Bi-axial Fatigue Testing of Wind Turbine Blades

Peter Greaves
Research Structural Engineer - Blades

28th January 2016

Background – Fatigue Analysis

- In order to define fatigue test loads a fatigue analysis must be performed
- The ORE Catapult has developed Blade Fatigue, which streamlines the fatigue analysis process
- It has been certified by DNV-GL for the fatigue analysis of wind turbine blades

Fatigue Analysis - Geometry
Fatigue Analysis - Materials

- For each analysis point a strain history is calculated for each load case by superposition.
- It is rainflow counted to convert the variable amplitude strain history into a series of constant amplitude cycles.
- The number of cycles which would cause failure is calculated for each cycle, allowing the damage to be calculated using the Palmgren-Miner rule.

Fatigue Analysis - Loading

Background – Test Load Calculation

- Test loads are calculated by finding the strain amplitude which would cause the same amount of damage as the service life at selected ‘key points’ on each blade cross section after a given number of cycles.
  - The flapwise test load is calculated to match the damage in the element most strained by an $M_y$ unit moment at each section.
  - The edgewise test load is calculated to match the damage in the most strained element by an $M_x$ unit moment at each section.
Blade Fatigue Test Methods

**Forced Displacement Testing**
- Blade is forced by a grounded linear actuator at a frequency lower than resonance
- ‘Quasi-static’ loading
- Not practical for large blades because of high forces and displacements
- Linear bending moment distribution between actuators/root
- Bi-axial fatigue test is straightforward because phase angle between flapwise and edgewise loads is easy to control

**Resonant Testing**
- Blade is either forced by a grounded linear actuator at resonance or by exciters mounted on the blade
- Bending moment distribution is dictated by the system mode shape which can be tuned by adding mass to the blade
- Suitable for testing large blades
- Bi-axial fatigue test is not easy because the flapwise and edgewise natural frequencies are very unlikely to be the same

Bi-Axial Fatigue Testing

Blade Fatigue Test Methods

Bi-Axial Test
Bi-Axial Test

Blade Test Load Calculation

- Mode shapes and natural frequencies are calculated using a beam finite element model of the blade
- Steady-state response of the blade during test is calculated using modal superposition
- The element uses a fully populated section stiffness and mass matrix, so it can account for bend-twist coupling etc.
- Air resistance is accounted for using an equivalent damping coefficient
- Validated against full-scale tests

Blade Test Load Optimisation

- Blade test load calculator is embedded in an optimisation routine
- Objective is to minimise the least squares sum of the percentage error between test loads and calculated test loads at each section
- Genetic algorithm to find solution close to global optimum
- Trust-region reflective algorithm to improve on this result

Test Block Optimisation

\[ \begin{align*}
\mathbf{D}_1 & = \mathbf{D}(\mathbf{S}_1) \\
\mathbf{D}_2 & = \mathbf{D}(\mathbf{S}_2) \\
& \vdots \\
\mathbf{D}_N & = \mathbf{D}(\mathbf{S}_N) \\
\end{align*} \]

subject to $x \geq 0$

PATENT FILED
Results – NREL 5MW Reference Blade

- A fatigue test has been designed for the 61.5m NREL 5MW reference blade [1]
- Blade loads were obtained using the NREL FAST wind turbine simulation tool for the fatigue load cases described in IEC 61400-1
- The blade material data, geometry and cross sectional stiffness and mass distribution were obtained from [2]
- Palmgren-Miner damage sum comparison at 812 (29 sections each with 28 analysis points) points for:
  - Service life
  - Optimised bi-axial test
  - Single axis tests


Results – Flapwise (Single Axis)

- 5 million cycles
- Test frequency: 0.675Hz
- 86 days
- Added mass:
  - 32m – 4750kg
  - 45m – 1530kg
  - 61m – 310kg
- Tip displacement: 2.6m

Results – Edgewise (Single Axis)

- 5 million cycles
- Test frequency: 0.893Hz
- 65 days
- Added mass:
  - 25m – 6740kg
  - 28m – 9360kg
- Tip displacement: 0.75m
Results – Bi-Axial

- 5 million flap cycles
- Flap frequency: 0.852Hz
- 68 days
- Added mass:
  - 11m – 2540kg
  - 25m – 8650kg
  - 60m – 50kg

<table>
<thead>
<tr>
<th>Level</th>
<th>Edgewise</th>
<th>Pitch Angle</th>
<th>Number of Flap Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>51%</td>
<td>73%</td>
<td>0°</td>
<td>120</td>
</tr>
<tr>
<td>51%</td>
<td>84%</td>
<td>162°</td>
<td>191</td>
</tr>
<tr>
<td>84%</td>
<td>51%</td>
<td>252°</td>
<td>393</td>
</tr>
<tr>
<td>84%</td>
<td>51%</td>
<td>270°</td>
<td>688</td>
</tr>
<tr>
<td>51%</td>
<td>84%</td>
<td>342°</td>
<td>640</td>
</tr>
</tbody>
</table>

Results – Damage Comparison

Summary

- Bi-axial resonant testing is significantly more representative of in-service fatigue than single-axis testing
- It also saves time on the overall blade testing process
  - Duration of fatigue part of test program can be halved
  - The method can be extended to large blades:
    - Grounded linear actuator exciting the flapwise direction
    - Blade mounted resonant excitation for the edgewise direction
Any Questions?