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

Dr. Lance Richards, Allen R. Parker, Dr. William L. Ko, Anthony Piazza
Dryden Flight Research Center, Edwards, CA
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

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

R_i – spectrum of i\textsuperscript{th} grating
n – effective index
L – path difference
k – wavenumber
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>
<th></th>
<th>FFT</th>
<th>iFFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>Time(T) &gt; Frequency(F)</td>
<td>Frequency(F) &gt; Time(T)</td>
</tr>
<tr>
<td>Optical</td>
<td>Wavelength($\lambda$) &gt; Length(L)</td>
<td>Length(L) &gt; Wavelength($\lambda$)</td>
</tr>
</tbody>
</table>

Spectral Mapping

- Wavelength($\lambda$) domain
- Length(L) domain

FFT
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

\[ y_i = \frac{(\Delta)^2}{6} \sum_{j=1}^{n} \frac{1}{c_j} \left[ 3(2j-1) - (3j-2) \frac{1}{c_{j-1}} \frac{c_{j-1}}{c_{j-1}} \right] + y_{0} + i\Delta \tan \theta_{0} \]

(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
    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

Optical targets
**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