Development and Ground-Test Validation of Fiber Optic Sensor Attachment Techniques for Hot Structures Applications

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Outline

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Background
Flight Loads Laboratory (FLL)

A unique laboratory for performing large-scale structural and thermal testing of aerospace vehicles and components

- Large 20,000 ft² high-bay test area
- Structural loading equipment including load frames, load cells, and hydraulic actuators
- Thermal structural testing in air and nitrogen purged atmospheres
- Quartz lamp and graphite heating systems
- Large channel capacity data acquisition system
- Strain, temperature, and heat flux measurements on metallics, metal matrix composites, superalloy honeycomb, C/C, C/SiC, etc.
- Sensor attachment techniques include epoxy, ceramic cements and thermal-spraying
- Fiber optic strain and temperature validation testing for ground and flight operations
Background

Hot-Structures Strain Measurement Research

1960-1970
Flame-sprayed Resistive

1980-1990
Weldable Resistive

2000-present
Weldable Capacitive

Improved measurement accuracy applying Silica and Sapphire EPFI Technology

Improved temperature-compensation using flame-sprayed resistive gages

Large temperature-related measurement uncertainties

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Research Motivation
Need for Sensor Development

Lack of Capability
- Hot structures are utilizing advanced materials that operate at temperatures that exceed our ability to measure structural performance
- Robust strain sensors that operate accurately and reliably beyond 1800°F do not exist

Implication
- Hinders ability to validate analysis and modeling techniques
- Hinders ability to optimization structural designs
Objectives

Develop Attachment Techniques
- Develop methods of handling fragile silica sensors during installation and coarse thermal spray processes
- Evaluate organic cement/epoxy attachments to 550°F
- Develop and evaluate thermal spray and cement attachments of EFPI’s for controlled laboratory testing

Obtain Optical Strain Measurements on Relevant Substrate Materials and Structures
- Graphite composite coupons for apparent strain ($\varepsilon_{\text{app}}$) characterization
- Monolithic Inconel load bars for baseline sensitivity characterization
- C-C and C-SiC substrates for sensitivity and $\varepsilon_{\text{app}}$ characterization
- Large scale hot-structures for NGLT, OSP, and X-37 Control Surfaces
Fiber Bragg Grating (FBG)

Sensor and Multiplexing

SM Polyimide Coated Fiber
125µm dia, 9µm core, 1550nm

Unstrained

Reflected λ

Tensile Load

Reflected λ

2 x 1 Coupler

Diode Tunable Laser

BBR

Strain (µε)
(δλ/λ) x 0.725

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Cavity Length ($L_C$), distance (microns) separating the two reflecting fiber surfaces

Gage Length ($L_G$), or sensitivity, distance (millimeters) separating the two points that attach the optical fiber to the substrate

Strain = $\Delta L_C / L_G$

where $L_G$ (or GF) = $\left[ 2(INAP) + OAP \right] / 3$

$$\varepsilon_{app} = (\alpha_{sub} - \alpha_{fiber}) \times \Delta T$$
Extrinsic Fabry Perot Interferometer (EFPI)

Fiber Optic Signal Conditioning

EFPI Delta Rosette on C-SiC
Installation and Attachment Techniques
Organic Cements (<550°F)

Two applications of MB610 sufficiently coat fiber

- Bonded FBG’s
- Type-K TC
- Refrasil Overbraid

Polyimide coated EFPI bonded with mixture of GA-61 and MB610
Installation and Attachment Techniques
Thermal Spray Process

Thermal Spray Equipment Room
- 80KW Plasma System
- Rokide Flame-Spray System
- Powder Spray System
- Sand-Blast Cabinet
- Micro-Blast System
- Water Curtain Spray Booth
Installation and Attachment Techniques
Thermal Spray Process (>600°F)

- Nextel Overbraid
- Ceramic Cement
- Plasma/Rokide Basecoat
- Gold Coated
- 8.5mm
- Quartz Tube
- Rokide Flame Spray
- Plasma Spray (4 mils)

Sensor-head fabrication under microscope
Laboratory Coupon Test Results
Fiber Bragg Gratings

FBG on Graphite/Epoxy Composite

Thermal Out (unbonded) = \((\alpha_{\text{fiber}} + \xi / P_e) \times \Delta T\)

where:
- Thermal Optic Effect \((\xi) = 3.78 \ \mu\varepsilon/F\)
- Strain Optic Constant \((P_e) = 0.725\)

\[
y = 0.0044x^2 + 3.6664x - 302.93
\]
Laboratory Coupon Test Results
Thermal / Mechanical Test Fixture

Constant Strain Load Bar

Strain Gage Evaluation System

Clamping Beam

Side B Loading

13in.

Loading Mandrels

B-Side Loading

A-Side Loading

LVDT’s Extensions

Load Bar

TOP VIEW
Laboratory Coupon Test Results
Gold-Coated EFPI Thermal Mechanical Test Results

EFPI Cantilever Beam Data at Room-Temp
±1000µε Mechanical Load

- Observations
  - EFPI within 3% of SG’s at RT
  - After standoff correction sensors within 1%
  - Subsequent testing at 500, 800, & 1200°F within 3% of RT slope
  - Little hysteresis

Standoff Correction Factor

\[ K_0 = \frac{c}{c+S_0} = \frac{0.189}{0.189 + 0.0055} = 0.972 \]

where:
- \( c \) = Distance from Neutral axis
- \( S_0 \) = Distance from centerline of fiber (in tube) to substrate

FS2000 Settings:
- Extended Range: ON
- Gap Limit: OFF
- Sample Interval: 100ms
- Analog Out: On (1:0.1)
Observations:
- In tension, output was noisy, sensor gap out of range (gap ≈ 203µm @14,450µε)
- Overall slope down 5% from RT slope @ 1600°F
- Repeat RT tests showed good correlation with prior data
- Subsequent sensors and tests indicate an inconsistency of maximum gap readability.

EFPI Cantilever Beam Data at 1600 °F

±1000 µε Mechanical Load

Strain vs. Time

Uncorrected Raw Data

RT

1600°F C2

Linear (RT)

Linear (1600°F C2)
Laboratory Coupon Test Results
Metalllic Dilatometer Results

EFPI on Inconel to 1650 °F

Heating rate: 7.2 °F/min
Coupon Substrate: IN601
File: LC2a900C1

Coupon (dL/L)
EFPI 3
EFPI 4
Dev EFPI3
Dev EFPI4

Strain (ue)
Dev from Coupon Expansion

+ 2.1 %
- 1.2 %
Laboratory Coupon Test Results
Dilatometer Results

EFPI Thermal Sprayed to C-C and C-SiC

Dilatometer Evaluation System

Sensor Characterization
- Evaluate bond integrity
- Evaluate sensitivity and accuracy
- Evaluate sensor-to-sensor scatter and repeatability
- Generate $\varepsilon_{app}$ correction curves
Large Scale Ground Test Structures
C-SiC Flaperon
Large Scale Ground Test Structures

Ceramic Composite Control Surfaces

2000°F
C/C Control Surface
March, 2003

2500°F
X-37 C/C Flaperon Qual Unit
August, 2005

2100°F
C/SiC Body Flap
Nov, 2003

2400°F
X-37 C/SiC Flaperon Subcomponent
May, 2004

2300°F
X-37 C/C Flaperon Subcomponent
August, 2004

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Concluding Remarks

Fiber Optic Strain Measurements
- Successfully attached silica fiber optic sensors to both metallics and composites
- Accomplished valid EFPI strain measurements to 1850°F
- Successfully attached EFPI sensors to large scale hot-structures
- Attached and thermally validated FBG bond and $\varepsilon_{\text{app}}$

Future Development
- Improve characterization of sensors on C-C and C-SiC substrates
- Apply application to other composites such as SiC-SiC
- Assist development of interferometer based Sapphire sensor currently being conducted under a Phase II SBIR
- Complete combined thermal/mechanical testing of FBG on composite substrates in controlled laboratory environment