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
Weldable Resistive
Weldable Capacitive
Large temperature-related measurement uncertainties

1980-1990
Improved temperature-compensation using flame-sprayed resistive gages

2000-present
Improved measurement accuracy applying Silica and Sapphire EFPI Technology

NASP
X-33
X-37
CEV

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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

Tensile Load

Reflected λ

Strain (με)
(δλ/λ) x 0.725

Diode Tunable Laser

BBR

2 x 1 Coupler

Unstrained

Reflected λ

E

IFFT

E

FFT

Freq / Dist

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Extrinsic Fabry-Perot Interferometer (EFPI)
Sensor Construction

- **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

\[
\text{Strain} = \frac{\Delta L_C}{L_G}
\]
where $L_G$ (or GF) = \[
\frac{2(IAP) + OAP}{3}
\]

\[
\varepsilon_{app} = (\alpha_{sub} - \alpha_{fiber}) \Delta T
\]
Extrinsic Fabry Perot Interferometer (EFPI) Sensor Conditioning

EFPI Delta Rosette on C-SiC

Fiber Optic Signal Conditioning

Power Splitter

BB Optical Source

Signal Processor

CCD

Lens

Mini Spectrometer

Diffraction Grating
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
- 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) = (\( \alpha_{\text{fiber}} + \frac{\xi}{P\varepsilon} \)) * \( \Delta T \)

where:

Thermal Optic Effect (\( \xi \)) = 3.78 \( \mu \varepsilon / F \)
Strain Optic Constant (\( P\varepsilon \)) = 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

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

**EFPI Cantilever Beam Data at Room-Temp**

\[ \pm 1000\mu\varepsilon \text{ Mechanical Load} \]

**Standoff Correction Factor**

\[ K_0 = \frac{c}{(c+S_o)} = 0.189 / 0.189 + 0.0055 = 0.972 \]

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

**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
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
Laboratory Coupon Test Results
Metallic Dilatometer Results

EFPI on Inconel to 1650 °F

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

Coupons:
- EFPI 3: Dev EFPI 3 = 2.1%
- EFPI 4: Dev EFPI 4 = 1.2%

Strain vs. Temp

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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 $\varepsilon_{\text{app}}$ correction curves

4 Hi-Temp EFPI’s in Sampleholder

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Large Scale Ground Test Structures
C-SiC Flaperon

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Large Scale Ground Test Structures
Ceramic Composite Control Surfaces

2000°F
C/C Control Surface
March, 2003

2100°F
C/SiC Bodyflap
Nov, 2003

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

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

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