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

Anirban Garai, Laslo Diosady, Scott Murman, Nateri Madavan

NASA Ames Research Center
Introduction

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

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

Periodic hill
LPT
Introduction

• High operating Reynolds number for HPT $\rightarrow$ 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
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
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

- 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

- \( \text{Re} = 10^6 \)
- \( \text{Ma}_{e,\text{is}} = 0.7 \)
- Experimental \( \text{Tu} \) 1%, 6%
- Spanwise extent 20% C
- Present simulations \( \text{Tu} \) 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 \( \text{Re}_\lambda \) of 62 and 110 for 7% and 20% Tu
- Inflow turbulence is generated using linear forcing method
- For nonzero Tu, PML is applied at the outflow only
- Different mesh resolutions are used for different Tu
Flow visualization

- 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

Vorticity magnitude in the $xy$ plane
Heat flux on the airfoil
Comparison with the experiment and RANS
Heat flux peaks at the leading edge, and turbulent flow region of the suction side.

0% Tu agrees well with the experiment.

7% Tu ($Re_\lambda$ 62) agrees with the experimental 4% Tu.

20% Tu ($Re_\lambda$ 110) agrees with the experimental 6% Tu.
• 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 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
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.
• 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

• NASA Advanced Air Transport Technology Project, Advanced Air Vehicles Program
• NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center
Thank You