Evaluation of Wing Load Calibration and Sensing Methods Using Conventional Strain Gages and a Fiber Optic Sensing System Installed on a Straight Tapered Wing

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Outline

• Introduction
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  • Linear Regression Methods
  • Operational Loads Estimation Algorithm
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Introduction

• Reasons for monitoring structural loads
  1. Airworthiness Clearance – Confidence in the loads for envelope clearance, do the loads match predictions?
  2. Health Monitoring – Insight into the operational loads environment allows for more informed inspections and maintenance decisions
  3. Structural Load Alleviation – Reducing the internal loading during maneuvers or gust encounters provide protection against structural overload
  4. Structural Optimization / Model Validation – New structures are being developed and the models need to be validated in relevant environments
  5. Aerodynamic Model Validation – The measured structural loads with inertial correction can be used to validate computational fluid dynamic (CFD) models

• It is important to understand what information is required before selecting the sensors and load monitoring methodology
Introduction

• New instrumentation techniques have been developed that allow a much greater number of sensors to be monitored thus allowing greater insight into the structural response of structures in-flight

• A straight tapered wing with 30ft semi span was instrumented with both conventional strain gages and fiber optic strain sensors

• A conventional loads calibration was conducted on the wing, known loads were applied to the wing and strain gage and fiber optic strain sensor data was recorded

• The loads test program was named the Calibration Research Wing or CREW Loads Test, it also served as a pathfinder for the Passive Aeroelastic Tailored Wing Testing
Historical Examples

X-29 Forward Swept Wing Aircraft

F-18 Active Aeroelastic Wing (AAW)
Structural Sensing Methods

• Methods discussed in this presentation:
  • Linear regression methods
  • Operational Loads Estimation Algorithm

• Other Methods:
  • Photogrammetry
  • Flight calibration methods
  • Finite element methods
Structural Load Sensing Scheme

Conventional scheme (strain gages located at a single spanwise station) provides ability to monitor loads at single spanwise station.

Fiber optic strain sensors provide the ability to monitor loads along the entire wing span providing multiple load measurement stations.
Methods – Linear Regression

- Strain gage, fiber optic strain sensing, and load data is collected during three load cycles
- The linear portion of cycle 2 or 3 (green arrow) is taken from the dataset for calibration

<table>
<thead>
<tr>
<th>Load measurement</th>
<th>Applied load</th>
<th>Gage A output</th>
<th>Gage B output</th>
<th>Gage C output</th>
<th>Gage D output</th>
<th>...</th>
<th>Gage n output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$V_1$</td>
<td>$\mu_{1,A}$</td>
<td>$\mu_{1,B}$</td>
<td>$\mu_{1,C}$</td>
<td>$\mu_{1,D}$</td>
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<td>$\mu_{1,n}$</td>
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<td>2</td>
<td>$V_2$</td>
<td>$\mu_{2,A}$</td>
<td>$\mu_{2,B}$</td>
<td>$\mu_{2,C}$</td>
<td>$\mu_{2,D}$</td>
<td>...</td>
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</tr>
<tr>
<td>3</td>
<td>$V_3$</td>
<td>$\mu_{3,A}$</td>
<td>$\mu_{3,B}$</td>
<td>$\mu_{3,C}$</td>
<td>$\mu_{3,D}$</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$m$</td>
<td>$V_m$</td>
<td>$\mu_{m,A}$</td>
<td>$\mu_{m,B}$</td>
<td>$\mu_{m,C}$</td>
<td>$\mu_{m,D}$</td>
<td>...</td>
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- Example: 3-gage equation that uses gages A, C, and D and shear load $V$

- The least squares solution for the coefficients $\beta$ can then be found
Methods – Operational Loads Estimation Algorithm

- Moment-strain relationship of the classical beam
  \[
  \frac{d^2 z(y)}{dy^2} = \frac{M(y)}{E(y)I(y)}
  \]

- Bending stress and normal stress strain relationship

  \[
  \sigma_{upper}(y) = \frac{M(y) \cdot c_{upper}(y)}{I(y)} = E(y) \cdot \varepsilon_{upper}(y) \quad \Rightarrow \quad \frac{M(y)}{E(y)I(y)} = \frac{\varepsilon_{upper}(y)}{c_{upper}(y)}
  \]

- Distance to the neutral axis

  \[
  c_{upper}(y) = \frac{h(y) \cdot \varepsilon_{upper}(y)}{\varepsilon_{lower}(y) - \varepsilon_{upper}(y)}
  \]

- Section properties of the beam structure

  \[
  E(y)I(y) = M(y) \cdot \frac{h(y)}{\varepsilon_{lower}(y) - \varepsilon_{upper}(y)}
  \]

- A single load case is applied to the wing to calculate the section EI properties

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Methods – Operational Loads Estimation Algorithm

- The bending moment can be calculated by knowing the strains and section properties
  \[ M(y) = E(y)I(y) \cdot \frac{\varepsilon_{lower}(y) - \varepsilon_{upper}(y)}{h(y)} \]

- Integrating moment strain relationship to calculate slope
  \[ \frac{\partial z}{\partial y} = \tan(\phi) \approx \phi_n = \phi_0 + \sum_{i=1}^{n-1} \left( \frac{M}{EI}_i + \frac{M}{EI}_{i+1} \right) \frac{\Delta L}{2} \]

- The displacement can be determined by integrating the slope
  \[ Z_n = Z_0 + \sum_{i=1}^{n} \sin(\phi_i) \cdot \Delta L_i \]

- Using small angle approximation \( \sin \phi \approx \phi \), the calculation for vertical displacement becomes
  \[ Z_{OLEA} = Z_0 + \sum_{i=1}^{n} \phi_i \cdot \Delta L_i \]
Methods - Operational Loads Estimation Algorithm

- **Initial Values:**
  - The wing displacement $Z_{OLEA}$ is calculated based on section properties and strains
  - Initial guess for shear load ($V_{Model}$) is provided

- The shear load ($V_{Model}$) is integrated 3 times to get a wing displacement ($Z_{Model}$)

- The $Z_{Model}$ is compared to the $Z_{OLEA}$
  - If $Z_{Model}$ is not within an error threshold, the $V_{Model}$ is multiplied by a correction factor and the model integration loop is repeated
  - If $Z_{Model}$ is within the error threshold
    - $V_{OLEA}$ and $M_{OLEA}$ are then calculated
Test Article – Instrumentation

- Foil strain gages
  - 5 spanwise stations with eight full-bridges per station
  - Eight internal full-bridge gages
  - 14 quarter-bridge gages co-located along optical fibers
Test Article – Instrumentation

Leading edge

Internal strain gage layout

Spar

Gage orientation
spar inner surface
Test Article – Instrumentation

- Fiber Optic Strain Sensing
  - Eight optical fibers installed on upper and lower surfaces
  - Each spar has a fiber on the upper and lower surfaces
  - Fiber along the 40% chord on upper and lower surfaces
  - Saw-tooth pattern on the upper and lower surfaces
Test Article – Instrumentation
Locating Instrumentation

- Laser scan of instrumentation locations was conducted and resulting points were transferred into a FEM model
Load Cases – Bending Torque Plot

![Bending Torque Plot](image)

Legend:
- Cases 2 to 19 Point Loads
- Cases 20 to 36 Distributed Loads
- Cases 37 to 40 Check Cases
- Case 30
- Case 37
- Case 40
Load Cases – Shear, Bending and Torque

Shear Plot

Bending Plot

Torque Plot

Cases 2 to 19 Point Loads
Cases 20 to 36 Distributed Loads
Cases 37 to 40 Check Cases
Test Results

• Result Cases:

<table>
<thead>
<tr>
<th>Method</th>
<th>Calculated loads</th>
<th>Calibration cases</th>
<th>Check cases</th>
<th>Instrumentation</th>
</tr>
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<tr>
<td>Linear regression</td>
<td>Shear, bending, and torque</td>
<td>Point load cases 2-19</td>
<td>Load case 37 and 40</td>
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<td>OLEA – shape method</td>
<td>Shear and bending</td>
<td>Load case 30</td>
<td>Load case 37 and 40</td>
<td>FOSS</td>
</tr>
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• Error Analysis:

\[
ERMS = 100 \times \sqrt{\frac{\sum_{j=1}^{m} (x'_j - x_j)^2}{\sum_{j=1}^{m} x_j^2}}
\]

What target errors should we expect for our high aspect ratio straight tapered wing?
• Shear: <5%
• Bending: <5%
• Torque: <20%
Comparison of Methods
Comparison of Methods

Torque Plot - Load Case 37

Torque Plot - Load Case 40

ERMS error, percent

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Comparison of Methods
Summary

• The project requirements for load monitoring play a key role in determining which sensor and calibration method should be used.
• Fiber optic measurement techniques allow for a greater number of strain sensors to be installed.
• One conventional approach and two new approaches were presented for deriving sensing loads on a straight wing:
  • Linear regression using metallic foil strain gages
  • Linear regression using FOSS
  • Operational Loads Estimation Algorithm using FOSS
• Linear regression techniques can work with FOSS sensors for deriving a distributed load along the wing span resulting in a greater number of load measurement stations.
• New methods such as the OLEA can provide an efficient method for monitoring distributed wing shear loads using only external surface strains:
  • Method only requires one calibration load case, thus simplifying the load calibration test.
Backup
## Load Sensing Recommendations for a High Aspect Ratio Wing

<table>
<thead>
<tr>
<th>Load type</th>
<th>Recommended sensor</th>
<th>Strain sensor orientation and location</th>
<th>Recommended number of load cases</th>
<th>Recommended calibration method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear – single wing station</td>
<td>Conventional strain gages</td>
<td>Shear rosette located on shear web Axial strain sensor located on spar caps</td>
<td>Number of load cases &gt; number of strain sensors in the equation</td>
<td>Linear regression</td>
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Discussion – Strain Gage vs FOSS Installation

• Metallic Foil Strain Gages
  • A lot of previous heritage from past projects
  • Full bridge provides built-in temperature compensation
  • A requirement for only a small number of strain sensors are most likely best handled by strain gages

• Fiber Optic Strain Sensors
  • Capability to be multiplexed serially allowing for multiple spanwise measurements on one fiber
  • Lightweight for number of strain sensors compared to weight of similar number of strain gages
  • Hermetically coated glass is chemically inert, not susceptible to corrosion, and does not have potential for ground loops, electrical faults, sparking, or Joule heating. These sensors also are not negatively impacted like common aircraft avionics systems with reactions to Electro-Magnetic Interference (EMI) or Electro-Magnetic Pulses (EMP).
  • Fiber can be installed much quicker than strain gages for equal number of sensors
  • Fiber is much better suited to open areas and may be much better suited to observing large global effects than strain gages
  • Fiber is much better suited for buckling than strain gages