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**Project Title:** Development of Health Assessment Tools for Utility-Scale Wind Turbine Towers and Foundations

**Contract Number:** RD4-14 **Milestone Number:** 3 **Report Date**: October 25, 2017

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**Congressional District (corporate office):** Minnesota's 3rd Congressional District

**Congressional District (project locations):** Minnesota's 1st and 2nd Congressional Districts

**MILESTONE REPORT**

**Executive Summary:** In accordance with Exhibit A of the contract, the Scope of Work for RD4-14, the research goal is to develop a cost effective method for evaluating the current health and remaining useful life of a wind turbine's tower and foundation.

The project objectives as stated in Exhibit A are as follows:

- Develop an economically viable and deployable system of sensors that can take the foundation and tower measurements required to perform a health and remaining useful life assessments.
- Develop a method of estimating the health and remaining useful life of the wind turbine tower and foundation using data from the developed sensor system and SCADA data from the win d turbine.
- Test the sensor system and estimation methods.

The project performance as stated in Exhibit A is planned to be achieved as follows:

- Accuracy and effectiveness of sensor system to be similar to the existing system on the Eolos wind turbine.
- Mobilization time of three days for installation of sensor system per turbine.
- Potential wind farm cost savings of $50,000 verses conventional sensing systems over the 20 year life of turbine.
- Development of a metric for estimating the remaining useful life of a wind turbine tower abd foundation based on wind turbine historical SCADA data.
- Potential reduction of up to 40% in equipment costs per wind turbine compared to the cost of the system installed on the Eolos wind turbine.

Milestone 3 is complete. In milestone 3, the project team developed a health analysis methodology and determined how it would be implemented.

**PROJECT FUNDING IS PROVIDED BY CUSTOMERS OF XCEL ENERGY THROUGH A GRANT FROM THE RENEWABLE DEVELOPMENT FUND.**

**Technical Progress:** The scope of work associated with milestone 3 has been completed. The following report describing the data analysis methodology and how it will be implemented is provided.

# 1.0 Data Processing Methodology

The following is an outline of the data processing plan for the wind turbine foundation structural heath monitoring and fatigue loading analysis. Structural health monitoring (SHM) includes using tower strain data to calculate an overturning moment on the turbine foundation and platform tilt measurements to understand how the foundation is responding. These measurements allow calculation of rotational stiffness for the foundation and thus provide a measure of the health of the foundation, i.e. that the rotational stiffness is within the range specified by the wind turbine manufacturer or that the relationship between tower overturning moment and foundation rotation is linear.

Another measure of the health of a wind turbine foundation can be obtained by examining the fatigue loading experienced by the foundation. The structural fatigue analysis method is used to estimate a fatigue damage equivalent load (DEL) for the history of the wind turbine under consideration. The fatigue DEL will be estimated from measured overturning moment data. The measured overturning moment data will be binned with power output to correlate DEL with discretized wind turbine power output. Using SCADA power data for the entire history of the wind turbine under consideration, a damage equivalent load will be calculated. This information will be used to estimate the remaining life of the wind turbine foundation.

# 2.0 Data Acquisition

The research team will investigate the most effective and efficient methods of acquiring strain and tiltmeter measurements. This includes optimizing (minimizing) the number of strain gauges used to calculate the maximum strain on the tower and optimizing (minimizing) the sampling rate used. To do this, the research team will compute both rotational stiffness and fatigue DEL for the Eolos wind turbine using a varying numbers of sensors and varying sensor rates shown in the table below. Comparing the resulting calculations of stiffness and DEL will inform the optimization (minimization) process.

## 2.1 SHM system optimization

To determine the minimum number of sensors and the lowest possible sample rate, the research team will make use of the foundation sensor system that has been collecting data nearly continuously since October 2011 on the University's Eolos wind turbine. The Eolos system is a large, robust, non-mobile measurement system comprised of 20 uni-axial strain gauges and 10 thermocouples.

The research team will start with the full Eolos sensor system of 20 strain gauges measuring at 20Hz and repeat the calculations multiple times with different subsets of sensors. The data will also be down sampled, simulating a slower sample rate. The results will show the point at which the calculations of stiffness and DEL deviate significantly from the calculations made with the full Eolos system of 20 strain gauges measuring at 20Hz.

**Table 1: Test Matrix showing the number of sensors and measurement rates that will be evaluated.**

| | | ***Measurement Rate*** | | |
|---|---|---|---|---|
| | | ***20Hz*** | ***5Hz*** | ***1Hz*** |
| ***Number of Strain Gauges*** | ***20*** | ✓ | ✓ | ✓ |
| | ***4*** | ✓ | ✓ | ✓ |
| | ***3*** | ✓ | ✓ | ✓ |
| | ***2*** | ✓ | ✓ | ✓ |

On May 30, 2017 the RDF foundation monitoring sensor system was installed on the Eolos wind turbine. Since this date, foundation data as well as ancillary data has been logged. Ancillary data consists of meteorological conditions (wind speed and direction, temperature, barometric pressure, and relative humidity) and SCADA which have been continuously recorded since the wind turbine was installed in October of 2011. This allows access to the entire history of power output from the turbine.

The strain gauge and tiltmeter data is sampled at 20 Hz. Data is stored locally until it is transmitted via cellular network to servers operated by the St. Anthony Falls Lab every 30 minutes.

3-D wind velocity from sonic anemometers is sampled at 20 Hz and cup anemometer, vane wind direction, and temperature measurements are captured at 1 Hz from the meteorological tower. Meteorological data are stored on network servers on site.

SCADA from the wind turbine include data on the state of the wind turbine such as rotor speed, blade position, operating region, etc. The critical measurement for this project is power output which will be correlated with strain measurements. SCADA is continuously logged at 1 Hz to network servers on site. Other wind facilities do not log SCADA data at 1Hz, but instead store averages of the data. This will be an important consideration when computing the historical fatigue DEL using historical power output data.

The RDF foundation monitoring system will be tested against the Eolos sensor system by computing the stiffness and the fatigue DEL using 3 strain gauges from the Eolos sensor system and the 3 tee-rosette strain gauges of the RDF sensor system. A similar value of stiffness and fatigue DEL computed with data from each of the systems will confirm that the RDF system is capable of accurately assessing the structural health of wind turbine foundations.

## 2.2 Sample Rate Optimization

Following the comparison of the stiffness and the fatigue DEL at different sample rates, the optimized sample rate for data acquisition of the tiltmeter and strain gauges will be confirmed by investigating the frequency content of measurements taken at a relatively high sampling rate of 20 Hz. This initial sampling rate of 20 Hz may be temporarily increased to confirm that no significant power is associated with frequencies above 10 Hz.

The following is an outline on how the sampling rate will be confirmed:

a) Perform frequency analysis on strain and tilt data that has been acquired at 20 Hz.
b) Determine the extent of the frequency band that contains the bulk (e.g. 99%) of the power and use this information to choose the minimum yet sufficient sampling rate based on the Nyquist Theorem.
c) Perform calculations of tower moment and tilt using data acquired at 20 Hz and data down-sampled to the lower frequency determined in part b).
d) Compare the 20 Hz and down-sampled data results, i.e. the ability of down-sampled data to estimate maximum values of strain and tilt using the 20 Hz data as the benchmark.

## 2.3 Sensor Number Optimization

To confirm the minimum number of sensors determined by the stiffness and fatigue DEL comparison outlined above, we propose to:

a) Analyze the maximum strain using the robust sensors of the Eolos system, this system will be used as the benchmark.
b) Analyze the max strain using a reduced number of sensors as shown in Table 1.
c) Compare results of a) and b), check for difference in maximum strain.

## 2.4 Temperature Correction Method comparison

The RDF sensor system and the Eolos sensor system use different methods to correct for the thermal expansion of the steel. The RDF system makes use of tee-rosette strain gauges which automatically compensation for thermal expansion, while the Eolos system uses measurements of the steel temperature to apply a computed correction factor in the datalogger. According to beam bending theory, the average of all strain gauges at any given time should be zero. Computing the average strain from all gauges over a period of a few days allows for an analysis of temperature affects due to diurnal temperature fluctuations. The research team will perform this analysis for both the RDF and the Eolos to evaluate the effectiveness of each thermal compensation method.

## 2.5 Data Processing: Engineering Units and Offsets

### 2.5.1 Strain Gauge

The datalogger measures the strain gauges initially as a voltage and applies a conversion factor to transform the measurement into units of micro-strain. Small differences with respect to how each strain gauge is installed on the tower can lead to significant differences in initial strain readings. Additionally, due to the turbine yaw position at the time of installation of the strain gauges, there is an imbalance in the strain at different positions on the tower. To compensate for this imbalance, the nacelle is rotated 360 degrees and an offset is calculated by taking the average of strain values during the rotation. During the yaw, the wind speed is low and the turbine blades are feathered to minimize aerodynamic loads applied to the tower. Figure 1 demonstrates the process of removing the strain bias. The plot on the left shows the raw strain variation during a full rotation of the nacelle. The right plot shows the corrected strain. The difference in amplitude between the maximum and minimum values is the same, however, the mean value has been shifted to be approximately zero.

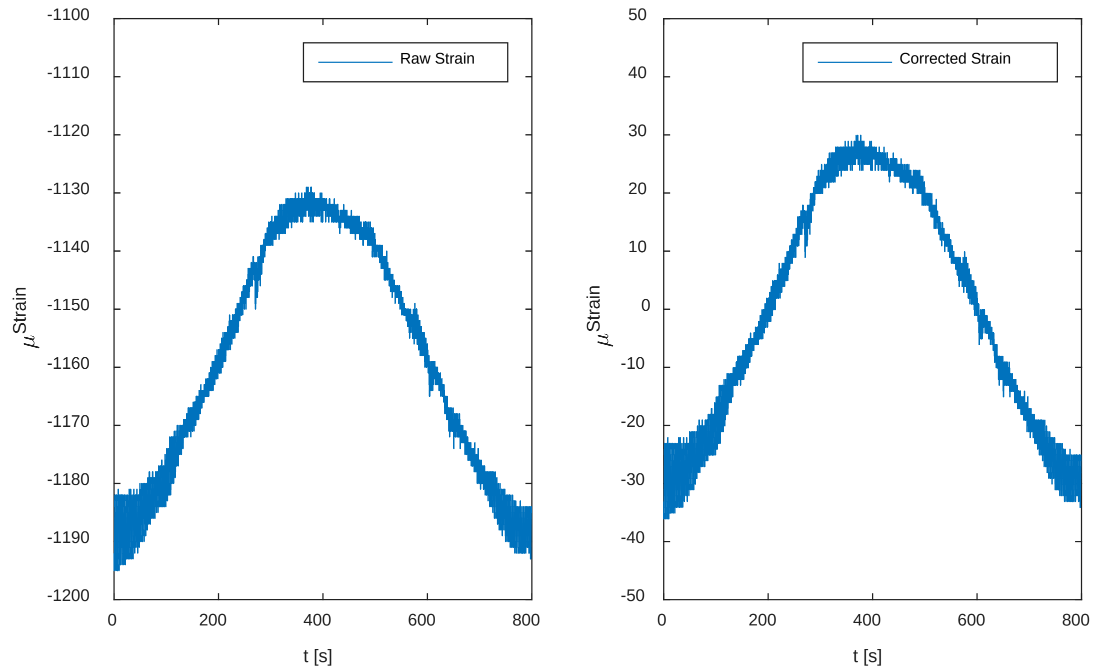


**Figure 1: Strain measurements during a nacelle rotation for the strain gauge located at position 1. The left plot gives the raw strain, the right plot is the corrected strain**

The maximum strain, $\varepsilon$, in the tower shell is interpolated from the three strain readings using the geometric relationship between the strain gauges, which are spaced 120 degrees apart. The method for determining the maximum strain is outlined in Appendix A.

Once the maximum strain in the tower has been calculated, the tower stress, $\sigma$, is calculated using Hooke's Law.

$$\sigma = \varepsilon * E$$

where E is the modulus of elasticity of the tower material.

The overturning moment, $M$, applied on the tower is then calculated from beam bending theory where the moment is equal to the stress times the section modulus:

$$M = \sigma * S$$

where $S$ is the section modulus which is computed from the thickness and diameter of the shell. Using the outer diameter, $OD$, and the inner diameter, $ID$, the section modulus is calculated by

$$S = \pi * (OD^4 - ID^4)/(32 * OD)$$

This will result in a time series of tower moments which will be further processed to remove any data outliers caused by electrical spikes.

In order to compare this data to power output, 1 second average moments will be calculated. The time base of the power output data dictates the averaging period for the moment calculations.

### 2.5.2 Tiltmeter Data Processing

Foundation tilt, $R$, is calculated by taking the magnitude of the x and y tilt measurements from the tiltmeter. Raw voltage data from each component is converted to degrees using the manufacturer supplied calibration scale factor. Before the tilt magnitude is calculated, an offset for each component is applied. This offset zeroes the sensor. The offset is determined by taking the average of the maximum and minimum tilt, for each component, during a 360 degree nacelle rotation (yaw).

Tilt magnitude will be averaged to 1 sec data to match the data rate of the power output. Some sites may require this averaging period to be 10 min.

# 3.0 SHM Analysis

To assess the health of the foundation, the research team will look at the behavior of the foundation as it undergoes varying loads. A plot of foundation tilt versus moment (i.e. stiffness) gives a good indication of the foundation health. A linear trend is expected, i.e. increasing tilt with increasing moment indicating constant stiffness.

A single value for rotational stiffness will be calculated and compared to the wind turbine manufacturer's specification. Rotational stiffness, $K_\theta$, is the overturning moment divided by the amount of rotation, $R$:

$$K_\theta = M/R$$

Some of the calculations that will be used to estimate the rotational stiffness are:

a) Average rotational stiffness, $\overline{K_\theta}$, which is the average moment divided by average rotation
b) $95^{th}$ percentile rotational stiffness
c) 95% confidence rotational stiffness
d) Minimum rotational stiffness

# 4.0 Fatigue Loading Analysis

This section discusses fatigue analysis which is intended to estimate a damage equivalent load on a wind turbine foundation as well as estimate the useful remaining life of the foundation. Data collection and initial processing of the strain gauges and tiltmeter has been discussed above.

## 4.1 Data Processing

The fatigue analysis procedure will use the calculated moments from the strain data, high resolution SCADA data taken during the strain and tilt measurements, and historical SCADA data from the life of the turbine of interest. The following is an overview of the analysis procedure.

a) Using 20 Hz processed moments, or the sample rate chosen from section 2.2, find the local maxima and minima using a peak finding function with thresholds on the minimum time between local minima and maxima

b) Use a rainflow counting program on the data set from a). This will give the number of cycles and the moment range and mean for each cycle.

The mean moment, $S_{m_i}$, is equal to the average of the minima and maxima of the $i^{\text{th}}$ cycle. Similarly, the moment range, $S_{r_i}$, is the difference between the maxima and minima of the $i^{\text{th}}$ cycle.

c) Compute the damage equivalent load using data from b)

The following equation is used to calculate the damage equivalent load:

$$S_{r,eq} = \left( \sum_{i=1}^{n} \frac{\left( S_{r,i} * \frac{S_u - |S_{m,eq}|}{S_u - |S_{m,i}|} \right)^m}{N_{eq}} \right)^{\frac{1}{m}}$$

Where: $S_{r,eq}$ is the damage equivalent load (computed)
$n$ is the total number of cycles (measured)
$S_{r,i}$ is the moment range of the $i^{\text{th}}$ cycle (measured)
$S_u$ is the ultimate design load (known)
$S_{m,eq}$ is the equivalent mean moment (known)
$S_{m,i}$ is the mean moment of the $i^{\text{th}}$ cycle (measured)
$N_{eq}$ is the equivalent number of load cycles (known)

d) Count the total number of cycles from the rainflow counter
e) Divide the number of cycles from d) by the total design cycles from the design fatigue spectrum. This gives a ratio for measured number of cycles to total design cycles. Apply the ratio to each bin of cycles in the design spectrum and calculate the design damage equivalent load using the prorated cycles and corresponding design mean and range.

The design damage equivalent load equation used will be based on the information available from the design fatigue spectrum.

f) From data set a) and b), determine the high resolution power output that occurred at each half cycle moment range/mean
g) Group the power outputs and half cycle means/ranges into bins of 25 kW intervals. At rated power, group the power outputs and half cycle means/range into 0.5 m/s wind speed bins starting at rated wind speed.
h) Compute an average mean moment, average moment range, and standard deviation for the average mean and range moments, for each power/wind bin. Count the number of cycles that occurred in each bin.
i) For each bin, calculate the design average mean and design average range based on a 99.0% confidence level
j) Calculate the damage equivalent load using the design average mean, design average range, and cycles in each bin. Compare this value with the damage equivalent load computed in c).

k) Apply an additional adjustment factor to correlate j) with c) if necessary.
l) Over the same measurement period, determine the 10 minute power averages that occurred.
m) Determine the natural frequency of the system from the strain measurements.
n) Use the natural frequency to determine the number of load cycles for each 10 minute average.

This method assumes that all of the oscillations are at the natural frequency. To test this assumption, we will compare the number of load cycles calculated using the method outline in n) with the method from a) and b) on a relatively large dataset, i.e. 1 month.

o) Compute the damage equivalent load using the cycles in (n) and the design mean and range from i), applying the adjustment factor from k) and compare the result in c) to see how good the averaging is at predicting the actual damage and apply an additional adjustment factor if necessary.
p) Compare o) with the design e) to see how much life was used during the measurement period
q) Finally, for all 10 minute power averages for the life of the wind turbine, determine the damage equivalent load using the method l) to p).

In addition to these steps, which are designed to perform the damage equivalent load calculation using relatively short measurement periods (e.g. 48 hours), the research team will use the existing foundation monitoring data at Eolos to explore how well a short measurement period can predict a lifetime damage equivalent load. At Eolos, the entire history of power output and tower moment is available. We plan to start with a relatively short measurement period and increase the period in steps to see when convergence is reached for the damage equivalent load.

**Additional Milestones:** Milestone number 4 is ready to begin. In this milestone, the team will implement the health analysis methodology, and analyze the health of the EOLOS wind turbine foundation, including an estimate of remaining life.

**Project Status:** The project is currently on schedule. Milestone number 4 has a duration of 3 months and is projected to be completed February 2018.

## LEGAL NOTICE

## Appendix A
## Strain gage interpolation procedure

The maximum strain on the tower can be interpolated using the following method. The example below provides the method for three strain gauges installed 120 degrees apart on the turbine tower, but the same method can be utilized for any number of strain gauges.

Estimate the angle of the neutral axis of bending with regards to the east-west line:

$$
\begin{array}{ll}
\theta = 15^o & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\theta = 60^o & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right) \\
\theta = 120^o & \text{if}\left(\epsilon_{2_{meas}} < 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right) \\
\theta = 180^o & \text{if}\left(\epsilon_{2_{meas}} < 0 \ \text{ AND } \ \epsilon_{3_{meas}} > 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right) \\
\theta = 240^o & \text{if}\left(\epsilon_{2_{meas}} < 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\theta = 300^o & \text{All other cases}
\end{array}
$$

Using this estimate of the neutral axis angle, we can use an iterative fitting function to compute the actual value of $\theta$. The input for the iterative fitting function is the following equation. The function will solve for the value of $\theta$ that makes the expression equal to zero.

$$
\begin{aligned}
&\sqrt{\left(\frac{\epsilon_{3_{meas}}}{\epsilon_{2_{meas}}} - \frac{\epsilon_{3_{ratio}}(\theta)}{\epsilon_{2_{ratio}}(\theta)}\right)^2 + \left(\frac{\epsilon_{1_{meas}}}{\epsilon_{2_{meas}}} - \frac{\epsilon_{1_{ratio}}(\theta)}{\epsilon_{2_{ratio}}(\theta)}\right)^2} \\
&+ \sqrt{\left(\frac{\epsilon_{2_{meas}}}{\epsilon_{3_{meas}}} - \frac{\epsilon_{2_{ratio}}(\theta)}{\epsilon_{3_{ratio}}(\theta)}\right)^2 + \left(\frac{\epsilon_{1_{meas}}}{\epsilon_{3_{meas}}} - \frac{\epsilon_{1_{ratio}}(\theta)}{\epsilon_{3_{ratio}}(\theta)}\right)^2} \\
&+ \sqrt{\left(\frac{\epsilon_{2_{meas}}}{\epsilon_{1_{meas}}} - \frac{\epsilon_{2_{ratio}}(\theta)}{\epsilon_{1_{ratio}}(\theta)}\right)^2 + \left(\frac{\epsilon_{3_{meas}}}{\epsilon_{1_{meas}}} - \frac{\epsilon_{3_{ratio}}(\theta)}{\epsilon_{1_{ratio}}(\theta)}\right)^2} \ = 0
\end{aligned}
$$

Where the $\epsilon_{1_{ratio}}$, $\epsilon_{2_{ratio}}$, $\epsilon_{3_{ratio}}$ are given by the following expressions:

$$
\begin{array}{ll}
\epsilon_{2_{ratio}}(\theta) = \cos(\theta) & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\epsilon_{2_{ratio}}(\theta) = \sin(90^0 - \theta) & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\epsilon_{2_{ratio}}(\theta) = -\sin(\theta - 90^o) & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\epsilon_{2_{ratio}}(\theta) = -\sin(\theta - 90^o) & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} > 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\epsilon_{2_{ratio}}(\theta) = -\sin(270^o - \theta) & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\epsilon_{2_{ratio}}(\theta) = \sin(\theta - 270^o) & \text{Otherwise}
\end{array}
$$

$$
\begin{array}{ll}
\epsilon_{3_{ratio}}(\theta) = -\sin(\beta_3 - 90^o) & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right) \\
\epsilon_{3_{ratio}}(\theta) = -\cos\left((\beta_3 - 90^o) - (90^o - \theta)\right) & \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right) \\
\epsilon_{3_{ratio}}(\theta) = -\sin(270^o - \theta - \beta_3) & \text{if}\left(\epsilon_{2_{meas}} < 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right) \\
\epsilon_{3_{ratio}}(\theta) = \sin(90^o - (360^o - \theta - \beta_3)) & \text{if}\left(\epsilon_{2_{meas}} < 0 \ \text{ AND } \ \epsilon_{3_{meas}} > 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right)
\end{array}
$$

$$\epsilon_{3_{ratio}}(\theta) = \cos(360^o - \beta_3 - \theta) \qquad \text{if}\left(\epsilon_{2_{meas}} < 0 \ \text{ AND } \ \epsilon_{3_{meas}} > 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right)$$
$$\epsilon_{3_{ratio}}(\theta) = \sin(450^o - \theta - \beta_3) \qquad \text{Otherwise}$$

$$\epsilon_{1_{ratio}}(\theta) = -\sin((\beta_1 - 90^o) - \theta) \qquad \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} < 0\right)$$
$$\epsilon_{1_{ratio}}(\theta) = \sin(\theta - (\beta_1 - 90^o)) \qquad \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right)$$
$$\epsilon_{1_{ratio}}(\theta) = \cos(\theta - \beta_1) \qquad \text{if}\left(\epsilon_{2_{meas}} < 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right)$$
$$\epsilon_{1_{ratio}}(\theta) = \sin(\beta_1 - (\theta - 90^o)) \qquad \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right)$$
$$\epsilon_{1_{ratio}}(\theta) = -\sin\left((\theta - 90^o) - \beta_1\right) \qquad \text{if}\left(\epsilon_{2_{meas}} > 0 \ \text{ AND } \ \epsilon_{3_{meas}} < 0 \ \text{ AND } \ \epsilon_{1_{meas}} > 0\right)$$
$$\epsilon_{1_{ratio}}(\theta) = -\cos(\beta_1 - (\theta - 180^o)) \qquad \text{Otherwise}$$

Where:
$\beta_3$ is the clockwise angle relative to south where the strain gauge 3 is installed
$\beta_1$ is the counterclockwise angle relative to south where the strain gauge 1 is installed.

Now that the actual value of $\theta$ has been computed, the maximum strain on the tower can be computed using the following equations.

$$\epsilon_{max} = \frac{\left|\epsilon_{1_{max}}\right| + \left|\epsilon_{2_{max}}\right| + \left|\epsilon_{3_{max}}\right|}{3}$$

Where:

$$\epsilon_{2_{max}} = \frac{\epsilon_{2_{meas}}}{\epsilon_{2_{ratio}}(\theta)}$$
$$\epsilon_{3_{max}} = \frac{\epsilon_{3_{meas}}}{\epsilon_{3_{ratio}}(\theta)}$$
$$\epsilon_{1_{max}} = \frac{\epsilon_{1_{meas}}}{\epsilon_{1_{ratio}}(\theta)}$$

The value of $\epsilon_{max}$ computed here can be used to compute the overturning moment applied on the foundation of the wind turbine by the tower.