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

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**Large Civil Tilt-Rotor**

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

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 lb_m/s

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

Exhaust

i = 46.5°

i = ±29.1°

β1 = 38.8°

disk diameter 6 ft.
Facility Operating Envelope

isentropic exit Mach number, \( Ma_{2,i} \)

\[
\frac{P_t}{P_2} \quad \text{pressure ratio,}
\]

\[
E^3 Ma_{2,\text{des}} = 0.74 \Rightarrow 1/4
\]

\[
Ma_2 = 0.34 \Rightarrow 1/8
\]

\[
P_1 = 14.7 \text{ psia}
\]

\[
\text{maximum inlet pressure} = 23.0 \text{ psia}
\]

\[
\text{minimum exhaust pressure}
\]

\[
\text{maximum mass flow} \approx 58 \text{ lbm/s}
\]

\[
\text{Facility Operating Envelope}
\]

previous studies

EEE Tip Section Blade

current study

isentropic exit unit Reynolds number, \( Re_{2,i} \times 10^{-6} \) [1/ft]
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

New Support Bars

New Exhaust Section

CW-22 Before Modifications

CW-22 After Modifications
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

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**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>

**Inlet Flow Angles**

<table>
<thead>
<tr>
<th>Inlet Angle $\beta_1$</th>
<th>Incidence Angle $\beta_{\text{B1-des}}$</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>

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**CW-22 Probe Slots with E³ Blades**

- $C_e = 5.119''$
- pitch = 5.119''
- $\beta_1 = 29.7^\circ$ (design inlet angle)
- $\beta_2 = -64.4^\circ$ (design exit angle)
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

New Exhaust Configuration
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.
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON EXIT SURVEYS
Effects of Reynolds Number and Pressure Ratio

\[ i = +29.1^\circ \]

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

**dashed** = old exhaust

**solid** = new exhaust

<table>
<thead>
<tr>
<th>( \frac{\text{Re}}{\text{Re}_{\text{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>

\( \beta \) [deg]

*PS* metal angle

*design exit flow angle*

*avg metal angle*

*SS* metal angle
Effects of Reynolds Number and Pressure Ratio

\( i = +9.1^\circ \)

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

- Solid = new exhaust
- Dashed = old exhaust

\[C_p \]

\[\beta \] [deg]

- PS metal angle
- SS metal angle
- Avg metal angle
- Design exit flow angle

\(-70\) \(-65\) \(-60\) \(-55\) \(-50\)

-2.0 \(-1.5\) \(-1.0\) \(-0.5\) 0.0 0.5

y/pitch

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

-0.0 0.75

1/2 0.75

1/4 0.75

1/4 0.34

1/8 0.34

Downstream Station 02 (\(x/C_x = 1.086\))

\(\beta_1 = 38.8^\circ (i=+9.1^\circ)\) midspan 3-hole probe measurements

\(M_{2,i}\)
Effects of Reynolds Number and Pressure Ratio

\[ i = -11.4^\circ \]

**Cp_t**

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

1.0 0.74
1/2 0.74
1/4 0.74
1/4 0.33
1/8 0.33

**β [deg]**

- PS metal angle
- Avg metal angle
- Design exit flow angle
- SS metal angle
Effects of Reynolds Number and Pressure Ratio

\[ i = -45.6^\circ \]
Effects of Inlet Flow Angle

\[ \text{Re}_{cx,2} = 683,000 \text{ (design)} \]
\[ M_2 = 0.74 \]

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

\[ C_{p_s} = \frac{P - P_2}{P_{1l} - P_2} \]

\( \text{Re}_{\text{des}}, M_2 = 0.74 \)

\( \text{Re}_{1/4}, M_2 = 0.74 \)

\( \text{Re}_{1/4}, M_2 = 0.35 \)

\( \text{Re}_{1/8}, M_2 = 0.35 \)

\( i = +29.1^\circ \)

\( i = +9.1^\circ \)

\( i = -11.4^\circ \)

\( i = -46.5^\circ \)
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON INTEGRATED LOSSES AND FLOW EXIT ANGLES
Loss Bucket

Loss Coefficient (Area-Averaged)

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

Re/Re$_{\text{des}}$ M$_{\text{i,2}}$ 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
Exit Flow Angle

\[ \beta_2 (\text{mass-averaged}) \]

\[ \text{Incidence } (\beta_1 - \beta_{\text{design}}), \text{ Degrees} \]

\[ \text{Average Exit Metal Angle} \]

\[ \text{Design Exit Flow Angle} \]

\[ \text{Re/Re_{des}} \quad M_{1,2} \quad \text{Passage} \]

- 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

\[ \text{Des Exit Flow Angle} \]

\[ \text{Avg Metal Angle} \]
Loss as a Function of Zweifel Coefficient

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

- Notation:
  - \( \omega \) is the loss coefficient.
  - \( Z_{w} \) is the Zweifel coefficient.
  - \( Re \) is the Reynolds number.

The graph shows the relationship between the loss coefficient and the Zweifel coefficient for different values of \( Re/Re_{des} \) and \( M_{x,2} \). The data points correspond to specific values of \( Re/Re_{des} \) and \( M_{x,2} \), as indicated in the legend:

- \( Re/Re_{des} \): 1, 1/2, 1/4, 1/8
- \( M_{x,2} \): 0.74, 0.35
- Passage: 4, 5

Each point on the graph represents a combination of these values, illustrating how the loss coefficient changes with respect to the Zweifel coefficient and Reynolds number.
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

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

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