Fiber Optic Wing Shape Sensing on NASA’s Ikhana UAV

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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
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

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

Helios Main Spar

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

Pure Torsion
\[ \phi_i = \frac{\Delta l}{c} \sum_{n=0}^{i-1} 2(1 + \nu)\varepsilon_i^p \]

Combined Bending and Torsion
\[ \bar{\varepsilon}_i = \frac{\varepsilon_i}{\cos \phi_i \cos \gamma_i} \]
Algorithm Development (Ikhana)

Ikhana Wing Geometry

Analytical Models

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

Computational Models

Analytical/Comp. Comparison

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

- **Original Fiber-Optic Ground System (2004)**
  - 3 components (CPU, FOID Box, and 19” rack mount laser)
  - Laser physical specifications: 17”W x 18”L x 5”H
  - Max. 2.5 sps (limited by laser tuning rate)
  - Single fiber system, with 100s of sensors
  - Laser cost: $45K
  - *Total system weight – approx. 44 lbs.*

- **Pathfinder Plus Flight System (2006)**
  - 1 component (8”W x 6”L x 6”H)
  - Laser physical specifications: 2”W x 3”L x 0.5”H
  - Laser integrated within PC stack
  - Approx. 1 sps (limited by the laser tuning rate)
  - Two fiber system, 960 sensors over two 40-ft sections
  - Accuracy: 3-5% of surface mounted strain gages
  - Laser cost: $10K
  - *Total system weight - < 5 lbs.*
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 @ 36 sps
    4 fibers @ 22 sps
  – Power 28VDC @ 4 Amps
  – User Interface Ethernet
  – Weight 23 lbs
  – Size 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
  - Select optimal 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 – Pathfinder Plus

Ground test setup

Test Results

Tip Deflection (in.)

Load (lbs.)

-7  -6  -5  -4  -3  -2  -1  0

Fiber Optics  Laser  Potentiometer
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
  - *Preliminary* agreement with FOWSS ~ 6%
  - Data reduction process on-going
Concluding Remarks

• Fiber Optic Wing Shape Sensing on Ikhana involves four 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

• Current Status
  – Dryden FOWSS system successfully qualified for Predator-B flight environment
  – FOWSS system currently being installed on Ikhana aircraft
  – Flights currently planned from February to April 2008
Backup Slides
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

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

Laser tuning
Grating region

Tuning direction

\( R_i \) – spectrum of \( i \)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

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<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)
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 @ 36 sps
    4 fibers @ 22 sps
  - Interface: Gigabit Ethernet
  - Power: 120 VAC
  - Weight: 12 lbs
  - Size: 9 x 5 x 11 in