Real-time In-Flight Strain and Deflection Monitoring with Fiber Optic Sensors

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Space Sensors and Measurements Techniques Workshop
Nashville, TN
August 5, 2008
Background

• Dryden’s Aerostructures Branch initiated fiber-optic instrumentation development effort in the mid-90’s
  – Dryden effort focused on atmospheric flight applications of Langley patented OTDR demodulation technique
• Dryden collaborated on X-33 IVHM Risk Reduction Experiment on F/A-18 System Research Aircraft
  – Focused on validating Lockheed Sanders FO VHM system
    • Flew fiber optic instrumented flight test fixture with limited success due to problem with laser
  – Lockheed Sanders system limited to 1 sample every 30 seconds
• Dryden initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight
Fiber Optic System Operation Overview

Fiber Optic Sensing with Fiber Bragg Gratings

- Immune to electromagnetic / radio-frequency interference and radiation
- Lightweight fiber-optic sensing approach having the potential of embedment into structures
- Multiplex 100s of sensors onto one optical fiber
- Fiber gratings are written at the same wavelength
- Typical gage lengths from 0.1mm to 100mm
- Uses a narrowband wavelength tunable laser source to interrogate sensors
- Typically easier to install than conventional strain sensors

\[ I_R = \sum_i R_i \cos(k2nL_i) \]

\[ k = \frac{2\pi}{\lambda} \]

- \( I_R \) – spectrum of \( i^{th} \) grating
- \( n \) – effective index
- \( L \) – path difference
- \( k \) – wavenumber

![Diagram of Fiber Optic Sensing with Fiber Bragg Gratings](image)
Fiber Optic System Operation Overview

- Fourier transforms (both forward and inverse) are used to discriminate between gratings
- The Fourier transform separates the $I_R$ waveform into sinusoids of different frequency which sum to the original waveform

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<thead>
<tr>
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<th>FFT</th>
<th>iFFT</th>
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<td>Traditional</td>
<td>Time(T) &gt; Frequency(F)</td>
<td>Frequency(F) &gt; Time(T)</td>
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<tr>
<td>Optical</td>
<td>Wavelength($\lambda$) &gt; Length(L)</td>
<td>Length(L) &gt; Wavelength($\lambda$)</td>
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Spectral Mapping

- Wavelength($\lambda$) domain
- Length(L) domain
Fiber Optic System Operation Overview

- By bandpass filtering around a specific frequency (grating location) within the length domain and performing an iFFT, the spectrum of each grating can be independently measured and strain inferred (FM radio).

- Using a centroid function the center wavelength can be resolved.

- The wavelength change is proportional to the induced strain:

\[
\frac{\Delta \lambda}{\lambda} = K \varepsilon
\]

\( K \) – proportionality constant (0.7-0.8)
Motivation – Helios Mishap

Helios wing dihedral on takeoff

In-flight breakup

Helios Mishap Report – Lessons Learned

• Measurement of wing dihedral in real-time should be accomplished with a visual display of results available to the test crew during flight

• Procedure to control wing dihedral in flight is necessary for the Helios class of vehicle
Wing Shape Sensing Background

• Current Wing Displacement Techniques
  – Optical Methods (Flight Deflection Measurement System)
    • 1980s - Highly Maneuverable Aircraft Technology (HiMAT)
    • 2000s - F/A-18 Active Aeroelastic Wing (AAW)
  – Strain Gage Approaches

• Limitations
  – Current techniques utilize approaches that are too heavy and not appropriate for weight-sensitive, highly-flexible structures
Research Objectives for Ikhana

- Flight validate fiber optic sensor measurements and real-time wing shape sensing predictions on NASA’s Ikhana vehicle (FY08)

- Validate fiber optic mathematical models and design tools (FY08)

- Assess technical viability and, if applicable, develop methodology and approach to incorporate wing shape measurements within the vehicle flight control system (FY08-FY09)

- Develop and flight validate advanced approaches to perform active wing shape control using
  - conventional control surfaces (FY09-FY10)
  - active material concepts (FY09-FY11+)
Research Areas

– Algorithm Development

– FBG System Development

– Instrumentation

– Ground Testing

– Flight Testing
Algorithm Development (Ikhana)

Ikhana Wing Geometry

Analytical Models

\[ y_i = \frac{(\Delta)^2}{6} \sum_{j=1}^{i} \left[ \frac{1}{c_{j-1}} \left( 3(j-1) - (3j-2) \frac{c_{j-1}}{c_{j}} \right) \right] c_{j}^{i-j} + (3j-2)c_{j-i}^{i-j} + y_0 + i \Delta \tan \theta_0 \]

\( i = 1, 2, 3, \ldots, n \)

Computational Models

Analytical/Comp. Comparison

- Algorithm (Leading-edge Fiber)
- FEA (LE fiber)
- Algorithm (Trailing-edge fiber)
- FEA (TE fiber)
Ikhana Fiber Optic Flight System

• Current flight system specifications
  – Fiber count 4
  – Max fiber length 40 ft
  – Max sensing length 20 ft
  – Max sensors / fiber 480
  – Total sensors / system 1920
  – Sample rate 2 fibers @ 50 sps
    4 fibers @ 24 sps
  – Power 28VDC @ 4 Amps
  – User Interface Ethernet
  – Weight (non-optimized) 23 lbs
  – Size (non-optimized) 7.5 x 13 x 13 in

• Environmental qualification specifications
  – Shock 8g
  – Vibration 1.1 g-peak sinusoidal curve
  – Altitude 60kft at -56C for 60 min
  – Temperature -56 < T < 40C
Flight Instrumentation

- **Instrumentation**
  - 2880 FBG strain sensors (1920 recorded at one time)
  - 1440 FBG sensors per wing
  - User-selectable number of FBG sensors for real-time wing shape sensing
  - 16 strain gages for FBG sensor validation
  - 8 thermocouples for strain sensor error corrections
Ground Test Validation - Ikhana

• Ground validation testing
  – Conducted ground validation testing January 16-18, 2008
  – Used Dryden’s high resolution / high speed optical measurement system as validation standard
  – 10 measurement stations placed on left wing (1 on center fuselage)
  – Five load cases applied
  – Good agreement between FOWSS and optical system

Left wing – aft view

Left wing – inboard view
Flight Test Validation - Ikhana

• Flight validation testing
  – Conducted first flight validation testing April 28, 2008
  – Believed to be the first flight validation test of FBG strain and wing shape sensing
  – Multiple flight maneuvers performed
  – FOWSS system performed well throughout entire flight – no issues
  – Data reduction and correlation on going

Video clip of flight data (from taxi to take-off) superimposed on Ikhana photograph
Concluding Remarks

- **Fiber Optic Wing Shape Sensing on Ikhana involves five major areas**
  - Algorithm development
    - Local-strain-to-displacement algorithms have been developed for complex wing shapes for real-time implementation (NASA TP-2007-214612, patent application submitted)
  - FBG system development
    - Dryden advancements to fiber optic sensing technology have increased data sampling rates to levels suitable for monitoring structures in flight (patent application submitted)
  - Instrumentation
    - 2880 FBG strain sensors have been successfully installed on the Ikhana wings
  - Ground Testing
    - Fiber optic wing shape sensing methods for high aspect ratio UAVs have been validated through extensive ground testing in Dryden’s Flight Loads Laboratory
  - Flight Testing
    - Real time fiber Bragg strain measurements successfully acquired and validated in flight (4/28/2008)
    - Real-time fiber optic wing shape sensing successfully demonstrated in flight

- **Current Status**
  - Dryden FOWSS system successfully qualified for Predator-B flight environment
  - FOWSS system currently installed on Ikhana aircraft
  - Flights being conducted from April - May 2008
Backup Slides
Dryden Fiber Optic System

- **Current ground system specifications**
  - Fiber count: 4
  - Max. fiber length: 40 ft
  - Max sensing length: 20 ft
  - Max. sensors / fiber: 480
  - Total sensors per system: 1920
  - Min. grating spacing: 0.5 in
  - Sample rate: 2 fibers @ 50 sps
    - 4 fibers @ 24 sps
  - Interface: Gigabit Ethernet
  - Power: 120 VAC
  - Weight: 12 lbs
  - Size: 9 x 5 x 11 in