High-Efficiency Megawatt Machine Rotating Cryocooler Conceptual Design

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HEMM addresses weight, efficiency, and thermal management technology barriers.
Electric Propulsion Machine Options

- Fully Superconducting
- Partially Superconducting
- PM Synchronous
- Single-fed Induction
- Double-fed Induction
Partially Superconducting Machine is a Near-term Technology

- Challenge is to highly integrate all systems:
  - improves fuel efficiency
  - reduces emissions
  - reduces low grade waste heat
  - reduces vehicle mass
Electric Machine Integration

**Turboelectric**

- Turboshift
- Electric Bus
- Motor
- Distributed Fans

**Turboelectric Aircraft with Aft Boundary Layer propulsion (STARC-ABL)**
- Conventional single aisle tube-and-wing configuration
- Twin underwing mounted N+3 (Far-term) geared turbofan engines with attached generators on fan shaft
- Ducted, electrically driven, boundary layer ingesting tailcone propulsor

**STARC-ABL Power System Architecture**

- 1.3 FPR engines
- 1984 HP (1.48 MW) generator
- 82 inch fan

- 1.25 FPR Electric Fan
- 3500 HP (2.61 MW) motor
- 74 inch fan

- 88.2% efficient transmission
- 1000 Volt electrical system

**Partial Turbo-electric Benefits From Efficient Generator**

**Parallel Hybrid**

- Electric Bus
- Turbofan
- Battery
- Motor
- Fan

**Parallel Hybrid Performance Improves with Energy Storage**
A pulse-tube cryocooler is suitable for usage in a rotating environment. The demonstrated test rig allowed testing to 1500 rpm. There is no evidence that a pulse-tube based rotating cryocooler would not be successful at speeds exceeding 1500 rpm. Our belief is that the integration of the cryocooler into the rotor structure may be done for any rotational speed and such an integration will not increase the complexity of the rotor design.

**Challenge:** Design high aspect ratio symmetrical cryocooler for higher speed operation.

**Solution:** Redlich Alternator with Single-Stage Pulse-Tube Cooler
HEMM is designed to operate as:

- 1.4 MW motor
- with direct drive
- High torque/low speed
- >98% efficient
- >16 kw/kg (active E-M parts)

Cryocooler Key Features:

- Cool superconducting rotor
- Fit inside rotating motor
- Integrates cooler and linear machine
- Operate rotating or stationary
- No cold moving parts

**Top Level Parameter** | **Value**
--- | ---
Frequency | 60 Hz
Gas | Helium
Pressure | 6.2 MPa
Heat Lifted @ 50K | 55W
Heat Rejected | 2000W
Electrical In | 2000W
Mechanical P Vin | 1661W
Coil Current Density | 4 A/mm²
Piston Amplitude | 1.3 cm

Machine is superconducting inside the rotor, but integrates with aircraft conventionally.
Current proposed solutions include:

- Ram air HX
  - adds weight and aircraft drag

- Convective skin cooling HX
  - adds weight, drag, and inefficient

- Dumping heat into fuel
  - limited thermal capacity

- Dumping heat into lubricating oil
  - limited thermal capacity

- Active cooling
  - adds weight and consumes engine power

- Phase change cooling
  - adds weight and limited thermal capacity

- Heat pipe, pumped multiphase, vapor compression
  - adds weight and consumes engine power

50kW to >800kW of low grade thermal heat trapped within composite aircraft body
Thermal Management Limits

**Dumping heat into:**

- Fuel (limited 50 kW)
- Outer mold line (limited 300 kW)
- Ram air (see below for losses)
- By-pass air (see below for losses)

<table>
<thead>
<tr>
<th></th>
<th>1% Hot Day</th>
<th>Standard Day</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Total Penalty (zero exit Velocity)</td>
<td>Total Penalty (non-zero exit Velocity)</td>
</tr>
<tr>
<td>900NM</td>
<td>4.98%</td>
<td>3.31%</td>
</tr>
<tr>
<td>3500NM</td>
<td>5.00%</td>
<td>3.62%</td>
</tr>
</tbody>
</table>

Electric Aircraft Propulsion Thermal management technology impacts performance and safety certification
<table>
<thead>
<tr>
<th>Component</th>
<th>Loss (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic Losses</td>
<td>9.3</td>
</tr>
<tr>
<td>Stator Core</td>
<td>3.9</td>
</tr>
<tr>
<td>Stator winding ($I^2R$)</td>
<td>4.6</td>
</tr>
<tr>
<td>Stator winding proximity</td>
<td>0.8</td>
</tr>
<tr>
<td>Rotor core</td>
<td>0.009</td>
</tr>
<tr>
<td>Rotor coils</td>
<td>0</td>
</tr>
<tr>
<td>Other Losses</td>
<td>4</td>
</tr>
<tr>
<td>Cryocooler Power</td>
<td>2</td>
</tr>
<tr>
<td>Bearings</td>
<td>1</td>
</tr>
<tr>
<td>Vacuum Seals</td>
<td>1</td>
</tr>
<tr>
<td>Total Losses</td>
<td>13.5</td>
</tr>
<tr>
<td>Total Losses (+20% margin)</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Under 50W Cryogenic Heat Load Expected
Basic Building Block for Electric Aircraft: Thermo-Acoustic Engine and Heat Pumping

KEY PROPERTIES
Can be used for thermal energy conversion:
- From heat to mechanical power
- From mechanical power to cooling
- From heat to heat pump when used in double configuration shown
No Moving Part Acoustic Heat Pump

Acoustic Mechanical Work Energy Moves Heat From Cold to Hot
Acoustic Heat Pump Efficiency

Reject at Higher Temperature

Hot reservoir

Accept at Lower Temperature

Cold reservoir

More input acoustic power required as the heat lifted from the cold reservoir increases and/or as temperature gap increases

<table>
<thead>
<tr>
<th>Th (k)</th>
<th>Tc (k)</th>
<th>Ratio (W/Qc)</th>
<th>Qout (W)</th>
<th>Workln (W)</th>
<th>Qin (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>300</td>
<td>1:3</td>
<td>1000</td>
<td>250</td>
<td>750</td>
</tr>
<tr>
<td>600</td>
<td>300</td>
<td>1:1</td>
<td>1000</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>900</td>
<td>300</td>
<td>2:1</td>
<td>1000</td>
<td>666.6667</td>
<td>333.3333</td>
</tr>
<tr>
<td>1200</td>
<td>300</td>
<td>3:1</td>
<td>1000</td>
<td>750</td>
<td>250</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>40:1</td>
<td>1025</td>
<td>1000</td>
<td>25</td>
</tr>
</tbody>
</table>
Represent all known physics in the Stirling Cycles and Maxwell Equations for Generator

Require specialized numerical resolution to combine hydrodynamics with acoustics

COMSOL cannot solve system for example

DELTAE frequency domain LANL

SAGE time-periodic domain GRC/Gedeon

Numerical Schemes
- Discontinuous Galerkin FE
- Compact Schemes
- Absorbing Boundary Layer
- Low Order Diffusion a Problem
- Space and Time Together Works with sinusoidal basis functions

Gas Bearing Hydrodynamics with Fluent FV
Basic Acoustic Traveling Wave Thermodynamic Cycle

Compression

Displacement, $P$ $\uparrow$

Expansion

Displacement, $P$ $\downarrow$

$W_{cmp} < W_{exp}$
Two-Stage Cascade

\[ \frac{W_{cmp}}{W_{exp}} \propto \left( \frac{T_{cold}}{T_{hot}} \right)^2 \]
• $P_1$ phasors everywhere nearly constant
• $U_1$ phasors progressively lag due to volume (compliance)
• Ideally, $P_1$ and $U_1$ in phase in regenerators
• Gas inertia (inertance) can be used to counter $U_1$ lag
• E.g. Swift inter-stage inertance tube (see reference 4)
End Transducer Options

High Impedance (Piezo or magnetorestrictive)

\[ P_1 \text{ high}, U_1 \text{ low} \]

Low Impedance (Moving Magnet actuator)

\[ P_1 \text{ low}, U_1 \text{ high} \]

Impedance is \( P_1 / U_1 \)
Quarter-wave solid resonator converts low Stirling impedance to high transducer impedance

- Low Dissipation losses critical
- Coef of restitution > 0.9999
- Three-dimensional effects?
- Piezo transducers prefer higher frequency than Stirling thermodynamics allows
Moving magnet linear transducers can intrinsically match stirling impedance

But have relatively high reciprocating mass compared to piezo transducers

\[ F = m w^2 A \]

Limiting maximum operating frequency without external springs

Low Impedance Matching

Accept 2kW @ 50K

Reject 2kW @ 353K

[Image of transducer and graph showing electro-acoustic conversion efficiency]
System Optimization

Optimization examples

- **Increased frequency**
  - alternator efficiency $\uparrow$
  - thermo-acoustic efficiency $\downarrow$

- **Increased pressure**
  - Mass of containment $\uparrow$
  - Power output per volume $\uparrow$

- **TAE topology**
  - Standing wave less complex,
    (Hence lighter for given efficiency)
  - Travelling wave more efficient
    (Hence less weight per Watt)

- **Working Gas**
  - Air is cheapest
  - Helium allows higher frequency
    (Hence lighter alternator and TAE)
Heat Pump Trade Study

1. Co-axial Pulse Tube: Efficient enough and fits in rotating shaft
2. GM-Pulse Tube: Not Efficient
3. Two-Stage Stirling Displacer: Very efficient, but challenging to rotate displacer
4. Inline Pulse Tube: Too long vs. Co-axial
5. Pulse Tube: Not as efficient as two-stage, Too long
6. Split Cycle: Not axi-symmetric for high speed rotation
• Overall design is axisymmetric for dynamic stability under rotation
• Redlich style permanent magnet linear machine increases force with axial length increases (high aspect ratio)
• No cold moving parts or bearings
• Single tight-clearance seal that can be supported with many radially stiff flexure bearings
• Fits within 100mm diameter torque tube
• Can be designed to lift 50W at 50K with reasonable efficiency and size
• Thermal rejection can be located outside the vacuum enclosed rotor area
Regenerators

- $f$ = Darcy friction factor
- $N_u$ = Nusselt Number, $h d / k$
- $N_k$ = effective gas conductivity due to thermal dispersion as a Fraction of molecular conductivity
- $Re$ = Reynolds number, $pud / k$
- $Pr$ = Prandtl number, $C_p \mu / k$
- $d$ = hydraulic diameter

$$F_M = \frac{1}{f \left( \frac{Re Pr}{4N_u} + \frac{N_k}{Re Pr} \right)}$$

- Wakes and eddies increase $\Delta P$ and thermal dispersion (axial conduction losses)
- Thermal dispersion was measured/simulated during DOE and NASA efforts
- Stagnation zones tend to decrease heat transfer
- Blowby at wall, wall-caused flow non-uniformities found to be potential random-fiber/wire screen regeneration losses
Piston Heat Flux Higher Fidelity Distribution
Increasing frequency and magnet length enables high aspect ratio geometry to fit inside narrow shaft.

And after combining equations (1) and (2) we find:

\[ F_p = C_f I \]  \hspace{1cm} (1)

\[ P = F_p V_x = VI \]  \hspace{1cm} (2)

\[ V_x C_f = V \]  \hspace{1cm} (3)

\[ V_x = A_x 2\pi f \]  \hspace{1cm} (4)
- Have some freedom in lamination thickness for structural and manufacturing
- All components are symmetrical about rotation axis
- Drilled copper used instead of screen mesh for strength
- Rotor shaft provides outer pressure vessel

### Redlich Linear Machine Design Considerations

<table>
<thead>
<tr>
<th>Lamination Thickness (mm)</th>
<th>Alternator Efficiency</th>
<th>Heat Lift at 50K (W)</th>
<th>Electric Power In (W)</th>
<th>Coil Current Density (A/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.83</td>
<td>55</td>
<td>1900</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>0.826</td>
<td>55</td>
<td>2000</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>0.79</td>
<td>53</td>
<td>1992</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0.74</td>
<td>48.6</td>
<td>1940</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>0.71</td>
<td>45</td>
<td>1884</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>0.67</td>
<td>40.7</td>
<td>1806</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>0.58</td>
<td>27.5</td>
<td>1562</td>
<td>4</td>
</tr>
</tbody>
</table>
Bearing Options

Gas Bearings – Hydrostatic and hydrodynamic
Flexure Bearings – Spiral and other
Rotating Bearings - Foil
### Flexure Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of arms</td>
<td>3</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>100 mm</td>
</tr>
<tr>
<td>Number of revolutions in a spiral arm</td>
<td>1.3</td>
</tr>
<tr>
<td>Spiral inner diameter (without stress relief)</td>
<td>20 mm</td>
</tr>
<tr>
<td>Spiral outer diameter (without stress relief)</td>
<td>85 mm</td>
</tr>
<tr>
<td>Spiral pitch</td>
<td>25 mm</td>
</tr>
<tr>
<td>Arm width</td>
<td>6.98 mm</td>
</tr>
<tr>
<td>Slot width</td>
<td>1.0 mm</td>
</tr>
</tbody>
</table>

### Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>1900</td>
</tr>
<tr>
<td>0.2% Yield Strength (MPa)</td>
<td>1500</td>
</tr>
<tr>
<td>Fatigue Strength (MPa) 5% Failure Rate</td>
<td>±750</td>
</tr>
<tr>
<td>Young's Modulus (GPa)</td>
<td>210</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>7700</td>
</tr>
</tbody>
</table>

### Stiffness and Moving Mass

<table>
<thead>
<tr>
<th>Property</th>
<th>0 RPM Test (n=3 samples)</th>
<th>0 RPM FEA prediction</th>
<th>6800 RPM FEA prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness (N/m) at 13 mm displacement</td>
<td>2642</td>
<td>2601</td>
<td>2937</td>
</tr>
<tr>
<td>Moving mass (g)</td>
<td>17.0</td>
<td>16.3</td>
<td>16.5</td>
</tr>
</tbody>
</table>

### Stress and Deformation

- **Von Mises Stress**
- **Deformation**
Next Step: Testing and Operations

### Stationary and Rotational Operating Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>0 RPM</th>
<th>6800 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston Oscillation Freq (Hz)</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Heat Lifted at 50K (W)</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>Electric Power In (W)</td>
<td>1860</td>
<td>1774</td>
</tr>
<tr>
<td>Effective Flexure Stiffness (N/m)</td>
<td>1.57e5</td>
<td>1.78e5</td>
</tr>
<tr>
<td>Reactive Power In (W)</td>
<td>2531</td>
<td>3121</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>154</td>
<td>176</td>
</tr>
<tr>
<td>Current (A)</td>
<td>20.4</td>
<td>20.4</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.59</td>
<td>0.49</td>
</tr>
</tbody>
</table>

**Supports 60 Hz Single-Stage Pulse-Tube Cooler**
Maximum benefit with electric aircraft is achieved by integrating at both the component level and the system level.

Thermal energy conversion technologies provide a fundamental building block for this integration.

**HEMM** enables flight-weight, high efficiency at MW-scale

Internal rotating cryocooler design identified that successfully installs inside the rotor shaft

Next step is prototype build and test