Overview of an Advanced Hypersonic Structural Concept Test Program

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Outline

• Hypersonics M&S Advanced Structural Concepts Development
  – C/SiC Ruddervator Subcomponent Test Article (RSTA)
    • Background
    • Task Objectives
    • Test Plan
    • Current Status

• Hypersonics M&S Experimental Methods
  – Extreme Environment Sensors
    • Instrumentation Needs
    • Sensors of Interest
    • Examples of ongoing efforts

• Conclusions
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Background

- One of the key technology efforts during the X-37 program was the development and validation testing of hot-structure control surfaces
  - Part of the risk mitigation effort was the parallel development of X-37 control surfaces using both carbon-carbon (C/C) and carbon-silicon carbide (C/SiC)

- Two separate design and manufacturing teams developed subcomponent test articles
  - C/C Flaperon subcomponent (built and tested)
  - C/C Ruddervator subcomponent (built and tested)
  - C/SiC Flaperon subcomponent (built and tested)
  - C/SiC Ruddervator subcomponent (built but not tested)

- The X-37 program down selected to C/C and proceeded with the development and testing of both ruddervator and flaperon qualification units
  - Flaperon thermally / mechanically tested at NASA Dryden
  - Ruddervator mechanically tested at Wright-Patterson, AFB
• NASA proposed the C/SiC RSTA as a testbed to support ARMD research objectives and worked to formulate a multi-partner program
  – Lockheed Martin (LM) is evaluating C/C and C/SiC control surface technology for hypersonic programs and expressed interest in collaborating

• The X-37 C/SiC RSTA provides an opportunity to
  – Apply both re-entry and trans-atmospheric derived thermal / structural loads to a hot-structure
  – Evaluate the thermal / structural performance of a C/SiC hot-structure control surface
  – Compare the thermal / structural performance of a C/SiC and C/C hot-structure control surface
  – Provide a testbed to evaluate the performance of advanced high-temperature instrumentation
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Team Roles and Responsibilities

NASA Dryden
- Overall task management and test requirements definition
- Thermal, structural, and ground-vibration testing
- Non-destructive evaluation
- High-temperature instrumentation

NASA Langley
- Acoustic, vibration, and modal testing
- Thermal / acoustic testing

Materials Research & Design
Wayne, PA
- C/SiC RSTA designer
- Test requirements support (X-37 & LM loads)
- RSTA thermal / structural / dynamic analysis

GE Aviation
Ceramic Composite Products
Newark, DE
- C/SiC RSTA manufacturer
- RSTA modifications and assembly
- Non-destructive evaluation support

Lockheed Martin
Palmdale, CA
- LM derived loads definition
- Oversight of LM related testing
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Test Objectives

• Evaluate the thermal, structural, and dynamic performance of the C/SiC RSTA through the application of relevant hypersonic thermal, structural, acoustic and vibration loads
  – Maintains and extends NASA’s core knowledge in testing hypersonic structures
    • Obtain unique data through the development of test techniques
    • Application and evaluation of unique high-temperature instrumentation
    • Multi-mission simulation
  – Perform NDE throughout RSTA testing to identify defects and track potential damage propagation

• Pre- and post-test structural analysis to support test operations and development of test database
  – Provides an extensive database for the evaluation of design and analysis methods for hypersonic structures
    • Provides data to validate advanced analysis techniques
      – High-temperature vibration analysis
      – Using test data, non-linear material properties, and contact elements at fasteners to determine force levels at interfaces and fastener stresses (linear versus non-linear analysis comparison)
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Test Plan

• Evaluate RSTA performance under two different hypersonic flight conditions
  – X-37: Re-entry conditions
    • Higher heating rates (i.e. higher surface temperatures) over shorter time periods
    • Mechanical loads over short time periods
    • Vibration / acoustic loads maximum at lift-off (i.e. low temperature conditions)
  – LM: Trans-atmospheric conditions
    • Lower heating rates (i.e. lower surface temperatures) over longer time periods
    • Mechanical loads over repeated cycles
    • Combined thermal / acoustic loads of interest

• Developed a four-phase test program for the RSTA
  – Phase 1: Acoustic and vibration loads to X-37 load conditions
  – Phase 2: Thermal and thermal / structural loading to X-37 and LM load conditions
  – Phase 3: Room-temperature mechanical loading to X-37 and LM load conditions
  – Phase 4: Vibration and thermal / acoustic testing to LM load conditions
**Objective:**
- Evaluate RSTA dynamic performance under X-37 vibration and acoustic loads

**Test Sequence:**
- Modal survey
  - Free-free / fixed boundary condition
- Pre-acoustic sine sweep
- Acoustic testing
- Vibration testing
  - Post-acoustic sine sweep
  - Random vibration testing
  - Post-random sine sweep

**Data Acquired**
- Accelerations
- Strains

**Database Elements**
- Test requirements document and test plan
- Instrumentation drawings and test data
- Test correlation report
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Phase 2 Tests (NASA Dryden, In Progress)

• **Objective:**
  – Evaluate RSTA performance under X-37 re-entry and LM thermal / mechanical load conditions

• **Test Sequence:**
  – Modal Survey *(completed)*
    • Free-free boundary condition
  – Room-temperature ground vibration test (GVT)
  – Elevated-temperature GVT
  – X-37 thermal loading (3 cycles)
  – X-37 thermal / mechanical loading (3 cycles)
  – LM thermal / mechanical loading (3 cycles)
  – Elevated-temperature GVT

• **Status:**
  – Pre-test predictions
    • LM thermal / mechanical test conditions *(completed)*
    • X-37 thermal / mechanical test conditions (in progress)
  – High-temperature sensor installations (in progress)
  – Thermal test hardware design *(completed)*
  – Thermal test hardware fabrication (in progress)
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Phase 3 & 4 Tests

- **Phase 3 Objective:** (NASA Dryden)
  - Evaluate RSTA performance under X-37 derived 100% DLL loads
- **Test Sequence:**
  - Multi-cycle loading to 100% DLL condition
    - Reverse loading
- **Data To Be Acquired**
  - Deflections (control surface and freeplay)
  - Strains
  - Input and reaction loads

- **Phase 4 Objective:** (NASA Langley, TBD)
  - Evaluate RSTA performance under LM derived vibration and thermal / acoustic loads
- **Test Sequence:**
  - Modal survey (free-free boundary condition)
  - Pre-acoustic sine sweep
  - Thermal / Acoustic testing
  - Vibration testing
    - Post-acoustic sine sweep
    - Random vibration testing
    - Post-random sine sweep
- **Data To Be Acquired**
  - Temperatures
  - Accelerations
  - Strains
Extreme Environment Structural Sensors
High-Temperature Instrumentation Needs

• Issues
  – Hypersonic structures are utilizing advanced materials that operate at temperatures that exceed current ability to measure structural performance
  – Robust structural sensors that operate accurately and reliably in hypersonic environments do not exist

• Implications
  – Hinders ability to validate analysis and modeling techniques
  – Hinders ability to optimize structural designs

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Extreme Environment Structural Sensors
Instrumentation Attachment Needs

• Hypersonic structural test or flight articles are usually one-of-a-kind, expensive, and time consuming to manufacture
  – Metallics
  – Metal matrix composites
  – Superalloys
  – High-temperature composites (i.e. C/C, C/SiC, SiC/SiC)

• Issues
  – Integrating structural sensors that do not compromise structural integrity
    • Drilling holes, mechanical fastening, etc. are typically not allowed
  – Developing sensor attachment methods that provide valid measurements for all environmental loading conditions without adversely affecting the substrate
    • Thermal conditions
    • Mechanical loading
    • Vibration and acoustic loads
    • Exposure to chemically reacting flows
Extreme Environment Structural Sensors
High-Temperature Structural Measurements of Interest

- **Strain**
  - Sapphire fiber-optic sensors
  - High-temperature Bragg Gratings
- **Temperature**
- **Heat Flux**
  - Calibration methods
- **Acceleration**
- **Deformation**

**Sensors and Sensory Materials**

**Bonding / attachment method**
**development throughout**
**structural component**
**operating range**

**Current Efforts:**
- SOA structural sensor assessment to coordinate NASA, NRA and SBIR opportunities
- Evaluate sensor / systems under laboratory, ground test, and flight test opportunities
Extreme Environment Structural Sensors
Example of Strain Sensing Technology Progression

1960-1970

- Flame-Sprayed Resistive
- Weldable Resistive
- Weldable Capacitive
- Large thermal outputs and measurement uncertainties

1980-1990

- Improved temperature-compensation using flame-sprayed resistive gages
- Improved measurement accuracy applying silica and sapphire fiber-optic technology

>2000

- Fiber-Optic Strain Sensor
- X-33
- NASP
- CEV
- X-37
Extreme Environment Structural Sensors
Examples of Strain and Temperature Sensors

Fiber-Optic Strain Sensor Installation

- Gold-coated silica fiber (125 micron)
- Nextel overbraid
- Ceramic cement
- Max use = 1850°F
- 8.5mm
- C/C
- Plasma spray (2 mils)
- Rokide flame spray

**Challenge**
- Advance strain sensing technology beyond 2000°F
- Develop durable high-temperature fiber-optic sensors
- Advance temperature sensing methods
- Develop sensor attachment techniques suitable for hypersonic environments (ground and flight testing)
Extreme Environmental Sensors
Examples of Acceleration, Heat Flux, Network Sensors

- **Accelerometers**
  - COTS sensors
  - NASA GRC

  ![NASA GRC High-Temperature SiC High-g sensor (1000°F)](image)
  ![COTS High-Temperature Accelerometer (900°F)](image)

- **Heat Flux Sensors**
  - Low profile
  - Rapid response

  ![Heat Flux Array ARMD ExCap NRA Effort (Tao Systems and Virginia Tech)](image)

- **Distributed Bragg Grating System**
  - Simultaneous measurements of strain, temperature, and deformation
  - Increase operating temperature

  ![Pressure Loading](image)
  ![Thermal Loading](image)

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Extreme Environmental Sensors
Validation of Sensor Outputs and Attachment Methods

• **Goal:** Provide valid sensor data to structural analysts
  – Validate sensor output through characterization testing
    • Compare sensor outputs to available standards
  – Validate and assess attachment techniques

**Typical Systems for Sensor Validation Testing**

- **Dilatometer**
  - (3000°F, inert / air)
  - High-temp FO sensors on C/C in sample holder

- **Strain Sensor Validation System**
  - LVDT
  - Clamp
  - Loading mandrel

- **Thermal Cycling Furnace**
  - 3000°F, inert / air

- **Black-Body Furnace**
  - 3000°F, inert / air
Conclusions

- Hypersonics M&S is developing
  - Advanced structural concepts for hypersonic vehicle applications
  - Ground test techniques to obtain data that validates structural performance and analysis techniques for design optimization
  - Sensor technology to acquire structural data subjected to hypersonic conditions for analysis validation and design optimization
  - A knowledge base for the technical community