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

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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

\[ I_R = \sum_i R_i \cos(k2nL_i) \quad k = \frac{2\pi}{\lambda} \]

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

\[ \left( \begin{array}{c} c \end{array} \right) \]

\[ \left( \begin{array}{c} \text{Laser tuning} \\ \text{Grating region} \\ \text{Tuning direction} \end{array} \right) \]

\[ \left( \begin{array}{c} \text{start} \\ \lambda \end{array} \right) \]

\[ \left( \begin{array}{c} \text{stop} \end{array} \right) \]

\[ \left( \begin{array}{c} \text{Laser light} \\ \text{Reflected light} (I_R) \end{array} \right) \]

\[ \left( \begin{array}{c} \text{Loss light} \end{array} \right) \]

\[ \left( \begin{array}{c} \text{L1} \\ \text{L2} \\ \text{L3} \end{array} \right) \]
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.

<table>
<thead>
<tr>
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<th>FFT</th>
<th>iFFT</th>
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<tr>
<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

\[ y_n = \frac{\Delta l^2}{6c} \left\{ (3n-1)\varepsilon_0 + 6 \sum_{i=1}^{n-1} (n-i)\varepsilon_i + \varepsilon_n \right\} \]
Algorithm Development (Ikhana)

Ikhana Wing Geometry

Analytical Models

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

(i = 1, 2, 3, ..., 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
  – 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 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
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