THREE-DIMENSIONAL UNSTEADY SIMULATION OF AERODYNAMICS AND HEAT TRANSFER IN A MODERN HIGH PRESSURE TURBINE STAGE

Unsteady 3-D RANS simulations have been performed on a highly loaded transonic turbine stage and results are compared to steady calculations as well as to experiment. A low Reynolds number k-ε turbulence model is employed to provide closure for the RANS system. A phase-lag boundary condition is used in the tangential direction. This allows the unsteady simulation to be performed by using only one blade from each of the two rows. The objective of this work is to study the effect of unsteadiness on rotor heat transfer and to glean any insight into unsteady flow physics. The role of the stator wake passing on the pressure distribution at the leading edge is also studied. The simulated heat transfer and pressure results agreed favorably with experiment. The time-averaged heat transfer predicted by the unsteady simulation is higher than the heat transfer predicted by the steady simulation everywhere except at the leading edge. The shock structure formed due to stator-rotor interaction was analyzed. Heat transfer and pressure at the hub and casing were also studied. Thermal segregation was observed that leads to the heat transfer patterns predicted by steady and unsteady simulations to be different.
Three-Dimensional Unsteady Simulation of Aerodynamics and Heat Transfer in a Modern High Pressure Turbine Stage

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### NASA Subsonic Transport System Level Metrics

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

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Noise (cum below Stage 4)</td>
<td>- 32 dB</td>
<td>- 42 dB</td>
<td>- 71 dB</td>
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<tr>
<td>LTO NOx Emissions</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
<tr>
<td>(below CAEP 6)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Performance: Aircraft Fuel Burn</td>
<td>-33%**</td>
<td>-40%**</td>
<td>better than -70%</td>
</tr>
<tr>
<td>Performance: Field Length</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit metroplex* concepts</td>
</tr>
</tbody>
</table>

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

**SFW Approach**
- Conduct Discipline-based Foundational Research
- Investigate Advanced Multi-Discipline Based Concepts and Technologies
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Enable Major Changes in Engine Cycle/Airframe Configurations
About this work…

- 3-D URANS simulations performed on highly loaded transonic turbine stage using TURBO (Chen et al.)

- Results are compared to steady calculations as well as experiment (Tallman, Haldemann et al. at OSU GTL).

- Effect of unsteadiness studied
  - shock structure
  - rotor heat flux
  - hub and casing heat flux
  - thermal segregation
Background

- HPT flow is unsteady due to wake passage and shock-wake interactions
- Stagnation point on rotor moves away from LE
- Shock moves from rotor crown to leading edge as wake passes (Denos et al., Paniagua et al.)
- Thermal segregation could occur (Shang and Epstein, Ameri et al., Kerrebrock and Mikolajczak)
Segregation

Velocity diagrams in the wake.
\[ T_{\text{time\_average}} < T_{\text{steady}} \]

Rotor-Stator interface

Steady

Unsteady wake

Lower temperature in wake directs cooler gas to suction side
TURBO

- Upwind Roe scheme with Newton sub iterations
  - No artificial dissipation
- Fully parallelized to use MPI
- Only need one blade per row using Phase lag
- Phase lag - ideal for single-stage simulation (Van Zante et al.)
- Uses low Re k-ε turbulence model
- Heat transfer simulation made possible by incorporating isothermal BC

Phase lag

Uses blade count of neighboring blade row to determine frequency
The Grid

- 38 Stators, 72 rotor blades
- ~2.5M cells (very fine grid)
- $y^+<1$ (at first point off wall)
- Coarser grids have shown satisfactory results (e.g. Green et al.)

**Rotor Features**
- 2.1% tip clearance
- blade speed ~ 9000 rpm
- $Re \sim 3 \times 10^6 / m$

Convergence determined using mass flow and surface heat transfer

Relative stator-rotor positioning for unsteady case and boundary conditions
Simulations

- **Steady**
  - Used circumferentially averaged vane exit total pressure and temperature profiles as rotor inlet profiles.
  - Periodic BC used in tangential direction

- **Unsteady**
  - Stator inlet total pressure and temperature, rotor exit static pressure specified
  - Phase lag BC in tangential direction
  - 50 steps per period stored
  - Sliding interface BC at stator-rotor interface
RESULTS
Shock Function at 15% span

\[ SF = \vec{V} \cdot \nabla p \]

- Boundaries of red regions are shocks
- (Large pressure gradient is in direction of flow velocity)
Shock Function at Mid-Span

Vane trailing edge shock sweeps across crown and LE of rotor

Minimum unsteadiness on suction side of rotor
Comparison with Schlieren

De la Loma, Paniagua, Verrastro, Adami, GT2007-27101

Dotted lines are reflected shocks
Shock Function at 90% Span

Vane trailing edge shock interacts with rotor trailing edge shock
Mid-span Pressure and Mach Number

Pressure

Mach no.
Fundamental Aeronautics Program
Subsonic Fixed Wing Project

Pressure Profiles

Unsteady envelope widest near LE, narrows towards TE

Rotor trailing edge shock
Pressure Profiles

- No shock near tip
- Thin envelope

Stag. Point moved to pressure side

b) 50%

c) 90%

P/P_{ref}

S (non dimensional distance along blade profile)
Stanton Number Profiles

Stanton Number Profiles

\[
St = \left(\frac{dT}{dn}\right)_{\text{wall}} \left[ \frac{\mu_{\text{wall}}}{(\rho V)_{\text{inlet}}} \right] \frac{1}{Re_{\text{ref}} \cdot Pr}
\]

- a) 15%
- B) 15%

S (non dimensional distance along blade profile)
Stanton Number Profiles

\[
St = \frac{dT}{dn_{wall}} \left[ \frac{\mu_{wall}}{T_{wall} - T_{ref}} \right] \left[ \frac{1}{(\rho V)_{inlet} \cdot Re_{ref}} \cdot Pr \right]
\]

b) 50%

c) 90%

S (non dimensional distance along blade profile)
Streamlines of relative velocity over suction side of rotor blade with rotor blade showing Stanton number contours.
Higher heat transfer at LE for Steady case

Comparison between steady and time-averaged Stanton number distribution on rotor blade pressure side.
Snapshots of Unsteady Heat Flux
In the Tip Gap

\[ \theta = \tan^{-1} \left( \frac{u}{w} \right) \]

*Isosurface*: \[ x - z \tan(\theta) = c \]

\[ V_{\text{plane}} = u \sin(\theta) + w \cos(\theta) \]

\( V_{\text{plane}} \) is positive (yellow through red colors) if flow is separated. This is only valid in the tip gap, where flow separation can be measured in the z-x plane.
In the Tip Gap – Plane 1

- Density gradient
- Separation
- Expands to pressure lower than suction side and then goes through series of compressions and expansions
In the Tip Gap – Plane 1 - Unsteady
In the Tip Gap – Plane 2

Beginning of separation

expansions
Casing Heat Transfer

Steady

Time-averaged

Corresponds to separation
Hub Heat Transfer

\[ \Delta_{St} = \frac{St_{\text{steady}} - St_{\text{time-averaged}}}{St_{\text{time-averaged}}} \times 100 \]

Percent difference between steady and time-averaged Stanton number on rotor hub.

Segregation effect

Blue: Time-averaged heat transfer higher

Red: Time-averaged heat transfer lower
Conclusions

- Over most of blade surface, steady simulation is accurate
- Thermal wake causes unsteady heat transfer over most of the blade to be higher than steady heat transfer except at leading edge.
- At the leading edge the effect of unsteadiness is most prominent
- Thermal redistribution was observed at the hub and on the blade surface
- Pressure and heat transfer distribution over blade is highly 3D
Backup slides
Time averaged P and Shock @ 50% span
The phase lag boundary condition for more than two blade rows

- In this example, adding the IGV wakes creates circumferential non-uniformities at the entrance to stator 1.
- At ‘B’ the phase lag boundary condition will apply the time history of ‘A’ with a phase shift but not the necessary change in the mean.
- This results in a spatial filtering of information for stator-stator (and rotor-rotor) interactions.
Pressure and Temperature Profile at Interface

**Radius vs. Total Pressure**

- Total Pressure

- Total Pressure (kPa)

**Radius vs. Total Temperature**

- Total Temperature

- Total Temperature (K)
Stanton No. Derivation

\[ St = \frac{h}{c_p \cdot \rho \cdot V} \quad \text{since} \quad h = \frac{q_{wall}}{T_{wall} - T_{ref}}, \quad \text{and knowing} \quad \dot{m} = \rho \cdot A \cdot V \]

\[ St = \frac{q_{wall}}{(\frac{\dot{m}}{A}) \cdot c_p \cdot [T_{wall} - T_{ref}]} \]

\[ St = \frac{1}{\rho \cdot V \cdot C_P} \cdot \frac{-k \cdot \frac{dT}{dn}|_{wall}}{T_{wall} - T_{ref}} \quad \text{knowing:} \]

\[ Pr = \frac{\mu_{wall} \cdot C_P}{k} \]

\[ \mu_{wall} = \frac{Pr \cdot k}{C_P} \]

\[ \mu_{wall} = \rho_{wall} \cdot V_{wall} \]

Multiply and divide by \( \mu_{wall} \) and simplify to obtain:

\[ St = \frac{-\frac{dT}{dn}|_{wall}}{T_{wall} - T_{ref}} \cdot \frac{\mu_{wall}}{\rho \cdot V} \cdot \frac{1}{Pr} \]

An expression in nondimensional terms:

\[ St = -\left[ \frac{\frac{dT}{dn}|_{wall}}{\bar{T}_{wall} - \bar{T}_{ref}} \right] \cdot \left[ \frac{\bar{\mu}_{wall}}{\bar{\rho} \cdot \bar{V}} \right] \cdot \left[ \frac{1}{Pr} \right] \cdot \left[ \frac{\mu_{ref}}{\rho_{ref} \cdot x_{ref} \cdot d_0} \right] \]
Rotor Hub Surface Heat Transfer - Steady

TURBO predictions

Stanton No. Comparisons

Stanton Number vs. Probe Number
Hub Endwall

- Experiment #5
- Experiment #6
- Tallman - CFD
- Turbo - CFD
Rotor Tip Heat Transfer – Steady

TURBO predictions

Stanton No. Comparisons

Stanton Number vs. Probe Number

Probe Number

Experiment #5
Experiment #6
Tallman - CFD
Turbo - CFD
Rotor Casing Surface Heat Transfer - Steady

TURBO predictions

No data available for comparison

Stanton Number vs. Probe Number
Casing Endwall

Stanton Number (ST)

Probe Number
## Statistics – Steady

<table>
<thead>
<tr>
<th>Results</th>
<th>TURBO vs. Tacoma</th>
<th>TURBO vs. Experimental</th>
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<tbody>
<tr>
<td>Vane Surface Pressure</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Vane Surface Heat Transfer</td>
<td>Good</td>
<td>Good</td>
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<tr>
<td>Blade Surface Pressure</td>
<td>Good</td>
<td>Good</td>
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<tr>
<td>Blade Surface Heat Transfer</td>
<td>Fair</td>
<td>16.3% difference (max: 25%)</td>
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<tr>
<td>Rotor Hub Surface Heat Transfer</td>
<td>13.4% difference</td>
<td>13.1% greater</td>
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<tr>
<td>Rotor Tip Heat Transfer</td>
<td>10.5% difference</td>
<td>15.5% greater</td>
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<table>
<thead>
<tr>
<th></th>
<th>Iterations</th>
<th>Estimated CPU Time</th>
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<tbody>
<tr>
<td>Stator</td>
<td>30,000</td>
<td>60 Hours</td>
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<tr>
<td>Rotor</td>
<td>40,000</td>
<td>120 Hours</td>
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