Simulations of Flow over Low-Pressure Turbine Blades with PyFR

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Motivation

• **Designing ‘greener aircraft’**
  • Engine weight is a critical parameter for the aircraft that uses gas turbine engines
  • Modern turbines are designed to use as few blades as possible
  • It results in higher-loading blades to turn flows, and thus *the flow is often separated*
  • Scale resolving simulations such as a **direct numerical simulation (DNS)** is demanded
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Construct precise database for turbulence modeling
Experimental setup

- MTU T161 low-pressure turbine blade with diverging end-walls

- Wind tunnel experiments by MTU Aero engines (turbulent inlet / 7 blades)
- Chord-based Reynolds number is Re=90,000 and 200,000
- $Ma \sim 0.6$ ($Ma_{inlet} = 0.38$, $Ma_{outlet} = 0.55$)
- Diverging end-walls
Simulation setup

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- Chord-based Reynolds number is $Re=90,000$ and $200,000$

- $Ma \sim 0.6$ ($Ma_{\text{inlet}} = 0.38$, $Ma_{\text{outlet}} = 0.55$)

- Laminar inlet simulation ($Re = 90,000$ and $200,000$)
  and Turbulent inlet simulation ($Re = 90,000$)
Simulation setup

- MTU T161 low-pressure turbine blade with diverging end-walls
- Flux-Reconstruction scheme (solution polynomial: $p = 4$)
- Number of total DoF = 2.3 billion (Re=90k), 11 billion (Re=200k)
- Average ~200 quantities for turbulent statistics including double/triple/quadruple products and gradient terms
- 660 point probes for time history of primitive variables
Simulation setup (laminar inflow)

- MTU T161 low-pressure turbine blade with diverging end-walls

- A total pressure $p_t$ is fixed => the velocity profile is determined as a ghost state

- The total pressure profile is set to follow
  the Blasius-like boundary layer velocity profile [1] in the span-wise direction


$$p_t = p_{t;+} + p_{t;-} - p_{t;mid}$$

$$p_{t;\pm} = p \left\{ c_p T_t \left[ c_p T_t - \frac{1}{2} w_2 \tanh \left( \frac{\eta_{ref} a_{bl} (h_2 \pm z)}{\delta_{bl}} \right) \right]^{2/n_{bl}} \right\}^{\gamma/\gamma-1}$$

$$p_{t;mid} = p \left\{ c_p T_t \left[ c_p T_t - \frac{1}{2} w_2 \right] \right\}^{\gamma/\gamma-1}$$

$$n_{bl} = 5/3, \quad a_{bl} = 0.33245, \quad \delta_{bl} = 0.2070, \quad \eta_{ref} = 5.075$$

- The static pressure is assumed to be uniform
### Governing Equations
Compressible and Incompressible Navier-Stokes

### Spatial Discretisation
- Arbitrary order Flux Reconstruction on mixed unstructured grids (*hexes*, *tets*, *prisms* etc.)
- p4 with full anti-aliasing option in this study (volume, flux, surf-flux)

### Temporal Discretisation
Explicit Runge-Kutta schemes (*RK45*) with time-step size controller

### Platforms
- CPU clusters (via C/OpenMP-MPI)
- Nvidia GPU clusters (via CUDA-MPI)
- AMD GPU clusters (via OpenCL-MPI)
Results

• Takes ~ **24 hours** of wall clock time per blade pass on **5,760 K20X GPUs** (for Re=200k case)

• Simulation for ~12 flow passes for time averaging
Re = 200,000 (laminar inlet)

Density gradient

Q isosurface
Re = 200,000 (laminar inlet)
Re = 200,000 (laminar inlet)

Isentropic Mach number on the mid-span blade surface

1BLI-200 simulation

Experiment: Re = 2.0 \times 10^5
Re = 200,000 (laminar inlet)

Total pressure loss in wake
Re = 200,000 (laminar inlet)

Total pressure loss in wake

PyFR

Experiment
Re = 200,000 (laminar inlet)

Blade shear stress LIC

Pressure side
Suction side

PyFR

Experiment
$Re = 200,000$ and $90,000$ (laminar inlet)
Re = 200,000 and 90,000 (laminar inlet)

Total pressure loss in wake

Re=200k

Re=90k
Inlet turbulence

- Impose **random velocity fluctuation** to the laminar profile (as a ghost state)
  - Digital filter (DF) technique proposed by

- Impose **density fluctuation** via the strong Reynolds analogy (SRA)
  \[
  \frac{\rho''}{\rho_1} = -\frac{T''}{T_1} = (\gamma - 1)Ma^2 \frac{u''}{u_1}
  \]
  by Guarini et al., JFM 2000
Re = 90,000

Laminar inlet

Turbulence inlet
Re = 90,000

Laminar inlet

Turbulence inlet
Re = 90,000

Laminar inlet

Simulation (laminar)
• Experiment (2% turbulence)

Turbulence inlet

Simulation (1.25% turbulence)

Pressure drop \((p_0 - p_2)/(p_1 - p_2)\)

Normalized pitch length \(u/t\)
Summary

- DNS for MTU T161 LPT cascade with non-parallel end-walls was performed using 5760 NVIDIA GPUs (K20X) on Titan at Oak Ridge National laboratories.

- Good agreement with experiments in Re=200k case without turbulence inlet condition.

- Re=90k case with/without inlet turbulence.

  - **Inlet turbulence delays separation on suction-side**

  - Re=90k case is relatively sensitive to the inlet turbulence compared to the Re=200k case.