Aerodynamic Investigation of Incidence Angle Effects in a Large Scale Transonic Turbine Cascade

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Aerodynamic measurements showing the effects of large incidence angle variations on an HPT turbine blade set are presented. Measurements were made in NASA’s Transonic Turbine Blade Cascade Facility which has been used in previous studies to acquire detailed aerodynamic and heat transfer measurements for CFD code validation. The current study supports the development of variable-speed power turbine (VSPT) speed-change technology for the NASA Large Civil Tilt Rotor (LCTR) vehicle. In order to maintain acceptable main rotor propulsive efficiency, the VSPT operates over a nearly 50% speed range from takeoff to altitude cruise. This results in 50° or more variations in VSPT blade incidence angles. The cascade facility has the ability to operate over a wide range of Reynolds numbers and Mach numbers, but had to be modified in order to accommodate the negative incidence angle variation required by the LCTR VSPT operation. Using existing blade geometry with previously acquired aerodynamic data, the tunnel was re-baselined and the new incidence angle range was exercised. Midspan exit total pressure and flow angle measurements were obtained at seven inlet flow angles. For each inlet angle, data were obtained at five flow conditions with inlet Reynolds numbers varying from $6.83 \times 10^5$ to $0.85 \times 10^5$ and two isentropic exit Mach numbers of 0.74 and 0.34. The midspan flowfield measurements were acquired using a three-hole pneumatic probe located in a survey plane 8.6% axial chord downstream of the blade trailing edge plane and covering three blade passages. Blade and endwall static pressure distributions were also acquired for each flow condition.
AERODYNAMIC INVESTIGATION OF INCIDENCE ANGLE EFFECTS IN A LARGE SCALE TRANSONIC TURBINE CASCADE

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Motivation for VSPT Technology

Principal Challenge
Variability in main-rotor speed:
- 650 ft/s VTOL
- 350 ft/s at Mn 0.5 cruise

Approaches
- Variable gear-ratio transmission
- Variable-speed power turbine (VSPT)
- or combination

VSPT Challenges
- Wide incidence variation
- Transitional Reynolds numbers

VSPT Approach
- Develop IT blade-set
- Modify cascade
- Re-baseline cascade
- Document blade performance over large Reynolds number and incidence angles variations

Large Civil Tilt-Rotor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGW</td>
<td>108k lbm</td>
</tr>
<tr>
<td>Payload</td>
<td>90 PAX</td>
</tr>
<tr>
<td>Engines</td>
<td>4 x 7500 SHP</td>
</tr>
<tr>
<td>Range</td>
<td>&gt; 1,000 nm</td>
</tr>
<tr>
<td>Cruise speed</td>
<td>&gt; 300 kn</td>
</tr>
<tr>
<td>Cruise altitude</td>
<td>28 – 30 kft</td>
</tr>
</tbody>
</table>

Transonic Turbine Blade Cascade

Blades:
- 11 blade passages
- span = 6.000" (fixed)
- pitch = 5.119" (fixed)
- axial chord = 5.119"

Inlet:
- dry, clean, ambient $T$
  (filtering: 98% of 0.35μm 99.9% of 2 μm)
- well-documented inlet; nominal $\delta_{in} \approx 1.0$ inch
- various static and blown turbulence generating grids available.
Transonic Turbine Blade Cascade Facility

Current Configuration with E³ Tip Section Blades at inlet flow angle of 38.8°

Supply Pressure = 40 psig

Max Plenum P = 14.7 psia
Max Mass Flow ~58 lbm/s

Exhaust pressure:
• min P ≈ 2 psia
• max = inlet P

Disk diameter 6 ft.
Facility Operating Envelope

isentropic exit Mach number, $Ma_{2,i}$

- $Ma_{2,i} = 1.0$
- $E^3 Ma_{2,des} = 0.74$
- $Ma_2 = 0.34$
- $P_t = 14.7$ psia
- maximum inlet pressure $= 23.0$ psia
- maximum mass flow $\approx 58$ lbm/s
- minimum exhaust pressure

previous studies
EEE Tip Section Blade
current study
Original Facility at Min & Max Incidence Angles

Minimum inlet flow angle = 33.8° from axial

Maximum inlet flow angle = 78.6° from axial
Facility Modifications

- Extended exhaust duct
- New support bars
- Discrete upper board extensions
- Added 12 exit static pressure taps
- ~95° inlet angle variation
Test Objectives

• Re-baseline cascade using existing geometry with previously acquired data.

• Develop initial experimental dataset that documents the trends of incidence angle and Reynolds number variations.
  – Improve understanding of effects of extreme incidence with wide Reynolds number variations
  – Generate dataset to be used for CFD code and model validation
Test Configuration

- GE EEE tip section blade, $\beta_{1,\text{des}} = 29.7^\circ$
- Seven incidence angles: $+29.1^\circ$ to $-46.5^\circ$
- Re-baseline measurements acquired for $i = +29.1^\circ$ and $i = +9.1^\circ$
- 5 flow conditions each

### Inlet Flow Angles

<table>
<thead>
<tr>
<th>Inlet Angle $\beta_1$</th>
<th>Incidence Angle $\beta_1 - \beta_{\text{design}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.8°</td>
<td>29.1°</td>
</tr>
<tr>
<td>48.8°</td>
<td>19.1°</td>
</tr>
<tr>
<td>38.8°</td>
<td>9.1°</td>
</tr>
<tr>
<td>33.8°</td>
<td>4.1°</td>
</tr>
<tr>
<td>18.3°</td>
<td>-11.4°</td>
</tr>
<tr>
<td>-2.4°</td>
<td>-32.1°</td>
</tr>
<tr>
<td>-16.8°</td>
<td>-46.5°</td>
</tr>
</tbody>
</table>

### Nominal Test Conditions

<table>
<thead>
<tr>
<th>Inlet Reynolds Number</th>
<th>Pressure Ratio</th>
<th>Exit Isentropic Mach Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>683,000 (Design)</td>
<td>1.44</td>
<td>0.74</td>
</tr>
<tr>
<td>341,500 (1/2 Design)</td>
<td>1.44</td>
<td>0.74</td>
</tr>
<tr>
<td>170,700 (1/4 Design)</td>
<td>1.44</td>
<td>0.74</td>
</tr>
<tr>
<td>170,700 (1/4 Design)</td>
<td>1.08</td>
<td>0.34</td>
</tr>
<tr>
<td>85,000 (1/8 Design)</td>
<td>1.08</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Measurements

• Total pressure and flow angles measured 8.5% $C_x$ downstream of trailing edge

• Blade and endwall static pressure measurements

• 12 new exit static taps located 3.5 axial chords downstream

• Inlet $P_t$, $P_s$, and $T_t$ measured 1.0 $C_x$ upstream
RE-BASELINE MEASUREMENTS
Exit Static Pressure Measurements

Original Exhaust Configuration

\[ \frac{P}{P_{t, in}} \]

- exit \( P_s \) (avg) (avg of 3 exit \( P_s \) taps)
- exit \( P_s \) taps (3 original \( P_s \) taps)
- blade base pressures
- endwall static taps at \( x = 10.000'' \)

\[ i = +9.1^\circ \]

New Exhaust Configuration

\[ \frac{P}{P_{t, in}} \]

- exit \( P_s \) (avg) (avg of 12 exit \( P_s \) taps)
- exit \( P_s \) taps (3 original \( P_s \) taps)
- blade base pressures
- endwall static taps at \( x = 10.000'' \)
- new exit \( P_s \) taps at \( x = 18.019'' \)

\[ i = +9.1^\circ \]
Exit Static Pressure Measurements

- Non-uniform exit static pressures at negative incidence angle.
- Blade row and back wall establish a converging exhaust section.
- Flow field is accelerated creating a negative pressure gradient.

\[ \frac{P}{P_{t,\text{in}}} \]

\( i = -46.5^\circ \)
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON EXIT SURVEYS
Effects of Reynolds Number and Pressure Ratio

$i = +29.1^\circ$

\[
\frac{Re}{Re_{des}} \quad M_{2,i}
\]

<table>
<thead>
<tr>
<th>$\frac{Re}{Re_{des}}$</th>
<th>$M_{2,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.75</td>
</tr>
<tr>
<td>1/2</td>
<td>0.75</td>
</tr>
<tr>
<td>1/4</td>
<td>0.61</td>
</tr>
<tr>
<td>1/4</td>
<td>0.34</td>
</tr>
<tr>
<td>1/8</td>
<td>0.34</td>
</tr>
</tbody>
</table>

\[
P_t = \frac{P_{t,1}}{\bar{P}_2}
\]

\[
C_{p_t} = \frac{P_t}{P_{t,1}}
\]

dashed = old exhaust
solid = new exhaust

PS
SS

\[
\beta [\text{deg}]
\]

-30
-40
-50
-60
-70

-2.0 -1.5 -1.0 -0.5 0.0 0.5

y/pitch

PS metal angle
avg metal angle
SS metal angle

design exit flow angle

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Effects of Reynolds Number and Pressure Ratio

\[ \frac{Re}{Re_{des}} M_{2,i} \]

\( i = +9.1^\circ \)

- **Cp_t**
  - dashed = old exhaust
  - solid = new exhaust

\[ \beta \text{ [deg]} \]

- PS metal angle
- avg metal angle
- design exit flow angle
- SS metal angle
Effects of Reynolds Number and Pressure Ratio

\[ i = -11.4^\circ \]

![Graph showing \( C_p \) and \( \beta \) for different Reynolds numbers and pressure ratios.](image)
Effects of Reynolds Number and Pressure Ratio

\[ i = -45.6^\circ \]

\[ C_p \]

\[ \frac{Re}{Re_{des}} \]

\[ M_{2,i} \]

\[ PS \]

\[ SS \]

\[ \beta [\text{deg}] \]

- PS metal angle
- avg metal angle
- design exit flow angle
- SS metal angle

Downstream Station 02 (x/Cx = 1.086)

\[ \beta_1 = -16.8^\circ (i = -46.5^\circ) \]
Effects of Inlet Flow Angle

Re_{cx,2}=683,000 (design)
M_2=0.74

Re_{cx,2}=85,000 (1/8 design)
M_2=0.35
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON BLADE LOADING
Blade Loadings

C_p = \frac{P - P_2}{P_{11} - P_2}

Re_{des}, M_2 = 0.74

Re_{1/4}, M_2 = 0.74

Re_{1/4}, M_2 = 0.35

Re_{1/8}, M_2 = 0.35

i = +29.1°

i = +9.1°

i = −11.4°

i = −46.5°
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON INTEGRATED LOSSES AND FLOW EXIT ANGLES
Loss Bucket

Loss Coefficient (Area-Averaged)

Incidence ($\beta - \beta_{design}$), Degrees

Re/Re_{des} M_{i2} Passage

- 1 0.74 4
- 1 0.74 5
- 1/2 0.74 4
- 1/2 0.74 5
- 1/4 0.74 4
- 1/4 0.74 5
- 1/4 0.35 4
- 1/4 0.35 5
- 1/8 0.35 4
- 1/8 0.35 5
Exit Flow Angle

- $\beta_2$ (mass-averaged)

- Incidence ($\beta_1 - \beta_{design}$), Degrees

- Average Exit Metal Angle

- Design Exit Flow Angle

- Re/Re\text{des} $M_{1,2}$ Passage

- 1 0.74 4
- 1 0.74 5
- 1/2 0.74 4
- 1/2 0.74 5
- 1/4 0.74 4
- 1/4 0.74 5
- 1/4 0.35 4
- 1/4 0.35 5
- 1/8 0.35 4
- 1/8 0.35 5

- Des Exit Flow Angle

- Avg Metal Angle
Loss as a Function of Zweifel Coefficient

\[ \omega \propto Z^2 \cdot Re^{-0.2} \]

<table>
<thead>
<tr>
<th>Re/Re_{des}</th>
<th>M_{k,2}</th>
<th>Passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.74</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>0.74</td>
<td>5</td>
</tr>
<tr>
<td>1/2</td>
<td>0.74</td>
<td>4</td>
</tr>
<tr>
<td>1/2</td>
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<td>5</td>
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<tr>
<td>1/4</td>
<td>0.74</td>
<td>5</td>
</tr>
<tr>
<td>1/4</td>
<td>0.35</td>
<td>4</td>
</tr>
<tr>
<td>1/4</td>
<td>0.35</td>
<td>5</td>
</tr>
<tr>
<td>1/8</td>
<td>0.35</td>
<td>4</td>
</tr>
<tr>
<td>1/8</td>
<td>0.35</td>
<td>5</td>
</tr>
</tbody>
</table>
Conclusions

- Successful modifications of the facility.
- Facility better suited for large incidence range measurements.
- Detailed exit total pressures, flow angles, and blade loading were documented over a wide range of incidence angles and flow conditions.
- Data show good repeatability, periodicity, and consistency with scaling laws.
- Loss levels decrease with negative incidence and increase with decreasing Reynolds number – narrower loss bucket at lower Reynolds number.
- Valuable and challenging data set for CFD Code Validation.
BACKUP SLIDES
3-D flow field measurements

\[ \text{Re}_{c_x,2} = 530 \text{ k}, \; M_2 = 0.72, \; \beta_1 = 40.0^\circ \text{ (N* 54\%, cruise)}, \; i = +5.8^\circ \]

\[ \text{Re}_{c_x,2} = 530 \text{ k}, \; M_2 = 0.67, \; \beta_1 = -2.5 \text{ (N* 100\%, takeoff)} \; i = -36.7^\circ \]