AERODYNAMIC EFFECTS OF TURBULENCE INTENSITY ON A VARIABLE-SPEED POWER-TURBINE BLADE WITH LARGE INCIDENCE AND REYNOLDS NUMBER VARIATIONS

2014 Turbine Engine Technology Symposium
Dayton, OH
September 10, 2014

Ashlie B. Flegel, NASA Glenn Research Center
Paul W. Giel, Vantage Partners, LLC
Gerard E. Welch, NASA Glenn Research Center
**Motivation for VSPT Technology**

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

\[ \approx 10 \text{ pts. in } \eta_{\text{prop}} \]

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

**VSPT Challenges**
- Efficiency at high cruise work factor
  - \( \Delta h_0 = D(u_q \cdot U) \approx \text{const. at cruise and takeoff} \)
  - \( \Delta h_0 / U^2 \) cruise is 3.5 x takeoff
- 40\(^0\) to 60\(^0\) incidence angle variations in all blade row (and EGV) with 50\% speed change
- Operation at low \( Re \) – transitional flow
  - 28 to 30 k-ft cruise leads to 60 k < \( Re_{cx,2} < 100 k \)
  - Transitional flow

**Large Civil Tilt-Rotor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</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>

Smith chart

VSPT Approach and Objectives

- Document blade performance over wide incidence angle range, a wide Reynolds number range, and at mission-relevant Mach numbers.
  - Initial test conducted at low inlet turbulence in order to admit transitional flow on the blade surface.
  - Expand the dataset to include LPT-relevant turbulence levels and complement the existing dataset.

Blade Details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stagger angle</td>
<td>20.4°</td>
</tr>
<tr>
<td>Uncovered turning</td>
<td>19.5°</td>
</tr>
<tr>
<td>Zweifel coefficient, $Z_{w_{des}}$</td>
<td>1.06</td>
</tr>
<tr>
<td>Solidity, $\Phi$</td>
<td>1.39</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Design Intent Blade Loading and Exp. Data at $i = +5.8^\circ$

\[
C_{p_x} = \frac{(P - P_2)}{(P_{t,1} - P_2)}
\]
Transonic Turbine Blade Cascade Facility

Exhaust Pressure:
Min $P \approx 2$ psia
Max = inlet $P$

Supply Pressure = 40 psig

Max Plenum $P = 14.7$ psia
Max Mass Flow $\approx 58$ lbm/s

Disk Diameter 6 ft.

Facility Inlet Angle Range: $-17^\circ \leq \beta_1 \leq +78.8^\circ$

Blade
Span: 6.000 inches
Pitch: 5.119 inches
Chord: 7.109 inches
Facility Operating Envelope

Nominal Test Conditions

<table>
<thead>
<tr>
<th>$Re_{inlet}$</th>
<th>PR</th>
<th>$M_{2, is}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.12 x 10^6</td>
<td>1.412</td>
<td>0.72</td>
</tr>
<tr>
<td>1.06 x 10^6</td>
<td>1.412</td>
<td>0.72</td>
</tr>
<tr>
<td>5.30 x 10^5</td>
<td>1.412</td>
<td>0.72</td>
</tr>
<tr>
<td>(Baseline)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.30 x 10^5</td>
<td>1.087</td>
<td>0.35</td>
</tr>
<tr>
<td>(Baseline)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.12 x 10^5</td>
<td>1.087</td>
<td>0.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isentropic exit Mach number, $Ma_{2,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isentropic exit unit Reynolds number, $Re_{2,i} \times 10^{-6}$ [1/ft]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
<tr>
<td>7.0</td>
</tr>
<tr>
<td>5.0</td>
</tr>
<tr>
<td>4.0</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>1.3</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.1</td>
</tr>
<tr>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isentropic exit Mach number, $Ma_{2,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ma_{2,i,des} = 0.72$</td>
</tr>
<tr>
<td>$Ma_{2,i} = 0.35$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure Ratio, $P_{t,1}/P_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>1.3</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.1</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.7</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.1</td>
</tr>
</tbody>
</table>

| minimum exhaust pressure $\approx 13.8$ kPa (2.0 psia) |
| max mass flow $\approx 26$ kg/s (58 lbm/s) |
| maximum inlet pressure $= 159$ kPa (23.0 psia) |
| $p_t = 14.7$ psia |

previous studies

current study
Test Configuration

- VSPT midspan section blade, $\beta_{1,\text{des}} = 34.2^\circ$
- Ten incidence angles tested: $+15.8^\circ$ to $-51.0^\circ$
- 5 flow conditions each

<table>
<thead>
<tr>
<th>Inlet Turbulence Intensity</th>
<th>Low Tu</th>
<th>High Tu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.24% - 0.40%</td>
<td>8% - 15%</td>
</tr>
</tbody>
</table>

| B-L Thickness [portion of half-span] | 39% - 56% | 19% - 29% |

<table>
<thead>
<tr>
<th>Inlet Flow Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inlet Angle</strong>, $\beta_i$</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>50.0°</td>
</tr>
<tr>
<td>45.0°</td>
</tr>
<tr>
<td><strong>40.0° (Cruise)</strong></td>
</tr>
<tr>
<td>34.2°</td>
</tr>
<tr>
<td>28.0°</td>
</tr>
<tr>
<td>18.1°</td>
</tr>
<tr>
<td>8.2°</td>
</tr>
<tr>
<td><strong>$-2.5^\circ$ (Takeoff)</strong></td>
</tr>
<tr>
<td>$-11.8^\circ$ (Mission Max-$i$)</td>
</tr>
<tr>
<td>$-16.8^\circ$</td>
</tr>
</tbody>
</table>
Measurements

- Total pressure and exit flow angles measured 7% $C_x$ downstream of trailing edge
- Blade and endwall static pressure measurements
- 12 exit static taps located 3 axial chords downstream
- Inlet $P_t$, $P_s$, and $T_t$ measured at Station 0.
- Inlet boundary layer and turbulence documented.
3-D FLOWFIELD RESULTS
Total Pressure Coefficient Contours and Secondary Flow Vectors

Low $Tu$

High $Tu$

$i = +5.8^\circ$
(Cruise)
$Re_{Cx,2} = Re_b$
$M_{2,i} = 0.72$

$i = -36.7^\circ$
(Takeoff)
$Re_{Cx,2} = Re_b$
$M_{2,i} = 0.67$
Pitchwise Integrated Data

(b) \( CP_t \) (Area Averaged)

\[ i = +5.8^\circ \] (Cruise)

(c) \( \beta \) [deg] (Mass Averaged)

(d) \( \gamma \) [deg] (Mass Averaged)

\[ i = -36.7^\circ \] (Takeoff)

(e) \( \beta \) [deg] (Mass Averaged)

(f) \( \gamma \) [deg] (Mass Averaged)
EFFECT OF INCIDENCE AND TURBULENCE ON BLADE LOADING
Blade Loading – Effects of Incidence at High $Tu$

\[ Cp_s = \frac{P - P_2}{P_{t,1} - P_2} \]

- $i = +15.8^\circ$
- $i = 0.0^\circ$
- $i = -16.1^\circ$
- $i = -36.7^\circ$
- $i = -51.0^\circ$

all data at $Re_{Cx,2} = Re_b$ and nominal design exit Mach number
Blade Loading – Indicators of Separation

**Low $Tu$**

- $i = +5.8^\circ$
- $Re = 1 \cdot Re_b$
- $M_2 = 0.72$

- $i = -51.0^\circ$
- $Re = 1 \cdot Re_b$
- $M_2 = 0.72$

**High $Tu$**

- $i = +5.8^\circ$
- $Re = 0.4 \cdot Re_b$
- $M_2 = 0.35$

- $i = -51.0^\circ$
- $Re = 0.4 \cdot Re_b$
- $M_2 = 0.35$
EFFECTS OF REYNOLDS NUMBER AND EXIT MACH NUMBER ON MIDSPAN EXIT SURVEYS
Effects of Reynolds Number and Mach Number at $i = +10.8^\circ$
Effects of Reynolds Number and Mach Number at $i = 0.0^\circ$

\[ C_{p_t} = \frac{P_{t,l} - P_t}{P_{t,l} - P_2} \]

Low Tu

High Tu

\[ C_{p_t} = \frac{P_{t,l} - P_t}{P_{t,l} - P_2} \]
Effects of Reynolds Number and Mach Number at $i = -36.7^\circ$
Effects of Reynolds Number and Mach Number at $i = -51.0^\circ$

$$C_{p_t} = \frac{P_{t,1} - P_t}{P_{t,1} - P_2}$$

**Low $Tu$**

**High $Tu$**

$$Re_{C_{x,2}} \quad Ma_{2,i}$$

- $4.0\cdot Re_b \quad 0.72$
- $2.0\cdot Re_b \quad 0.72$
- $1.0\cdot Re_b \quad 0.62$
- $1.0\cdot Re_b \quad 0.35$
- $0.4\cdot Re_b \quad 0.35$
E **ffects of Inlet Flow Angle**

\[
Re_{C_x,2} = 2.12 \times 10^6 (4 \cdot Re_b); \quad M_2 = 0.72
\]

\[
Re_{C_x,2} = 2.12 \times 10^5 (0.4 \cdot Re_b); \quad M_2 = 0.35
\]
Effects of Inlet Flow Angle

Low Tu

High Tu

Low Tu

High Tu
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON MIDSPAN LOSS
Midspan Loss Bucket

Low $Tu$

High $Tu$

\[ \omega = \frac{(P_{t,1} - P_{t,2})}{(P_{t,1} - P_2)} \]

\( i, \) Incidence [deg]

\( Re_{C_{x,2}} \)

\( Re_b \)

\( M_{2,i} \) passage

\( \omega \) (Area Averaged)
Midspan Loss Scaling

**Low Tu**
*Re*\(^{-0.5}\) Scaled Loss Bucket

**High Tu**
*Re*\(^{-0.1}\) Scaled Loss Bucket

![Graph showing midspan loss scaling for low and high Tu conditions.](chart.png)
Ainley-Mathieson Midspan Loss Scaling

Low $Tu$

High $Tu$

\[
\frac{Re_{C_{x,2}}}{Re_b} \quad M_{2,i} \text{ passage}
\]

- Low $Tu$
  - $Re_{C_{x,2}}/Re_b = 4.0, 0.72, 4$
  - $Re_{C_{x,2}}/Re_b = 4.0, 0.72, 5$
  - $Re_{C_{x,2}}/Re_b = 2.0, 0.72, 4$
  - $Re_{C_{x,2}}/Re_b = 2.0, 0.72, 5$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.72, 4$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.72, 5$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.35, 4$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.35, 5$
  - $Re_{C_{x,2}}/Re_b = 0.4, 0.35, 4$
  - $Re_{C_{x,2}}/Re_b = 0.4, 0.35, 5$

- High $Tu$
  - $Re_{C_{x,2}}/Re_b = 4.0, 0.72, 4$
  - $Re_{C_{x,2}}/Re_b = 4.0, 0.72, 5$
  - $Re_{C_{x,2}}/Re_b = 2.0, 0.72, 4$
  - $Re_{C_{x,2}}/Re_b = 2.0, 0.72, 5$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.72, 4$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.72, 5$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.35, 4$
  - $Re_{C_{x,2}}/Re_b = 1.0, 0.35, 5$
  - $Re_{C_{x,2}}/Re_b = 0.4, 0.35, 4$
  - $Re_{C_{x,2}}/Re_b = 0.4, 0.35, 5$
Ainley-Mathieson Midspan Loss Scaling at High $Tu$

\[
\frac{Re_{C_{x,2}}}{Re_b} \frac{M_{2,i}}{passage}
\]

- $4.0 \ 0.72 \ 4$
- $4.0 \ 0.72 \ 5$
- $2.0 \ 0.72 \ 4$
- $2.0 \ 0.72 \ 5$
- $1.0 \ 0.72 \ 4$
- $1.0 \ 0.72 \ 5$
- $1.0 \ 0.35 \ 4$
- $1.0 \ 0.35 \ 5$
- $0.4 \ 0.35 \ 4$
- $0.4 \ 0.35 \ 5$

\[\omega / \omega_{i=opt} \]

\[\frac{(i - i_{opp})}{(i_s - i_{opp})} \]

Ainley-Mathieson correlation
Conclusions

- Well documented dataset that spans a large incidence range at engine relevant transonic flow conditions at two different turbulence conditions.

  - Low $Tu$ test admits suction side transitional flow within wide Reynolds number range tested.
    - Transitional flow makes this a valuable and challenging data set for CFD code validation and turbine designers.

- The turbulence grid effectively reduced the inlet boundary layer thickness by half, leading to less aerodynamic blockage in the test section.

- For the high $Tu$ test, the flow remains largely attached over all the flow and incidence conditions.
Acknowledgement

The authors would like to acknowledge the contributions of Dr. Steven G. Gegg of Rolls-Royce North American Technologies.

It was our great honor to have worked with him.
Exit Flow Angles

Low $Tu$

$i = +10.8^\circ$

High $Tu$

$i = -16.1^\circ$

$i = -51.0^\circ$
Average Exit Flow Angle

\[ \Delta \beta_2 = \beta_2 + 55.54^\circ \]