40 kW Turbo-Alternator Hybrid-Electric Range Extender

AHS Transformative Vertical Flight Concepts Workshop

Rory Keogh, Ph.D.  |  Lead Propulsion Engineer
August 2015

structural health monitoring
multi-functional materials
lean enterprise solutions
Overview

• Introduction to Metis Design
• Project Background
• Technology Overview
  – Turbomachinery and generator
  – Waste heat recovery (recuperation)
  – Performance metrics and scalability
  – Noise
• Summary
• Offer novel multi-disciplinary defense, aerospace & energy solutions

• Diverse engineering staff
  - solid fundamental principles (10/14 staff hold Ph.D.’s)
  - hands-on experience from 42 SBIR/BAA contracts over 12 years
  - Boston MA headquarters & satellite offices in CA & NM

• MDC has invented multiple disruptive technologies
  - Microturbine range extender
  - Carbon nanotube (CNT) de-icing & anti-icing system for composite wings
  - Distributed SHM/HUMS sensor digital infrastructure
Background Projects

- Micro-Turbofan for small scale high performance aircraft
- Turbo-generator to flight test sub-scale electric aircraft
- Microturbine battery electric vehicle range extender
- Microturbine for residential combined heat and power
Metis Design Corporation (MDC)

- **Rory Keogh**
  - Joined Metis Design in 2010 to lead DARPA funded jet engine project
  - B.E. Mech. from NUI Galway, M.S. & Ph.D. from MIT Dept. of Aero and Astronautics
  - 5 years experience at Boeing (Mechanical Systems) and 6 years management consulting

- **Greg Thomas**
  - Joined Metis Design in 2010 to work on DARPA funded jet engine project
  - M.Eng. and D.Phil. in Engineering Science from the University of Oxford
  - Worked at McLaren international and Schlumberger

- **Seth Kessler**
  - Founded Metis Design in 2002 & completed over 40 govt. research contracts (SBIR & BAA)
  - B.S., M.S. & Ph.D. from MIT Department of Aeronautics and Astronautics
  - Worked at Lockheed Skunk Works

- **Todd Engel**
  - B.S. Mechanical Engineering UCSB 2005, M.S. Mechanical Engineering USC 2010
  - 10 years at Rolls Royce / Hyper-Therm High Temperature Composites

- **Antoine Corbeil**
  - 19 years P&W Canada / Rolls Royce Canada / Ingersoll Rand / Brayton Energy Canada
Microturbine Systems

State-of-the-art

Metis Design

Unique two-spool gas turbine with pre-combustion power turbine
• **Aerodynamically coupled co-rotating power turbine**
  - Design efficiency ~92%
  - Gearing ratio of 2 to 4

• **High pressure ratio centrifugal impeller**
  - Design efficiency 92 - 95% (w/o tip gap loss)

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**Engine Cycle T-S Diagram**

- **OPR** = 6.0
- **$\pi_b$** = 0.95
- **$\eta_{45}$** = 0.85

**Equivalent Compression Process**

<table>
<thead>
<tr>
<th>$\pi_{23a}$</th>
<th>$\eta_{3a3}$</th>
<th>$\eta_{23}$</th>
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</thead>
<tbody>
<tr>
<td>16</td>
<td>0.95</td>
<td>0.90</td>
</tr>
<tr>
<td>6.3</td>
<td>0.92</td>
<td>0.88</td>
</tr>
<tr>
<td>1.4</td>
<td>0.92</td>
<td>0.85</td>
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</tbody>
</table>
• ~50% impeller / 50% diffuser pressure rise
• ~80% impeller pressure rise comes from loss free centrifugal acceleration (efficiency 92-95%)
• Diffusers are very lossy (power loss proportional to $V^3$)
• Rotating diffuser relative velocity in the diffuser can be halved and streamtube length can be reduced (by ~70%)
• Power turbine can be extract work at $\frac{1}{4}$ to $\frac{1}{2}$ of the speed of the impeller with similar efficiency to microturbines
Generator Design Space

![Graph showing generator design space with speed on the x-axis and electrical design on the y-axis. The optimum generator speed is indicated by a green arrow.]

<table>
<thead>
<tr>
<th>Feature</th>
<th>Slow</th>
<th>Medium</th>
<th>Fast</th>
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</thead>
<tbody>
<tr>
<td>Weight</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Efficiency</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cooling</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Bearings</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Rotordynamics</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Cost</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
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</table>

Optimum generator speed
Generator / Turbomachine Integration

Capstone C30

R-Jet (aviation)
Turbomachinery and generator (Phase I)

Recuperator

Combustor

Generator

Compressor Scroll

Low-Speed Power Turbine

Rotor Magnets

Stator

Return Iron

Turbine Volute

Inlet Port

Turbine Impeller

High-Speed Shaft

High-Speed Bearings

Generator stator

High speed spool

Bearing carrier

Low speed spool
Metis Generator (Phase I)

Metis low cost multi stage axial flux coreless motor/generator
Turbomachinery and generator (Phase II)

Non-recuperated turbo-alternator

Turbo-alternator cross-section
Generator Thermal Control

CFD simulation:
- Stator wall heat flux of 5.85kW/m²
- Rotor wall speed of 40krpm
- Inlet temperature of 15°C
- Only modelling the cooling passage

Results
- Stator heat loss = 160W
- Stator temp = 54°C av, 100°C max
- Rotor temp = 66°C av, 95°C max
Recuperator Summary

GAP Waste Heat Recuperator
Designed and operated within a FP7 CleanSky project

**Overall dimensions:**
- Global HxLxW: 780x760x960mm
- Core diameter: ~420mm
- Global Weight: 50kg
- Core only: ~30kg

**Overall features:**
- Nominal Effectiveness: 75%
- Nominal Power Range: 90kW
- Temperature Range: from 200°C to 650°C
## Performance Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NASA</th>
<th>High OPR</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Power (SLS/18kft)</td>
<td>40/23</td>
<td>56/32</td>
<td>kW</td>
</tr>
<tr>
<td>OPR</td>
<td>3.0</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>TIT</td>
<td>950</td>
<td>1050</td>
<td>C</td>
</tr>
<tr>
<td>Recuperator Eff. (SLS/18kft)</td>
<td>60/70</td>
<td>60/70</td>
<td>%</td>
</tr>
<tr>
<td>Electrical Eff. (SLS/18kft)</td>
<td>21/26</td>
<td>24/31</td>
<td>%</td>
</tr>
<tr>
<td>SFC (SLS/18kft)</td>
<td>391/319</td>
<td>319/267</td>
<td>g/kW.hr</td>
</tr>
<tr>
<td>Specific Weight</td>
<td>2.4</td>
<td>3.2</td>
<td>kW/kg</td>
</tr>
<tr>
<td>Specific Volume</td>
<td>2.2</td>
<td>3.1</td>
<td>kW/L</td>
</tr>
</tbody>
</table>
Preliminary 300kW Configuration

- Reverse flow annular combustor
- Uncooled two stage axial turbine
- Preliminary estimates using GasTurb12

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (SLS/18kft)</td>
<td>300/168</td>
<td>kW</td>
</tr>
<tr>
<td>OPR</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>TIT</td>
<td>1050</td>
<td>C</td>
</tr>
<tr>
<td>Recup. Eff. (SLS/18kft)</td>
<td>60/70</td>
<td>%</td>
</tr>
<tr>
<td>Elect. Eff. (SLS/18kft)</td>
<td>32/37</td>
<td>%</td>
</tr>
<tr>
<td>SFC (SLS/18kft)</td>
<td>262/226</td>
<td>g/kW.hr</td>
</tr>
<tr>
<td>Sp. Weight</td>
<td>4.4</td>
<td>kW/kg</td>
</tr>
<tr>
<td>Sp. Volume</td>
<td>4.9</td>
<td>kW/L</td>
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## Noise Source Benchmarking

<table>
<thead>
<tr>
<th>Noise Source</th>
<th>Capstone C30</th>
<th>Metis 40kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow turbulence in intake, compressor, flow passages, turbine and exhaust</td>
<td>Broadband 1,000 to 5,000 Hz</td>
<td>Similar</td>
</tr>
<tr>
<td>Compressor and turbine Blade passing tones</td>
<td>Comp: 14,400 kHz Turbine: 20,800 kHz</td>
<td>Similar</td>
</tr>
<tr>
<td>Generator rotor-stator tonal interaction</td>
<td>3,200 Hz</td>
<td>Minimal – ironless core stator</td>
</tr>
<tr>
<td>Combustion</td>
<td>Broadband peaks from 400 to 800 Hz</td>
<td>Less noise – lean premixed combustion</td>
</tr>
<tr>
<td>Noise pathways</td>
<td>Inlet, outlet and case radiated</td>
<td>Inlet, outlet and case radiated</td>
</tr>
</tbody>
</table>

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## Noise Level Benchmarking

### Capstone C30 measured noise

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency, Hz</th>
<th>Generator</th>
<th>Compressor</th>
<th>Turbulence</th>
<th>Combustor</th>
<th>Broadband Noise</th>
<th>Tonal Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear, 5M</td>
<td>100-200 Hz</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td></td>
<td>200-300 Hz</td>
<td>Low</td>
<td>High</td>
<td>High</td>
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<td>High</td>
<td>Low</td>
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<tr>
<td></td>
<td>300-400 Hz</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
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<td>Low</td>
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<tr>
<td></td>
<td>400-500 Hz</td>
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<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>500-600 Hz</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
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<tr>
<td></td>
<td>600-700 Hz</td>
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<td>Low</td>
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<tr>
<td></td>
<td>700-800 Hz</td>
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<td>Low</td>
<td>Low</td>
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<td>Low</td>
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<td>800-900 Hz</td>
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<td>Low</td>
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<tr>
<td></td>
<td>900-1000 Hz</td>
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<td>1000-1200 Hz</td>
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<td>1200-1500 Hz</td>
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<td>1500-2000 Hz</td>
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<tr>
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<td>2000-2500 Hz</td>
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<td>Low</td>
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<td>High</td>
<td>Low</td>
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<td>2500-3000 Hz</td>
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<td>Low</td>
<td>High</td>
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<td>Low</td>
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<tr>
<td></td>
<td>3000-4000 Hz</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
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<tr>
<td></td>
<td>4000-5000 Hz</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
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<tr>
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<td>5000-6000 Hz</td>
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<tr>
<td></td>
<td>6000-8000 Hz</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
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<tr>
<td></td>
<td>8000-10000 Hz</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
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<tr>
<td></td>
<td>10000-15000 Hz</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>15000-20000 Hz</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

### Graphs

- **Capstone C30 measured noise**
- **Rear, 5M**
- **Front, 5M**

- **Noise Level, dB**
- **Frequency, Hz**

- **Graphs showing noise level across different frequencies with comparison among No recuperator, Recuperator, and Recuperator + exhaust silencer.**
Conformal Multi-functional Assemblies

- Conformal assemblies for composite & metallic host structures
  - Central carbon nanotube (CNT) layer is core to these properties
  - Surrounded by electrically insulating layers (film adhesive and/or GFRP)
  - Selective electrodes integrated to steer current flow

- No impact to physical structure, 100 - 200 μm & 5 - 10 g/m²
  - Can be co-cured with composite laminate
  - Can be installed over composite or metallic skin in secondary process

- Enable multi-functional capabilities: heating, sensing, conducting
Ice Protection Systems (IPS)

- Quasi-uniform, efficient resistive heating across large areas
- Heat delivered to iced surface interface to reduce energy required
- Tunable resistivity (material property) for optimal power setting
Triton UAS Full-Scale Wing-Extension Integration
CNT-IPS Benefits

• Manufacturing
  ➢ CNT has similar negative CTE to CFRP, eliminate warpage & residual stress
  ➢ Thin in nature so can be inserted anywhere in laminate without LE impact
  ➢ Can drill countersunk attachment points ANYWHERE without inserts

• Weight
  ➢ CNT sheet are 50 μm → 5-10 gsm of heater area
  ➢ Electrodes are 50 μm → 10-15 gsm of heater area
  ➢ Total 10-25 gsm of heater area → ~3 g for a heating zone on Triton
  ➢ Approximate total system weight over full 150’ wingspan of 1 kg

• Power
  ➢ Simple to calculate using patch resistance and input voltage
  ➢ Can make very efficient by matching resistance around chord profile
  ➢ Less than 50% of uniform power for Triton
CNT-IPS Ice Tunnel Testing

- Ice tunnel testing performed per NAVAIR specified test matrix
  - Heavy icing conditions \((125 \text{ mph}, -22^\circ\text{F}, 1.1\% \text{ LWC})\)
  - CNT-IPS fully integrated for Predator UAV tail (1 meter span by 10% chord)
- Testing validated predicted capabilities for CNT as heaters
  - Effective for de-ice without mechanical assist > \(0^\circ\text{F}\), with mechanical < \(0^\circ\text{F}\)
  - Effective for anti-icing (maintaining skin temperature just above freezing)
Summary

• A highly integrated two spool turbine and generator enable a very compact, high power density gas turbine generator

• Moderate levels of recuperation (60-70%) dramatically reduce SFC while maintaining high power density
  - SFC and power density improve at increased power levels (100’s of kW)
  - Recuperation dramatically reduces noise emitted from the gas turbine generator

• Microturbine testing planned for December 2015
Technical & Business Contact

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