Novel method of strain gauging wind turbine blades

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Abstract. A new method of interpreting strain data in full scale static and fatigue tests has been implemented as part of the Offshore Renewable Energy Catapult's ongoing development of bi-axial fatigue testing of wind turbine blades. During bi-axial fatigue tests, it is necessary to be able to distinguish strains arising from the flapwise motion of the blade from strains arising from the edgewise motion. The method exploits the beam-like structure of blades and is derived using the equations of beam theory. It offers several advantages over the current state of the art method of calibrating strain gauges.

1. Introduction

The rotor blades are some of the most critical components of a wind turbine. Structural failure of a blade can cause widespread damage to the turbine and its surroundings, so certifying bodies require full scale testing of new designs of blades to ensure that they can withstand the loads which are predicted in service.

These tests are typically performed by cantilevering the blade from a static hub and applying loads to it. During the process of testing a full size wind turbine blade both static and fatigue tests will be performed.

Static tests involve using winches to load the blade at several points along its length, and are designed to demonstrate that the blade can survive the extreme loads which are expected in service. The loads are introduced using saddles, which closely conform to the surface profile of the blade at the location at which they are mounted.

Fatigue tests can be performed using several methods, but the overall goal is always to demonstrate that the blade can survive its fatigue life. This is done by calculating loads that would cause an equivalent amount of damage to the service life after a given number of test cycles at multiple points along the blade length, with the number of cycles chosen so that the duration of the test is acceptable without increasing the loads so much that unrealistic failure modes occur.

During their service life, blades are loaded aerodynamically in the flapwise (out of the rotor plane) direction and by gravity in the edgewise (in the rotor plane) direction. These loads occur simultaneously and they interact, so it is desirable to perform a fatigue test in which the flapwise and edgewise loads are applied together. A literature review discussing different approaches to this problem is performed in [1].

The work presented here was performed by the Offshore Renewable Energy (ORE) Catapult to enable test loads to be monitored during bi-axial resonant testing, in which the first flapwise and edgewise modes of the system (the blade with test equipment mounted on it) are excited simultaneously. The methods used to optimize the test configuration are described elsewhere [2]. However, the strain gauging method presented is equally applicable to other methods of fatigue testing and static testing, as well as load monitoring in service.

Clearly, it is essential during both static and fatigue tests that the applied loads along the blade length can be monitored, and this is usually done using strain gauges. There will usually be 4 strain gauges mounted around each cross section of the blade, with cross sections every few meters along the blade length. On a 70m blade we might therefore expect to see around 100 strain gauges being used to monitor the test loads. These strain gauges must be calibrated several times during a test campaign with a known load, which allows the applied load to be inferred from strain readings during the test. Several calibration methods are available, with the so called 'cross-talk matrix' method described in [3] being the current state of the art.

The method presented here exploits the fact that wind turbine blades are beam-like structures, and uses beam theory to derive applied loads from strains measured on the blade surface.

2. Method

During tests, wind turbine blades will have multiple strain gauges around each cross section being monitored (typically 4, with gauges placed at the leading and trailing edge of the blade, and on the pressure and suction side spar caps). Multiple cross sections along the blade length will be monitored.

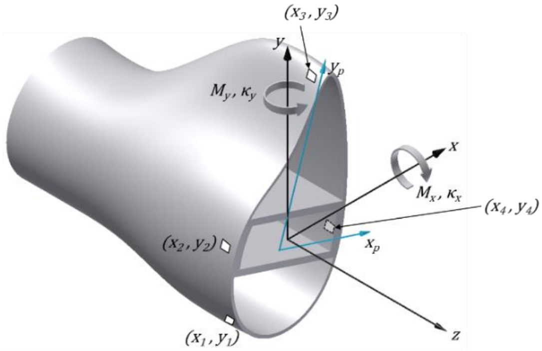

Figure 1. Cross section of a typical wind turbine blade.

Figure 1 shows a cross section through a typical wind turbine blade, along with several strain gauges defined by their location relative to the blade reference axis (marked by x_i, y_i) and the sign convention adopted for bending moments and curvatures (M and κ). The blue axes are the principal axes of the blade, with their origin at the elastic centre.

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} \gamma_x \\ \gamma_y \\ \varepsilon_z \\ \kappa_x \\ \kappa_y \\ \kappa_z \end{Bmatrix} \tag{1}$$

There exists a matrix relating the applied forces and moments on a beam cross section and the resulting strains and curvatures as shown in equation (7). During a blade test, we are interested in monitoring the applied bending moments - M_x and M_y.

$$\begin{Bmatrix} M_x \\ M_y \end{Bmatrix} = \begin{bmatrix} C_{44} & C_{45} \\ C_{54} & C_{55} \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix} \tag{2}$$

Assuming that bend-twist coupling can be ignored and that only bending moments and axial force contribute to strains in the axial direction (Necessary assumptions which capture the most important effects during a blade test) we can reduce equation (1) to the form shown in equation (7).

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix} = \begin{bmatrix} y_1 & -x_1 \\ y_2 & -x_2 \\ \vdots & \vdots \\ y_n & -x_n \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix} = [\boldsymbol{P}]\{\boldsymbol{\kappa}\} \tag{3}$$

Using beam theory, the axial strain at any number of strain gauges can be represented using equation (7). This matrix can also take a block diagonal form which allows the curvature from multiple calibration pulls to be calculated.

$$\begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix} = \left([\boldsymbol{P}]^{\boldsymbol{T}}[\boldsymbol{P}]\right)^{-\mathbf{1}}[\boldsymbol{P}]^{\boldsymbol{T}} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix} = [\boldsymbol{Q}]\{\boldsymbol{\varepsilon}\} \tag{4}$$

Taking the pseudo-inverse of equation (7) as shown in equation (7), we can arrive at an expression for the bending curvature from the strains.

$$\begin{bmatrix} M_{x\,F} & M_{x\,E} \\ M_{y\,F} & M_{y\,E} \end{bmatrix} = [\boldsymbol{A}] \begin{bmatrix} k_{x\,F} & k_{x\,E} \\ k_{y\,F} & k_{y\,E} \end{bmatrix} \tag{5}$$

$$[\boldsymbol{A}] = \left(\left(\begin{bmatrix} k_{x\,F} & k_{x\,E} \\ k_{y\,F} & k_{y\,E} \end{bmatrix}^T \right)^{-1} \begin{bmatrix} M_{x\,F} & M_{x\,E} \\ M_{y\,F} & M_{y\,E} \end{bmatrix}^T \right)^T \tag{6}$$

Using calibration pulls, which need not be performed in line with the x and y axes as they are with the cross-talk matrix method, a matrix $[\boldsymbol{A}]$ which relates the applied moment to the curvature can be obtained, as shown in equations (5) and (6). This method can readily be extended to incorporate the results of multiple calibration pulls, and will result in a 'least squares' best fit for $[\boldsymbol{A}]$.

$$\begin{Bmatrix} M_x \\ M_y \end{Bmatrix} = [\boldsymbol{A}][\boldsymbol{Q}]\{\boldsymbol{\varepsilon}\} \tag{7}$$

Finally, during test the strain gauge data from each section can be processed to obtain the bending moments using equation (7).

3. Results and Conclusions

A new method of calibrating and processing strain gauge data on wind turbine blades has been described.

It is currently being used to monitor a full scale bi-axial fatigue test. Early results show that the method offers an improvement over the cross-talk matrix method, because it allows the results of an arbitrary amount of strain gauges to be incorporated and because it allows any combination of calibration moments to be applied. This means that the effect of winch cable angle can be accounted for. The method can also be applied to monitoring blade loads in service, and can be extended to estimate deflections during service on the basis of the blade curvature about each axis at multiple stations.

4. Learning Objectives

Attendees can expect to learn about current methods of strain gauging wind turbine blades. They will also learn about a new method which allows much more accurate calibrations to be performed, and which can be used to estimate blade deflections.

References

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