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

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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**
- 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° to 60° 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

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**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>

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*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.

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

Blade Details
- Stagger angle: 20.4°
- Uncovered turning: 19.5°
- Zweifel coefficient, $Zw_{des}$: 1.06
- Solidity, $\Phi$: 1.39
- Aspect Ratio: 0.84
Transonic Turbine Blade Cascade Facility

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

Supply Pressure $= 40$ psig

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

Blade
Span: 6.000 inches
Pitch: 5.119 inches
Chord: 7.109 inches

Disk Diameter
6 ft.

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

Nominal Test Conditions

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

- Isentropic exit unit Reynolds number, $Re_{2,i} \times 10^{-6}$ [1/ft]
- Isentropic exit Mach number, $Ma_{2,i}$
- Pressure Ratio, $P_{t,1}/P_2$

Previous studies and current study:
- Minimum exhaust pressure: ≈13.8 kPa (2.0 psia)
- Maximum mass flow: ≈26 kg/s (58 lbm/s)
- Maximum inlet pressure: 159 kPa (23.0 psia)
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>
<tr>
<td>B-L Thickness [portion of half-span]</td>
<td>39% - 56%</td>
<td>19% - 29%</td>
</tr>
</tbody>
</table>

**Inlet Flow Angles**

<table>
<thead>
<tr>
<th>Inlet Angle, $\beta_i$</th>
<th>Incidence Angle, $i$</th>
<th>$Zw$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0°</td>
<td>15.8°</td>
<td>1.22</td>
</tr>
<tr>
<td>45.0°</td>
<td>10.8°</td>
<td>1.13</td>
</tr>
<tr>
<td><strong>40.0° (Cruise)</strong></td>
<td><strong>5.8°</strong></td>
<td><strong>1.06</strong></td>
</tr>
<tr>
<td>34.2°</td>
<td>0.0°</td>
<td>0.99</td>
</tr>
<tr>
<td>28.0°</td>
<td>-6.2°</td>
<td>0.92</td>
</tr>
<tr>
<td>18.1°</td>
<td>-16.1°</td>
<td>0.82</td>
</tr>
<tr>
<td>8.2°</td>
<td>-26.0°</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>-2.5° (Takeoff)</strong></td>
<td><strong>-36.7°</strong></td>
<td><strong>0.65</strong></td>
</tr>
<tr>
<td>-11.8° (Mission Max-$i$)</td>
<td>-46.0°</td>
<td>0.58</td>
</tr>
<tr>
<td>-16.8°</td>
<td>-51.0°</td>
<td>0.53</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.
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

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

\( i = -36.7^\circ \) (Takeoff)
EFFECT OF INCIDENCE AND TURBULENCE ON BLADE LOADING
Blade Loading – Effects of Incidence at High $Tu$

$$C_p = \frac{P - P_2}{P_{t,1} - P_2}$$

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

**Low $Tu$**

$i = +5.8^\circ$

$Re = 1 \cdot Re_b$

$M_2 = 0.72$

$C_{ps}$

$i = -51.0^\circ$

$Re = 1 \cdot Re_b$

$M_2 = 0.72$

$C_{ps}$

Low $Tu$

**High $Tu$**

$i = +5.8^\circ$

$Re = 0.4 \cdot Re_b$

$M_2 = 0.35$

$C_{ps}$

$i = -51.0^\circ$

$Re = 0.4 \cdot Re_b$

$M_2 = 0.35$

$C_{ps}$
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 $i = 0.0^\circ$
Effects of Reynolds Number and Mach Number at $i = -36.7^\circ$

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

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

Low $Tu$

High $Tu$
Effects of Reynolds Number and Mach Number at $i = -51.0^\circ$
Effects of Inlet Flow Angle

\[ Re_{C_2} = 2.12 \times 10^6 \ (4 \cdot Re_b); \]
\[ M_2 = 0.72 \]

\[ Re_{C_2} = 2.12 \times 10^5 \ (0.4 \cdot Re_b); \]
\[ M_2 = 0.35 \]
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**

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

**High Tu**

![Graph showing the relationship between incidence and area-averaged loss for Low Tu and High Tu cases.]

- **Low Tu**
  - Symbols: ●, ○, ▼, ▲
  - Values: (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)

- **High Tu**
  - Symbols: ●, ○, ▼, ▲
  - Values: (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)
Midspan Loss Scaling

Low $Tu$
$Re^{-0.5}$ Scaled Loss Bucket

High $Tu$
$Re^{-0.1}$ Scaled Loss Bucket
Ainley-Mathiesion Midspan Loss Scaling

**Low Tu**

<table>
<thead>
<tr>
<th>$\frac{Re_{C_{x,2}}}{Re_b}$</th>
<th>$M_{2,i}$ passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>4</td>
</tr>
<tr>
<td>4.0</td>
<td>5</td>
</tr>
<tr>
<td>2.0</td>
<td>4</td>
</tr>
<tr>
<td>2.0</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>5</td>
</tr>
<tr>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>0.4</td>
<td>5</td>
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**High Tu**

<table>
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<tr>
<th>$\frac{Re_{C_{x,2}}}{Re_b}$</th>
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<tr>
<td>4.0</td>
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</tr>
<tr>
<td>2.0</td>
<td>4</td>
</tr>
<tr>
<td>2.0</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>5</td>
</tr>
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<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>0.4</td>
<td>5</td>
</tr>
</tbody>
</table>
Ainley-Mathieson Midspan Loss Scaling at High $Tu$

The graph shows the relationship between $\omega / \theta_{i=iopt}$ and $(i - i_{opp}) / (i_s - i_{opp})$ for different values of $Re_{Cx,2} / Re_{b}$ and $M_{2,i}$ passage.

The Ainley-Mathieson correlation is represented by the red dashed line, and the data points are differentiated by different symbols and colors, indicating various values of $Re_{b}$ and $M_{2,i}$ passage.
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

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