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

Anthony Piazza, Larry D. Hudson, and W. Lance Richards

NASA Dryden Flight Research Center
Edwards, CA

SensorsGov Expo and Conference
Hampton Roads Convention Center
Hampton, VA
December 6-8, 2005
Outline

- Background
- Research Motivation
- Objectives
- Sensor Overview
  - Fiber Bragg Grating
  - Extrinsic Fabry-Perot Interferometer
- Sensor Attachment Techniques
- Laboratory Validation Testing
- Large-Scale Ground Applications
- Concluding Remarks
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
Dryden Flight Research Center

**Background**

**Hot-Structures Strain Measurement Research**

- **1960-1970**
  - Flame-sprayed Resistive
  - Weldable Resistive

- **1980-1990**
  - Weldable Capacitive

- **2000-present**
  - Improved measurement accuracy applying Silica and Sapphire EFPI Technology
    - Improved temperature-compensation using flame-sprayed resistive gages

**Large temperature-related measurement uncertainties**

**NASP**

**X-33**

**X-37**

**CEV**
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

Strain (µε)
(δλ/λ) x 0.725

Tensile Load

Diode Tunable Laser

2 x 1 Coupler

Unstrained

Reflected λ

Freq / Dist

Strain (µε)

IFFT

Diode Tunable Laser

BBR

E

IFFT

E

FFT

Dryden Flight Research Center
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

Strain = $\frac{\Delta L_C}{L_G}$

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

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

EFPI Delta Rosette on C-SiC

Fiber Optic Signal Conditioning

BB Optical Source

Signal Processor

Power Splitter

CCD

Lens

Mini Spectrometer

Diffraction Grating
Installation and Attachment Techniques

Organic Cements (<550°F)

Two applications of MB610 sufficiently coat fiber

Polyimide coated EFPI bonded with mixture of GA-61 and MB610

Bonded FBG’s

Type-K TC

Refrasil Overbraid

4-inches
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
- Gold Coated
- Plasma/Rokide Basecoat
- 8.5mm
- Quartz Tube
- Rokide Flame Spray
- Plasma Spray (4 mils)

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

\[ y = 0.0044x^2 + 3.6664x - 302.93 \]

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

where:

- **Thermal Optic Effect** \((\xi) = 3.78 \mu\epsilon/F\)
- **Strain Optic Constant** \((P_e) = 0.725\)

FBG on Graphite/Epoxy Composite

Heating/Cooling Rate: 0.5°F/sec

Bonded to substrate
Not bonded to substrate
Free in air (off coupon)
Laboratory Coupon Test Results

Thermal / Mechanical Test Fixture

Strain Gage Evaluation System

Constant Strain Load Bar

Dryden Flight Research Center
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

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

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)
Laboratory Coupon Test Results

Thermal Mechanical Test Results

EFPI Cantilever Beam Data at 1600 °F
±1000 µε Mechanical Load

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

Strain vs. Time

Dryden Flight Research Center
Laboratory Coupon Test Results
Metallic Dilatometer Results

EFPI on Inconel to 1650 °F

- Heating rate: 7.2 °F/min
- Coupon Substrate: IN601

Strain (ue)
Dev from Coupon Expansion

+ 2.1 %
- 1.2 %
Laboratory Coupon Test Results

Dilatometer Results

Sensor Characterization
- Evaluate bond integrity
- Evaluate sensitivity and accuracy
- Evaluate sensor-to-sensor scatter and repeatability
- Generate $\varepsilon_{app}$ correction curves

EFPI Thermal Sprayed to C-C and C-SiC

Dilatometer Evaluation System

4 Hi-Temp EFPI’s in Sampleholder
Large Scale Ground Test Structures

C-SiC Flaperon

Dryden Flight Research Center
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

Dryden Flight Research Center
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 $\varepsilon_{app}$

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