Active Truss for Fast Response Tip Clearance Modulation

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NASA Aeronautics Research Mission Directorate (ARMD)
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Outlines

• The innovation
• Technical approach
• Impact of the innovation
• LEARN Phase I Results
• Summary
• Next steps
Need for Innovation

Current State of Technology

- Thermal expansion and contraction of entire shroud/case (Active Case Cooling)
- Slow response and scheduled modulation
  - huge thermal mass with seal segments directly mounted on engine casing,
  - ineffective heating or cooling of the shroud via convection between shroud surfaces and air.
- No asymmetry modulation

Prior Research

- Mechanical/Smart materials/Hydraulic/Pneumatic
- External to engine case/shrouds and moving parts
- Incompatibility with environment for HPT

Need for Innovation

- Fast Response Tip Clearance Modulation Mechanism
- Light weight, compact and environmental compatible to HPT
- Integral to shroud-case structure w/o moving parts

DeCastro, etc, 2005
Impact of Innovation

A Fast Response Tip Clearance Modulation

• Enable turbine tip clearance set to “optimal” during longest flight segment (cruise)
• Reduce specific fuel burn (SFC) and exhaust gas temperature (EGT)
  • 0.01” in turbine blade tip clearance equals:
    – 1 % in SFC
    – 10° C in EGT
• Low CO₂ emission
• More time on wing
Innovation-Active Truss Modulation

Approach:
- Variable geometry active truss for tip clearance modulation
- Truss actuation by thermally induced strains
- Low thermal mass and large surface area for heat exchange

Benefits:
- Sustain beauties of thermal expansion approach
- Fast Response-one order of magnitude improvement
- Light weight and integral to shroud-case structure
- Asymmetric and symmetry clearance modulation
Active Truss Modulation (ATM)
Core Elements of Truss Actuation

Prime Movers

Dual Tetrahedron

Dual Pyramid

Parallel \textit{Theta} Ring (2D)

• Actuation by linear thermal expansion
• Structural amplification of displacement
• Multiple inputs and single output actuation
• Low thermal mass and volume density (<0.1)
• One order of magnitude faster response than engine case cooling (ACC)
Principle of Truss Actuation

For thermally induced actuation
- Displacement
- Stiffness
- Response
- Temperature

\[
H = 2 \sqrt{l_d^2 - \frac{l_b^2}{3}} = 2l_d \sqrt{1 - \cos^2 \omega}
\]

Actuation displacement
\[
\frac{\partial H}{\partial l_d} = \frac{2l_d}{\sqrt{l_d^2 - \frac{l_b^2}{3}}} = \frac{2}{\sqrt{1 - \cos^2 (\omega)}}
\]
\[
\frac{\partial H}{\partial l_b} = \frac{-2}{3} \frac{l_b}{\sqrt{l_d^2 - \frac{l_b^2}{3}}} = -\frac{2\sqrt{3}}{3} \cos (\omega)
\]

Tip clearance modulation
\[
\Delta H_t = \sum_{j=1 \sim 6} \frac{\partial H}{\partial l_d^j} dl_d^j - \sum_{i=7 \sim 9} \frac{\partial H}{\partial l_b^i} dl_b^i
\]

Thermal expansion in each members
\[
dl_d = l_d^j C_{ted} \Delta T_{l_d}
\]
\[
dl_b = l_b^i C_{teb} \Delta T_{l_b}
\]
**Principle of Truss Actuation**

Structural stiffness

\[ K_D = \frac{9k_d k_b \sin^2 \omega}{4k_d \cos^2 \omega + 6k_b} \]

Total displacement modulation

\[ \Delta H = \Delta H_t + \frac{F}{K_D} \]

Member buckling \((L/r)\text{ slenderness}\)

\[ \sigma_{cr} = \frac{4\pi^2 E}{(L_b / d)^2} \]

Volume density (weight)

\[ \bar{\rho} = \frac{\pi(3+2\sqrt{3}/\cos^2 \omega)}{\tan(\omega)}(d / l_b)^2 \]
Design of Tetrahedron Truss

Kinematic and Structural Design Envelope

- Amplification vs. design angle, omega °
- Stiffness vs. design angle, omega °

**Graphs:**
- Red line: \( \frac{dH}{dL_d} \)
- Blue line: \( \frac{dH}{dL_b} \)
Design of Tetrahedron Truss

Kinematic and Structural Design Envelope

Case design

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Design of Tetrahedron Truss

Δ T=300 °F applied to 1 diag. member

Δ T=300 °F applied to 3 diag. members

Thermal expansion field

Thermal expansion field
Design of Tetrahedron Truss

FEM Model (cont’d)

ΔT=300 °F applied to 3 horizontal members

Thermal Expansion

- Linear summation of thermal expansion by each member
- Max principal stress $\sigma_{\text{max}} < \sigma_{\text{yield}}$ & $\sigma_{\text{cr}}$ under $\Delta P = 180$ psi

Deformation field under load
Electric Activation of Truss Matrix

Direct resistive heating topologies
• Heating each member individually
• Group collective heating (base and diagonal)
• Combination of series and parallel heating
• Intelligent heating-Wheatstone bridge effect

Challenge: Large current and low voltage

- Cell to cell series connection
- Full actuation
- Fail safe
- Embedded wiring in case
Electric Activation of Truss Matrix

Series connection and partial grouping (2/3 activation)

Parallel/series connection and partial grouping (1/2 activation)
Air Cooling- Activation and Deactivation

Air Cooling Modeling
- Steady state heating/cooling
- Transient cooling

Remain activated, electric power on

Deactivated, electric power off
Air Cooling - Activation Mode

To maintain temperature difference while electrically heated

<table>
<thead>
<tr>
<th>Member temperature contours</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
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<tr>
<td><img src="image2.png" alt="Diagram" /></td>
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<tr>
<td><img src="image3.png" alt="Diagram" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Air flow (m/s)</th>
<th>0.1</th>
<th>0.1</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature difference between heated and unheated wires (°C)</td>
<td>100</td>
<td>110</td>
<td>180</td>
</tr>
<tr>
<td>Heat dissipation rate (W)</td>
<td>7.04</td>
<td>6.9</td>
<td>42.2</td>
</tr>
</tbody>
</table>

- Six members being electrically heated at 899 °C (1650°F) while being air cooled
- Three members being air cooled to 732°C (1350°F)
Air Cooling-Deactivation Mode

To cool to ambient temperature after electrical power turn off

Member temperature change during cool-down with air velocity of 20 m/s

T_{low}: 732°C (1350°F)
# System Design Case

<table>
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<tr>
<th>Design Parameters</th>
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<tr>
<td>Clearance modulation, in</td>
<td>0.05-0.1 N/A</td>
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<tr>
<td>Max. Deflection @ 2200, lbf</td>
<td>N/A</td>
</tr>
<tr>
<td>No of actuator s per shroud</td>
<td>1</td>
</tr>
<tr>
<td>No. of shroud segments</td>
<td>20</td>
</tr>
<tr>
<td>Shroud surface area, in^2</td>
<td>12</td>
</tr>
<tr>
<td>Headroom between case and shroud, in</td>
<td>2</td>
</tr>
<tr>
<td>Air temp. between case and shroud, °F</td>
<td>1300</td>
</tr>
<tr>
<td>Deactivation time, s</td>
<td>N/A</td>
</tr>
<tr>
<td>Power to maintain activated, w</td>
<td>N/A</td>
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## Design Parameters

- **20 truss cells per shroud**  
  structurally in parallel  
  electrically in series  
  two actuation modes

- **Truss cell material**  
  Inconel 718

- **Therm. expansion coef.**  
  8.5e-6/ °F

- **Elastic modulus**  
  24 Mpsi

- **Cell dimensions**  
  Lb=1”, d=0.059”

- **Volume density**  
  ρ=0.11

- **Design angle ω**  
  35°

### Design Angle

- **Nominal requirement**  
  0.05-0.1

### Tetrahedron truss cell

- **Nominal requirement**  
  0.035

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<td>12</td>
<td>2</td>
<td>1300</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Tetrahedron truss cell</td>
<td>0.035</td>
<td>0.005</td>
<td>28</td>
<td>20</td>
<td>12</td>
<td>1.5</td>
<td>1650</td>
<td>13</td>
<td>1344</td>
</tr>
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*DeCastro, 2005
Perspective on Materials

- Baseline materials: High temperature alloys
  - Marginal CTE for large tip clearance modulation
  - Use of material phase transformation induced strain: 10x in stroke

- Commercially available Shape Memory Alloy (Nitinol SMA): 2~4% recovery and Af <100 °C
  - Applicable to Fan clearance modulation

- High temperature SMA in development
  - Ni30Pt20Ti50 by NASA GRC,
  - Recovery >2% and Af>250°C
  - High TRL and in useful form (NASA)
  - Applicable to HPC clearance modulation

- Ru-50 Nb and RuTa based high temperature SMA:
  - Martenstic transformation temperature > 800 °C
  - In early stage development
  - Potentially applicable to HTP clearance modulation

Thermo-mechanical test of N30Pt20Ti50 at 198 Mpa, Courtesy of NASA, M. Nathal, etc. 2013
Proof of Concept Experiment

In progress

Test apparatus

Nitinol Tetrahedron Actuator
- Thermal expansion: 6.1e-6 /°F
- Electrical resistivity: 39 mΩ-in

Anticipated results

Qualitatively Evaluation of
- Displacement output
  - Linear and binary thermal expansion
- Response time in cooling
- Structural stiffness

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Summary

• Active truss tip clearance modulation by thermal expansion is conceptually viable
  • kinematically, structurally and thermally
• Fast response is analytically verified to be within tens of seconds at HPT environment
• Modulation by material linear thermal expansion is adequate for small and mi-size engines
• Experimental validation of tetrahedron truss actuation in progress

• Challenges identified in materials
  • High induced strain for large transport engine
  • High temperature to enable HPT
  • High resistivity to ease direct electric heating
Next Steps

• LEARN Phase I
  • Enhance modeling fidelity of single cell-truss actuation
    • Structural FEM model close loop with air cooling models
    • Air cooling models close loop with electric heating
  • Experimental validation of Tetrahedron Actuation in room temperature.

• LEARN Phase II
  • Expanding structural and air cooling models to large scale repetitive Active Truss Matrix structure
  • Notional design and analysis of tip modulation on a notional engine
  • Electric heating and control of truss modulation
  • High temperature shape memory alloy (HTSMA)
In 2012, NARI awarded ARMD LEARN Fund grants to make deliberate investments in early-stage and potentially revolutionary aviation concepts and technologies that are aligned with NASA's mission. These grants went to teams external to NASA. The objectives of this three-day seminar are to increase awareness of LEARN activities within NASA projects, to provide technical feedback to LEARN principal investigators, and educate/inform the public. This will help facilitate transfer of LEARN-developed technologies within NASA and disseminate LEARN findings to the external aeronautics community, including academia, industry, and the general public.

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