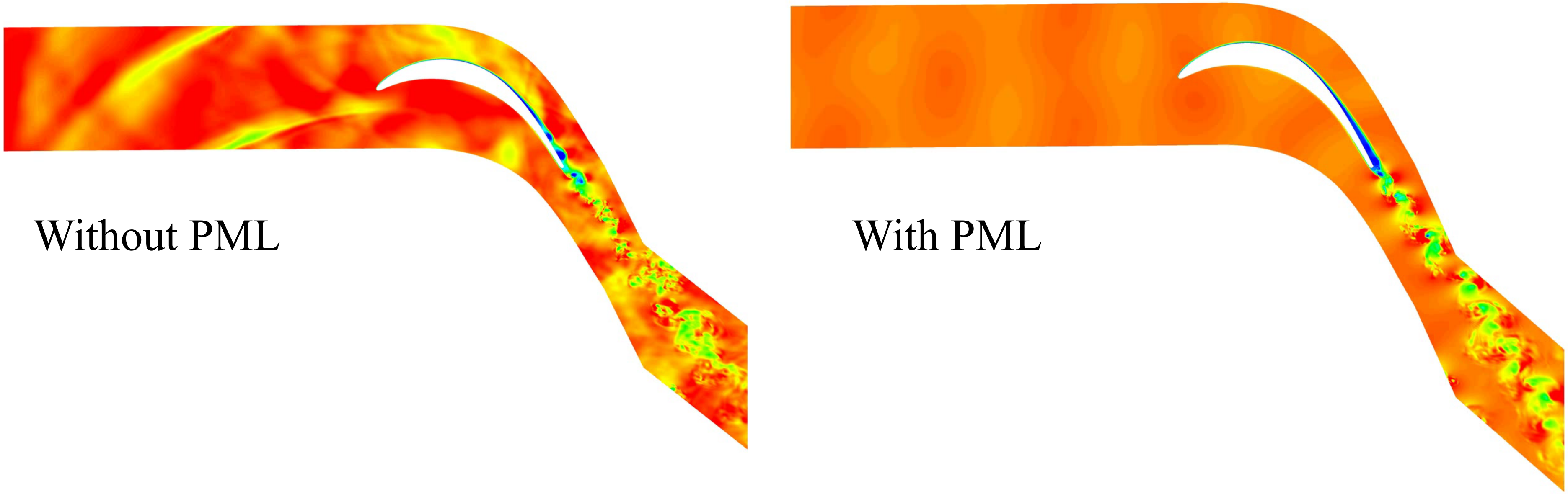
Morkovin, NASA CR 181693

Objective

- Conduct scale-resolving simulations of HPT cascade to document effect of inflow turbulence on transition
- Arts et al. 1990 measured heat flux characteristic for a wide range of Reynolds number, Ma, inflow turbulence of an HPT blade
- RANS fails to predict transition characteristics, hence thermal load
- Previous DNS, LES, DESs also have difficulty on predicting transition and heat transfer characteristics
- To understand why numerical simulations fail to predict experimentally observed transition and heat transfer characteristics

Inflow-Outflow Boundary Condition Perfectly Matched Layer

Instantaneous total pressure

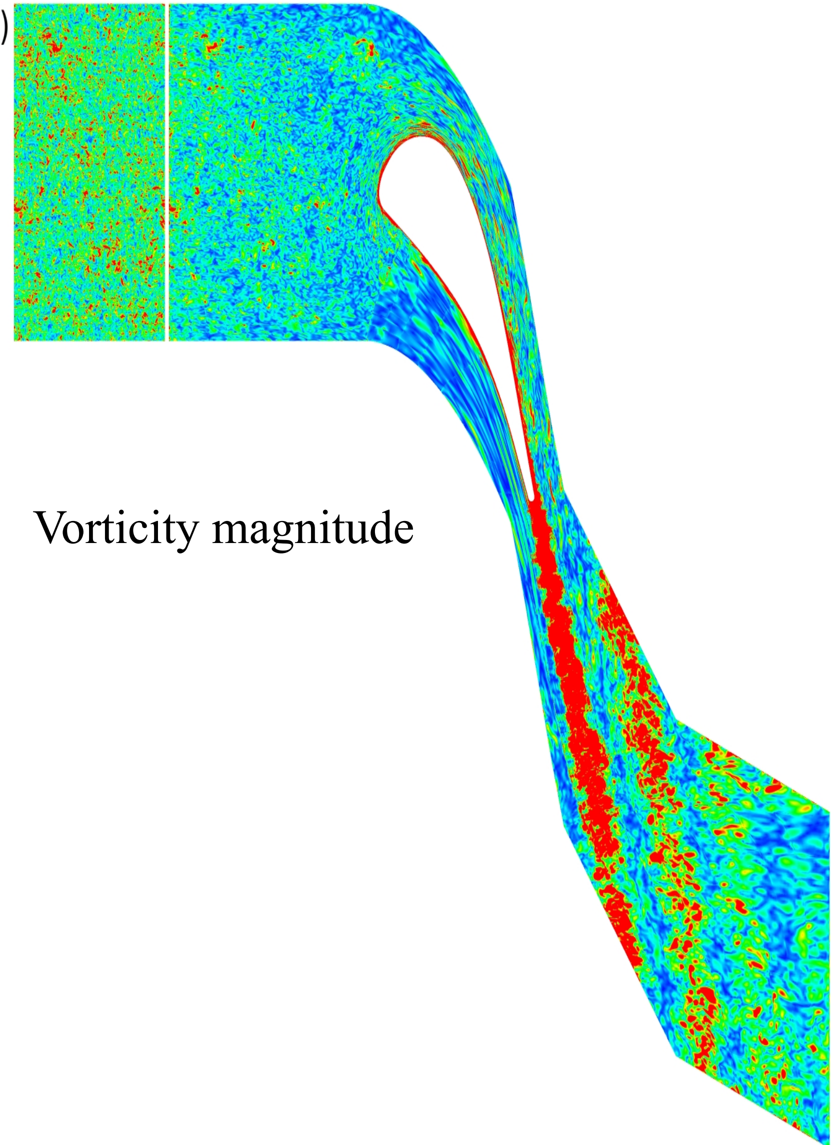


Without PML

With PML

- Proper BC specification at artificial computational boundaries a major challenge especially for DNS or LES of unsteady turbomachinery flows
- Spurious acoustic reflections from boundaries can contaminate simulations
- Effect of reflections is severe for high-order low-dissipation schemes
- Authors successfully implemented the PML approach of Parrish and Hu in DG framework (presented at SciTech 2016)

Inflow Turbulence Generation Method: Linearforcing method

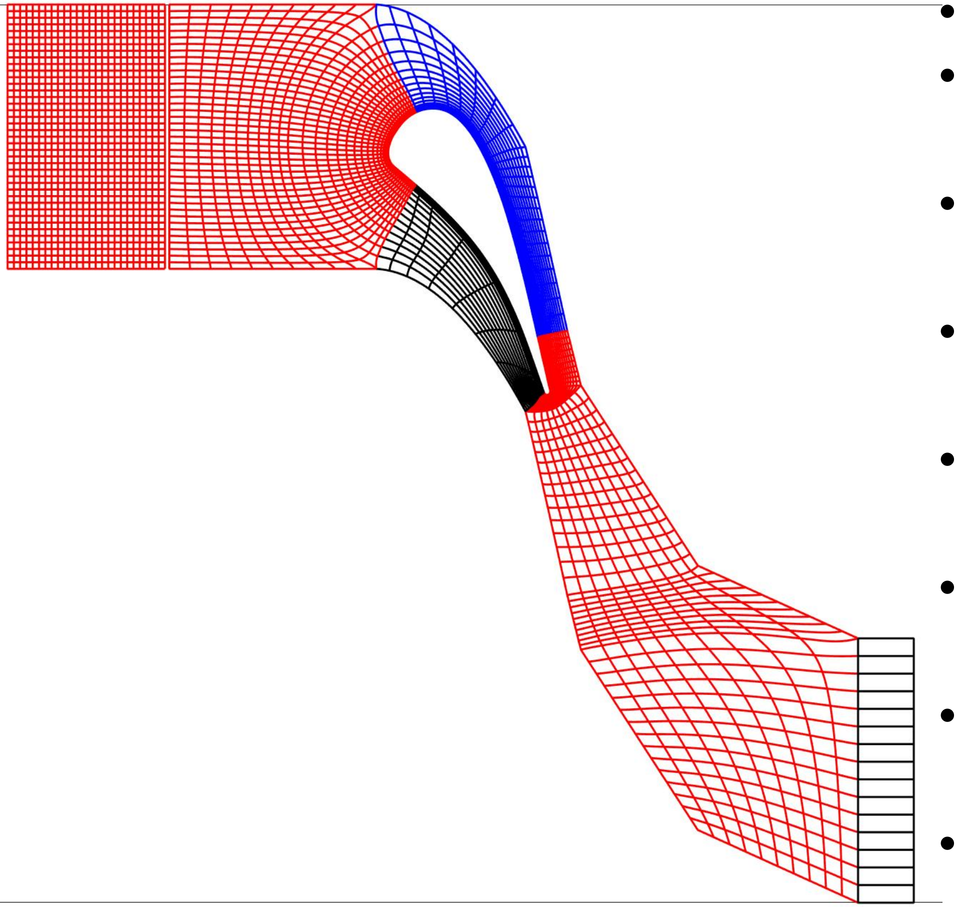


Vorticity magnitude

- HIT-based “linear forcing” method
- Extension of linear forcing to anisotropic domains a challenge since all the wavenumbers are forced
- Multiple, stacked, individually-forced cubes used to avoid large-scale turbulent structures
- Generated turbulence is fed into the computational domain by solving a numerical Riemann problem
- Introduces recycling scale in the main computational domain
- Recycling scale is at least one eddy-turnover time of HIT by stacking HIT cubes in streamwise direction

Problem Setup

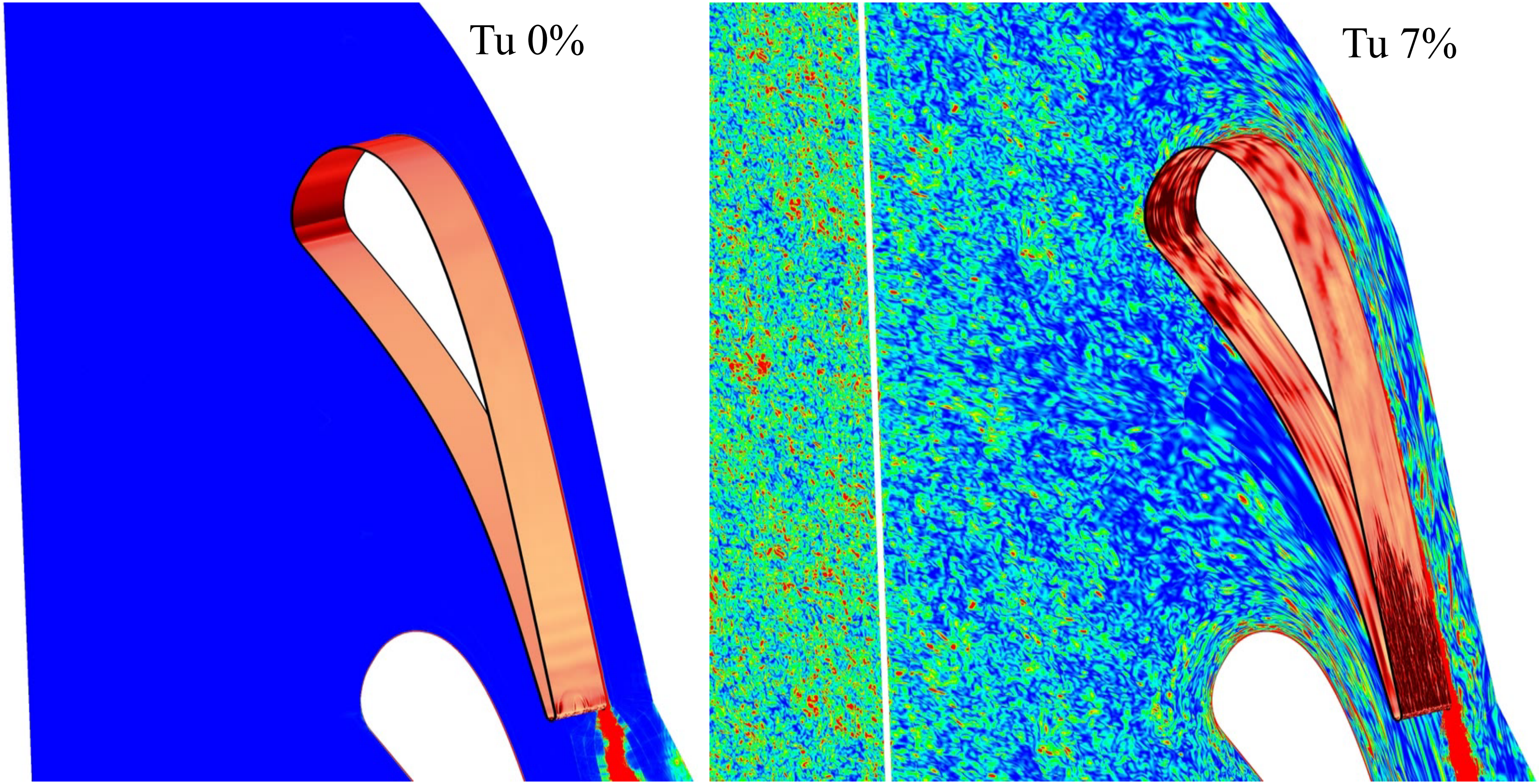
4th order
8th order
16th order



- Re = 10^6
- $Ma_{e,is} = 0.7$
- Experimental Tu 1%, 6%
- Spanwise extent 20%C
- Present simulations Tu 0%, 7%, 20%
- PMLs are applied at the inflow and outflow for 0% Tu
- Inflow turbulence length scale not reported in the experiment
- For present simulations we consider 4%C as inflow turbulence length scale
- Results in Re_λ of 62 and 110 for 7% and 20% Tu
- Inflow turbulence is generated using linearforcing method
- For nonzero Tu, PML is applied at the outflow only
- Different mesh resolutions are used for different Tu

Flow visualization

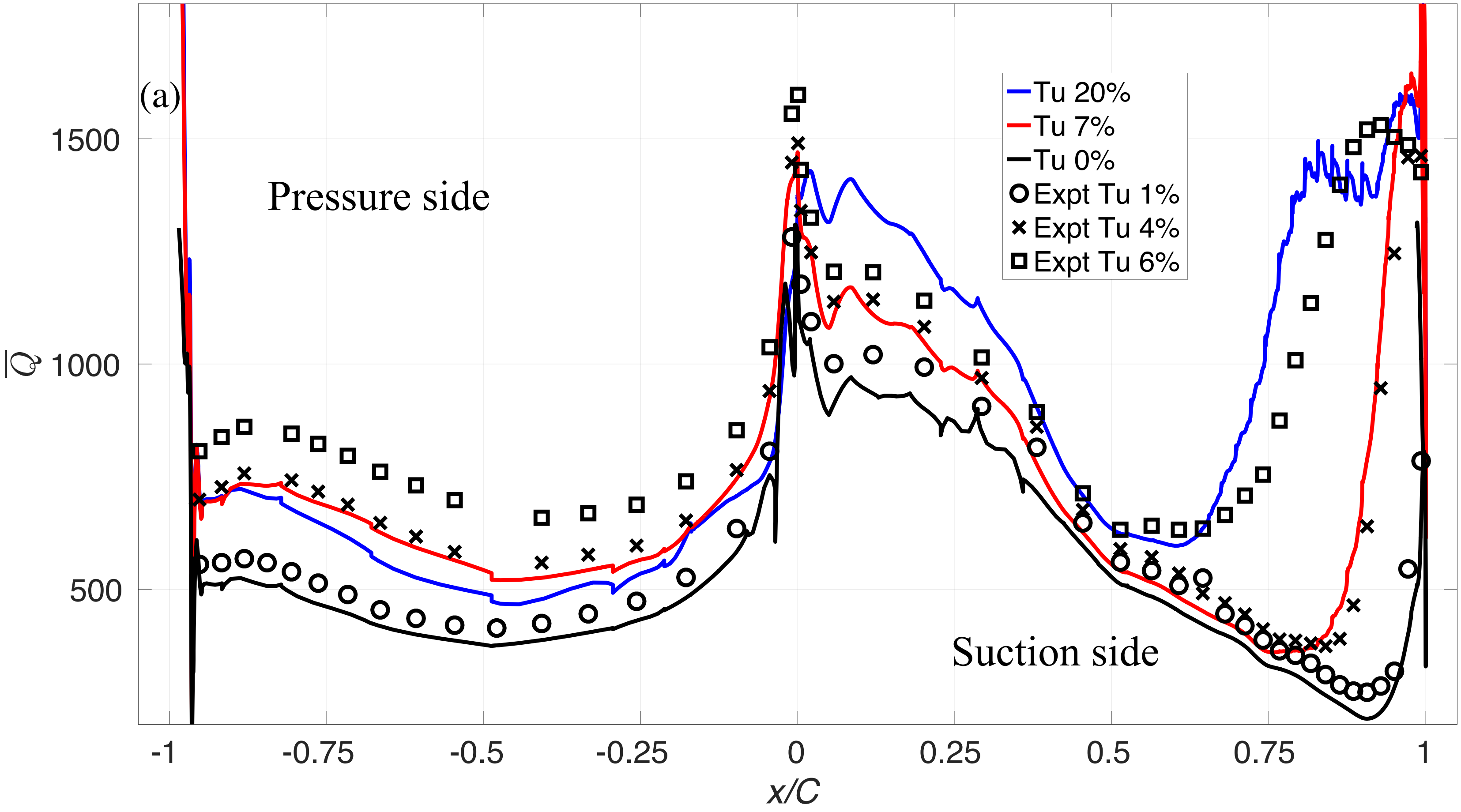
Vorticity magnitude in the xy plane
Heat flux on the airfoil



- High heat flux fore section of the airfoil
- Spanwise 2D TS waves, 3D turbulence close to the trailing edge for clean flow
- Streamwise Klebanoff modes, turbulent spots for 7% Tu
- Breakdown to turbulence is highly intermittent

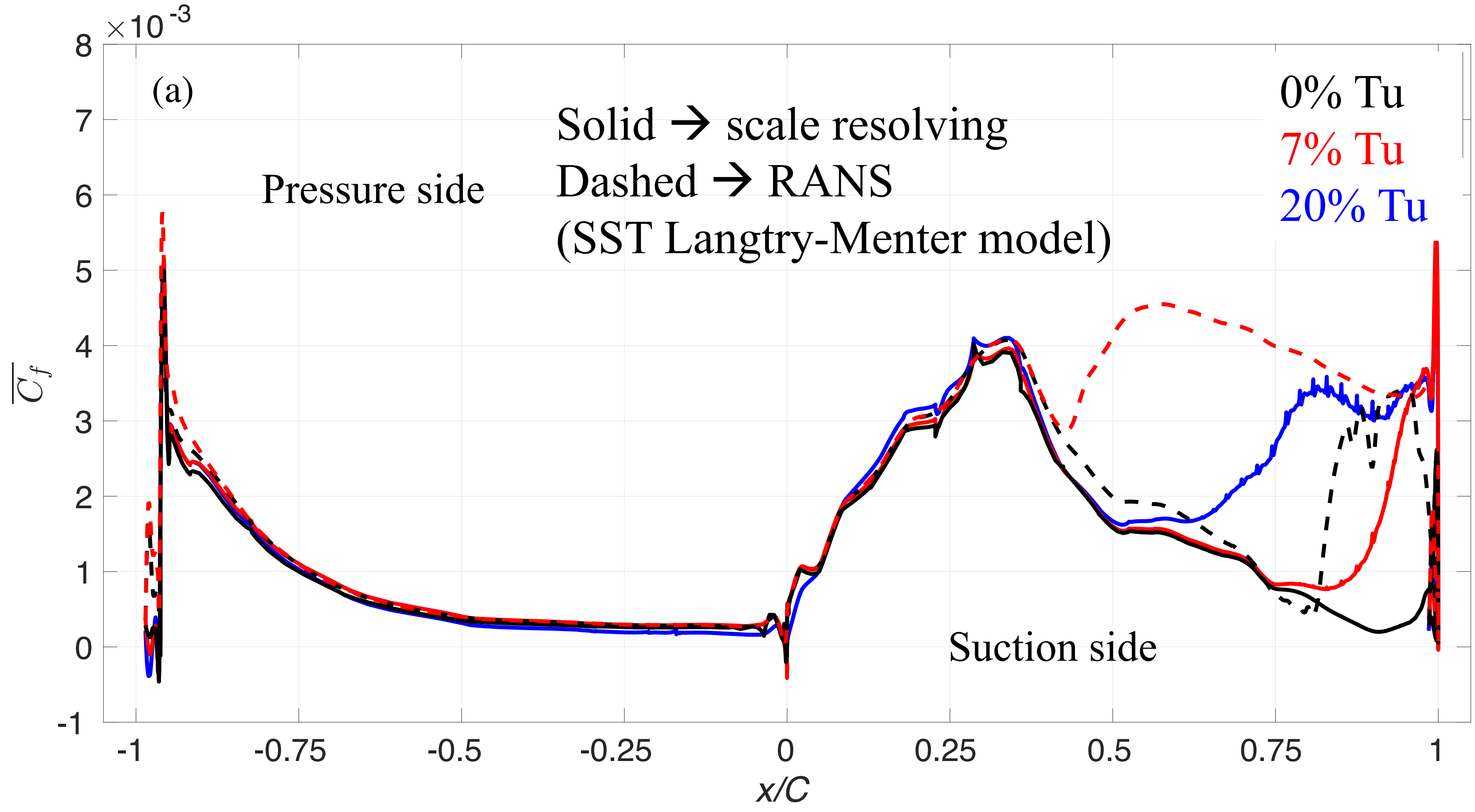
Comparison with the experiment and RANS

Mean Heat flux



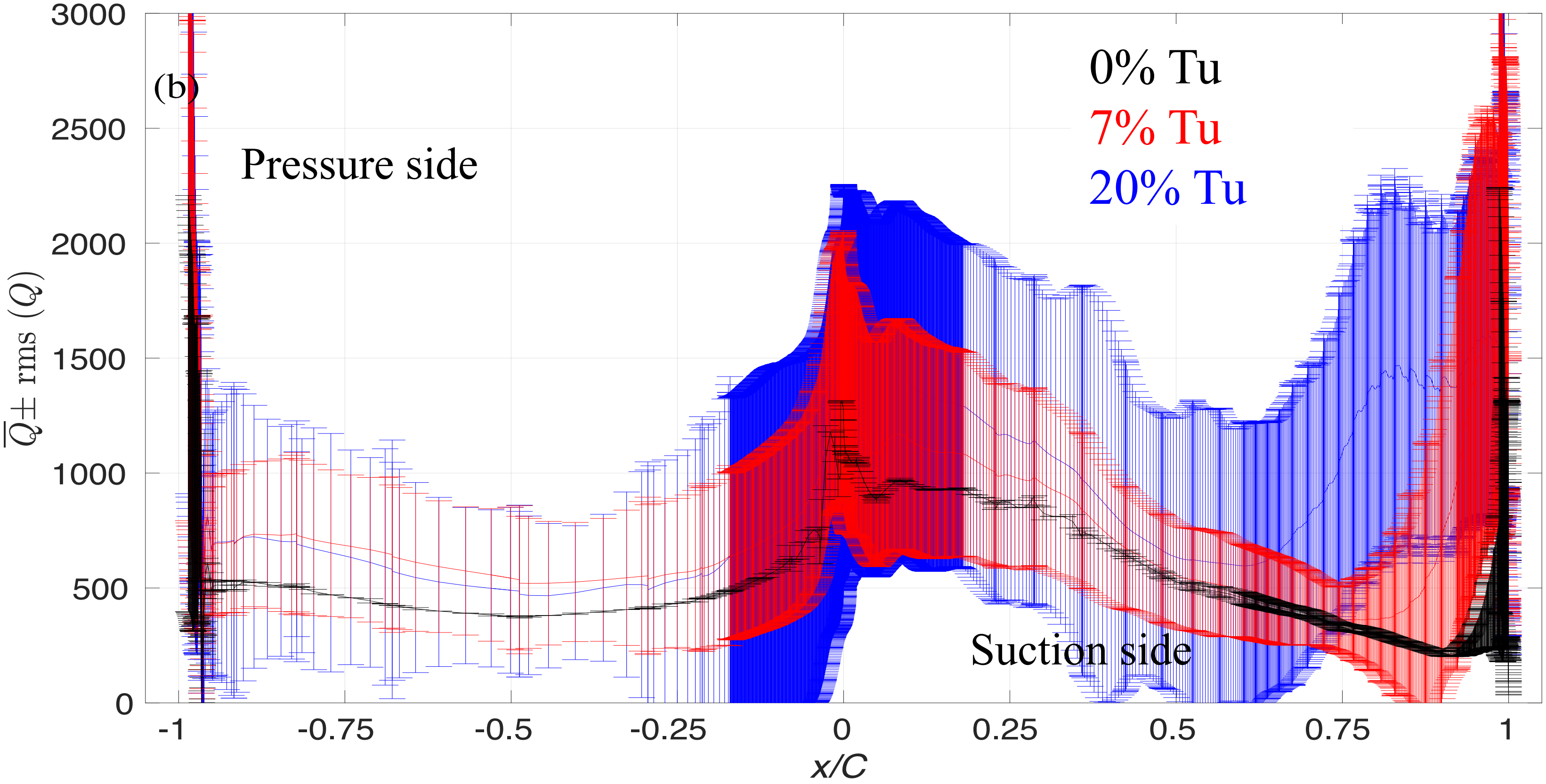
- Heat flux peaks at the leading edge, and turbulent flow region of the suction side
- 0% Tu agrees well with the experiment
- 7% Tu (Re_λ 62) agrees with the experimental 4% Tu
- 20% Tu (Re_λ 110) agrees with the experimental 6% Tu

Mean Skin friction



- Unlike heat flux, friction coefficient peaks at the suction peak, and at the turbulent region
- RANS predicts transition location further upstream compared to experimental observation, even for 0% Tu

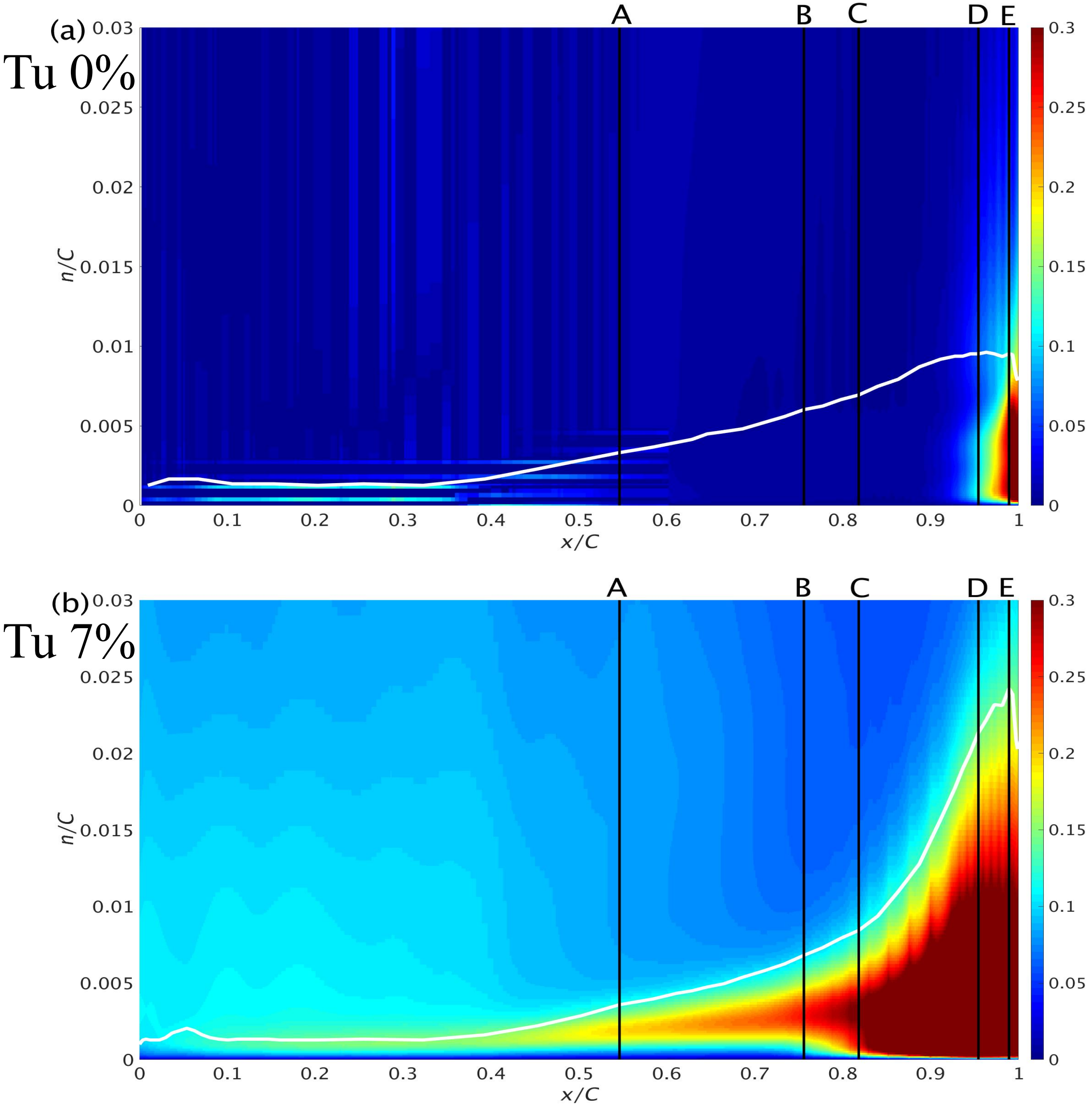
Heat flux unsteadiness



- For 0% Tu, heat flux unsteadiness is negligible except near the trailing edge, where transition occurs
- For high Tu, high heat flux unsteadiness is present even before the transition occurs, due to Klebanoff modes
- Instantaneous heat flux is much greater than the mean heat flux

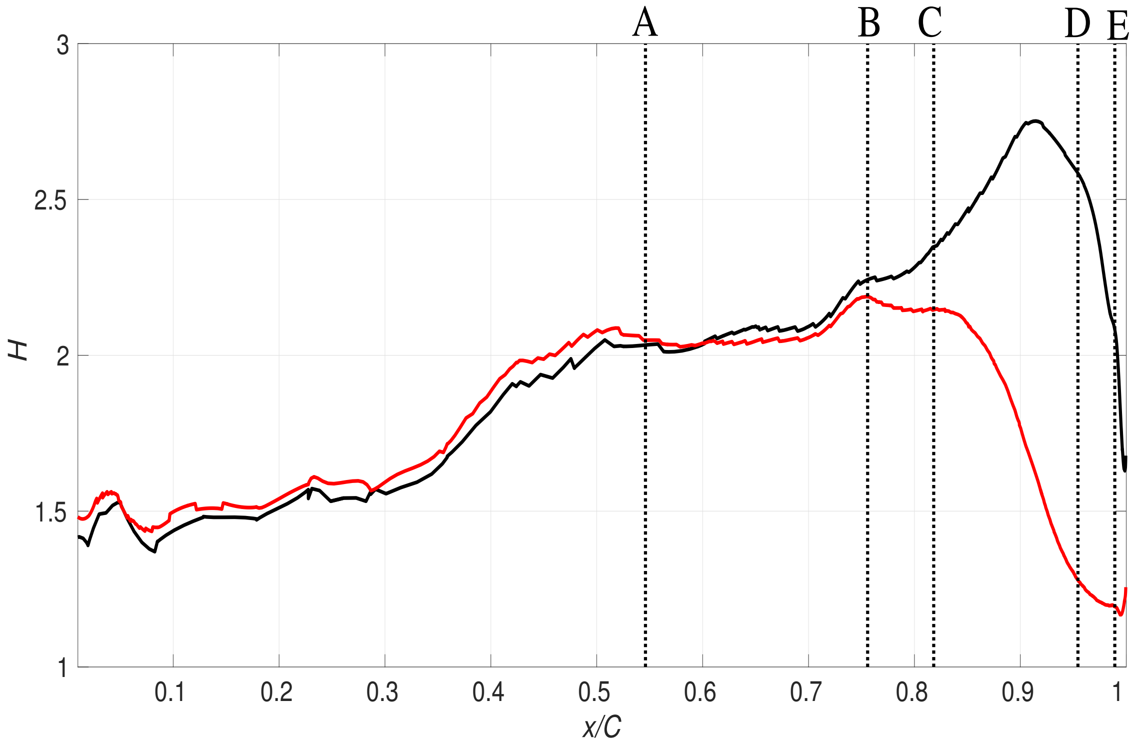
Suction side boundary layer

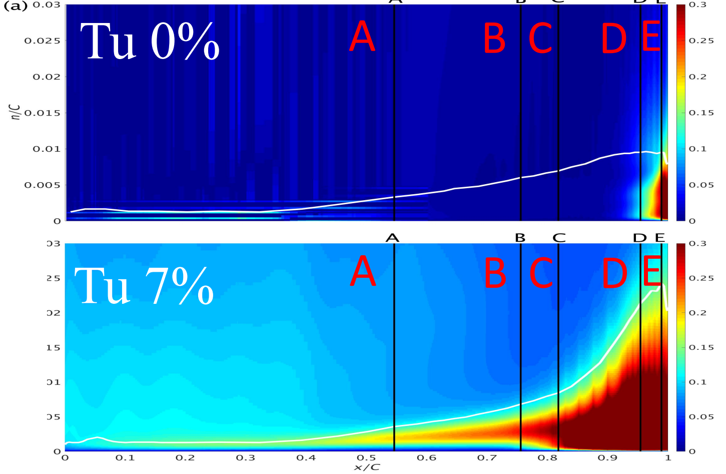
Turbulent kinetic energy



- For 0% Tu, tke is high close to the trailing edge
- For 7% Tu, high tke is present at the boundary layer edge at the fore section of airfoil → Klebanoff mode
- This high tke region penetrates towards the wall → 'top-down' mechanism of bypass transition
- Boundary layer thickness grows rapidly as boundary layer transitions

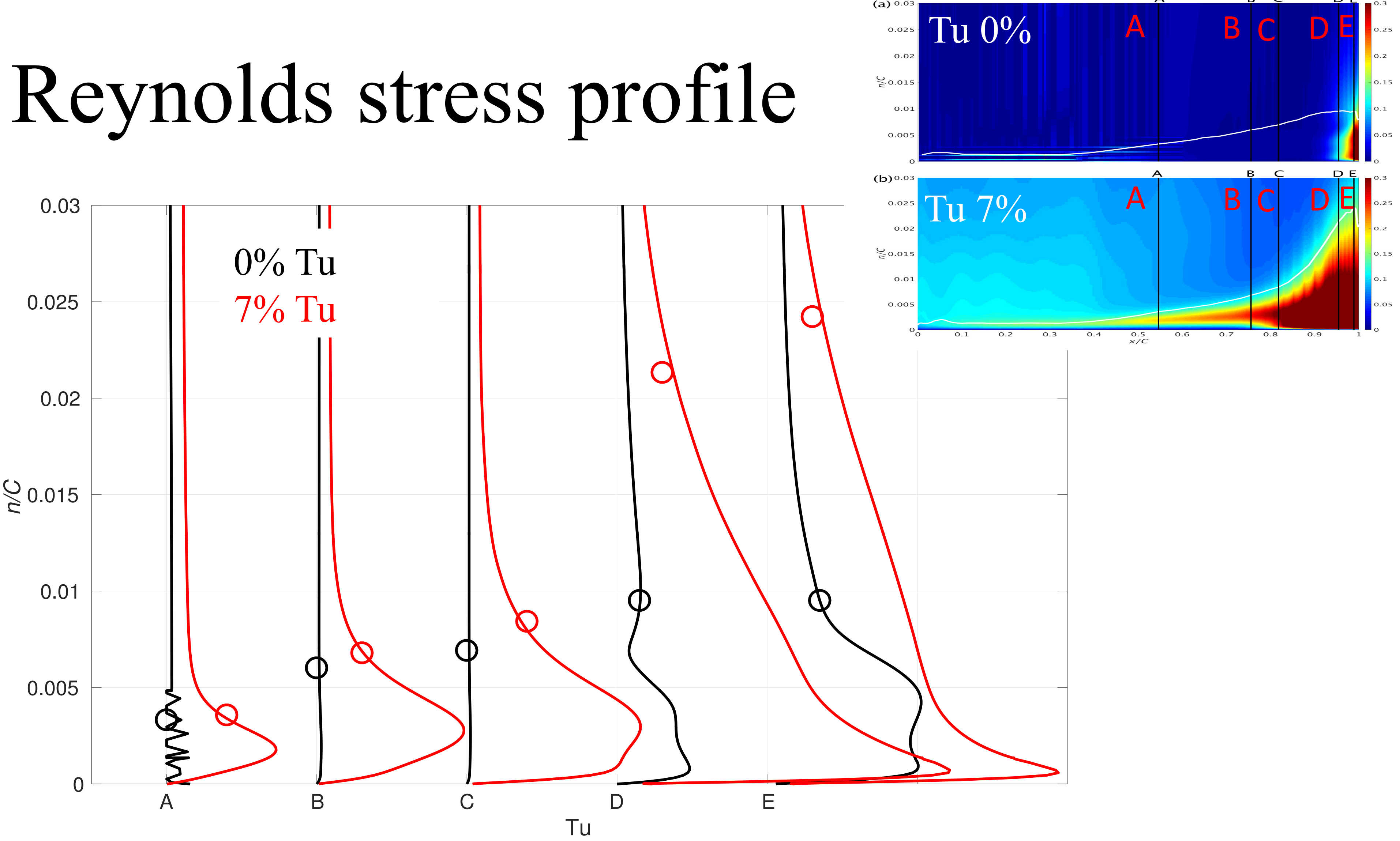
Shape factor





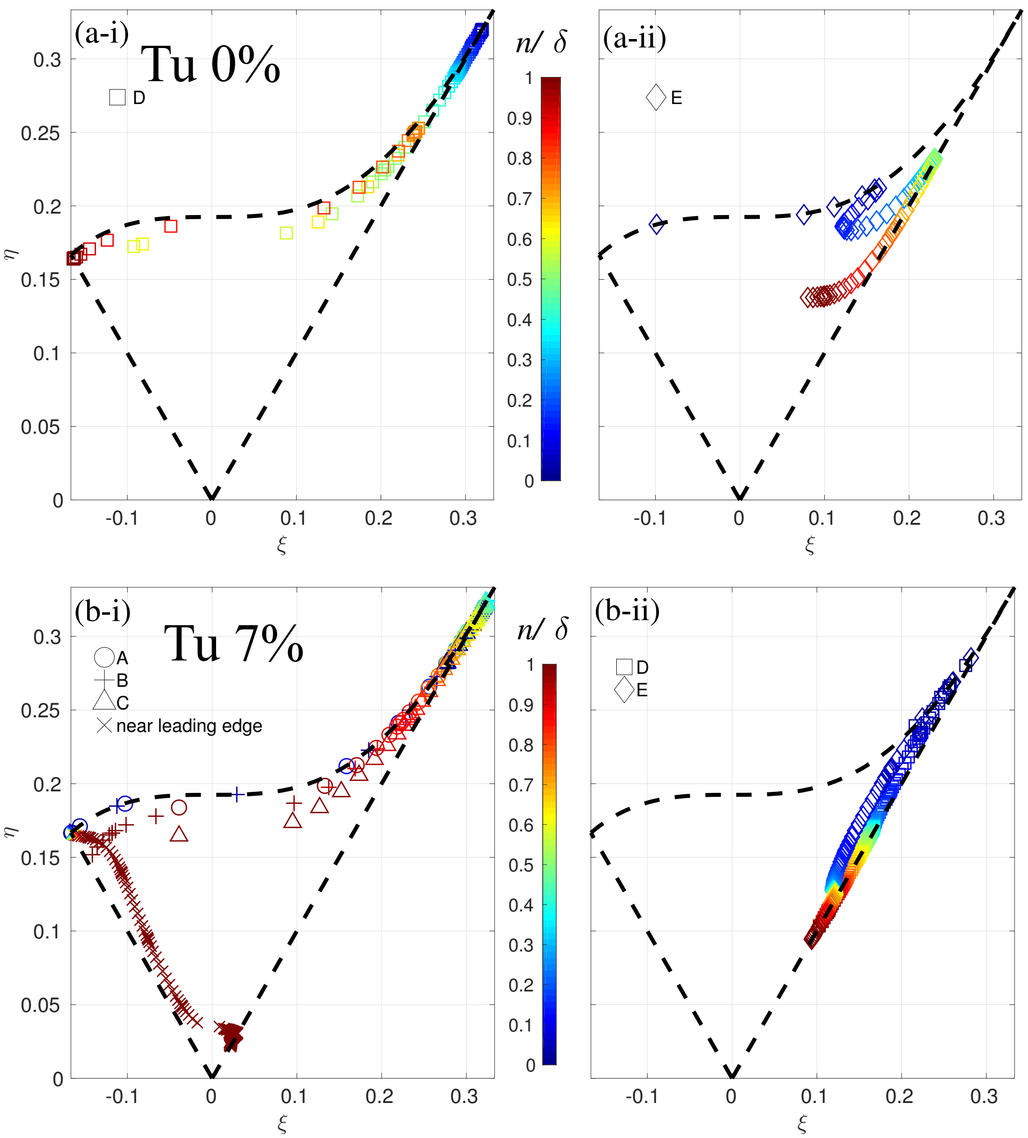
- Shape factor is much less than Blasius value before suction peak, where flow accelerates
- After suction peak it starts to increase
- For clean inflow it attains Blasius profile value before transition occurs
- As flow transition occurs, it drops to the turbulent boundary layer value

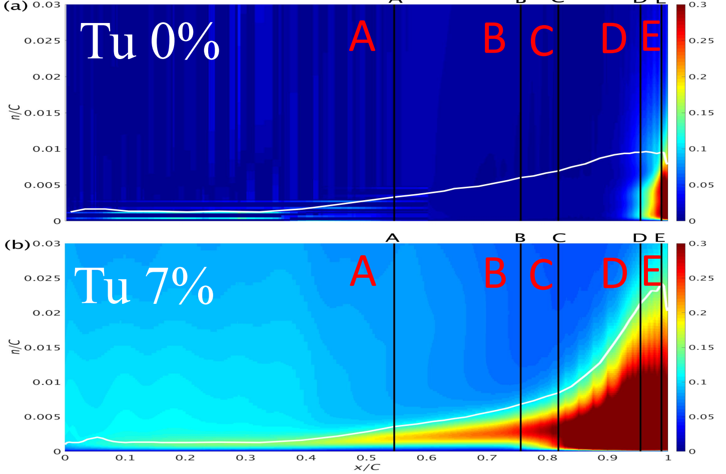
Reynolds stress profile



- 0% Tu tangential profiles shows signature of most unstable mode for TS waves (primary peak near the wall, secondary peak near the boundary layer edge)
- 7% Tu has much higher values. Before transition it peaks close to the the boundary layer edge, after transition it peaks close to the wall

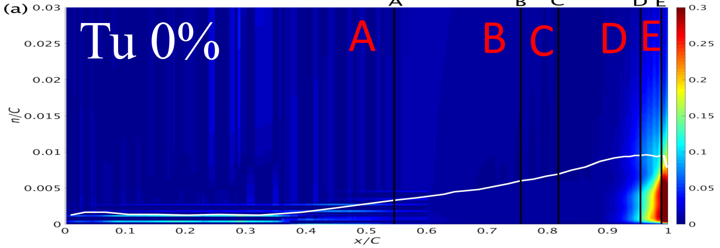
Lumley triangle

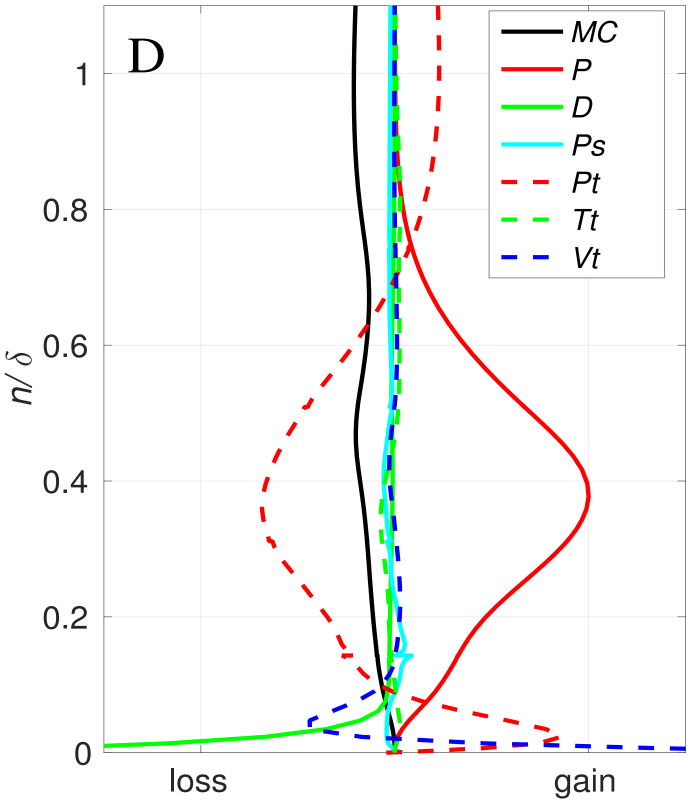


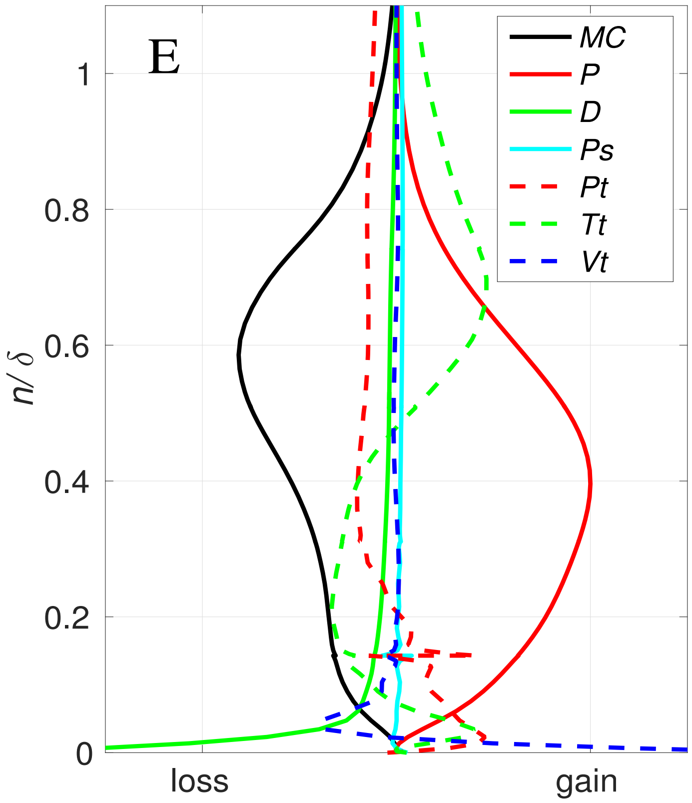


- Reynolds stress characteristics are different during the transition process for natural and bypass transition
- Inflow turbulence has isotropic structures that undergo strong stretching due to flow acceleration
- For 7% Tu, when the boundary layer becomes fully turbulent, the characteristics matches that of turbulent channel flow

TKE budget: 0% Tu

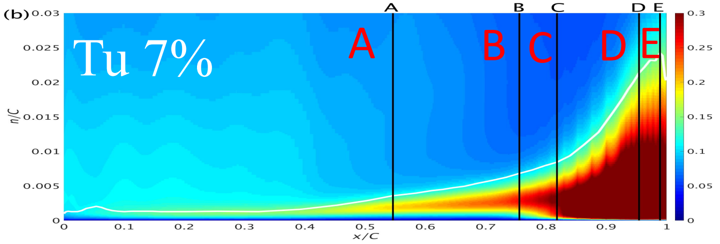


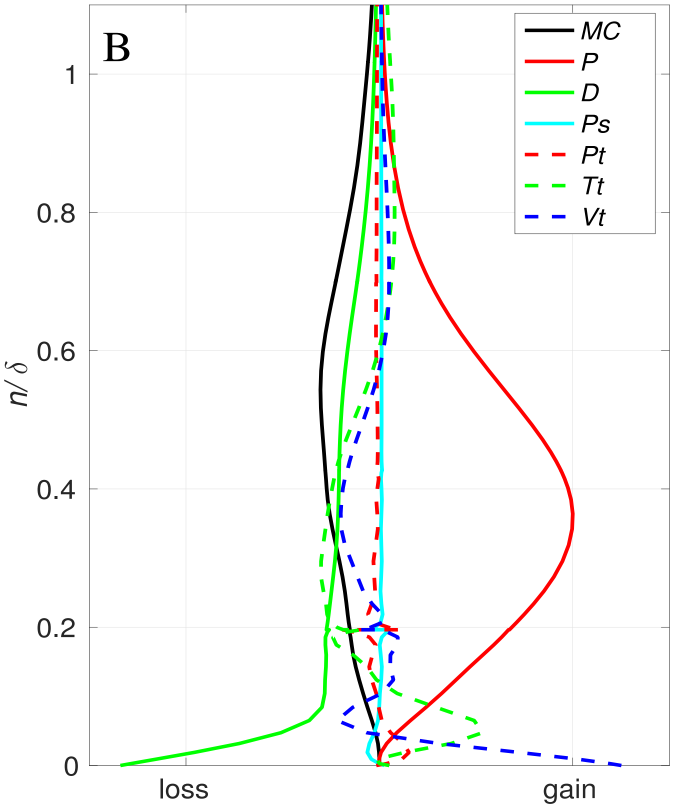


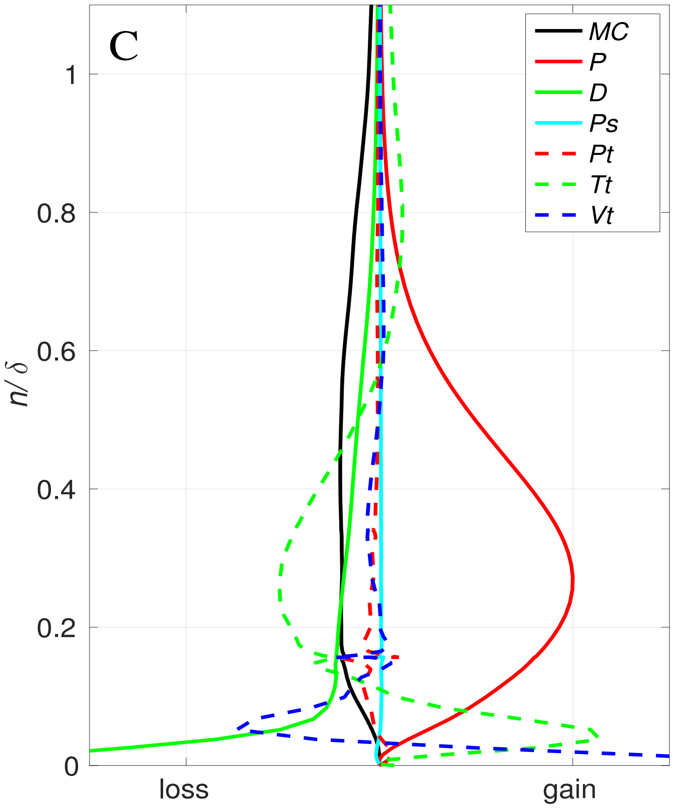


- Pressure transport plays significant role for initial phase of TS wave propagation
- Mean convection balances production and turbulent transport during the transition for majority of the boundary layer

TKE budget: 7% Tu

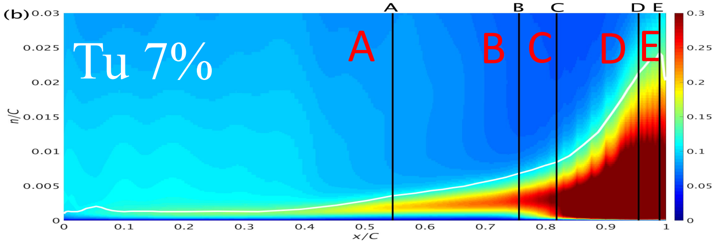


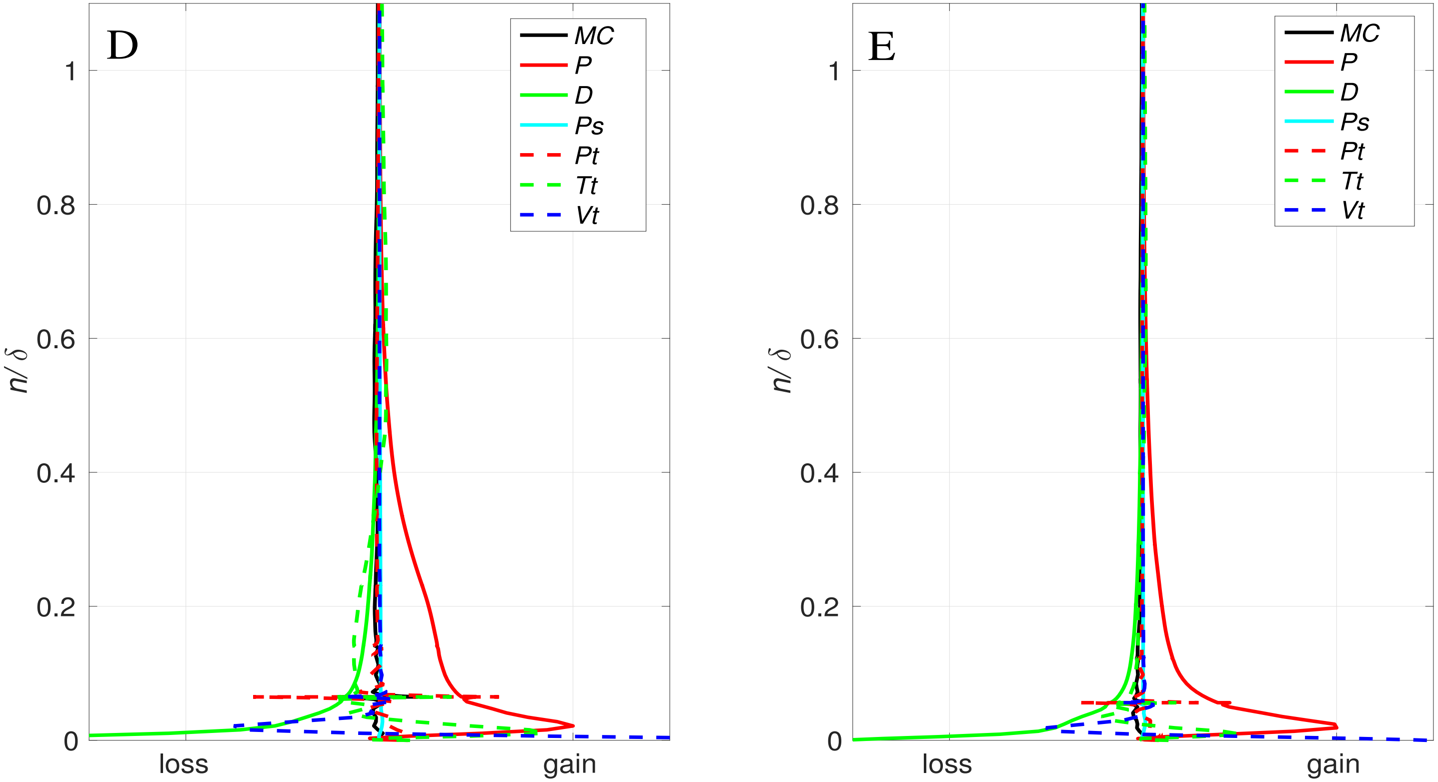




- Pressure transport contribution is negligible for the bypass transition
- Dissipation, mean convection, and turbulent transport balances production for majority of the boundary layer

TKE budget: 7% Tu





- When the boundary layer becomes fully turbulent, non zero budget terms occur close to the wall boundary
- For 7% Tu, the tke budget does not balance to zero -> indicating inadequate mesh resolution close to trailing edge

Summary

- Studied the natural and bypass transition for high pressure turbine airfoil
- 0%, 7% ($Re_\lambda = 62$), 20% ($Re_\lambda = 110$) Tu results agree well with the experimental 1%, 4% and 6% Tu
- Turbulent structures result in unsteady heat flux, comparable to the mean at the airfoil
- Mean heat flux and skin friction distributions are different near the leading edge
- Turbulent characteristics are different for natural and bypass transition

Future Work

- Looking for better documented experimental result
- Wall modeled LES with transition models
- Efficient generation of inflow turbulence
- Adjoint driven mesh adaptation

Acknowledgment

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Thank You