Using virtual strain gauges to correlate with bending and torsion measured on a helicopter tail cone using strain gauges.

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Abstract

This paper describes the use of virtual strain gauges in order to correlate a full scale structural test of a helicopter with a finite element model. It focuses on the correlation of bending and torsion moments in the tail cone. These arise from lateral loads applied at the tail.

Introduction

Strain gauges have been used successfully for many years to measure direct strains in a local area. By combining several carefully located gauges in a Wheatstone Bridge, this analysis can be extended to measure the macroscopic loading applied to the structure in terms of bending and torsion moments. A typical Wheatstone Bridge configuration is illustrated in Figure 1.

This paper describes how groups of ‘virtual’ strain gauges are used in the context of a FE model to derive bending and torsion moments in the tail cone of a helicopter. Rather than correlating individual local strains, which are significantly affected by local stress concentrations and non-linear effects, this approach allows the correlation of the applied loads and moments. These measurements are often much cleaner and more intuitively recognisable by the engineer. The ‘virtual’ Wheatstone Bridge is modelled mathematically in the process and produces analysis output in terms of applied bending and torsion moments.

Virtual strain gauges have been available in commercial software packages since the 1990’s. FE post-processor packages such as nCode DesignLife have used this concept to recover strains at specified locations and compute fatigue lives in an approach analogous to traditional test-based fatigue analysis.

Test Structure Strain Gauge Configuration

A full Wheatstone Bridge configuration is used to measure bending and torsion as shown in Fig 1 [1]. In these configurations strain gauge 1 (SG1) is R1, SG2 is R2, etc; the bridge excitation voltage $V_{IN}$ is applied across (2) and (3), and the bridge output voltage $V_{OUT}$ (i.e. the bending or torsion moment), is measured across (1) and (4).

Finite Element Model Strain Gauge Configuration

Whereas the test structure was configured using full Wheatstone Bridges in all locations, the FE approach considers both half bridge (2 gauges) and full bridge (4 gauges). The FE model of the helicopter tail cone is shown in Fig 2 with virtual strain gauges applied using nCode DesignLife [2]. This shows forward and aft groups of strain gauges, measuring vertical bending, lateral bending and torsional shear. For clarity, only the half bridge strain gauge configuration is shown here.

The virtual strain gauge analysis process and results are shown in Fig 3. Results are normalised as a ratio of the measured experimental results in order to conceal the real values for purposes of confidentiality.
Results show satisfactory agreement between measured loads and those estimated from the finite element model, particularly for higher lateral bending and torsion moments resulting from the lateral load applied at the tail. The table includes results for both full and half-bridge virtual strain gauge configurations. Differences between both sets of results are attributable to the sensitivity to strain gauge positions. The results for the half bridge are from virtual strain gauges at FE nodes points on the ‘original’ mesh (the regular rectangles in Fig 2) whereas strain gauge locations used in the full bridge analysis are located at FE nodes in a ‘refined’ mesh. This approach was used to determine mesh density effects. Generally we see that resulting forces and moments are insensitive to the local mesh density in the region of the strain gauges. A good load-transfer mesh is adequate for the purpose of this analysis.

The “FE & Excel” results were calculated manually by extracting FE node results and processing through an Excel spreadsheet. The manual approach involves considerable copying and pasting and is prone to user errors. The use of nCode DesignLife and the concept of virtual strain gauges has created a far more efficient and reliable process for correlating the finite element model with the test structure.

References
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9th International Conference on Advances in Experimental Mechanics
Agenda

• General finite element fatigue procedure

• Helicopter airframe with tail loads

• Virtual strain gauges

• Helicopter tail cone with strain gauges

• nCode DesignLife Analysis Process

• Results

• Conclusions
General Finite Element Fatigue Procedure

**Analysis Test**

**Finite Element Analysis**
- Static superposition
- Modal superposition
- Transient
- Non-linear time step
- Random vibration

**Damage Modeling**
- Stress-Life (S-N)
- Local strain (ε-N)
- Multiaxial
- Welds and spot welds
- Adhesive joints
- Bolted joints
- High temperatures
General Finite Element Fatigue Procedure

Load Time Histories

Local Stress Histories

Local Strain Histories

Rainflow Cycle Counting

Fatigue Analysis

Calculate stress for combined loads

$\sigma_A$

$\varepsilon_A$

Strain Range

Mean stress
Fatigue Life Contour Plots
Helicopter Airframe with Tail Loads

- Full Airframe Structural Test
- Many strain gauge measurements on the structure
  - Mostly single strain gauges (~100)
  - Some bending and torsion bridges (~10)
- Many static load cases
  - Individual loads (~20)
  - Combined loads (~1000)
- This considers 2 individual static loads
  - Tail vertical
  - Tail lateral
Each static load case is slowly loaded and unloaded (~1 hour per load case) and in 5% steps to 100% target load (with a long dwell at some steps: 30, 50, 65, 80, 90, 100)
Helicopter Airframe with Tail Loads

- Measured strain - from test data acquisition
- Predicted strain - from finite element results
- Excel spreadsheet setup to compare predicted finite element strain with measured strain
- Single strain gauges compared OK

...but having difficulty correlating the bending and torsion gauges
• Strain gauges configured as full bridges on the tail cone to measure bending and torsion
• The challenge is to correlate the finite element model with the measured bending and torsion strains
nCode DesignLife Virtual Strain Gauges

• The type of strain gauge can be:
  • Single, Tee, Rosette, and Delta

• The orientation can be controlled by:
  • XYZ Vector
  • 2 Nodes
  • Angle Offset
Helicopter Tail Cone with Strain Gauges

- Forward Gauges
  - Lateral Bending
  - Vertical Bending
  - Torsional Shear
- Aft Gauges
  - Lateral Bending
  - Vertical Bending
  - Torsional Shear
Forward Gauges

- Torsional Shear
- Lateral Bending
- Vertical Bending
Aft Gauges
Mesh Refinement Example

- **Forward Vertical Bending (Top)**
  - Full bridge configuration (4 gauges), at nodes on a refined mesh, as close as possible to their location on the real structure
  - Half bridge configuration (2 gauges), at nodes on the original coarse mesh
nCode DesignLife Analysis Process
nCode DesignLife Analysis Process

Strain Gauges - FEInput2

Current Gauges

<table>
<thead>
<tr>
<th>Gauge ID</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWD-Top-V-B-1</td>
<td>Single</td>
</tr>
<tr>
<td>FWD-Bot-V-B-2</td>
<td>Single</td>
</tr>
<tr>
<td>FWD-Stb-L-B-1</td>
<td>Single</td>
</tr>
<tr>
<td>FWD-Prt-L-B-2</td>
<td>Single</td>
</tr>
<tr>
<td>FWD-Top-T</td>
<td>Tee</td>
</tr>
<tr>
<td>AFT-Top-V-B-1</td>
<td>Single</td>
</tr>
<tr>
<td>AFT-Bot-V-B-2</td>
<td>Single</td>
</tr>
<tr>
<td>AFT-Stb-L-B-1</td>
<td>Single</td>
</tr>
<tr>
<td>AFT-Prt-L-B-2</td>
<td>Single</td>
</tr>
<tr>
<td>AFT-Top-T</td>
<td>Tee</td>
</tr>
</tbody>
</table>

- Save gauges
- Rotate model to selected gauge

Add... Delete Edit... Close Help
nCode DesignLife Analysis Process

Finite Element Results for 2 unit load cases
- Vertical
- Lateral
Load Sequence
(#1) Vertical 100%, Lateral 0%
(#2) Vertical 0%, Lateral 100%

Material Parameters
nCode DesignLife Analysis Process

Calculate Bending and/or Torsion

As Full Bridge (4 gauges)

[ or Half Bridge (2 gauges) ]
## Results

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Measured (%)</th>
<th>DesignLife Half Bridge (%)</th>
<th>DesignLife Full Bridge (%)</th>
<th>FE &amp; Excel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Vertical Bending</td>
<td>100% [*]</td>
<td>129%</td>
<td>145%</td>
<td>50%</td>
</tr>
<tr>
<td>Forward Lateral Bending</td>
<td>100%</td>
<td>93%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Forward Torsional Shear</td>
<td>100%</td>
<td>118%</td>
<td>89%</td>
<td>not available</td>
</tr>
<tr>
<td>Aft Vertical Bending</td>
<td>100% [*]</td>
<td>71%</td>
<td>73%</td>
<td>76%</td>
</tr>
<tr>
<td>Aft Lateral Bending</td>
<td>100%</td>
<td>101%</td>
<td>98%</td>
<td>90%</td>
</tr>
<tr>
<td>Aft Torsional Shear</td>
<td>100%</td>
<td>98%</td>
<td>92%</td>
<td>not available</td>
</tr>
</tbody>
</table>

[*] These strain levels are <100ue, so are not well represented by % values. The other strains are >400ue.
Conclusions

- The finite element model is validated by successful correlation of the bending and torsion strains with measured strains on the static test.

- In this example, the unrefined load transfer mesh is adequate for correlation of the tail cone bending and torsion.

- What are the “Advances in Experimental Mechanics”?
  - Usability and simplification for the finite element analysis engineer.
  - From a very interactive process, using an FE post-processor to identify strain values at nodes, copying and pasting to an Excel spreadsheet for further calculation, that can only reasonably be applied to simple static loads.
  - To an automated repeatable process, that can be applied to complex dynamic loads.
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