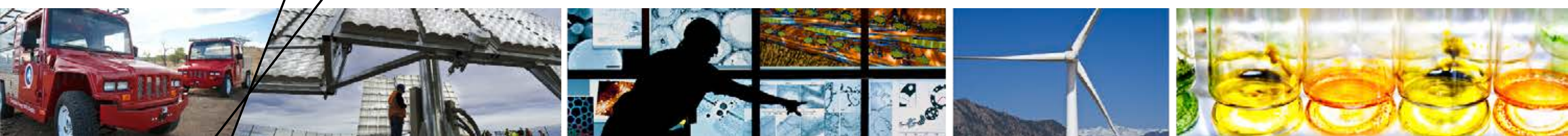
Improving Bending Moment Measurements on Wind Turbine Blades



2016 Wind Energy Research Workshop

Dr. Nathan L. Post

Lowell, Massachusetts

March 15, 2016

NREL/PR-5000-65996

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

- **Measure dynamic loads for model verification, nondestructive evaluation, and accelerated structural testing.**
  - International Electrotechnical Commission (IEC) 61400-13 (2015): Measurement of Mechanical Loads
  - IEC 61400-23 (2014): Full-Scale Structural Testing of Rotor Blades
- **Test resonance fatigue testing.**
  - Single axis
  - Biaxial
- **Measure mathematical approaches to bending moment using strain gauges.**
  - Traditional single axis
  - Cross-talk matrix IEC 61400-13
- **Demonstrate and evaluate errors.**
- **Expand cross-talk matrix to include torsion.**

IEC 61400-13 blade coordinates: Coordinates are fixed to blade root.

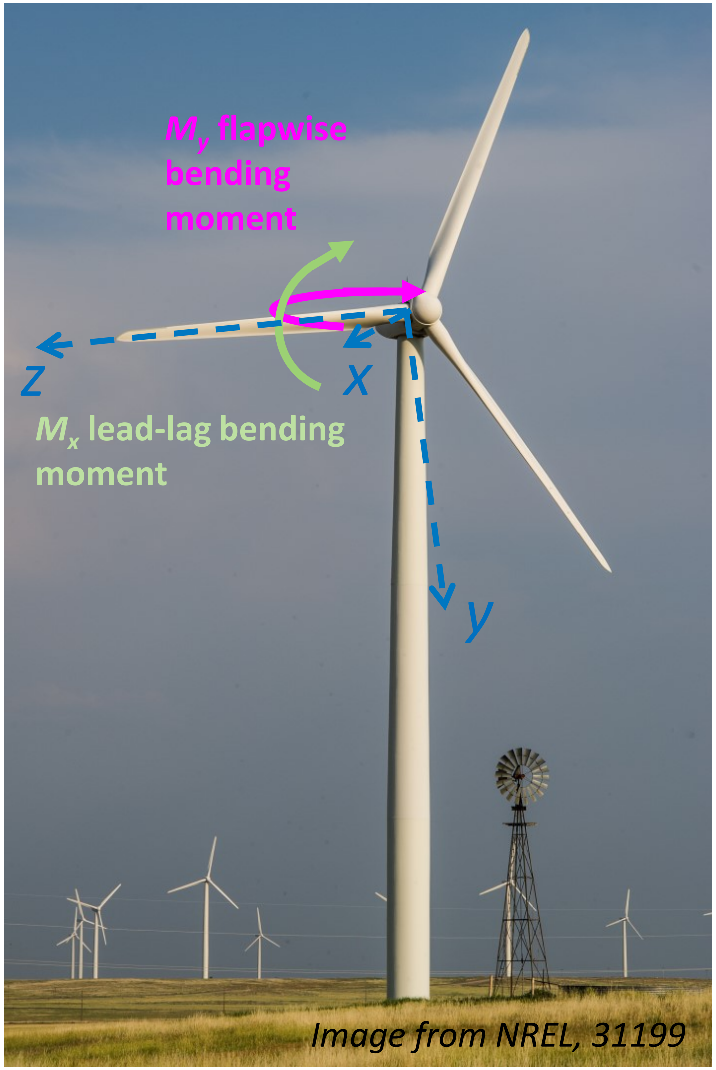


Image from NREL, 31199

Resonance Fatigue Testing

- **Goal: Constant amplitude fatigue test**
- **Excite blade at first flap or first lead-lag mode shape.**
  - Excite using moving mass (shaker) on blade.
  - Excite using hydraulic actuator where force is 90 degrees out of phase with displacement.
  - Adjust mode shape (bending moment distribution) by adding masses as required.
- **Force (energy) input is related to damping; not the applied bending moment.**
- **Must measure applied load independently using strain gauges.**

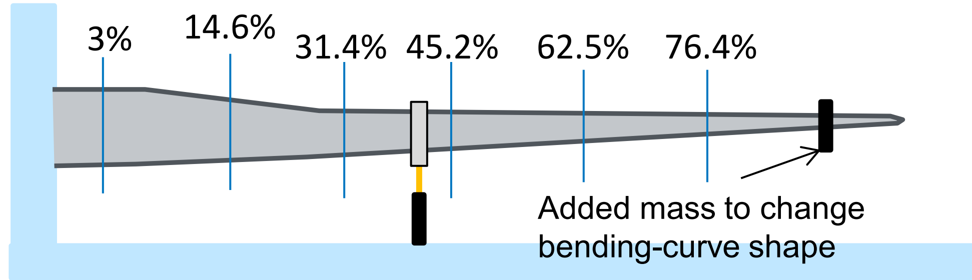
Flap fatigue test at Wind Technology Testing Center, Boston, MA

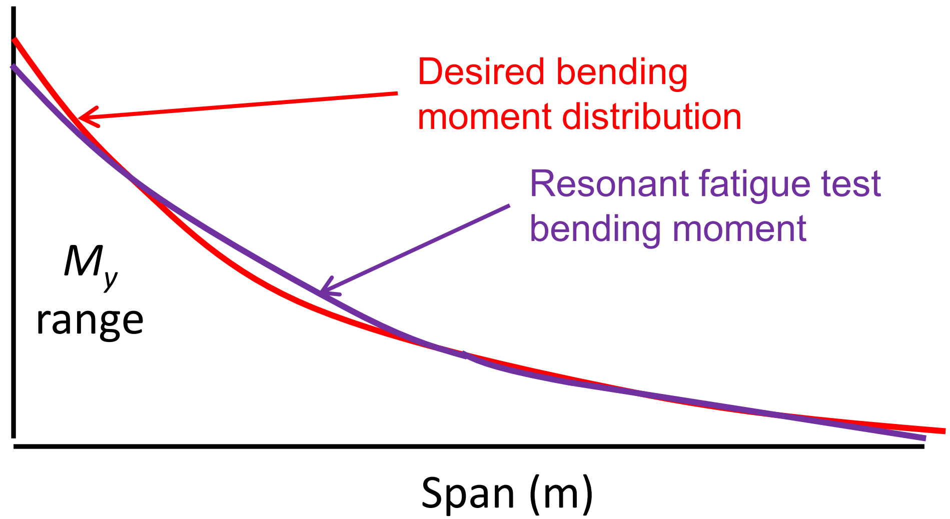
Inertial mass flap fatigue test at National Wind Technology Center, Boulder, CO

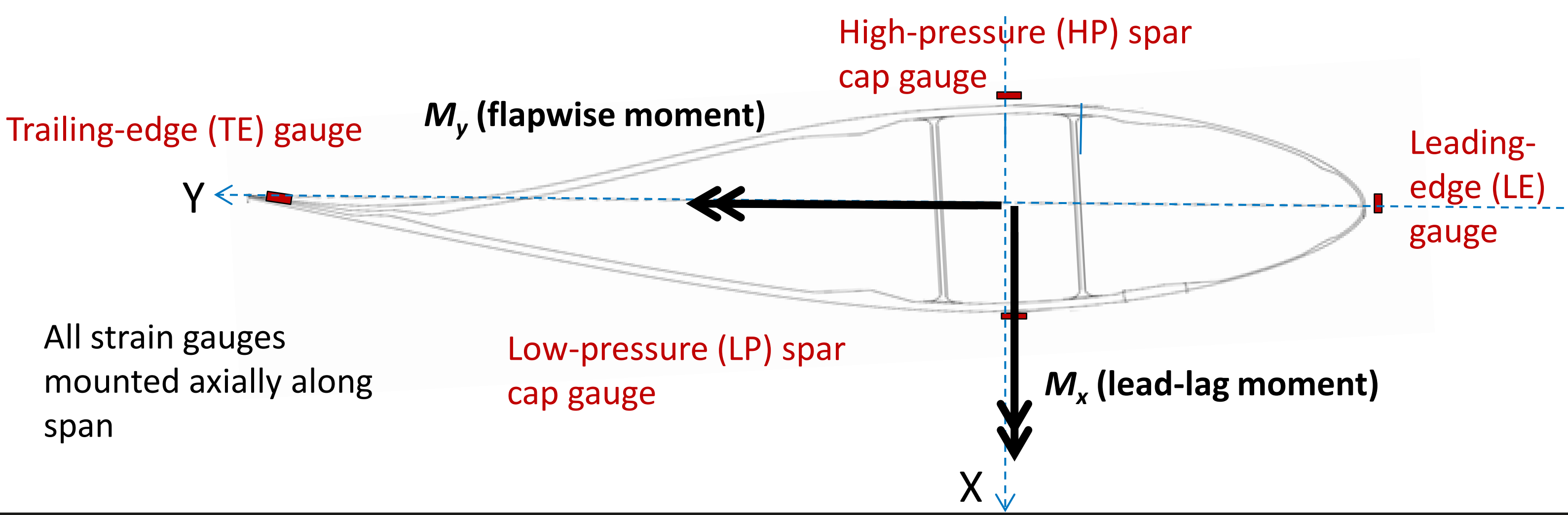
Instrumentation

Traditional instrumentation for bending moment measurement

- Four strain gauges each at selected span locations
  - May be configured as half bridges (in-service turbines)
- Root is typically round, then transitions to airfoil
- In-service measurements near root (2–3% span) and at about 30% span







Calibration

- **In laboratory:**
  - Apply force at known angle (typically perpendicular to pitch axis).

  Moment: $M = FL\cos\theta$

  Sensitivity: $A = \frac{\varepsilon_1 - \varepsilon_0}{M_1 - M_0}$

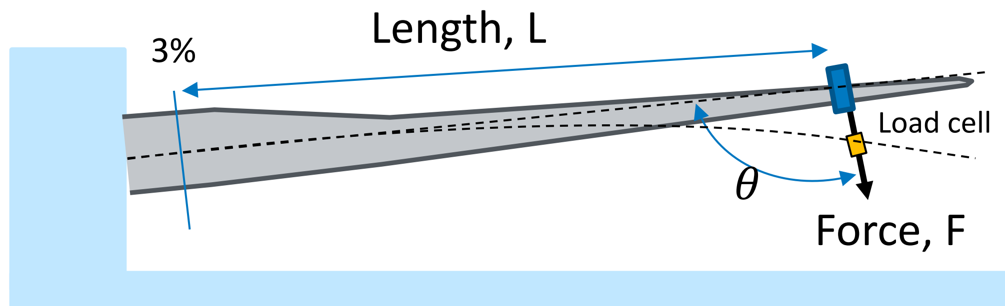


Image from NREL, 25867

- **On turbine:**
  - Use self-weight in low wind.

  Moment: $M = mgL\cos\theta$

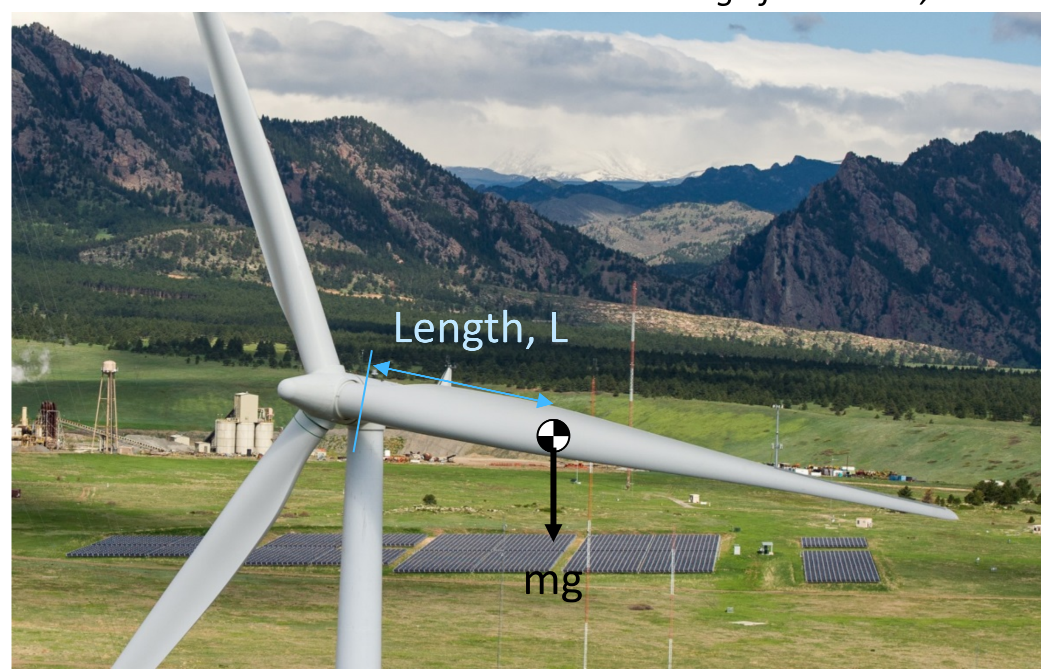
  With blade horizontal pitch at 0, 90, 180, 270 deg.

  Sensitivity:

$$A_{FLAP} = \frac{\varepsilon_{90} - \varepsilon_{270}}{2\,mgL}$$

$$A_{LEAD-LAG} = \frac{\varepsilon_0 - \varepsilon_{180}}{2\,mgL}$$

- **Or calculate from curve-fitting data as load is applied or blade is rotated.**



Cross-Talk Matrix Approach

- **Based on method in IEC 61400-13**
- Relate moments to strains at a section with a cross-talk matrix under the assumption that the measured strain is due to the linear response to each moment superimposed:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \begin{Bmatrix} M_x \\ M_y \end{Bmatrix}$$

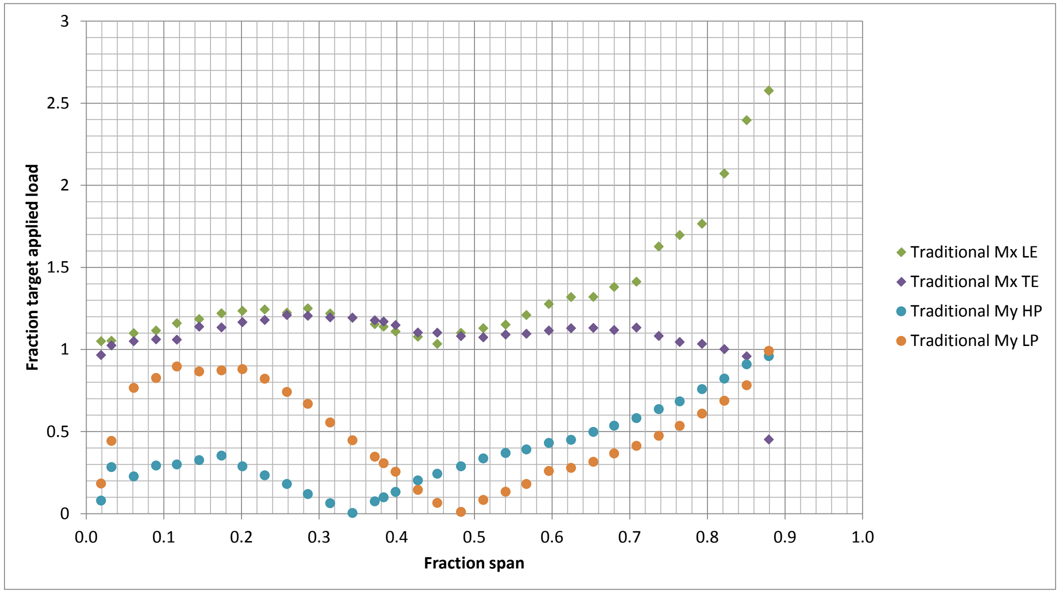
- ε_1 and ε_2 are two strain measurements, ideally primarily sensitive to M_x and M_y, respectively.
- Common method for determining components of A:
  - Apply pure M_x load and fit $\varepsilon_1 = A_{11}\, M_x$ for A_{11} and $\varepsilon_2 = A_{21}\, M_x$ for A_{21}.
  - Apply pure M_y load and find slope linear fit of $\varepsilon_1 = A_{12}\, M_y$ for A_{12} and $\varepsilon_2 = A_{22}\, M_y$ for A_{22}.
- Invert A matrix to calculate moments during fatigue or turbine operation.

$$\begin{Bmatrix} M_x \\ M_y \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}^{-1} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}$$

Traditional Approach: Neglect Cross-Talk

- **The applied moment range during single-axis (flap or lead-lag) resonance fatigue tests has traditionally been measured using only the gauges that are most sensitive to that loading, neglecting cross-talk terms.**
- **Thus:** $$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} = \begin{Bmatrix} M_x \\ M_y \end{Bmatrix}$$
- **Typically:**
  - Only a single calibration direction is required in the loading direction to obtain the sensitivity.
  - For a lead-lag test, use the LE or TE gauges separately.
  - For a flap test, the HP or LP gauges are used.
- **However, in most cases, the perpendicular moment is not zero. And the cross-talk sensitivity A_{12} and A_{21} terms are not zero.**

Example bending moment distribution measured during lead-lag fatigue test



Applying Cross-Talk: ¼ vs. ½ Bridge

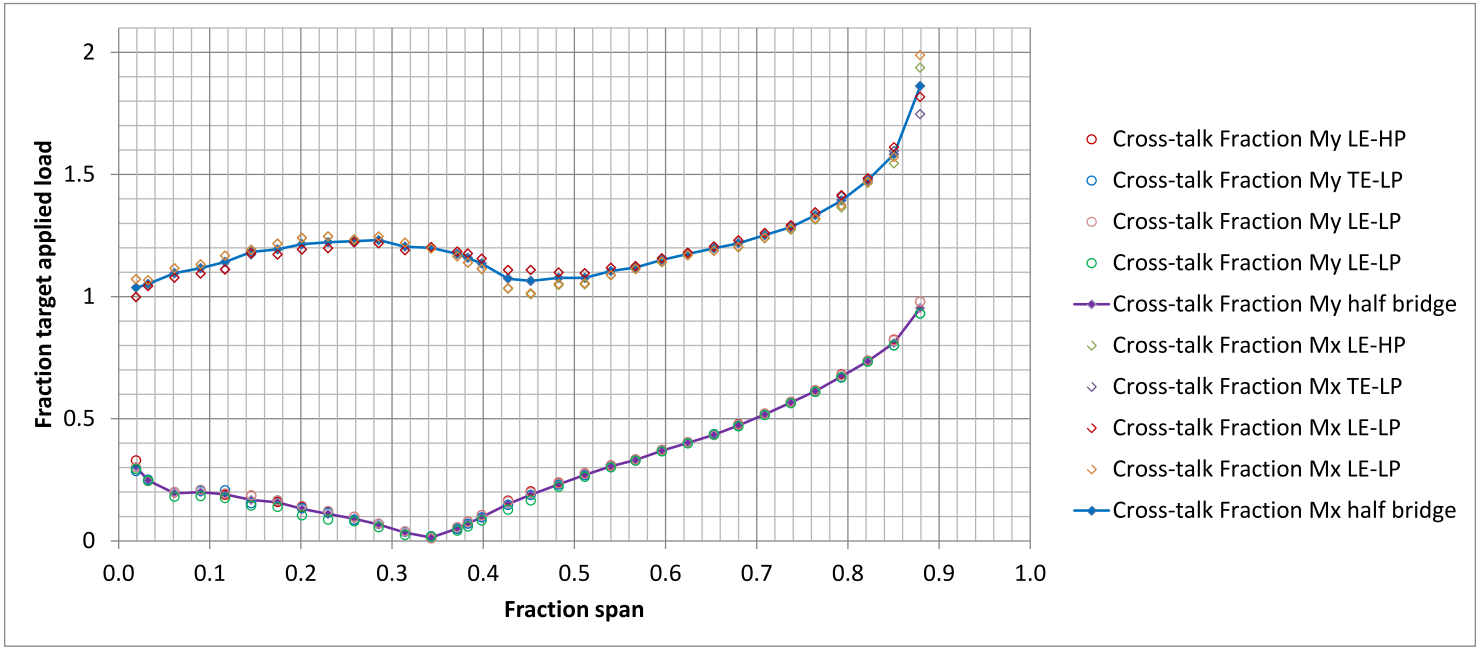
- ε_1 **and** ε_2 **can be single-strain gauges read using a ¼ bridge.**
  - Typically, evaluate moment for gauge pairs: {LE,HP}, {LE,LP}, {TE,HP}, {TE,LP}.
  - Four separate calculations of moment are achieved.
  - Experimentally, each pair results in slightly different answers (sometimes by several percentage points) for the moment due to the nonlinearity and random variation of the physical system.
  - Advantage: if one strain gauge fails, the remaining two pairs still offer functional measurement.

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\end{Bmatrix} = \begin{bmatrix}A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix} = \begin{Bmatrix}M_x\\ M_y\end{Bmatrix}$$

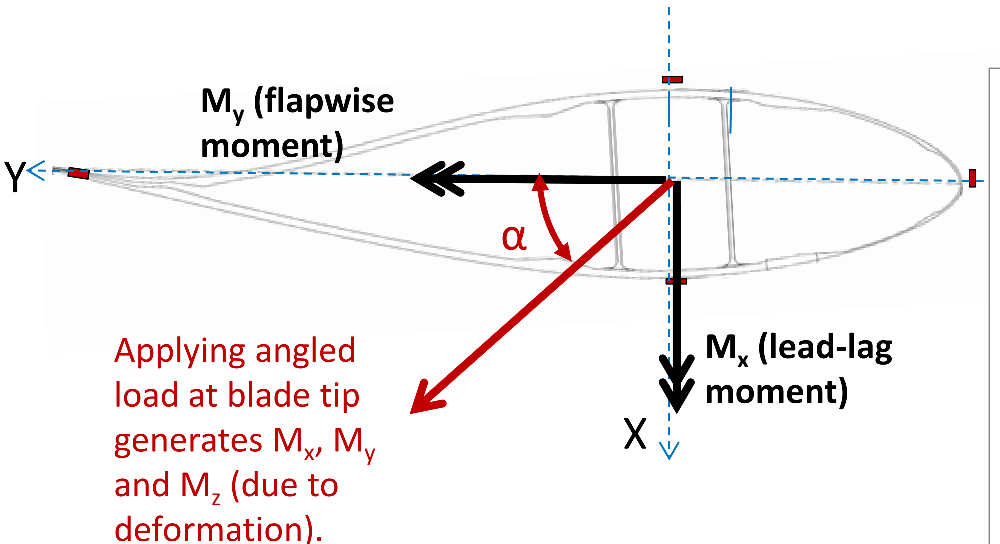
- Alternatively, use half bridges for calibration and subsequent calculation such that:

  $\varepsilon_1 = \varepsilon_{LE} - \varepsilon_{TE}$ and $\varepsilon_2 = \varepsilon_{HP} - \varepsilon_{LP}$
  - This results in a single calculation of moment for a given cross-section incorporating all strain data.
  - It typically falls in the middle of scatter from ¼-bridge strains.

Example bending moment distribution measured during lead-lag fatigue test



Biaxial Verification Loading Results

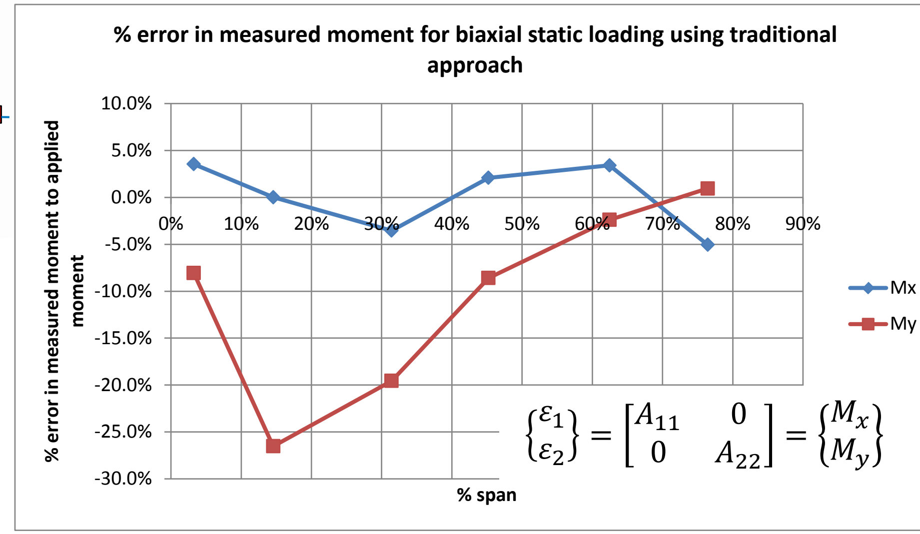


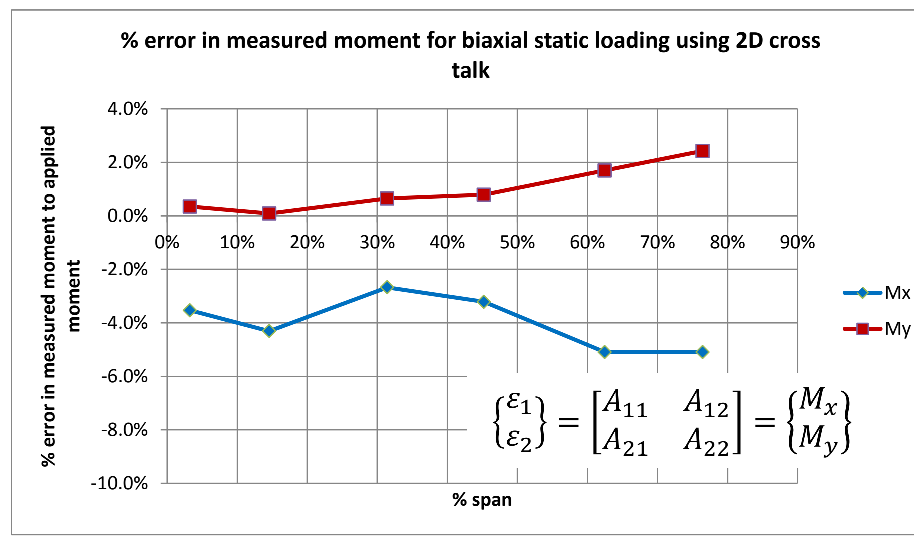
- **Calculate resulting applied M_x and M_y:**

$$M_x = F\ L\ \cos\alpha$$
$$M_y = F\ L \sin\alpha$$

- **Compare to moment results from measured strain:**
  - Significant errors occur when not accounting for cross-sensitivity.
  - Two-dimensional cross-talk approach still gives 4% error in M_x at blade root.

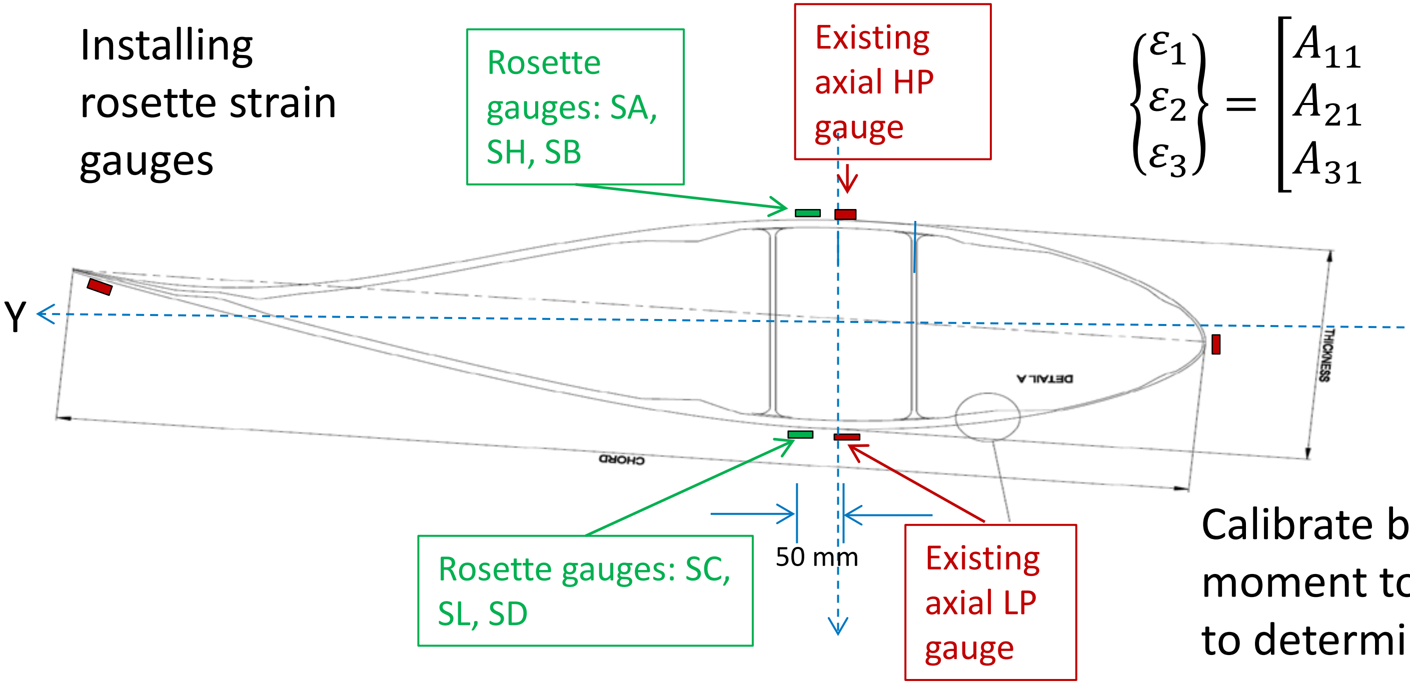
Using half-bridge signals





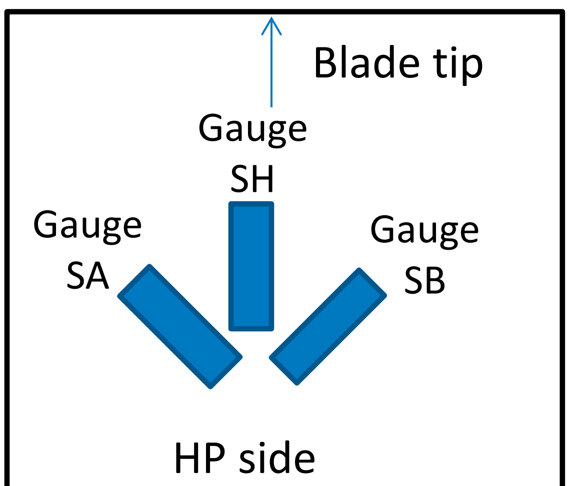
Extending Cross-Talk to Include Torsion (M_z)

Installing rosette strain gauges



$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} = \begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix}$$

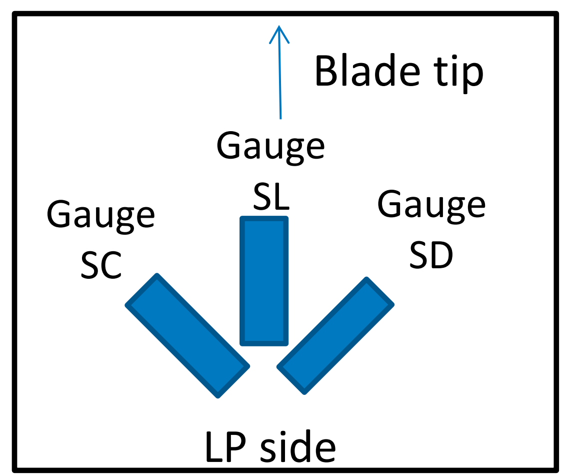
Calibrate by applying pure moment to blade using a couple to determine: A_{13}, A_{23}, A_{33}.



Full-bridge torque strain

$\varepsilon_3 = \varepsilon_{SA} - \varepsilon_{SB} + \varepsilon_{SC} - \varepsilon_{SD}$

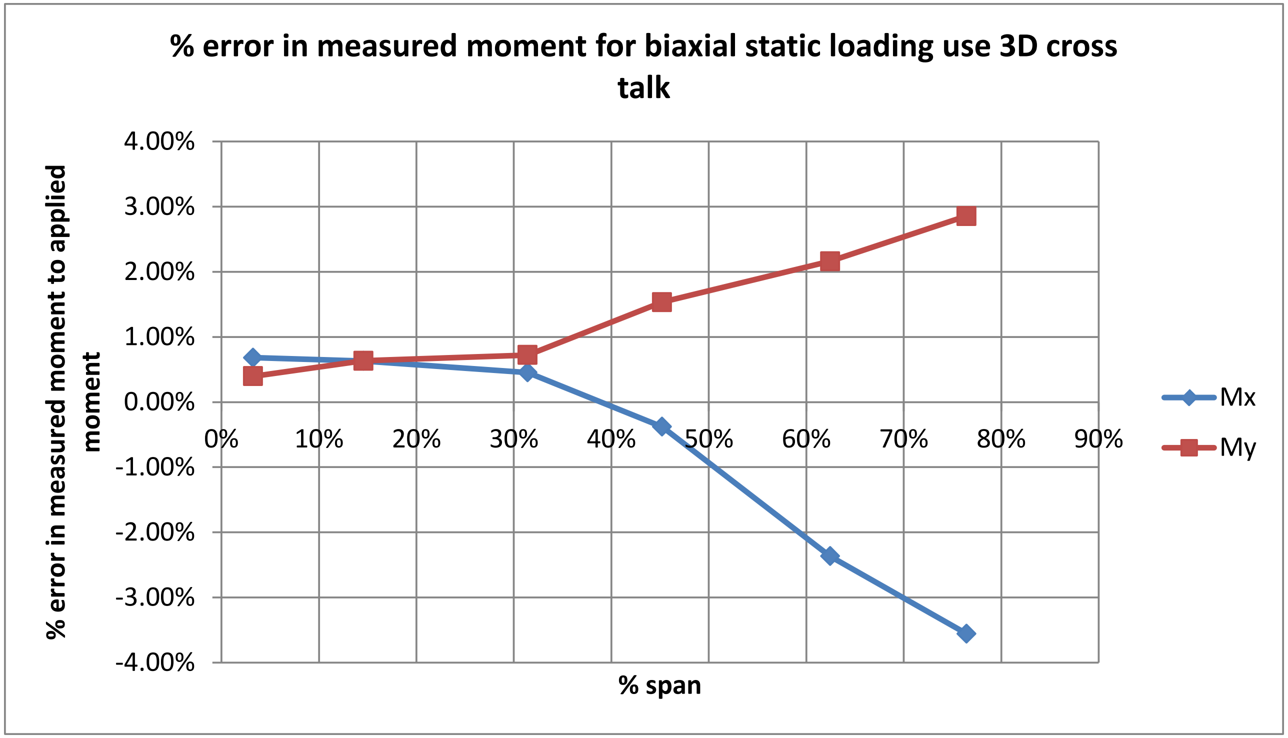
Compensates for most bending, axial, and thermal strains.



Biaxial Verification with Torsion

- Including torsion reduces errors near blade root to <1%.
- Outboard errors are likely due to not accounting for large deformations and torsion increasing the actual local flap moment and decreasing the local edge moment.

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} = \begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix}$$

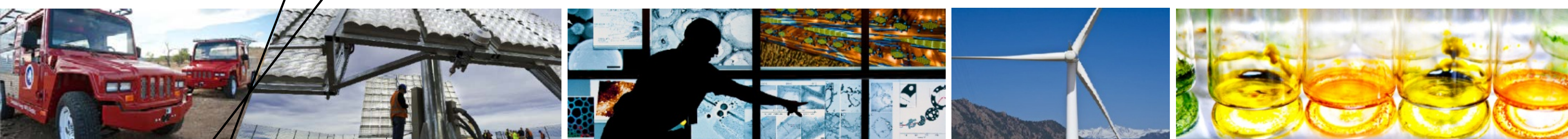


Future Work and Conclusions

- **Future work**
  - Account for large deformation
    - For calibration
    - For calculating reference moment.
  - Optimize methodology.
  - Calculate total uncertainty for measurement process.

Demonstrated significant improvement in moment measurement possible with inclusion of cross-talk and further improvement when including torsion as a third degree of freedom.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Thank you!

Contact:
Nathan Post
nathan.post@nrel.gov