Aerodynamic Measurements of an Incidence Tolerant Blade in a Transonic Turbine Cascade

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An overview of the recent facility modifications to NASA’s Transonic Turbine Blade Cascade Facility and aerodynamic measurements on the VSPT incidence-tolerant blade are presented. This work 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 Transonic Turbine Blade 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. Details of the modifications are described.

An incidence-tolerant blade was developed under an RTPAS study contract and tested in the cascade to look at the effects of large incidence angle and Reynolds number variations. Recent test results are presented which include midspan exit total pressure and flow angle measurements obtained at three inlet angles representing the cruise, take-off, and maximum incidence flight mission points. For each inlet angle, data were obtained at five flow conditions with exit Reynolds numbers varying from 2.12×10^6 to 2.12×10^5 and two isentropic exit Mach numbers of 0.72 and 0.35. Three-dimensional flowfield measurements were also acquired at the cruise and take-off points. The flowfield measurements were acquired using a five-hole and 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.
Fundamental Aeronautics Program

Subsonic Rotary Wing Project

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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

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

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

VSPT Challenges
- Wide incidence variation
- Transitional Reynolds numbers

VSPT Approach
- Incidence tolerant blade
- Reynolds number variation
- Detailed measurements for CFD code/model validation needed.

### 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>

Blades:
- 11 blade passages
- span = 6.000” (fixed)
- pitch = 5.119” (fixed)
- axial chord ~5” (typical)

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 Facility Configuration with VSPT incidence-tolerant blade set at the baseline 40.0° inlet angle

Exhaust pressure:
- min $P \approx 2$ psia
- max = inlet $P$

Supply Pressure = 40 psig

Max Plenum $P = 14.7$ psia
Max Mass Flow $\sim 55 \text{ lb}_m/s$

disk diameter 6 ft.

optional turbulence grid

Exhaust

+40°

-51°
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
Facility Operating Envelope

-\( Ma_{\text{2,des}} = 0.72 \)
-\( Ma_2 = 0.35 \)
VSPT Aerodynamic Measurements

- Inlet flow angles: +40.0°, -2.5°, -11.8°.
- 5 flow conditions each.
- 5-hole and 3-hole pneumatic probes.
- Total pressure and flow angles measured 7.0% $C_x$ downstream of trailing edge.
- Blade and endwall static pressure measurements.

Blade and Survey Planes

VSPT Blades

$C_x = 7.109''$

pitch = 5.119''

span = 6.000''

stagger = 20.35°

three–hole boundary–layer probe

five–hole pitch/yaw probe
CW-22 Test Configurations

40.0° Inlet Angle (i = +5.8° Cruise)

-2.5° Inlet Angle (i = -36.7° Take-Off)

-11.8° Inlet Angle (i = -46.0° Maximum Incidence Condition)
Midspan Probe Loss & Angle Measurements

\[ \text{Re}_{C_{x,2}} = 530,000 \text{ (baseline) } \text{Ma}_{2} = 0.72 \text{ (PR des) } \]

\[ \beta_1 = 40.0^\circ \text{ (Cruise) } i = +5.8^\circ \]
Midspan Probe Loss Measurements

Effects of Reynolds Number and Pressure Ratio at $\beta_1=40.0^\circ$ (Cruise) $i=+5.8^\circ$

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

$Re_{C_x,2}$ $PR$
Midspan Probe Flow Angle Measurements

Effects of Reynolds Number and Pressure Ratio on Flow Angle at $\beta_1 = 40.0^\circ$ (Cruise) $i=+5.8^\circ$

$Re_{Cx,2} \ PR$

$\beta$ [deg]

$SS$ exit metal angle

PS exit metal angle

avg exit metal angle
3-D Flowfield Measurements

\[ \text{Re}_{C_x,2} = 530,000 \text{ (design)} \quad \text{Ma}_2 = 0.72 \text{ (design)} \quad \beta_1 = 40.0^\circ \text{ (Take-Off)} \quad i=+5.8^\circ \]
Blade Loadings at $\beta_1=40.0^\circ$

Effects of Reynolds Number and Pressure Ratio at $\beta_1=40.0^\circ$ (Cruise) $\iota=+5.8^\circ$

- $Re_{C_x,2} = 4.0 \times \text{des}, Ma_2 = 0.72$
- $Re_{C_x,2} = 2.0 \times \text{des}, Ma_2 = 0.72$
- $Re_{C_x,2} = 1.0 \times \text{des}, Ma_2 = 0.72$
- $Re_{C_x,2} = 1.0 \times \text{des}, Ma_2 = 0.35$
- $Re_{C_x,2} = 0.4 \times \text{des}, Ma_2 = 0.35$
CW-22 Test Configurations

40.0° Inlet Angle (i = +5.8° Cruise)

-2.5° Inlet Angle (i = -36.7° Take-Off)

-11.8° Inlet Angle (i = -46.0° Maximum Incidence Condition)
Midspan Probe Loss Measurements

Effects of Reynolds Number and Pressure Ratio at $\beta_1 = -2.5^\circ$ (Take-off) $i = -36.7^\circ$

$$C_{p_{tot}} = \frac{P_{t,l} - P_t}{P_{t,l} - P_2}$$

- $Re_2 = 4.0 \times \text{des}$; $PR = \text{des}$
- $Re_2 = 2.0 \times \text{des}$; $PR = \text{des}$
- $Re_2 = 1.0 \times \text{des}$; $PR = 0.95 \times \text{des}$
- $Re_2 = 1.0 \times \text{des}$; $PR = 0.77 \times \text{des}$
- $Re_2 = 0.4 \times \text{des}$; $PR = 0.77 \times \text{des}$
Midspan Probe Flow Angle Measurements

Effects of Reynolds Number and Pressure Ratio on Flow Angle at $\beta_1 = -2.5^\circ$ (Take-off) $i = -36.7^\circ$
3-D Flowfield Measurements

Re_{Cx,2} = 530,000 (design) \quad Ma_2 = 0.67 (PR=0.95\times\text{design}) \quad \beta_1 = -2.5 \text{ (Take-Off)} \quad i=-36.7^\circ
Blade Loadings at $\beta_1 = -2.5^o$

Effects of Reynolds Number and Pressure Ratio at $\beta_1 = -2.5^o$ (Take-off) $i = -36.7^o$

- $Re_{Cx,2} = 4.0 \times \text{des}, Ma_2 = 0.72$
- $Re_{Cx,2} = 2.0 \times \text{des}, Ma_2 = 0.72$
- $Re_{Cx,2} = 1.0 \times \text{des}, Ma_2 = 0.67$
- $Re_{Cx,2} = 1.0 \times \text{des}, Ma_2 = 0.35$
- $Re_{Cx,2} = 0.4 \times \text{des}, Ma_2 = 0.35$
CW-22 Test Configurations

40.0° Inlet Angle (i = +5.8° Cruise)

-2.5° Inlet Angle (i = -36.7° Take-Off)

-11.8° Inlet Angle (i = -46.0° Maximum Incidence Condition)
Midspan Probe Loss Measurements

Effects of Reynolds Number and Pressure Ratio at $\beta_1 = -11.8^\circ$ ($i = -46.0^\circ$)

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

- $Re_2=4.0 \times \text{des}$; $PR=\text{des}$
- $Re_2=2.0 \times \text{des}$; $PR=\text{des}$
- $Re_2=1.0 \times \text{des}$; $PR=0.95 \times \text{des}$
- $Re_2=1.0 \times \text{des}$; $PR=0.77 \times \text{des}$
- $Re_2=0.4 \times \text{des}$; $PR=0.77 \times \text{des}$
Midspan Probe Flow Angle Measurements

Effect of Reynolds Number and Pressure Ratio on Flow Angle at
$\beta_1 = -11.8^\circ$ (Max Incidence) $i = -46.0^\circ$
Blade Loadings at $\beta_1 = -11.8^\circ$

Effects of Reynolds Number and Pressure Ratio at $\beta_1 = -11.8^\circ$ ($i = -46.0^\circ$)

- $Re_{C_x,2} = 4.0 \times \text{des}$, $Ma_2 = 0.72$
- $Re_{C_x,2} = 2.0 \times \text{des}$, $Ma_2 = 0.72$
- $Re_{C_x,2} = 1.0 \times \text{des}$, $Ma_2 = 0.65$
- $Re_{C_x,2} = 1.0 \times \text{des}$, $Ma_2 = 0.35$
- $Re_{C_x,2} = 0.4 \times \text{des}$, $Ma_2 = 0.35$
Midspan Probe Loss Measurements

Effects of Inlet flow angle at:

\[ \text{Re}_{cx,2} = 4.0 \times \text{design} \quad M_2 = 0.72 \]
\[ (2.12 \times 10^6) \]

\[ \text{Re}_{cx,2} = 0.4 \times \text{design} \quad M_2 = 0.35 \]
\[ (0.21 \times 10^6) \]
Loss vs. Inlet Angle

Loss Coefficient (Area-Averaged)

Inlet Flow Angle, $\beta_1$

Future Test Points

Re$_{Cx,2}$  PR  Passage
- 4x des  1xdes  4
- 4x des  1xdes  5
- 2xdes  1x des  4
- 2xdes  1xdes  5
- 1xdes  1xdes  4
- 1xdes  1xdes  5
- 1xdes  0.77xdes  4
- 1xdes  0.77xdes  5
- 0.4xdes  0.77xdes  4
- 0.4xdes  0.77xdes  5

Loss Measurements