Complementary Aerodynamic Performance Datasets for Variable Speed Power Turbine Blade Section from Two Independent Transonic Turbine Cascades

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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
  \[ \Delta h_0 = \Delta (u_q \cdot U) \approx \text{const. at cruise and takeoff} \]
  \[ \Delta h_0/U^2 \text{ cruise is } 3.5 \times \text{takeoff} \]
- 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

Large Civil Tilt-Rotor
<table>
<thead>
<tr>
<th>TOGW</th>
<th>108k lbm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>90 PAX</td>
</tr>
<tr>
<td>Engines</td>
<td>4 × 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>

VSPT Approach and Objectives

- Document blade performance over wide incidence angle range, a wide Reynolds number range, and at mission-relevant Mach numbers.
  - NASA’s initial test conducted at low inlet turbulence in order to admit transitional flow.
  - NASA subsequently repeated tests at higher, engine-relevant inlet $Tu$ (8%-15%).
- UND facility smaller scale, able to achieve lower Reynolds numbers.
- UND also measured blade surface heat transfer for transition locations.

### Blade Details
- Stagger angle: $20.4^\circ$
- Uncovered turning: $19.5^\circ$
- Zweifel coefficient, $Zw_{des}$: 1.06
- Solidity, $C_x / Pitch$: 1.39
**NASA Facility Operating Envelope**

### Inlet Angle, $\beta_i$

<table>
<thead>
<tr>
<th>Angle</th>
<th>$i$</th>
<th>$Zw$</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0°</td>
<td>15.8°</td>
<td>1.22</td>
<td>NASA</td>
</tr>
<tr>
<td>45.0°</td>
<td>10.8°</td>
<td>1.13</td>
<td>NASA</td>
</tr>
<tr>
<td>40.0°</td>
<td>5.8°</td>
<td>1.06</td>
<td>both</td>
</tr>
<tr>
<td>34.2°</td>
<td>0.0°</td>
<td>0.99</td>
<td>both</td>
</tr>
<tr>
<td>28.0°</td>
<td>−6.2°</td>
<td>0.92</td>
<td>both</td>
</tr>
<tr>
<td>18.1°</td>
<td>−16.1°</td>
<td>0.82</td>
<td>both</td>
</tr>
<tr>
<td>8.2°</td>
<td>−26.0°</td>
<td>0.74</td>
<td>both</td>
</tr>
<tr>
<td>−2.5°</td>
<td>−36.7°</td>
<td>0.65</td>
<td>both</td>
</tr>
<tr>
<td>−11.8°</td>
<td>−46.0°</td>
<td>0.58</td>
<td>both</td>
</tr>
<tr>
<td>−16.8°</td>
<td>−51.0°</td>
<td>0.53</td>
<td>both</td>
</tr>
</tbody>
</table>

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National Aeronautics and Space Administration
Experimental Facilities

**NASA Transonic Turbine Blade Cascade**

**Flow Parameters**

<table>
<thead>
<tr>
<th>Exit $Re_{Cx}$</th>
<th>Exit $Ma_{ls}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.12 \times 10^6$ (4.0•$Re_b$)</td>
<td>0.72</td>
</tr>
<tr>
<td>$1.06 \times 10^6$ (2.0•$Re_b$)</td>
<td>0.72</td>
</tr>
<tr>
<td>$5.30 \times 10^5$ (1.0•$Re_b$)</td>
<td>0.72</td>
</tr>
<tr>
<td>$5.30 \times 10^5$ (1.0•$Re_b$)</td>
<td>0.35</td>
</tr>
<tr>
<td>$2.12 \times 10^5$ (0.4•$Re_b$)</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**UND Compressible Flow Facility**

**Flow Parameters**

<table>
<thead>
<tr>
<th>Exit $Re_{Cx}$</th>
<th>Exit $Ma_{ls}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5.27 \times 10^5$ (1.00•$Re_b$)</td>
<td>0.72</td>
</tr>
<tr>
<td>$2.12 \times 10^5$ (0.40•$Re_b$)</td>
<td>0.72</td>
</tr>
<tr>
<td>$6.12 \times 10^4$ (0.12•$Re_b$)</td>
<td>0.72</td>
</tr>
<tr>
<td>$4.64 \times 10^4$ (0.09•$Re_b$)</td>
<td>0.72</td>
</tr>
<tr>
<td>$5.27 \times 10^5$ (1.00•$Re_b$)</td>
<td>0.35</td>
</tr>
<tr>
<td>$2.12 \times 10^5$ (0.40•$Re_b$)</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Test Configurations

**NASA**

- $C_x = 7.109\,^\circ$
- $\delta_1$
- $span = 6.000\,''$

**UND**

- Pressure Surface
- Bleed Blocks
- Streamlines $\beta = 40°$
- $\beta = -17°$
- Exit Survey Plane
- Tailboard
- Exit $P_s$
- Inlet $P_s$
- Suction Surface
- Bleed Blocks

Diagram:
- Sta. 0
- Sta. 2
- Passage 3
- Passage 4
- Passage 5
- Passage 6
- $y/pitch$
- $x/C_x = 0.415$
- $x/C_x = 1.070$
# Blade and Inlet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NASA Value</th>
<th>UND Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Chord, $C_x$ [inch]</td>
<td>7.109</td>
<td>2.673</td>
</tr>
<tr>
<td>True Chord [inch]</td>
<td>7.655</td>
<td>2.878</td>
</tr>
<tr>
<td>Pitch, $S$ [inch]</td>
<td>5.119</td>
<td>1.925</td>
</tr>
<tr>
<td>Span, $H$ [inch]</td>
<td>6.000</td>
<td>2.000</td>
</tr>
<tr>
<td>Solidity, $C_x/S$</td>
<td>1.389</td>
<td>1.388</td>
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<tr>
<td>Aspect Ratio, $H/C_x$</td>
<td>0.844</td>
<td>0.748</td>
</tr>
<tr>
<td>Throat Dimension [inch]</td>
<td>2.868</td>
<td>1.062</td>
</tr>
<tr>
<td>Stagger Angle [deg.]</td>
<td>20.35°</td>
<td>20.35°</td>
</tr>
<tr>
<td>Inlet Metal Angle [deg.]</td>
<td>34.2°</td>
<td>34.2°</td>
</tr>
<tr>
<td>Uncovered Turning deg.</td>
<td>19.47°</td>
<td>19.47°</td>
</tr>
<tr>
<td>Exit Metal Angle [deg.]</td>
<td>$-55.54°$</td>
<td>$-55.54°$</td>
</tr>
</tbody>
</table>

### Inlet Flow Parameters

<table>
<thead>
<tr>
<th></th>
<th>NASA</th>
<th>UND</th>
<th>Inlet $Tu$</th>
<th>$\delta$ (span/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>low $Tu$</td>
<td>0.24% - 0.40%</td>
<td>39% - 56%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>high $Tu$</td>
<td>8% - 15%</td>
<td>19% - 29%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>NASA</th>
<th>UND</th>
<th>Inlet $Tu$</th>
<th>$\delta$ (span/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>low $Tu$</td>
<td>0.32% - 0.42%</td>
<td>3% - 10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>high $Tu$</td>
<td>3.4% - 4.5%</td>
<td>7% - 11%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: NASA inlet boundary thickness estimated from inlet Reynolds number scaling. UND inlet boundary layer thickness estimated from power-law assumption from $\theta$ measurements.
BLADE LOADING MEASUREMENTS
\[ C_{P_s} = \frac{P - \bar{P}_2}{P_{t,1} - \bar{P}_2} \]

\[ Re_{C_{x,2}} = 0.4 \times Re_b \]

\[ Ma_{2,i} = 0.72 \]

Low \( Tu \)

High \( Tu \)

\[ \beta_1 = 40.0^\circ \]

\[ i = +5.8^\circ \]

(Cruise)
Blade Loading – Highest Negative Incidence

\( \beta_1 = -16.8^\circ \)

\( i = -51.0^\circ \)

\( \alpha \)

\( \delta \)

\( C_{p_s} = \frac{P - P_2}{P_{t,1} - P_2} \)

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

\( 4.0 \times Re_b \) \( 0.72 \)

\( 2.0 \times Re_b \) \( 0.72 \)

\( 1.0 \times Re_b \) \( 0.72 \)

\( 1.0 \times Re_b \) \( 0.35 \)

\( 0.4 \times Re_b \) \( 0.35 \)

\( x / C_x \) \( x / C_x \)
Blade Loading – Effects of Negative Incidence

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

\[ Re_{C_x,2} = 4.0 \times Re_b \]
\[ Ma_{2,i} = 0.72 \]

Low Tu

\[ Re_{C_x,2} = 0.4 \times Re_b \]
\[ Ma_{2,i} = 0.35 \]

High Tu

Facility Match Point

Determination of PS cove separation

\[ i = -51.0^\circ \]

\[ \beta_1 = -16.8^\circ \]

\[ i = -51.0^\circ \]
HALF-SPAN FLOWFIELD RESULTS
Total Pressure Coefficient Contours and Secondary Flow Vectors

**NASA**

$Re_b; \ M_{2,i} = 0.72; \ low \ Tu$

$Re_{C_{x,s}} = 0.09 \cdot Re_b; \ M_{2,i} = 0.72; \ high \ Tu$

$i = -36.7^\circ$

(Takeoff)

$i = +5.8^\circ$

(Cruise)

$C_p_t, \ \Omega = \frac{P_{t,1} - P_t}{P_{t,1} - P_2}$

**UND**

$i = -36.7^\circ$

(Takeoff)

$i = +5.8^\circ$

(Cruise)
Pitchwise Integrated Data, $i = +5.8^\circ$ (Cruise)

(a) $C_p$ (Area Averaged)

(b) $C_p$ (Area Averaged)

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

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

$Re_{Cx,2}$ $M_{2,i}$

- 527,000 0.72
- 212,000 0.72
- 61,250 0.72
- 46,400 0.72
- 212,000 0.35

Und.
MIDSPAN HEAT TRANSFER MEASUREMENTS
Midspan Stanton Number Distributions

influence of Reynolds number at high Tu

\[ i = +5.8° \text{ (Cruise)} \]

\[ i = -36.8° \text{ (Takeoff)} \]

Influence of Reynolds number at high Tu:

- **Laminar Flow**
- **Transitional Flow**

**PS** and **SS**

- Inflection indicates laminar separation.
- Slope reversal indicates transition start.

Separation and downstream reattachment.
MIDSPAN EXIT SURVEYS
Effects of Reynolds Number and Mach Number at $i = +5.8^\circ$

**Low $Tu$**

- $0.09\cdot Re_b$ with $Ma_{2,i} = 0.72$
- $0.12\cdot Re_b$ with $Ma_{2,i} = 0.72$
- $0.40\cdot Re_b$ with $Ma_{2,i} = 0.72$
- $1.00\cdot Re_b$ with $Ma_{2,i} = 0.72$

**High $Tu$**

- $0.09\cdot Re_b$ with $Ma_{2,i} = 0.72$
- $0.12\cdot Re_b$ with $Ma_{2,i} = 0.72$
- $0.40\cdot Re_b$ with $Ma_{2,i} = 0.72$
- $1.00\cdot Re_b$ with $Ma_{2,i} = 0.72$

**UND**
Effects of Reynolds Number and Mach Number at $i = -51.0^\circ$

**Low $Tu$**

**High $Tu$**

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

- $Re_{Cx,2}$
- $Ma_{2,i}$

<table>
<thead>
<tr>
<th>$Re_{b}$</th>
<th>$Ma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>0.72</td>
</tr>
<tr>
<td>2.0</td>
<td>0.72</td>
</tr>
<tr>
<td>1.0</td>
<td>0.62</td>
</tr>
<tr>
<td>1.0</td>
<td>0.35</td>
</tr>
<tr>
<td>0.4</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**NASA**
Effects of Reynolds Number at $Ma_{2,i} = 0.72$, $i = -51.0^\circ$

UND

$Re_{Cx,2}$

- $0.09 \cdot Re_b$
- $0.12 \cdot Re_b$
- $0.40 \cdot Re_b$
- $1.00 \cdot Re_b$

High $Tu$

$\beta_1 = -16.8^\circ$

$i = -51.0^\circ$
Effects of Inlet Flow Angle

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

\[ Re_{C_x,2} = 5.30 \times 10^5 \ (1.0 \cdot Re_b) \; ; \quad M_2 = 0.72 \; ; \quad \text{Low Tu} \]
Effects of Inlet Flow Angle

$Re_{C_{x,2}} = 4.64 \times 10^4 (0.09 \cdot Re_b)$; \quad $M_2 = 0.72; \quad$ High $Tu$
LOSS BUCKETS
Half-Span Average Loss Buckets

Low $Tu$

High $Tu$

Facility $Re/Re_b$ $M_{2,i}$

$\triangle$ UND 0.09 0.72

$\triangle$ UND 0.12 0.72

$\triangle$ UND 0.40 0.72

$\triangle$ UND 1.00 0.72

$\bigcirc$ NASA 1.00 0.72

$\bigcirc$ NASA 0.40 0.35

$\Omega$, $C_p t$

incidence, $i$ [deg]
Midspan Loss Buckets

Low $Tu$

High $Tu$

Facility $Re/Re_b$ $M_{2,i}$

NASA: solid = passage 4
open = passage 5
Summary

• Complementary facilities provided data over a wider range of flow conditions:
  – NASA’s larger scale provided higher Reynolds number data;
  – UND’s smaller scale provided lower Reynolds number data and match points.

• Data highlighted the effects of:
  – Reynolds number;
  – Exit Mach number;
  – Inlet turbulence levels;
  – Wide incidence range;
  – Relative inlet boundary layer thickness;

• On the following:
  – Blade loading;
  – Wake profiles;
  – Blade row loss levels;
  – Blade row turning levels;
  – Blade surface boundary layer state;
  – Exit flow field characteristics.
Midspan Loss Buckets

**Low $Tu$**

**High $Tu$**

\[ \text{Facility } Re/Re_b, M_{2,i} \]

- **Low $Tu$**
  - UND: 0.09, 0.72
  - UND: 0.12, 0.72
  - UND: 0.40, 0.72
  - UND: 1.00, 0.72
  - NASA: 4.00, 0.72
  - NASA: 2.00, 0.72
  - NASA: 1.00, 0.72
  - NASA: 1.00, 0.35
  - NASA: 0.40, 0.35

- **High $Tu$**
  - UND: 0.09, 0.72
  - UND: 0.12, 0.72
  - UND: 0.40, 0.72
  - UND: 1.00, 0.72
  - NASA: 4.00, 0.72
  - NASA: 2.00, 0.72
  - NASA: 1.00, 0.72
  - NASA: 1.00, 0.35
  - NASA: 0.40, 0.35

*NASA: solid = passage 4, open = passage 5*
Midspan Loss Scaling

Low $Tu$

$Re^{-0.5}$ Scaled Loss Bucket

<table>
<thead>
<tr>
<th>$Re_{C_x,2}$</th>
<th>$Re_b$</th>
<th>$M_{2,j}$ passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>0.72</td>
<td>4</td>
</tr>
<tr>
<td>4.0</td>
<td>0.72</td>
<td>5</td>
</tr>
<tr>
<td>2.0</td>
<td>0.72</td>
<td>4</td>
</tr>
<tr>
<td>2.0</td>
<td>0.72</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>0.72</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>0.72</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>0.35</td>
<td>4</td>
</tr>
<tr>
<td>1.0</td>
<td>0.35</td>
<td>5</td>
</tr>
<tr>
<td>0.4</td>
<td>0.35</td>
<td>4</td>
</tr>
<tr>
<td>0.4</td>
<td>0.35</td>
<td>5</td>
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</tbody>
</table>

High $Tu$

$Re^{-0.1}$ Scaled Loss Bucket

<table>
<thead>
<tr>
<th>$Re_{C_x,2}$</th>
<th>$Re_b$</th>
<th>$M_{2,j}$ passage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>0.72</td>
<td>4</td>
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<tr>
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<td>0.4</td>
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<td>4</td>
</tr>
<tr>
<td>0.4</td>
<td>0.35</td>
<td>5</td>
</tr>
</tbody>
</table>
Ainley-Mathieson Midspan Loss Scaling

**Low Tu**

**High Tu**

![Graph showing Ainley-Mathieson Midspan Loss Scaling](image)

<table>
<thead>
<tr>
<th>$Re_{Cx}$</th>
<th>$Re_b$</th>
<th>$M_{2,i}$</th>
<th>Passage</th>
</tr>
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<tbody>
<tr>
<td>4.0</td>
<td>0.72</td>
<td>4</td>
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<td>4.0</td>
<td>0.72</td>
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<td>2.0</td>
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<td>4</td>
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<td>0.72</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.35</td>
<td>4</td>
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</tr>
<tr>
<td>1.0</td>
<td>0.35</td>
<td>5</td>
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</tr>
<tr>
<td>0.4</td>
<td>0.35</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>0.35</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

www.nasa.gov
Exit Flow Angles

Low $Tu$

$i = +10.8^\circ$

High $Tu$

$i = +10.8^\circ$

$i = -16.1^\circ$

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

Low $Tu$

High $Tu$

$$\Delta \beta_2 = \beta_2 + 55.54^\circ$$