Design and Test of a Structurally-Integrated Heat Sink for the Maxwell X-57 High Lift Motor Controller

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Presented By
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Thermal & Fluids Analysis Workshop
TFAWS 2019
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NASA Langley Research Center
Hampton, VA
X-57

- **Fully Electric Aircraft Demonstrator**
  - Two 60 kW Cruise Motors
  - Twelve 12kW High Lift Propulsors
    - Primarily used for lift augmentation for take-off and landing
  - Li Battery powered DC bus

- **Distributed High Lift System**
  - Enables low profile wing shape, reducing unnecessary drag during cruise
  - Motor controllers and inverters are located in the nacelle with each motor
  - Inactive for majority of flight, driving the need for low mass and drag
GIMC-HEIST Background

- Generalized Intelligent Motor Controller (GIMC)
- OML Cooled proof of concept for
  - 10-14 KW

RPM vs Induced Velocity - LEAPTech

GiMC-Heist Test Configuration
Design Requirements

• Thermal
  – Dissipate controller and inverter waste heat for a 12 kW high lift system
  – Prevent components from exceeding their maximum operating temperatures
    • Particularly the High Power SiC MOSFETs
      – 100C Maximum Tj (150 C – 50 C de-rating)
Environmental Requirements

- Qualification testing per DO-160G

- Worst Case Hot Environment
  - Stopped on runway with HLP at max power
    - 45°C Ambient, 50 W/m²°C (Prop Wash) Convection

- Worst Case Cold Environment
  - Cruise with HLP off
    - -25°C Ambient, 110 W/m²°C Convection

- Qualification Test Margin
  - ±15°C

![Environmental Temperature Extremes for Qualification Testing]

-40°C to +60°C
Design Process

• Initially greatly over weight
  – HEIST was prepackaged (multiple thermal interfaces)
  – Separately designed thermal, structural, and power electronics

• Rapid redesign process
  – Weekly iterations
    • Quick turnaround analysis tools
  – In house controller design greatly increased electronics efficiency
    • Enabled by subsystem cooperation

• Structural Thermal design iterations
  – Competing requirements
  – Very low mass margins
GIMC Design

- MOTOR
- CENTER SECTION
- PCB/HEAT SINK ASSEMBLY
- HIGH LIFT NACELLE AFT (9)

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High Power Electronics Thermal Design

- High Power Electronics
  - Thermally sunked to external flow
  - Aluminum external sink conforms to OML
  - SiC MOSFETs are distributed around the circumference of the sink to minimize temperature gradient
  - Designed External Sink Surface Area
    - 640 cm²
Low Power Electronics (LPE)

- Two copper thermal planes on each PCB to distribute heat
  - 1.4 mil (1 oz copper)
- PCBs are thermally linked together through aluminum standoffs which are in contact with the thermal planes
- Secondary Low Power Heat Sink with heat pipe conductor
  - Low Power Sink is thermally insulated from High Power Sink with G10 standoffs
  - Sintered Wick Copper Heat Pipe
    - Water working fluid
    - 27W Capacity
    - 30 to 120°C Temperature range
- Additional convection to internal nacelle environment
• **RANS (SST) Turbulence Model**
  • Enhanced wall treatment for heat transfer
  • Design points based on uniform inlet temperature, speed, and dissipated power.
High Lift Power Electronics Thermal Performance - CFD Model vs Test

- Uniform Freestream Speed (m/s)
- Surface Average Heat Transfer Coeff. (W/m²-K)

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• All boards have two 2oz copper thermal layers
  – 1.4 mil thickness
  – Additional ground and bus planes will help distribute heat
• Thermal vias located throughout boards
• Heat Pipe interface boundary
  – 65C
• High Temperature Sink boundary
  – 72C
• Natural Convection
  – 5W/m²C @ 60C

• Majority of active components have maximum operating ambient air temperature limits
  – Results show we can keep all components below their maximum ambient temperature limit
    • Conservative due to actual component maximum operating temperature being higher than ambient operating temperature
### PCB Thermal Model Component Results

#### Component
<table>
<thead>
<tr>
<th>Component</th>
<th>Part</th>
<th>Qty</th>
<th>Pwr (mW) ea</th>
<th>Pwr (mW) Tot</th>
<th>Max Operating Temp</th>
<th>Model Temp</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Capacitor</td>
<td>B32778G1206K000</td>
<td>3</td>
<td>83</td>
<td>249</td>
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<tr>
<td>Current Sensor</td>
<td>LA 100-P</td>
<td>2</td>
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<td></td>
<td></td>
<td>323</td>
<td>729</td>
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#### Total

<table>
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<tr>
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<tr>
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<td>MMSZ5233B-7-F</td>
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<td>195.18</td>
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<td>HS Driver PS</td>
<td>ATA00H1BS-L</td>
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<td>80.02</td>
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<td>77.6</td>
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<tr>
<td>LS Driver PS</td>
<td>ATA00H1BS-L</td>
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<td>240.07</td>
<td>240.07</td>
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<td>Opto Driver</td>
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<td>1440</td>
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<th>Model Temp</th>
<th>Notes</th>
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<tbody>
<tr>
<td>ADC Buffer Amp</td>
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<tr>
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<td>27.6</td>
<td>27.6</td>
<td>6%</td>
<td>98.2*</td>
<td>77.7</td>
<td>Derated Ambient Temp</td>
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<tr>
<td>3.3V Delfino CVTR</td>
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<td>12V CVTR</td>
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<td>15%</td>
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<td>1.2V Regulator</td>
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<td>13%</td>
<td>85*</td>
<td>78.6</td>
<td>Derated Ambient Temp</td>
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<tr>
<td>1.8V Supply</td>
<td>TPS72118DBVT</td>
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<td>79</td>
<td>Max dissipation 154mW</td>
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<td>EEPROM</td>
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<td>Ethernet TxRx</td>
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</table>
High Power Heat Sink Thermal Analysis

- Analysis assumptions
  - FETs
    - $\theta_{jc} = 0.27 \, \text{C/W}$
    - Junction mass = 5g
    - Junction $c_p = 0.9 \, \text{J/g*}\text{C}$
  - Heat Sink
    - Mass = 380g
    - $c_p = 0.9 \, \text{J/g*}\text{C}$
    - Surface Area = 640 cm$^2$
  - Environment
    - 20s/90s Transient
      - Temperature = 60C
      - Convection Coefficient = 50 W/m$^2$C
    - Flight Profile
      - Worst case flight maximums

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration (Seconds)</th>
<th>Input Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi from NASA</td>
<td>600</td>
<td></td>
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<tr>
<td>TO Checklist</td>
<td>120</td>
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<tr>
<td>Cruise Runup</td>
<td>30</td>
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<tr>
<td>HLP Runup</td>
<td>30</td>
<td>11.4 136.7</td>
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<tr>
<td>Flight go/no-go</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Ground roll</td>
<td>10</td>
<td>11.4 136.7</td>
</tr>
<tr>
<td>Climb to 1500'</td>
<td>90</td>
<td>5.7 68.4</td>
</tr>
<tr>
<td>Cruise Climb</td>
<td>540</td>
<td></td>
</tr>
<tr>
<td>Cruise</td>
<td>300</td>
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<tr>
<td>Descent to 1500'</td>
<td>450</td>
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<tr>
<td>Final approach</td>
<td>180</td>
<td>5.7 68.4</td>
</tr>
<tr>
<td>Go Around to 1500'</td>
<td>90</td>
<td>5.7 68.4</td>
</tr>
<tr>
<td>Approach pattern</td>
<td>90</td>
<td></td>
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<tr>
<td>Final approach</td>
<td>180</td>
<td>5.7 68.4</td>
</tr>
<tr>
<td>Rollout and turnoff</td>
<td>60</td>
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<tr>
<td>Taxi to NASA</td>
<td>600</td>
<td></td>
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</tbody>
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Mod 4 HLP Flight Profile from AFRC
C# Model GUI

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Results

20s Full Power/90s Half Power Transient

Phase Duration (s) Dissipation (W) Env Temp (C) Conv Coef (W/m2C)
HLP Runup 30 250 45 57
Fight go/no-go 30 0 45 15
Ground Roll 10 250 45 57
Climb to 1500' 90 125 25 57
Cruise 900 0 25 110
Final Approach 180 125 45 110
*GoAround 90 125 45 110
Approach Pattern 90 0 45 110
Final Approach 180 125 45 110
Ground 20 0 45 57

Transient results with heat sink mass, thermal resistance, temperature, and convection modeled at profile power.
Testing

- **Steady State Thermal Extremes**
  - Sea level Thermal Chamber
  - -40C to +60C Extremes
  - Functional & Workmanship Testing
  - Water cooled test heat sink

- **Transient Wind Tunnel Testing**
  - Sea level & Altitude (15kft) Testing
  - Flight Heat Sink performance and Model Validation
  - Functional testing at worst case conditions
Wind Tunnel Test Unit Build

- Additively manufactured aluminum heat sink
- 3D printed forward Nacelle and Motor Section analog
Testing Results (Transient)

Transient Test Case 4
- 20s 100% power
- 90s 50% power
- Environment
  - 20m/s
  - 12.7 psi (4000 ft)
  - 60 degC

![Graph showing temperature over time for different components under specified conditions.](image-url)
Steady State Test Case 2
- Continuation from previous test
- 100% power
- Environment
  - 20m/s
  - 9.6 psi (11300 ft)
  - 20 degC
Developed models for heat transfer characterization and transient modeling of passive 'OML' cooled power electronics

Designed, built, and tested well-integrated multidiscipline motor controller package for X57

Completed design successfully met all operational and environmental requirements at worst case conditions