GL Garrad Hassan

TECHNICAL NOTE

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Client	National Renewable Energy Laboratory
Contact	Dennis Elliott
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Classification	Client's Discretion
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Approved	Clint Johnson

History

Issue	Date	Summary
A	13 February 20112	Draft for Client review
B	20 April 2012	Slightly modified structure and text following talks with Client. Added appendix on sensitivity analysis with respect to tower solidity. Added recommendations for the use of the CFD application.
C	4 May 2012	Minor amendments and updates as per Client request

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1 INTRODUCTION

At the request of **National Renewable Energy Laboratory** (**NREL**, or the "**Client**"), **GL Garrad Hassan Canada,** Inc. (**GL GH**) has developed an application which attempts to adjust the recorded wind speeds measured by a cup anemometer considering the wind flow distortion caused by its supporting lattice meteorological tower.

The application is based on the results of a CFD analysis of wind flow distortion (shadow effect analysis) around a generic lattice tower previously performed by GL GH in collaboration with the École de Technologie Supérieure ("**ETS**") [2]. In agreement with the Client, the previous CFD simulation results were used without any modifications to account for specific characteristics of the NREL tower.

2 DESCRIPTION OF THE TOWER AND MOUNTING INSTRUMENTS

The tower under study is located at the National Wind Technology Center in Jefferson County in the state of Colorado. The tower is a 440-foot (134 m) galvanized guyed lattice tower with triangular cross sections manufactured by Rohn (Rohn 80 G model). The tower has a face width of 41" (104 cm) and is designed around an equilateral triangle supported by solid tubular legs, reinforced with double angle braces.

Based on tower dimensions and drawings provided by the Client[1], a tower solidity of approximately 0.26 was estimated. This value corresponds to a drag coefficient of 0.4 in accordance with Annex G of IEC61400-12-1 [1].

The tower is fitted with a number of instruments at several heights. Notably, several meteorological instruments including several models of anemometers and wind vanes are installed at different levels on booms of varying lengths. For this Study, GL GH focused on two anemometers installed at two different heights; namely i) a Met One SS201cup anemometer installed at 88 m agl and supported by a boom extending 12 feet from the tower side and ii) an ATI K-Type sonic anemometer installed at 76 m agl and supported by a boom extending 24 feet from the tower side. Both anemometers are oriented 285° relative to true North.

[1] Email received from A. Clifton (NREL) on January 6th 2012 and drawing presented in Appendix D.

3 DESCRIPTION OF THE APPLICATION

3.1 Assumptions and Flow Modeling

One source of uncertainty in mechanical wind speed measurement is the influence of the tower itself. A numerical study of the wind flow around a lattice tower was conducted in 2010 by GL GH and ETS. The study is reported in detail in reference [2]. The following paragraphs provide a brief summary of the main simulation assumptions and parameters.

The CDF simulation was performed using the ANSYS CFX 11.0 software package. A 2-dimensional simulation was carried out using a Sheer Stress Transport (SST) turbulence closure model. Model constants were modified for the simulation of atmospheric flow.

A generic lattice tower was modeled using the actuator disk theory by applying a drag force on the front face of the tower without considering its geometrical elements. Additionally, simulations assumed circular symmetry around the lattice tower. This assumption is deemed valid for distances greater that two tower face widths from the tower centre [3]. Lastly, the simulations were calibrated and validated for a lattice tower with a solidity of 0.1.

3.2 Description of the Tool

The application provided to the Client uses a 2D speed-up look-up table based on the results of the CFD flow simulation described above and thoroughly reported in [2].

Tower face-width, boom length, and boom orientation are entered by the user. Flow distortion (speed-up factor) is estimated using the boom length and wind direction. The speed-up factor deduced from the look-up table is then applied to each wind speed record to provide an estimate of the free-stream wind speed.

3.3 Limitations

It is noted that GL GH did not perform any specific CFD analysis for the NREL tower. Consequently, the results should be interpreted with caution. Additionally, the following should be borne in mind when considering the results:

- 3D effects were not considered;
- Only flow distortion due to the tower was considered. Potential effect of booms, mounting tubes, or other nearby obstacles such as proximate instruments were not simulated;
- Simulations are not deemed valid at distances closer than two (2) face-widths relative to tower centre;
- Simulations are not deemed valid in sectors under direct wake of the tower;
- Simulations were validated for a generic lattice tower with a solidity of 0.1 only. Larger flow distortion is to be expected for lattice towers with higher solidity values.

Amongst the above-cited limitations, potential under-estimation of flow distortion due to NREL's tower solidity value was identified as a critical issue requiring further investigation. The approach adopted by GL GH to deal with this issue is described in Section 4.

4 SENSITIVITY ANALYSIS

GL GH proposed to perform a sensitivity analysis based on experimental data from a number of lattice towers with various solidity values to come up with conclusions as per the use of the CFD application for NREL tower with its specific solidity value. The following subsections outline the approach while detailed results are presented in Appendix C.

4.1 Assumptions and Simplified Analysis

According to IEC [1], the normalized centre-line wind velocity Ud for a lattice tower is approximately given by:

$$Ud = 1 - (0.062Ct^2 + 0.076Ct)\,[0.082/(Lb/L)]$$

Where Lb/L is the boom length over face-width ratio and Ct is the tower thrust coefficient. For a triangular-base lattice tower of solidity s, Ct is approximated by:

$$Ct = 2.1(1 - s)s\ ,\ 0.1 < s < 0.3$$

To the first order, and for small values of s, Ud is proportional to s and inversely proportional to Lb/L. Generalizing this approximation to regions away from the centre line, one can assume that tower-induced flow distortion remains proportional to s and inversely proportional to Lb/L. Under such an assumption, it is possible to estimate flow distortion for a given solidity s, using the one estimated by the CFD application for a solidity s = 0.1 by artificially reducing the Lb/L ratio by a factor k proportional to 1/s.

To implement this approach, the ratio of wind speeds as measured by redundant cup anemometers at the same height above ground level were compared to those predicted by the CFD application. Several triangular-base lattice towers with various solidity ratios and boom lengths were considered. In each case, the CFD application was used with actual and reduced Lb/L ratio to determine the "correction factor" k providing a qualitatively good fit between measurements and simulations. Results – presented in Appendix C – were analyzed on a directional basis using wind direction data provided by tower wind vanes.

It is noted that whenever required, boom orientations used for CFD estimates were adjusted to fit experimental data before the analysis was performed. This adjustment is necessary when wind vanes are prone to systematic bias due to tower shadow or flow distortion, or when actual boom orientations differ from design specifications.

Table 4-1 presents a summary of the test cases. Experimental data are reported in figures presented in Appendix C.

Table 4-1: Test cases for sensitivity analysis

Test Case	Tower Id/Description	Anemometry Used	Lb/L[1]	Solidity Ratio[2]
A	PR/91-m lattice tower	Redundant WindSensors @ 61 m agl	5.6	0.15
B	QW/90-m lattice tower	Redundant Vaisalas @ 72 m agl	4.0	0.18
C	BC/100-m lattice tower	Redundant NRG#40s @ 90 m agl	6.3	0.21
D	AP/100-m lattice tower	Redundant WindSensors @ 80 m agl	6.2	0.21
E	Same as D	Redundant NRG#40s @ 60 m agl	6.3	0.21

1. Average value calculated from 2 booms.
2. Estimated from available information and drawings.

4.2 Results of Sensitivity Analysis

Based on comparisons presented in Appendix C, the suggested correction factors (k) are presented in Table 4-2 (see also Figure 4-1).

Table 4-2: Sensitivity analysis results

Tower Solidity s	1/s	Correction Factor k
0.10	10.0	1.0 (base case)
0.15	6.7	0.7 – 0.8
0.18	5.6	0.6 – 0.7
0.21	4.8	0.5 – 0.6
0.26	3.8	To be determined (see below)

Assuming a simple linear relationship between k and 1/s as discussed at the beginning of Section 4.1, results of the CFD application could be used for a solidity of 0.26 (NREL tower), with a correction factor of 0.5 as suggested by Figure 4-1.

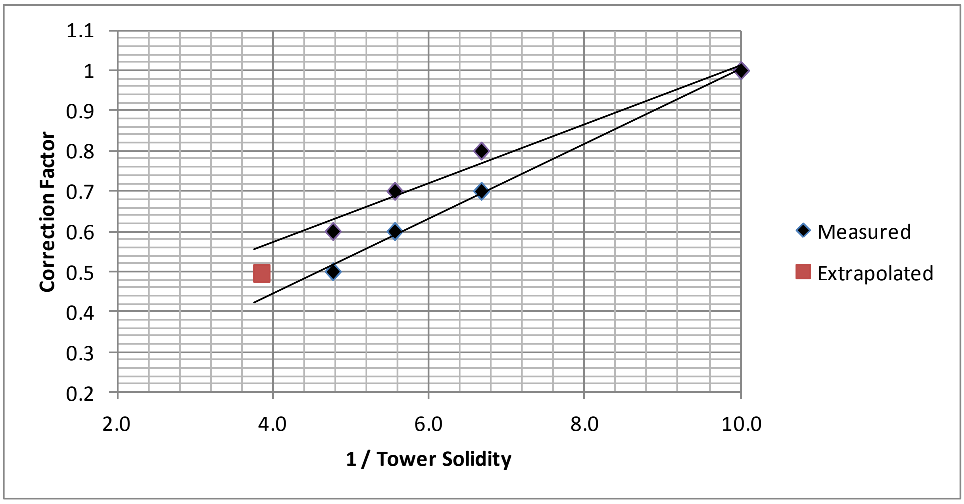


Figure 4-1: Correction factor (k) extrapolation

5 DISCUSSIONS

NREL tower solidity – as estimated by GL GH from information provided by Client – is higher than the value of 0.1 for which the CFD application was initially validated. A sensitivity analysis was performed to assess the impact of higher solidity values when using the CFD application. Test cases and results are briefly reported in Appendix C.

Based on the simplified model and the experimental results presented in Appendix C, it is confirmed that, as expected, flow distortion is underestimated for solidity ratios greater than 0.1. It is further argued that by artificially reducing the boom-length over tower-face-width ratio Lb/L by a factor k<1, it is possible to fit the CFD simulations to experimental data.

Based on the conclusions reported in Section 4, it is concluded that the CFD application could provide better flow distortion estimates for the NREL tower by artificially reducing the Lb/L ratio by a factor of two (correction factor k=0.5). Therefore, when using the CFD application, it is recommended to input a boom length reduced by a factor of two or, equivalently, to input a face width dimension increased by a factor of 2.

Using this approach, typical results and flow distortion estimates for a cup anemometer at 88 m agl and a sonic anemometer at 76 m agl mounted on the NREL tower were estimated and are reported in Appendix B.

The above statements must be considered in light of the following remarks:

- GL GH did not have access to met towers with solidity ratios as high as that of NREL tower, namely 0.26. The suggested correction factor is based on a simplified model supported by experimental data available from a number of towers with solidity ratios ranging from 0.15 to 0.21.
- GL GH did not have access to met tower data with booms as short as those of NREL tower. It has been assumed that flow distortion results of the CFD application were valid for boom lengths as short as those of NREL tower.
- Within the scope of the current project, GL GH did not perform a systematic investigation to assess potential combined effects of relatively short booms and high solidity ratios.

Further investigation of presented results and discussions would require good quality data measured by redundant anemometers mounted at the same height on the NREL (or similar) tower.

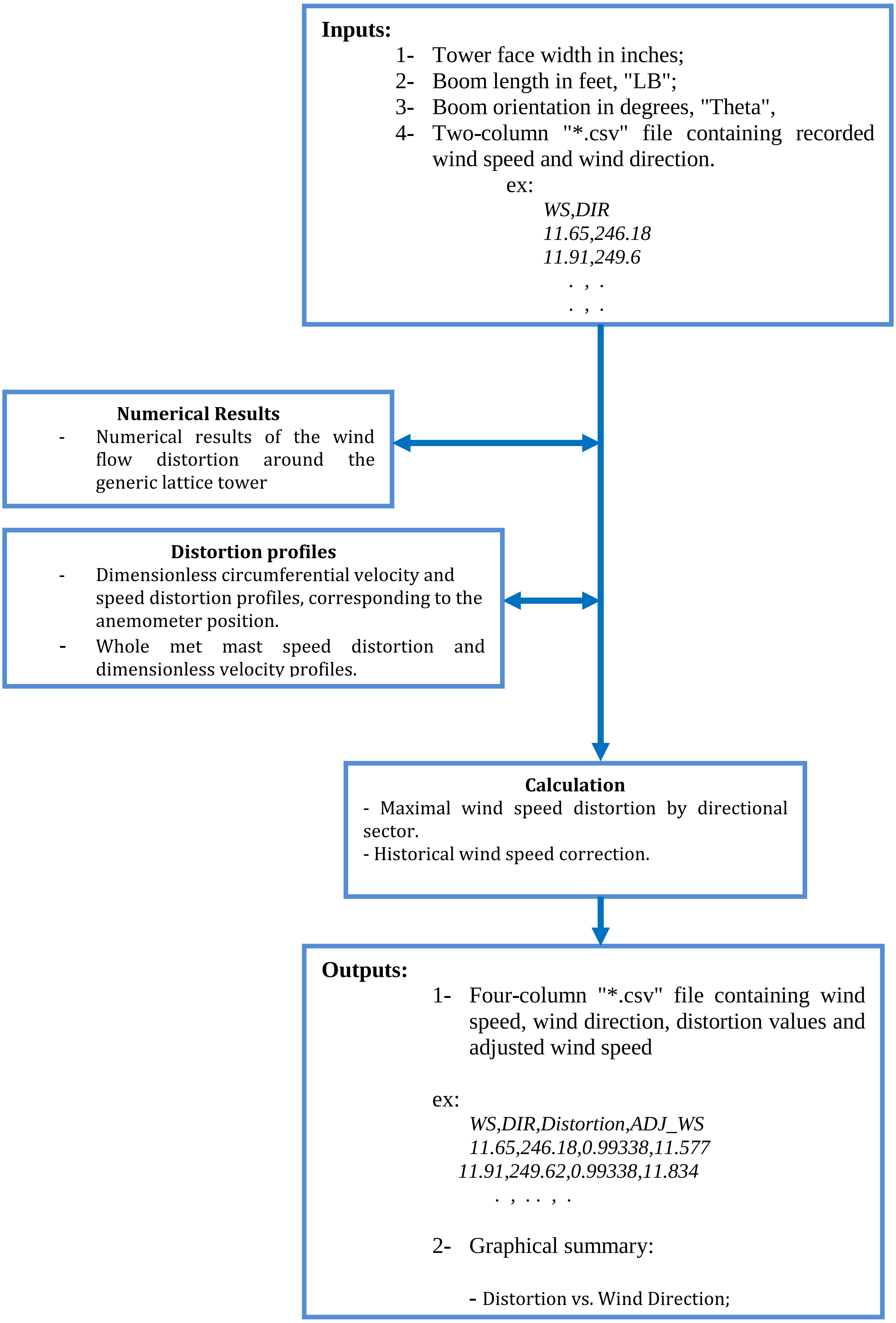
6 REFERENCES

[1] IEC 61400-12-1, “Power Performance Measurement of Electricity Producing Wind Turbines,” Annex G, 2005.

[2] Tusch M, Masson C, Héraud P, 2011, “Modeling of Turbulent Atmospheric Flow Around Tubular and Lattice Meteorological Masts” Journal of Solar Energy Engineering, February 2011.

[3] Hansen, M. O. L., and Pedersen, B.M., “Influence of the Meteorology Mast on a Cup Anemometer,” ASME J. Sol. Energy Eng., 121, 1999, pp. 128–134.

APPENDIX A CFD APPLICATION FLOW CHART



APPENDIX B RESULTS FOR NREL TOWER ANEMOMETERS

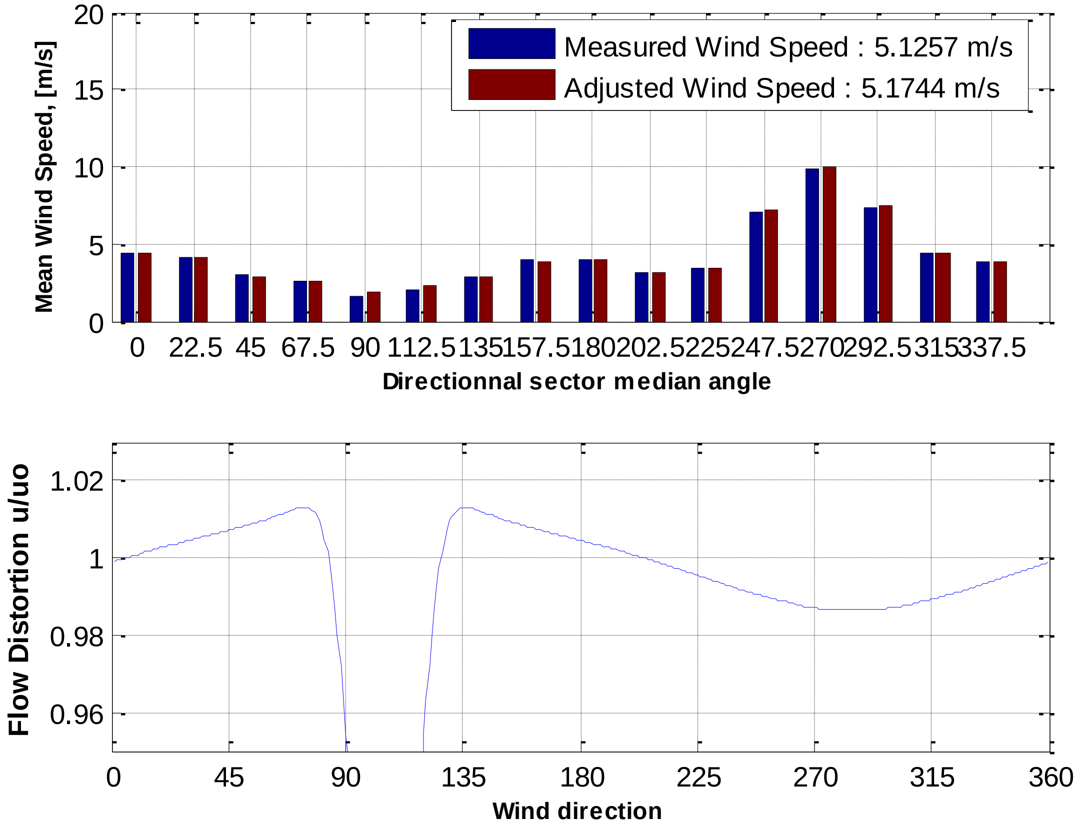


Figure B-1: Flow Distortion - NREL tower: Cup anemometer @ 88 m agl; Boom length: 12'; Boom orientation: 285 ° – Applied correction factor k = 0.5.

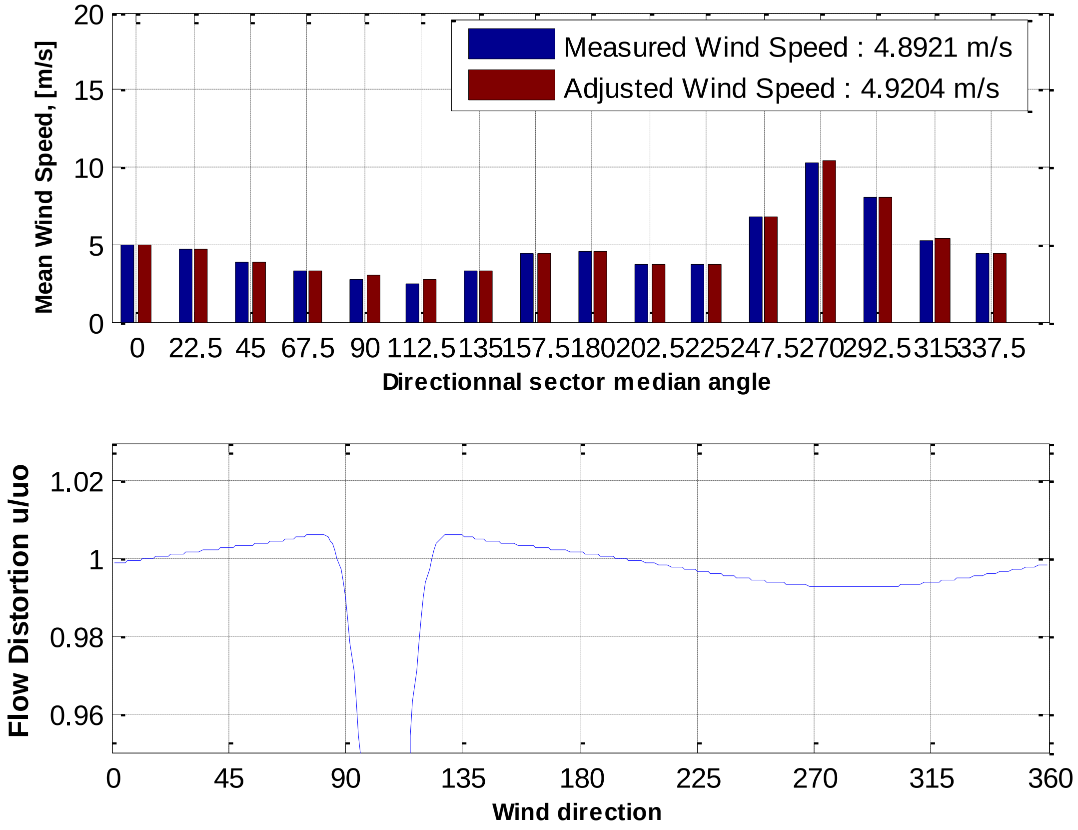
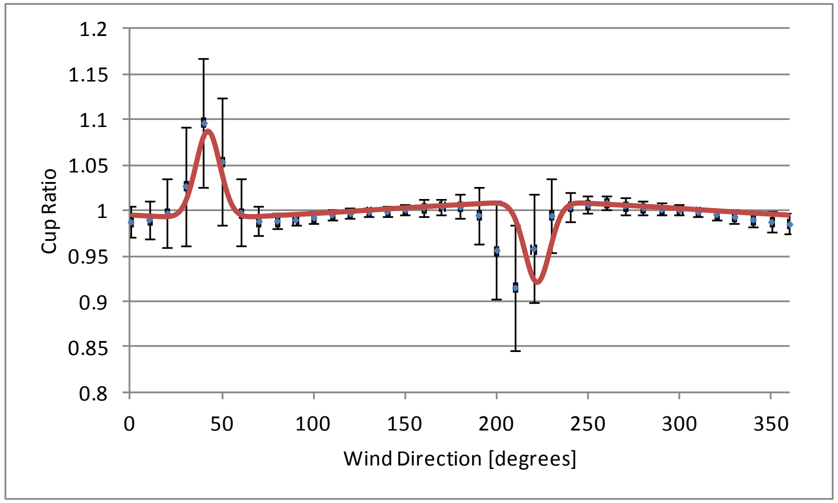


Figure B-2: Flow Distortion - NREL tower: Sonic anemometer @ 76 m agl; Boom length: 24'; Boom orientation: 285 ° – Applied correction factor k = 0.5.

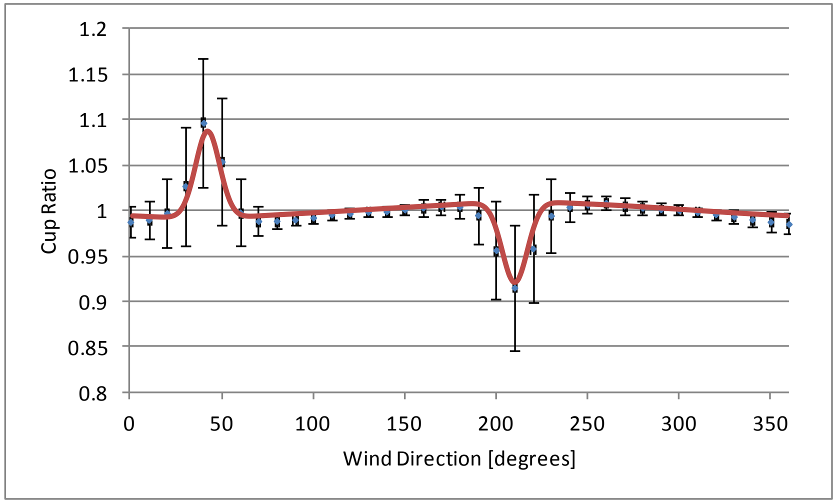
APPENDIX C EXPERIMENTAL DATA FOR SENSITIVITY ANALYSIS

The following figures present the results of the sensitivity analysis described in Section 4. Experimental data are presented as data points with vertical bars representing one standard deviation. CFD simulations are presented by solid red lines.

Test Case A

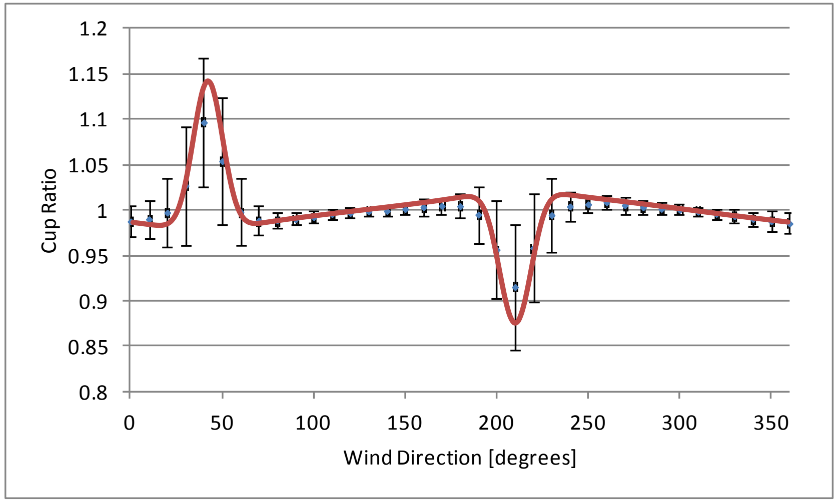


Before wind vane bias correction.

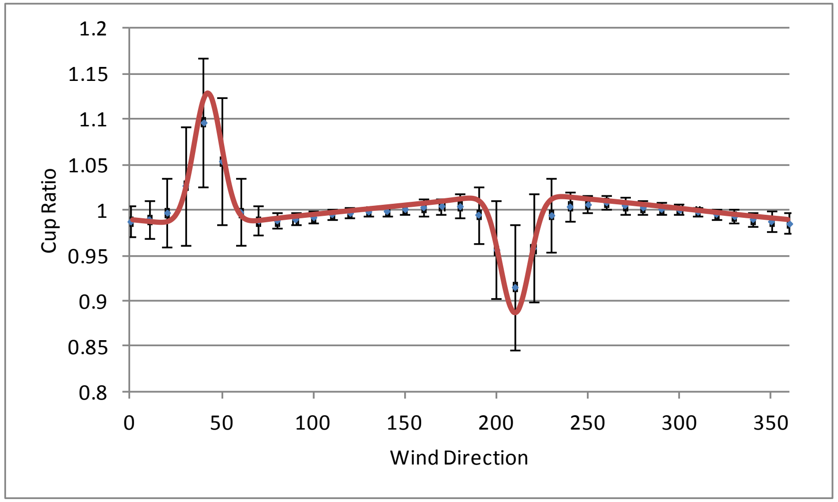


After wind vane bias correction.

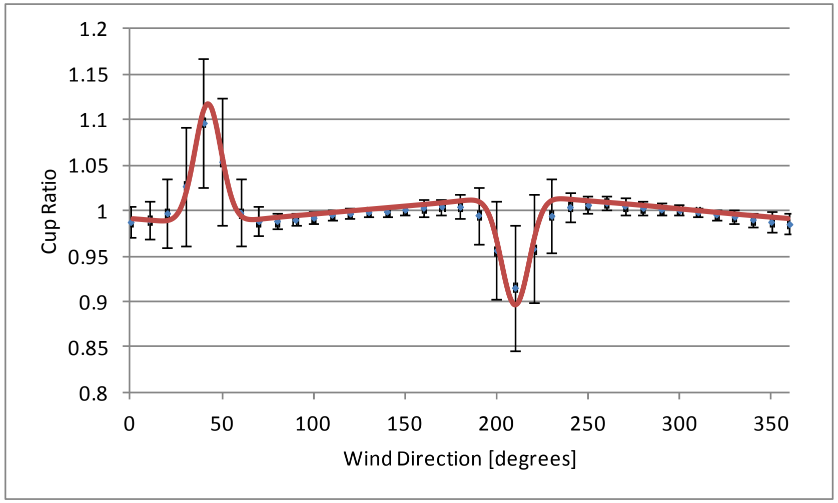
Figure C-1: Test case A: Experimental vs. simulated (red) flow distortion – k=1.



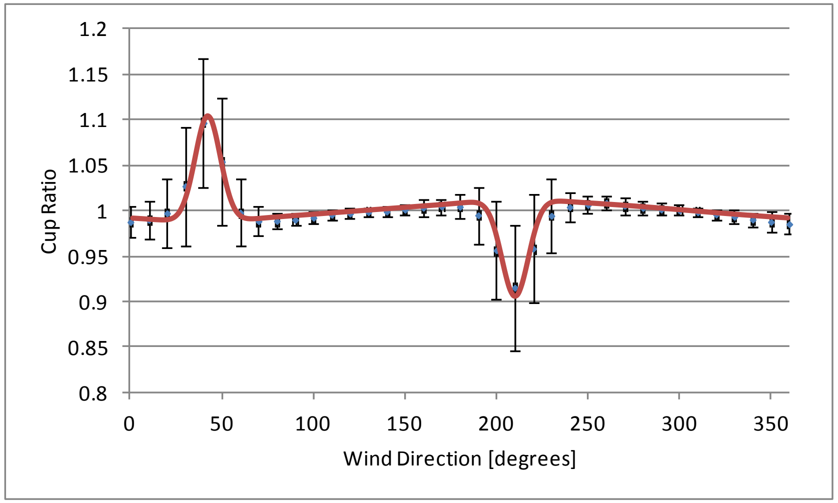
Lb/L reduced by a factor of k=0.5.



Lb/L reduced by a factor of k=0.6.



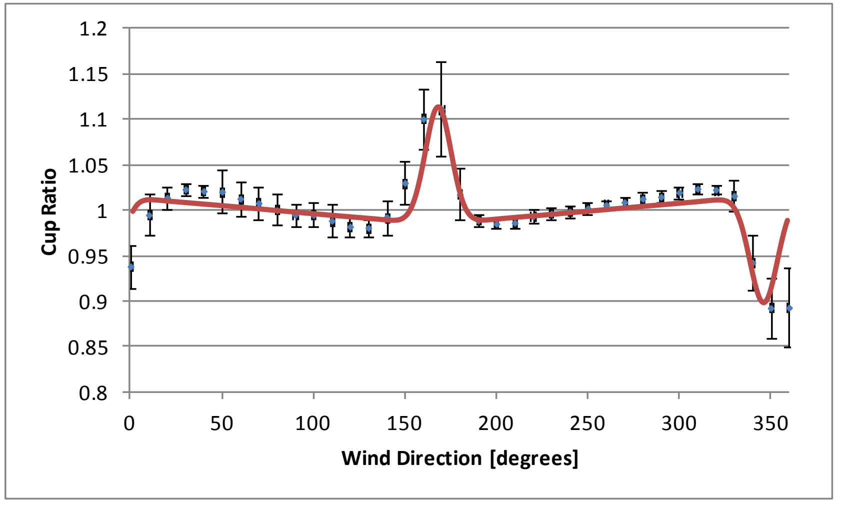
Lb/L reduced by a factor of k=0.7.



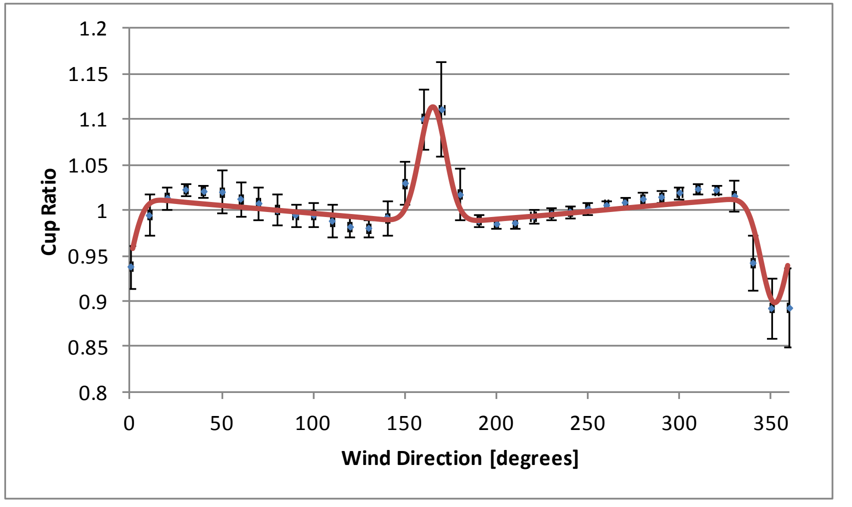
Lb/L reduced by a factor of k=0.8.

Figure C-2: Test case A: Experimental vs. simulated (red): Sensitivity analysis.

Test Case B

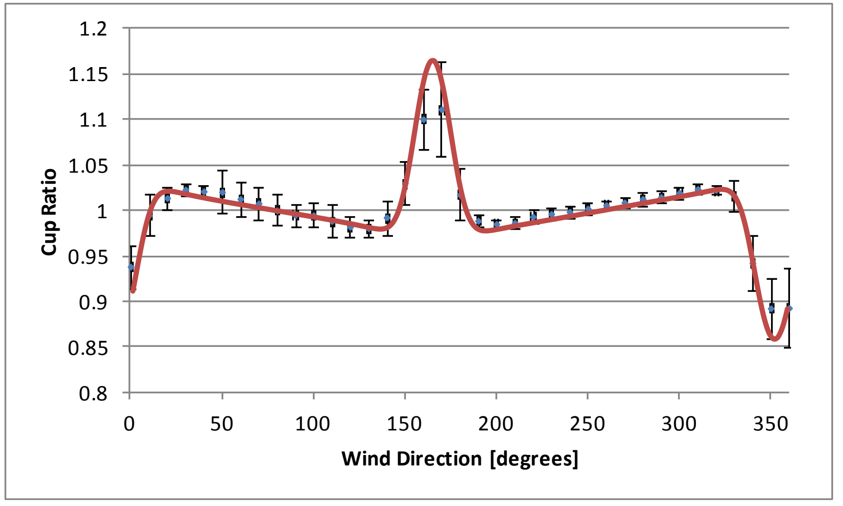


Before wind vane bias correction.

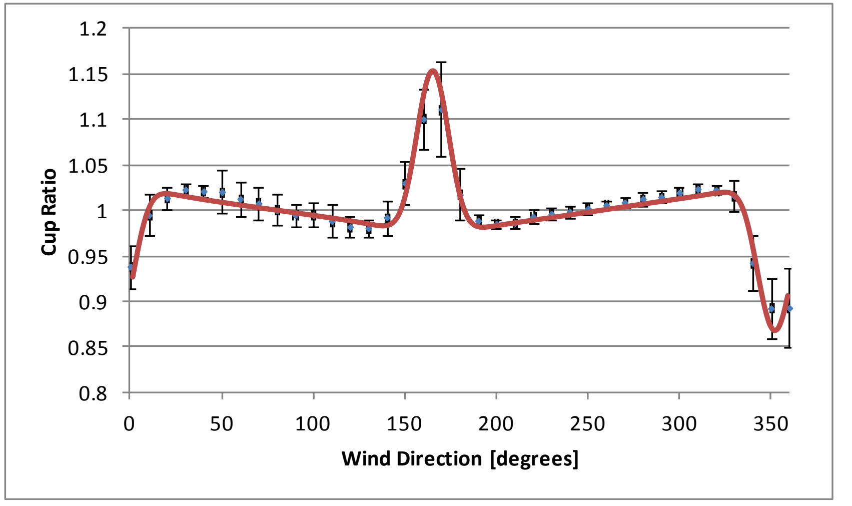


After wind vane bias correction.

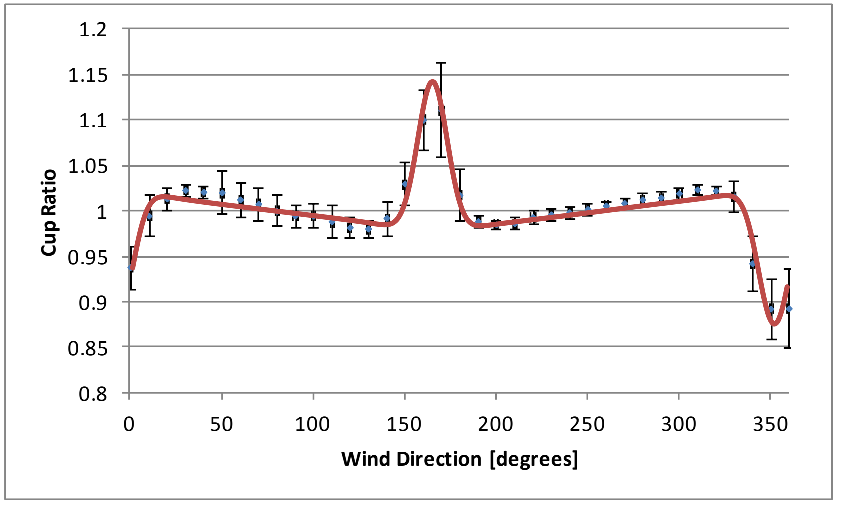
Figure C-3: Test case B: Experimental vs. simulated (red) flow distortion – k=1.



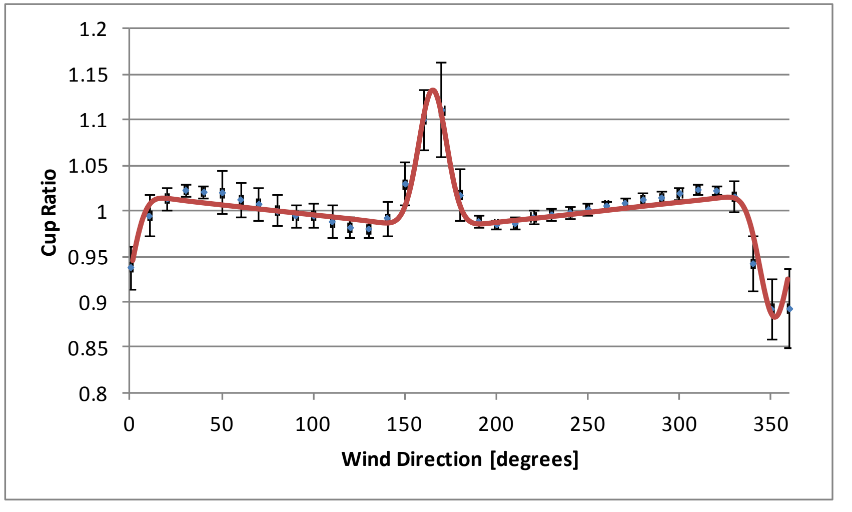
Lb/L reduced by a factor of k=0.5.



Lb/L reduced by a factor of k=0.6.



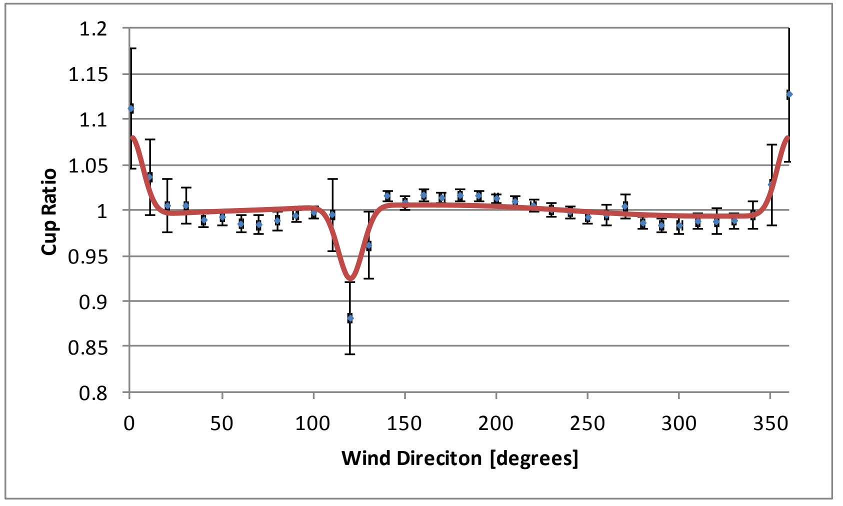
Lb/L reduced by a factor of k=0.7.



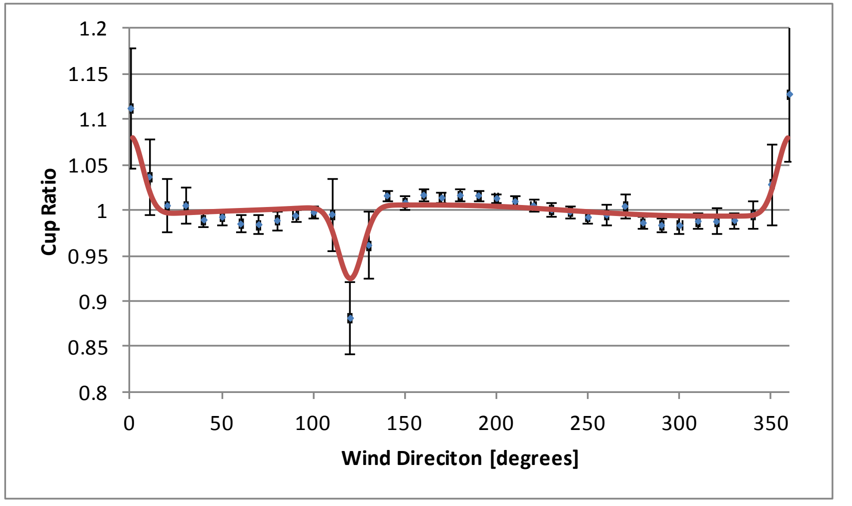
Lb/L reduced by a factor of k=0.8.

Figure C-4: Test case B: Experimental vs. simulated (red): Sensitivity analysis.

Test Case C

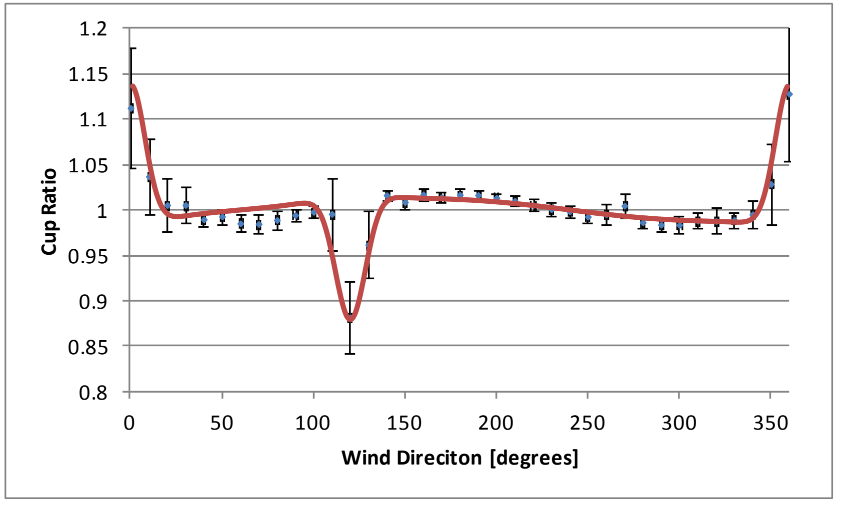


Before wind vane bias correction.

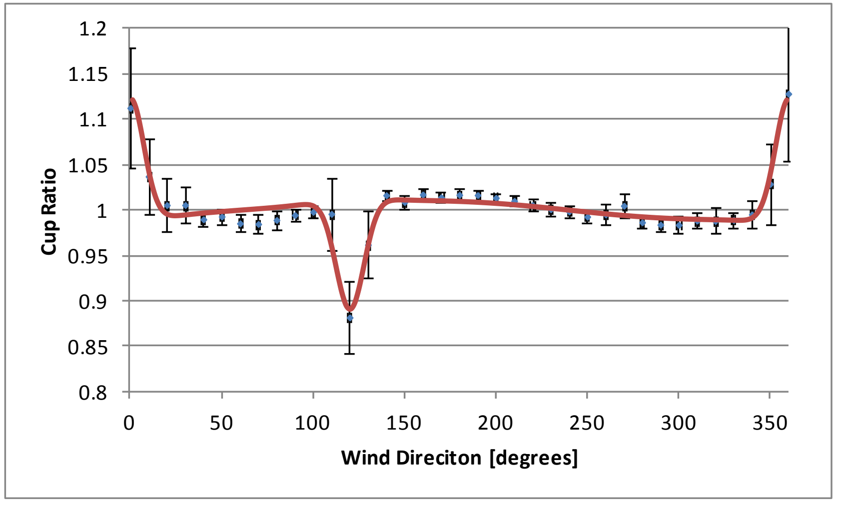


After wind vane bias correction.

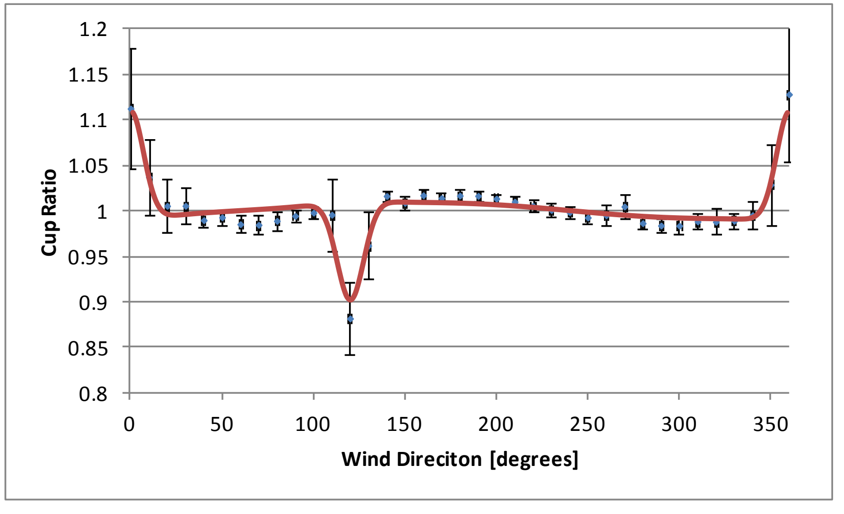
Figure C-5: Test case C: Experimental vs. simulated (red) flow distortion – k=1.



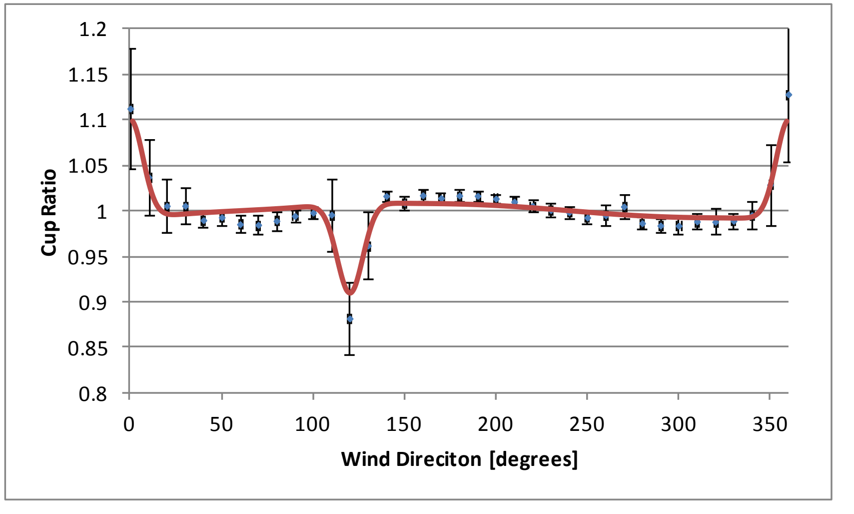
Lb/L reduced by a factor of k=0.5.



Lb/L reduced by a factor of k=0.6.



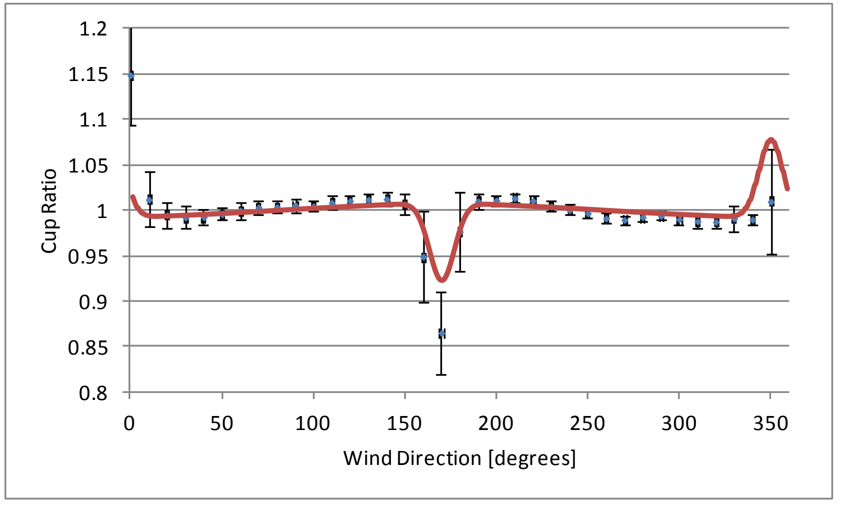
Lb/L reduced by a factor of k=0.7.



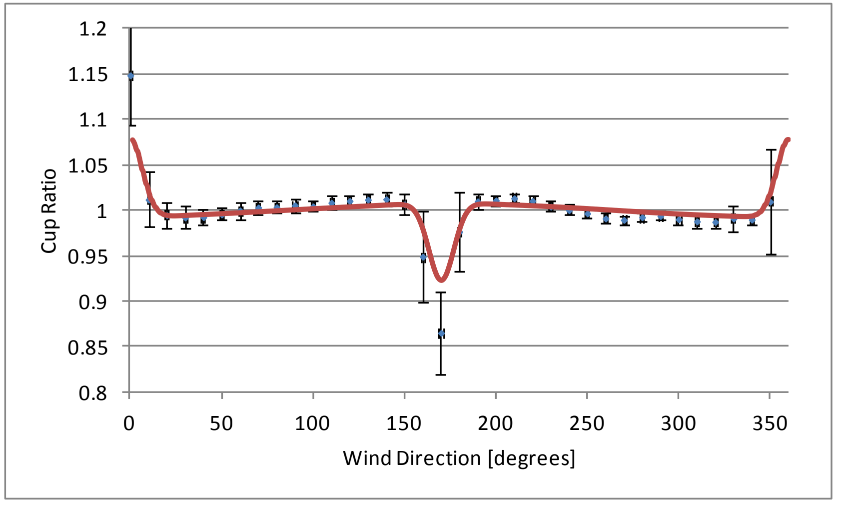
Lb/L reduced by a factor of k=0.8.

Figure C-6: Test case C: Experimental vs. simulated (red): Sensitivity analysis.

Test Case D

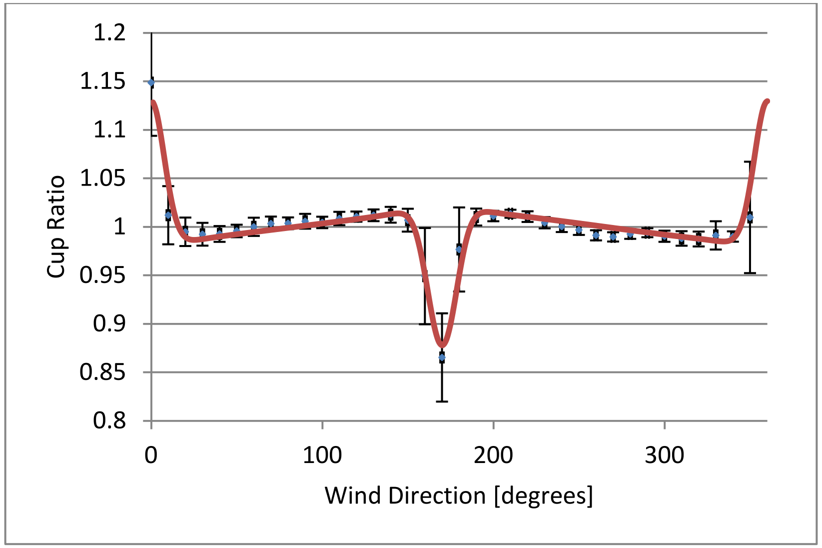


Before wind vane bias correction.

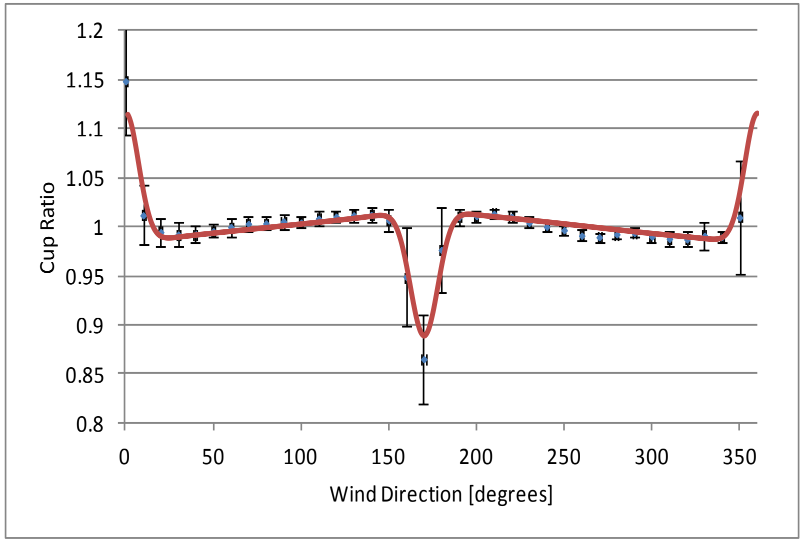


After wind vane bias correction.

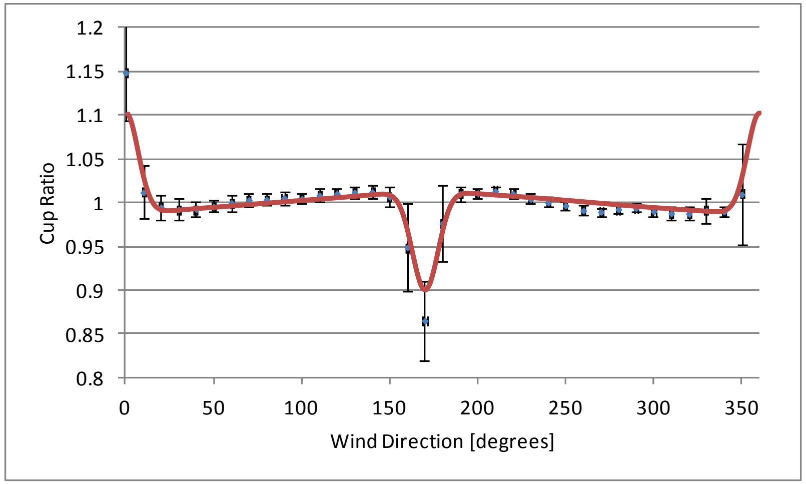
Figure C-7: Test case D: Experimental vs. simulated (red) flow distortion – k=1.



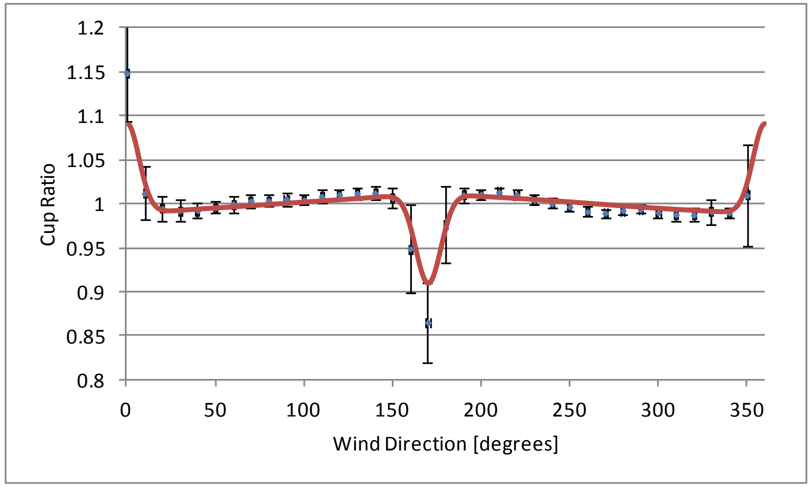
Lb/L reduced by a factor of k=0.5.



Lb/L reduced by a factor of k=0.6.



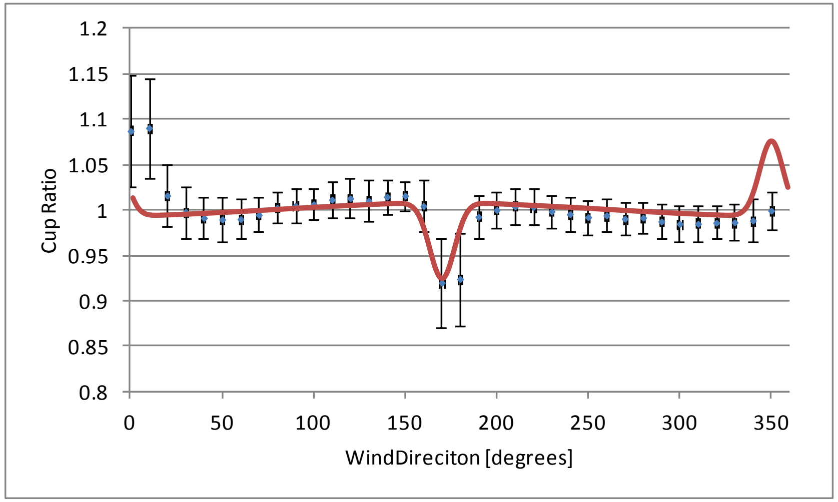
Lb/L reduced by a factor of k=0.7.



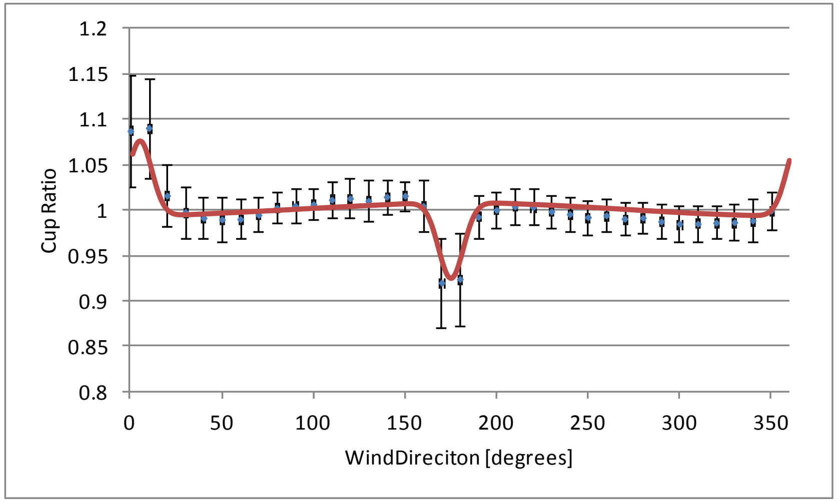
Lb/L reduced by a factor of k=0.8.

Figure C-8: Test case D: Experimental vs. simulated (red): Sensitivity analysis.

Test Case E

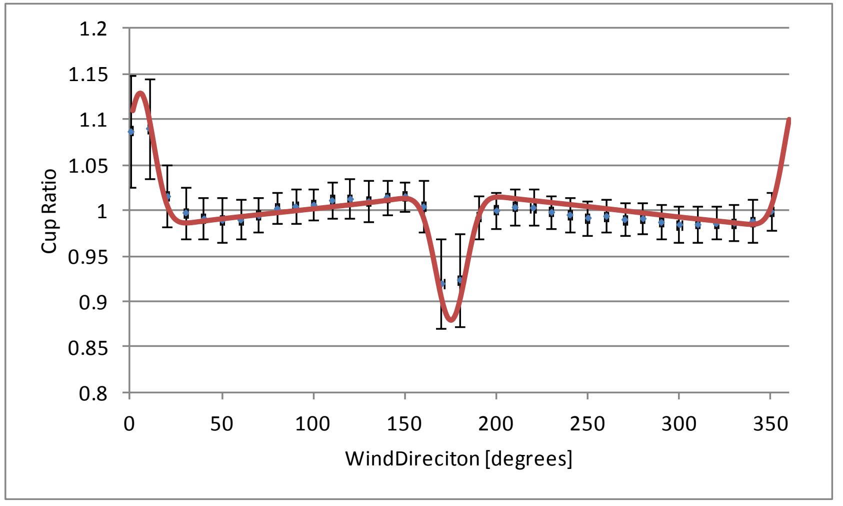


Before wind vane bias correction.

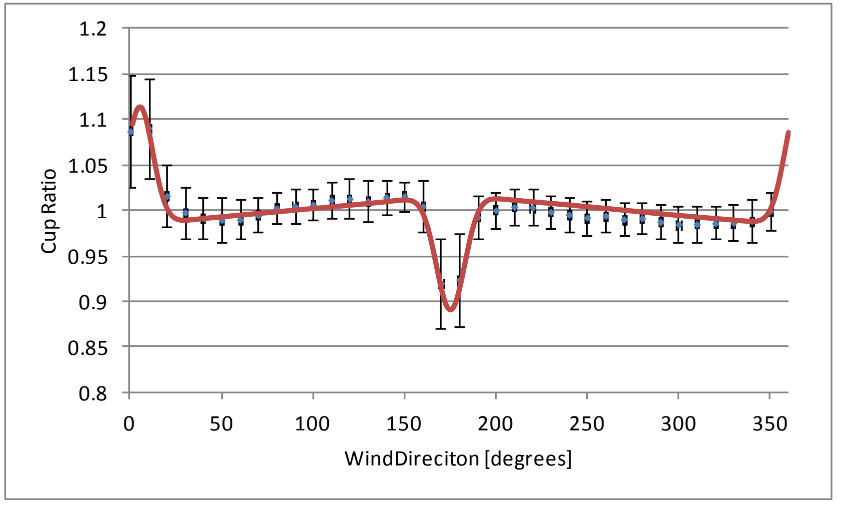


After wind vane bias correction.

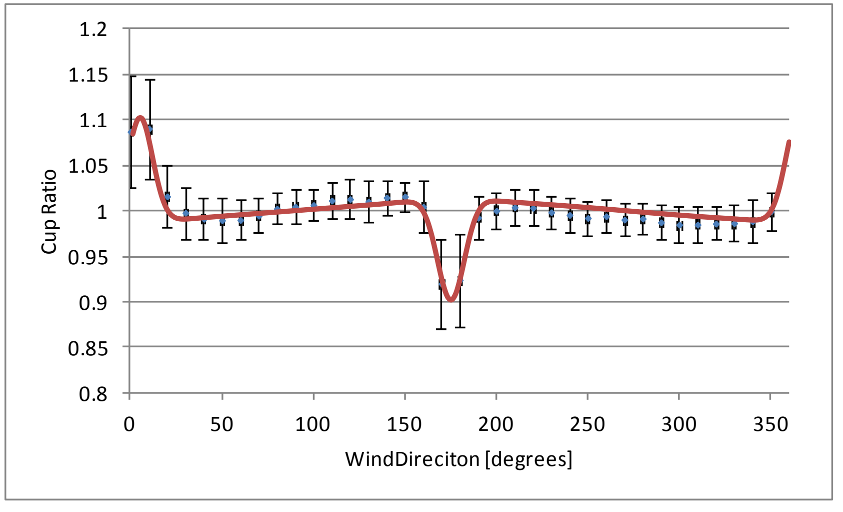
Figure C-9: Test case E: Experimental vs. simulated (red) flow distortion – k=1.



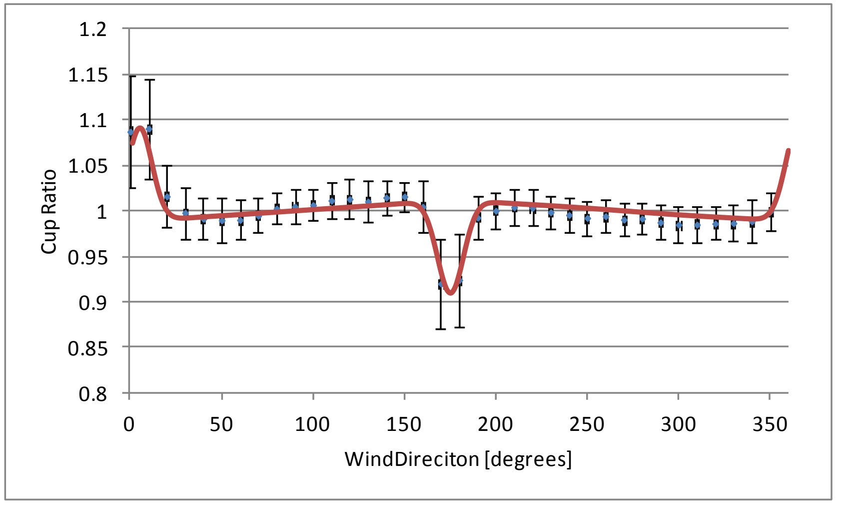
Lb/L reduced by a factor of k=0.5.



Lb/L reduced by a factor of k=0.6.



Lb/L reduced by a factor of k=0.7.



Lb/L reduced by a factor of k=0.8.

Figure C-10: Test case E: Experimental vs. simulated (red): Sensitivity analysis

APPENDIX D NREL TOWER SECTION DRAWING

NREL tower is a double-braced Rohn tower depicted below (right).