Overview of Variable-Speed Power-Turbine Research

The vertical take-off and landing (VTOL) and high-speed cruise capability of the NASA Large Civil Tilt-Rotor (LCTR) notional vehicle is envisaged to enable increased throughput in the national airspace. A key challenge of the LCTR is the requirement to vary the main rotor speeds from 100% at take-off to near 50% at cruise as required to minimize mission fuel burn. The variable-speed power-turbine (VSPT), driving a fixed gear-ratio transmission, provides one approach for effecting this wide speed variation. The key aerodynamic and rotordynamic challenges of the VSPT were described in the FAP Conference presentation. The challenges include maintaining high turbine efficiency at high work factor, wide (60 deg.) of incidence variation in all blade rows due to the speed variation, and operation at low Reynolds numbers (with transitional flow). The PT-shaft of the VSPT must be designed for safe operation in the wide speed range required, and therefore poses challenges associated with rotordynamics. The technical challenges drive research activities underway at NASA. An overview of the NASA SRW VSPT research activities was provided. These activities included conceptual and preliminary aero and mechanical (rotordynamics) design of the VSPT for the LCTR application, experimental and computational research supporting the development of incidence tolerant blading, and steps toward component-level testing of a variable-speed power-turbine of relevance to the LCTR application.
Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Overview of variable-speed power-turbine research

Dr. Gerard E. Welch
Technical Lead, Propulsion/Engines

2011 Technical Conference
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Cleveland, OH

www.nasa.gov
VSPT research team

NASA in-house
- ARL-VTD / G. Skoch, D. Thurman
- NASA RTT / A. McVetta, S. Chen, Dr. G. Welch
- NASA RTM / C. Snyder
- NASA RXN / Dr. S. Howard
- NASA DER / M. Stevens
- ASRC / Dr. P. Giel
- U. Toledo / Dr. W. To
- Ohio State U. / Dr. A. Ameri

RTAPS contracts on VSPT

Rolls-Royce
Williams International
Overview of VSPT research

• Introduction
  – Need for variable-speed tilt-rotor
  – Solution approach using variable-speed power turbine (VSPT)

• Key technical challenges / research needs

• Research activities

• Summary
Alleviate airport congestion utilizing LCTR

Large Civil Tilt-Rotor

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<table>
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<td>TOGW</td>
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<tr>
<td>Payload</td>
<td>90 PAX</td>
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<td>Engines</td>
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<tr>
<td>Range</td>
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</tr>
<tr>
<td>Cruise speed</td>
<td>&gt; 300 kn</td>
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<td>Cruise altitude</td>
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Principal challenge for LCTR is required variability in main-rotor speed:

– 650 ft/s VTOL
– 350 ft/s at Mn 0.5 cruise

Approach to vary main-rotor speed

- Fixed-speed PT w/ multi-gear-ratio transmission
  - High efficiency design-point operation from take-off to cruise
  - Complexity and weight of variable transmission
  - Need to shift gears

- Variable-speed PT w/ fixed gear-ratio transmission
  - Wide PT speed range, 54% < \( N_{PT} < 100\% \)
  - Lower efficiency potential
  - Added weight to turbine/shafting

Avoid complexity and weight of variable transmission & the need to shift gears
Impact of variable-speed power turbine on cruise efficiency

Martin D’Angelo, GE-Lynn
NASA CR/1995-198380
Key technical challenges for VSPT

• Aerodynamics
  – Efficiency at high work factor
  – Incidence variation required by speed change
  – Operation at low Reynolds number

• Rotordynamics
  – Avoidance / management of shaft modes through speed range
Aerodynamics – efficiency at high work factor

- Specific power is approximately $200 \text{ SHP}/(\text{lb}_{\text{m}}/\text{s})$ at 2 kft take-off and 28 kft cruise

\[ \frac{\dot{W}}{\dot{m}} = \Delta h_0 = \Delta (u_\theta r\Omega) \approx \text{Const} \]

- If 50% speed reduction
  \[ r\Omega \downarrow 2 \]
  then
  \[ \Delta u_\theta \uparrow 2 \]
  and
  \[ \psi = \frac{\Delta h_0}{U^2} \uparrow 4 \]
Incidence variation & low Reynolds number

• Required incidence variation with speed
  – Impact of aerodynamic loading level (Zweifel)
  – Impact of loading schedule
  – Use of variable stators/EGVs

• Low Reynolds number at take-off and cruise (30 to 50k/in.)
  – Impact on design-point loss (efficiency lapse)
  – Impact on incidence-range at acceptable loss levels
  – Influence of unsteadiness
VSPT aero research and technology development needs

- MDO of variable-speed PT at component and engine level

- Efficient high-load, high-turn aerodynamics
  - Secondary flow management using 3-D blading (lean and bow) and endwall contouring

- Aerodynamics of high negative incidence
  - Characterize 2-D and 3-D loss mechanisms at high (40 to 60 deg.) negative incidence

- Aerodynamics of low-Re number flows
  - Turbulence sub-models for transitional flow into RANS/URANS solvers
  - Multistage experiments and 3-D URANS simulation capability – unsteadiness
RESEARCH ACTIVITIES
Research activities

• Conceptual aero-design, optimization, and analysis

• Cascade testing of incidence-tolerant blading

• Computational methods for LPT/PT

• Rotordynamics of LCTR PT rotor

• VSPT component / engine testing
Conceptual aero-design of VSPT for LCTR

- **In-house effort** (AFRL TDAAS system)
  - Meanline analysis using F. Huber’s meanline tools
  - Design at cruise with AN\(^2\) limit at take-off: 4-stage
  - 2-D blade profiles set in AFRL TDAAS
  - 3-D analysis using SWIFT RANS mixing-plane code

- **Williams International study contract**
  - Mission fuel burn sets design speed
  - Evaluated work and flow coefficients and blade thickness (nominal & thin): 4-stage
  - FOILGEN (blades) & VORTEX (analysis)

- **Rolls-Royce (RRC / RR-NAT) study contract**
  - Tailored to high flow coefficient
  - Technology curves: 4-stages
  - Loss buckets biased to +5-deg. incidence at cruise
  - Optimized blade shapes using AIRFOILOPT
3-D computational analysis of embedded stage with speed variation

Variable-speed power turbine for the Large Civil Tilt Rotor

Draft final report

Mark Suchezy
Williams International Co., LLC
3-D computational analysis of rotor of 4-stage VSPT

Loss bucket of embedded rotor 2 of 4-stage VSPT
NASA GRC transonic linear cascade

- Aero and heat transfer testing at wide range of $M$, $Re$, $Tu$, and flow incidence.

Tunnel test conditions

Schematic diagram of NASA transonic linear cascade
• Completed mid-span surveys of EEE tip-section
• Test cell modification for negative incidence range requirements
• First-entry VSPT blading in preparation

Total-pressure coefficient as a function of pitchwise position

a.) -5 degrees incidence
b.) +10 degrees incidence

P. Giel & A. McVetta
Computational methods for LPT/PT

- Turbulence sub-model for transitional flow in LPTs (A. Ameri)
  - Evaluated turbulence models for RANS solvers
  - Selected 3-eqn model ($\kappa_l$, $\kappa$, $\omega$) of Walters & Leylek
  - Compared to heat transfer data from GE2 LPT blade (Giel, Boyle, and Bunker)

- Multistage URANS simulation capability (W. To)
  - Utilize in-house code TURBO (J. P. Chen)
  - Applied to 1.5 stage LSRR turbine (Dring, UTC)
  - Openly available geometry and steady & unsteady data sets

- AeroDynamic Solutions, Inc. (ADS) WAND/LEO codes
Rotordynamics

- Rotordynamics model for LCTR w/ 50% speed range (A. Howard)
  - Model of LCTR2 HP, LP, and VSPT rotors
  - Geometry from WATE code (Doug Thurman)
  - Some assumptions on bearing location modeled after T700

- Rotordynamics model of T700-700 created
  - Supporting assessment of component test capability

Critical speed map showing first four critical speeds of PT-shaft in LCTR2 operating range (A. Howard)
Integrated Aero/Propulsion system (IAPS) FY25

<table>
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<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
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<td>Variable speed engine/gearbox system analysis 2</td>
<td>Plan for HPC follow-on activity in OE-18</td>
<td>VSPT Component Test</td>
<td>TTR installation checkout (T18)</td>
<td>Advanced drive concepts</td>
<td>Axial centrifugal compressor experiment</td>
<td>Integrated fixed engine/variable transmission</td>
<td>Simulation of controls for variable speed rotor</td>
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**Notional layout for integrated engine/transmission demo**

(M. Stevens)
VSPT component testing – first steps

- Assessment of in-house VSPT test capability (G. Skoch)
  - T700-700 engine in the Engine Component Research Laboratory (ECRL)
    - Engine and power absorption capability
    - Engine controls
    - Integration of rating / survey instrumentation
    - PT rotordynamics / shaft mode interactions
  - NASA GRC warm turbine test facility (W-6)

- RTAPS study contracts
  - Williams International
    - 4-stage VSPT in W-6
    - Match first and last stage Re
  - Rolls-Royce
    - Growth AE1107
    - 3.5 stage VSPT/EGV in W-6
    - Match Re at take-off & cruise

- External options being explored
  - Planned AATD 6.2 component program

Notional instrumentation layout for VSPT component test in T700 (M. Stevens)

Williams Int. VSPT for LCTR (M. Suchezky & Scott Cruzen)
Summary

• Key aerodynamic challenges of VSPT
  – Attainment of high efficiency (> 0.88) at high work factors (2.5 to 3.5)
  – Wide incidence variation over mission - high negative incidence
  – Low unit Reynolds numbers (30 < Re/c_x < 50k/in.)

  **Shared by variable-speed PT and fixed-speed PTs**

• Needs:
  – Low-loss, incident-tolerant vane, blade, and EGV blading
  – Ability to manage / avoid engine shaft critical speeds during VSPT speed change

• VSPT research effort at NASA GRC
  – Develop experimentally validated design methods and computational tools/modeling for design/optimization of low-loss, incidence tolerant blading
  – Continue work with industry and DoD partners to refine VSPT design / blading, and path to component and engine test
Acknowledgements

• Mr. Robert J. Boyle (former Distinguished Research Associate, NASA GRC) for early assistance in formulation of VSPT research effort

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• Dr. John P. Clark (AFRL) for providing the AFRL Turbine Design and Analysis System

• Dr. Lisa W. Griffin (NASA MSFC) for permission to use the Huber meanline codes

**NASA Fundamental Aeronautics program**

**Subsonic Rotary Wing project**
BACK-UP CHARTS
NASA GRC warm turbine test facility

Turbine Test Article

work platform for secondary air circuits

Air heaters

Flow measurement venturi

Air supply: 40 psig Combustion Air (clean, dry, ambient temperature)

Flow measurement

Exhaust at 26” Hg
to Altitude

Gearbox

Sync. machine