CORRECTION FACTORS FOR NRG #40 ANEMOMETERS POTENTIALLY AFFECTED BY DRY FRICTION WHIP

Characterization, Analysis, and Validation

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ABSTRACT

Over 50,000 NRG Systems #40 anemometers manufactured between May 2006 and December 2008 are potentially affected by a self-excited vibratory phenomenon termed Dry Friction Whip (DFW). Affected anemometers can report wind speeds that are lower than true speeds by up to several percent. An analysis of post-deployment wind tunnel calibration tests on 99 anemometers manufactured in this period found that about 85% were affected by the problem. The mean wind speed bias between 4 - 16 m/s for most of the anemometers compared to pre-deployment tests ranged from -1.5% to -3.0%, and for some, the bias was as large as -6.5%. This finding was confirmed by field tests carried out for a mostly different sample of 53 potentially affected anemometers deployed in pairs with WindSensor P2546A or Vector A100LK anemometers. The field tests further indicated that the problem tends to worsen over time and varies with wind speed. However, the pattern of response varies greatly among anemometers. Based on this research, a method of adjusting data from NRG #40 anemometers manufactured in this period is proposed. The adjustments eliminate the mean bias in the field test data set, although significant scatter remains.

1. INTRODUCTION

The accuracy of wind plant production estimates depends on the accuracy of wind speeds measured within the wind project area. The NRG #40 anemometers manufactured by NRG Systems, Inc., are widely used for this purpose.

In the fall of 2007 and spring of 2008, reports began to surface within the wind industry of problems with some NRG #40 anemometers, including calibration drift and biases with respect to other leading anemometer models. In May 2008, NRG Systems released a technical support bulletin which acknowledged performance issues with NRG #40 anemometers shipped between January 1, 2006 and March 28, 2008 (serial numbers 26130 to 65750). According to this report, the problem manifested itself as a tendency for the anemometers to under-report wind speeds. NRG Systems attributed this to an uncontrolled assembly process that resulted in excess epoxy on the anemometer shaft. NRG Systems estimated that the issue potentially affected 15-20% of the instruments within the serial number range. Following this finding, NRG Systems instituted a process change which attempted to mitigate the epoxy interference.[1]

In subsequent reports, NRG Systems announced that the epoxy problem was not the root cause of the slowdown. NRG Systems' current position is that the anemometers are affected by "a self-excited vibratory phenomenon termed dry friction whip (DFW)" caused by an in-specification change in the manufacturing of the anemometer stator. NRG states that this problem affects a portion of anemometers manufactured between May 2006 and December 2008 (serial numbers 29000 to 94999). Affected anemometers are reported to exhibit degraded performance within 2 to 26 weeks after deployment.[2]

According to NRG Systems, DFW does not occur in anemometers manufactured after December 2008, and no reports of problems with sensors manufactured since then have been reported in the literature.

2. DETECTING DRY FRICTION WHIP

For the purposes of this study, NRG #40 anemometers are classed in the following vintages:

- Type A - Manufactured before May 2006; serial numbers less than 29,000.
- Type B - Manufactured between May 2006 and December 2008, serial numbers 29,000 - 94,999.
- Type C - Manufactured on or after January 1, 2009; serial numbers 95,000 and greater.

This study assessed only Type B anemometers.

Two ways to identify anemometers affected by DFW have been proposed. The first is to compare speed readings from pairs of sensors deployed in the field at the same height, and the second is to remove the sensors from the field and subject them to calibration tests. These two methods are discussed in the following sections.

2.1. Wind Tunnel Tests

By conducting a calibration test after removing a sensor from the field, it should be possible to detect significant performance degradation due to DFW. Calibration tests conducted in a certified wind tunnel establish the response of an anemometer over a range of wind speeds according to a standard measurement protocol. The outcome is a linear function fitted to the data with a specified offset and slope.[3] NRG Systems recommends the following criteria to identify affected sensors by this method: abnormal residuals, a standard error greater than 0.12 m/s, and an increase in the offset of greater than 0.15 m/s compared to a pre-deployment calibration test.[2] The NRG offset change criterion, in particular, may not be stringent enough to detect substantially all DFW-affected anemometers, however. At a nominal speed of 8 m/s, a change in offset of 0.15 m/s represents a shift of 1.9% in the reported speed, which is well outside the normal range of expected performance degradation for properly functioning anemometers. In a study using Type A anemometers, Lockhart and Bailey found the uncertainty in the mean speed reported by calibrated #40 sensors in a controlled environment (such as a wind tunnel) to be 0.4%.[4] Thus, an anemometer could deviate up to five standard deviations from accepted behavior without failing the NRG offset-change test.

A more demanding criterion of a 1.0% shift in the transfer function at 10Hz (~8.0 m/s), or 2.5 standard deviations from observed deviations in unaffected sensors, is proposed. This threshold should produce a negligible rate of false alarms (good anemometers that suggest a shift in the transfer function > 1%) while detecting a larger proportion of anemometers significantly affected by DFW.

2.2. Paired Sensors

Both quantitative and graphical methods can be used to compare readings from paired sensors and detect DFW.[2] Figure 1 shows a graphical approach using a scatter plot of the speed ratio for each data record as a function of direction. (Except where otherwise noted, all data displayed in tables and figures are from AWS Truepower.) The relatively large and bimodal scatter over all directions is a sign of DFW[1]. The fact that the ratio strays both above and below zero suggests that DFW is affecting both anemometers. Other plots, such as X-Y scatter plots, can also be used. Table 1 lists quantitative criteria recommended by NRG to detect abnormal sensor performance in paired sensors.

Comparisons of paired sensors are effective at detecting anemometers impacted by DFW when it is certain that one of the two sensors is not affected (for example, if the second sensor is a NRG #40 Type A or Type C anemometer or is from another manufacturer). However, the results of such comparisons can be ambiguous or misleading if both sensors are affected. As an example of this problem, Figure 2 presents weekly mean wind speed ratios from two NRG #40 Type B sensors. For the first 30 weeks, the ratio did not exceed the criteria set forth by NRG. When one of the anemometers was replaced, however, there was a jump in the ratio, which demonstrated that both of the original sensors were, in fact, affected. After 10 to 15 weeks, the ratio once again fell within the normal range, indicating that the new anemometer (a Type B) was also affected by DFW.

3. RESEARCH OBJECTIVE

The research was performed in two phases. Phase I was focused on wind tunnel calibration tests performed before and after anemometer deployments of varying duration. The goal was to estimate the proportion of anemometers affected by DFW and to obtain insight into the magnitude of the impact on wind speed measurements. Phase II was a field test campaign in which NRG #40 Type B anemometers were paired with IEC Class I anemometers.[5] The goal of this phase was to independently verify the wind tunnel results, improve understanding of the magnitude and rate of DFW-induced performance degradation, and derive suitable correction functions.

3.1. Phase I – Wind Tunnel Testing

The objectives of Phase I were as follows:

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[1] Variations in the mean ratio by direction apparent in Figure 1 reflect various tower influences, most importantly tower shadow.

- Estimate, through wind tunnel tests, the percentage of a sample of NRG #40 sensors affected by DFW.
- Assess the utility of wind tunnel tests for quantifying the response of anemometers affected by DFW.
- Investigate the linearity of the sensor response when affected by DFW.

Initial and post-deployment calibration test results were acquired for 99 NRG #40 Type B anemometers that had been deployed in various wind climates across North America, including Texas, Wyoming, Hawaii, Illinois, Iowa, and Ontario. The wind tunnel tests (most of which were paid for by NRG Systems) were all performed by OTECH Engineering.[6] The calibration forms provided by OTECH Engineering included the tunnel reference mean wind speed and anemometer output at approximately 2.0 m/s intervals, a linear best fit transfer function to convert the anemometer signal to wind speed, and the residual at each speed interval.

Table 2 lists the number of sensors failing the performance tests according to the NRG Systems criteria – a change in the offset of 0.15 m/s or a residual standard error of 0.12 m/s - and the proposed criteria – a 1.0% decrease in the reported speed at 10Hz (8.0 m/s) or a residual standard error of 0.12 m/s. Using the two quantitative criteria recommended by NRG Systems, 68.7% of the anemometers in the sample were found to fail either or both tests; with the proposed criteria, the proportion increased to 86.9%.

All sensors showed at least some decrease in response at 10 Hz; the largest drop was just over 5%. The mean change in response was -2.2%, with a standard deviation of 1.3%. Table 3 tabulates the mean speed, offset, and slope changes. It is evident that a change in the transfer function offset was the main cause of the shifts in speed.

NRG reports that abnormal residual patterns in calibration tests are a sign of DFW. Indeed the residual patterns of affected sensors typically show anomalies between 4 m/s and 16 m/s, although not in every wind speed interval. The lack of uniformity suggests that the problem is intermittent; this is supported by bimodal patterns seen in scatter plots comparing 10-minute readings from paired sensors (like that shown in Figure 1).

While calibration residuals can be used to detect DFW, they may not reliably determine the magnitude of the response shift. Scatter plots indicate that affected sensors do not always enter DFW in a particular wind speed range, but rather exhibit a higher probability of entering the mode over certain speed ranges. Therefore, a single calibration test may not be representative of long-term performance.

To test the consistency of anemometer response to DFW, several previously deployed NRG #40 Type B anemometers were sent to OTECH Engineering for consecutive calibration tests. Each anemometer was subjected to a total of five calibration tests: the initial calibration, the post-deployment test immediately after tower tilt-down, and three consecutive tests at a later date. The results varied substantially among the tests.

Figure 3 presents the results of one such test. The initial calibration, shown in black, is the baseline for comparison. As indicated by the arrows, the sensor appears to have switched into DFW mode at least once at 6 m/s, 8 m/s, 10 m/s, 12 m/s, and 14 m/s during one of the four post-deployment tests. Furthermore, the residuals varied widely within each test and between tests (not shown), which indicates that the DFW problem was sporadic and that the anemometer response was generally less linear than in the pre-deployment test. These problems appeared much less often at wind speeds of 16 m/s and higher.

For this particular anemometer, each test after the initial calibration yielded a different transfer function, although the anemometer remained the same and no field deployment occurred after the second test. It is concluded that standard post-deployment calibration tests are unable to precisely assess and quantify the changed response of an NRG #40 sensor affected by DFW. This is likely due to the abbreviated testing intervals and intermittent character of the DFW phenomenon.

Based on this analysis, the following conclusions from the Phase I research are reached:

- According to the proposed criteria, about 85% of NRG #40 Type B anemometers are affected by DFW.
- The shift in the sensor response manifests itself most often as an increase in the transfer function offset; the slope is not as greatly affected.
- One of the main indicators of a changed response is the standard error of the calibrated transfer function, indicating that the anemometer response versus wind speed becomes increasingly non-linear.
- Sensor degradation appears to worsen over time.

- Post-deployment calibration appears to be an effective tool to determine if a sensor is affected by DFW.
- Post-deployment calibration results are not repeatable for sensors affected by DFW, and, therefore, are not suitable for correcting data from sensors deployed in the field.

4. PHASE II – FIELD TESTING AND DATA ANALYSIS

The objectives of Phase II were as follows:

- Estimate the percentage of sensors affected by DFW and compare findings to wind tunnel results.
- Develop and validate a method to correct NRG #40 data affected by DFW.
- Estimate the uncertainty in the corrected mean speeds relative to a trusted reference.

4.1. Datasets

NRG #40 Type B and IEC Class I anemometers (WindSensor P2546A and Vector A100LK) were paired at the same height on 17 tall towers in varying environments across the United States. A total of 53 pairs were available for study. Of these, 48 were NRG-WindSensor pairs and five were NRG-Vector pairs. The anemometers were deployed at four potential wind project sites in Texas, Wyoming, and Hawaii. The test periods ranged from 26 to 45 weeks. All of the WindSensor and Vector sensors were new at the time of their deployment. Of the NRG #40 anemometers, 21 were new, while the remaining 32 had been in operation for varying periods. Six were among the 99 anemometers subjected to post-deployment tests in Phase I of this study; the rest were not. The Phase II anemometer serial numbers were between 34,000 to 86,000, and fall within the defined range for Type B sensors potentially affected by DFW.

All of the anemometers were installed on NRG tubular towers under the supervision of AWS Truepower personnel. The booms were mounted on each mast with orientations designed to mitigate the effects of tower-induced flow distortions on the measurements from the most frequent wind directions. The top anemometers on each mast were mounted at least 1.0 m below the top of the mast to mitigate the effects of flow over the top. The data were collected at each tower with an NRG Symphonie logger in 10-minute intervals.

The WindSensor P2546A and Vector A100LK anemometers were calibrated at the Svend Ole Hansen wind tunnel testing facility, and the NRG #40 sensors were calibrated at the OTECH Engineering facility. The raw P2546A and Vector A100LK data were converted to speed using the transfer functions specified on each instrument's calibration form. This is in accordance with IEC 61400-12-1, which requires that turbine performance tests be carried out with calibrated Class I anemometers, and that the calibration constants be used for the test.[7] The raw NRG #40 data were converted using the consensus transfer function defined by Lockhart and Bailey.[4] Research using nine NRG #40-WindSensor P2546A pairs deployed in the field found the average speed reported by the NRG anemometer, when raw NRG #40 data was converted to wind speed values using the consensus transfer function, to be in close agreement with that reported by the WindSensor anemometer (-0.1% mean bias with a standard deviation of 1.2%).[8] Since no such comparisons were available for anemometers calibrated by Otech, it was decided to apply the consensus function.

Differences in the dynamic response of the WindSensor P2546A anemometer and the NRG #40 are well documented. The most significant known factor responsible for these differences is turbulence. The following correction was applied to the NRG data to reduce the impact of turbulence on the results of this study:[9]

$$v_{corrected} = \frac{v_{observed}}{0.095TI + 0.992}$$

TI is the turbulence intensity, which is defined as the standard deviation of 2-second speeds within a 10-minute interval divided by the corresponding 10-minute mean speed.

To minimize differences in the impact of the tower on the speeds measured by each anemometer in a pair, it is usually recommended that only observations falling in a small directional window (generally 20-40 degrees) bisecting the midpoint between the two anemometer booms be used for comparison. The drawback of this approach is that it limits the data sample size. To increase the amount of useable data, a tower-effects correction was applied based on research by Filippelli and Mackiewicz, who used a computational fluid dynamics model to describe the wind flow around tubular towers.[10] With a correction derived from this work, it was judged possible to employ a 135-degree window (+/- 67.5 degrees from the midpoint between the two booms).

4.2. Comparisons with Class I Anemometers

The field test campaign compared readings from NRG #40 Type B anemometers to readings from one of two types of IEC Class I anemometer: the WindSensor P2546A and Vector A100LK. To test whether the Class I anemometers provide a sufficiently stable baseline for this purpose, pre- and post-deployment calibration reports were obtained from WindSensor for 19 P2546A anemometers, most of which had spent three or four years in the field. (The anemometers were not among those used in the present study.) The tests were all performed at the Svend Ole Hansen wind tunnel. None of the sensors reported speeds differing by more than +/- 1.0% at 12.5 Hz (~8.0 m/s), the criteria used to identify DFW affected NRG #40 anemometers. The range of the calibration changes was -0.9% to 0.7% and their standard deviation was 0.4%, indicating much smaller shifts than those observed in the sample of NRG #40 anemometers. This result was deemed satisfactory. Although no similar test data were available for the Vector instruments, it was assumed that they exhibit a similarly stable response.

Mean wind speeds were calculated for each sensor pair using valid concurrent data only. The distribution of mean wind speed differences is shown in Figure 4. Also plotted are the results from Phase I comparing the shift in response at 10 Hz between initial and post-deployment calibration tests. Although the anemometers tested (with the exception of six) are not the same and the methods of comparison differ between the two sets of data, the distributions observed are similar. This suggests that both wind tunnel and field tests can be used to detect shifts in NRG anemometer response caused by DFW, with similar results. In total, 47 of the 53 (88.7%) NRG anemometers deployed in the field were deemed to be affected by DFW according to the proposed criteria of Table 2; of these, 46 anemometers demonstrated a mean bias of at least -1.0% relative to the reference and one displayed a large scatter signature.

4.3. Investigation

As an initial step, scatter plots of the 10-minute mean wind speed differences for each anemometer pair as a function of wind speed were created. It was found that for several pairs the mean bias depended on speed, and that the bias pattern was highly variable from pair to pair. As an illustration, Figure 5 presents scatter plots from three anemometer pairs. A wide dispersion of points is evident in all three plots, supporting the inconsistent behavior noted earlier with regard to the wind speed residuals derived from multiple calibration tests (Section 3.1). The NRG sensor in Pair A exhibits a negative mean bias relative to its reference at all wind speeds. The mean starts at about -0.2 m/s at 4 m/s and becomes gradually more negative, reaching about -0.3 m/s at 16 m/s. The scatter decreases markedly above 12 m/s. The NRG sensor in Pair B exhibits a very wide scatter below 6 m/s, with a mean bias of about -0.3 m/s. The scatter narrows and the bias becomes more negative at around 7 m/s. The mean bias then gradually becomes more positive, reaching nearly zero at 16 m/s. The NRG sensor in Pair C exhibits a very wide scatter and significant negative bias in the mid-range of speeds. The scatter decreases somewhat with increasing speed and the mean bias moderates to around -0.3 m/s.

For comparison, Figure 6 presents a difference scatter plot between a properly-functioning NRG #40 (Type C) a WindSensor P2546A. The plot shows much less scatter with no significant dependence on wind speed or bimodal behavior.

Based on the results of Phase I, it was suspected that the severity of DFW depends on the amount of time the anemometer is deployed in the field. This hypothesis was tested by observing the change in the bias for each anemometer pair as a function of the cumulative number of cycles (revolutions) of NRG anemometer operation. (The number of revolutions is assumed to be a good analog for sensor wear and stress that may contribute to the onset and progression of DFW.) The mean bias was calculated for each test pair for every 10,000 cycles of operation (about one calendar week on average) in speed bins of 1 m/s width. At least 30 valid records were required to compute the bias for a given speed and deployment time interval; otherwise no value was reported.

For the entire sample of 47 affected anemometers, it was found that both the change in bias over time and its variance depended on speed. Figure 7 depicts the mean and standard deviation of the rate of bias change over time from 4 to 16 m/s. On average, the most rapid degradation occurs at around 7 m/s. After removing the mean bias change with time from each anemometers wind speeds, the remaining mean bias from 4 to 16 m/s is shown in Figure 8. Although the influence of time in the field has been eliminated, the affected sensors nevertheless exhibit a consistent negative bias compared to the reference anemometers. This suggests that the DFW problem was already present at, or soon after, the sensors were deployed. The maximum initial bias occurs at around 10 m/s.

5. STANDARD AND CALIBRATED CORRECTIONS

Based on the concepts described above and results depicted in Figure 7 and Figure 8, three methods to correct NRG #40 Type B data potentially affected by DFW are proposed. Two corrections are to be used when there is no paired Class I anemometer with which to perform an in-field calibration. In Standard Correction I it is assumed that the NRG #40 has been verified to be affected by DFW through, e.g., a post-deployment calibration test. In Standard Correction II it is assumed that the NRG #40 status is unknown. The third method employs a paired IEC Class I sensor to adjust the NRG #40 data.

5.1. Standard Correction I

In the absence of a paired Class I anemometer, a post-deployment calibration test should be performed, if possible, to determine whether a particular NRG #40 Type B sensor is affected by DFW. If the sensor fails this test, then Standard Correction I, which is calculated from the 47 affected anemometers in the field data sample, is applied to the data. The parameters for this correction are listed in Table 4. The parameters should be applied as follows:

$$v_{adjusted} = Offset + v_{unadjusted} \times Slope$$

where $v_{unadjusted}$ is the speed reported by the anemometer and converted using its usual calibration coefficients. This correction assumes that the 47 affected anemometers constitute a representative sample of all Type B anemometers that might found to be affected by DFW. We believe it is a reasonable assumption considering the size of the sample, the fact that the anemometers have a wide range of serial numbers (i.e., they did not come all from the same manufacturing batch), and the fact that the distribution of biases in anemometer response at 10 Hz is similar to that observed in the 99 NRG anemometers tested in a wind tunnel.

5.2. Standard Correction II

When it cannot be determined whether a NRG #40 Type B sensor is affected by DFW (for example, if the sensor has been damaged or is unavailable for post-deployment testing), Standard Correction II parameters based on 53 anemometer pairs, including six NRG anemometers unaffected by DFW, is recommended. The parameters are listed in Table 5. The parameters should be applied using the equation shown above. This correction assumes that the 53 anemometers constitute a representative sample of all Type B anemometers, whether affected by DFW or not. We believe it is a reasonable assumption for the same reasons mentioned above regarding Standard Correction I. In addition, since the proportion of DFW-affected sensors in this sample is nearly identical to that found among the 99 anemometers tested in a wind tunnel, it is reasonable to conclude that this proportion is similar to that of the Type B population as a whole.

5.3. Calibrated Correction

If a Class I sensor has been deployed with a NRG #40 for at least several months, then a Calibrated Correction (the mean bias of the Class I and NRG #40 speeds) can be calculated for the concurrent period and applied as necessary to correct the concurrent #40 data. If the NRG sensor was present for a period before the Class I sensor was deployed, then a Calibrated Correction determined from the wind speed biases during the concurrent period can be extrapolated back in time in a linear fashion so that the initial bias equals the mean initial bias from Standard Correction I. This method reduces the error associated with the standard correction's time dependence by measuring the NRG #40 response relative to the Class I sensor at a moment in time.

5.4. Validation and Uncertainty

Standard Correction I and Standard Correction II were validated using the “jackknife method”.[11] The correction parameters for the sample dataset were calculated with one sensor pair excluded at a time; the correction was then applied to the excluded NRG anemometer, and the mean error with respect to its reference was determined. This process was repeated for each pair. For the Calibrated Correction a two- to four-week window (the retrofit window) at the end of each sensor pair's period of record was identified. It was assumed that this window captured a sufficient amount of data to determine the biases as a function of wind speed. The correction was then extrapolated back in time as described previously, and the correction was applied to the NRG data for that pair. The errors were evaluated only over the time between the sensor installation and the beginning of the retrofit window. The adjusted mean bias and other error statistics for all three correction methods were then calculated.

Table 6 presents the mean errors and standard deviations of errors for each of the three correction methods compared to the same without correction. (The error is defined as the mean difference in speed between the NRG #40 and reference anemometers for a particular pair over the test period; the mean error and standard deviation of errors are calculated over all pairs subject to the particular correction, i.e., 47 pairs for Standard Correction I and 53 pairs for Standard Correction II and the Calibrated Correction.) Both versions of the standard correction eliminate the mean error; Standard Correction I produces a slightly lower standard deviation of adjusted errors (1.3%) compared to Standard Correction II (1.4%). The Calibrated Correction is significantly more accurate than both standard corrections, with a standard deviation of mean errors of 0.7%. Figures 9 to 11 present the distribution of the errors using each correction method, in addition to the fitted Gaussian distribution for each.

The standard deviation of the mean errors among a representative sample of anemometer pairs is a measure of the uncertainty in the adjusted mean speed for an arbitrary NRG #40 Type B sensor. It is reasonable to suppose that this uncertainty depends on the size of the correction. This is confirmed in Figure 12, which plots the five-point rolling standard deviation of mean errors as a function of the rolling average size of the correction for Standard Correction I and Standard Correction II. (The size of the rolling window strikes a compromise between keeping the scatter small while providing sufficient definition of the relationship between uncertainty and the DFW correction magnitude.) For both, the uncertainty increases with larger adjustments, from roughly 0.5-1% for adjustments of 1.5-2%, to 2.5-3% for adjustments of about 3%. The linear equations shown on the plot provide a good fit (r^2= 0.77 for Standard Correction I and r^2=0.71 for Standard Correction II) to the data.

The Calibrated Correction results, presented in Figure 13, reveal a smaller uncertainty as well as less dependence on the size of the adjustment. The linear correlation is considerably weaker than for the two standard corrections. Therefore, it is recommended in this case to apply a constant uncertainty rather than one that increases with the size of the correction.

The fitted uncertainty functions for each type of correction are presented in Table 7. The minimum uncertainty for the two standard corrections is set to 0.7%, which is the fixed uncertainty in the calibrated correction. The minimum is interpreted as the lowest uncertainty that can reasonably be achieved considering the known performance of properly functioning NRG #40 sensors and IEC Class I sensors. The minimum uncertainty is imposed for adjustments less than 2% for Standard Correction I and less than 1.8% for Standard Correction II. In real-world applications, the functions should be adjusted to account for other sources of uncertainty, such as tower effects, turbulence, and in-flow angle.

6. CONCLUSIONS

Through an analysis of initial and post-deployment wind tunnel tests and field comparisons between paired NRG #40 Type B and IEC Class I anemometers, it is concluded that about 85% of NRG #40 Type B anemometers are significantly affected by DFW. Standard wind tunnel tests appear to be capable of detecting anemometers affected by DFW. However, due to the transitory and unpredictable nature of this phenomenon and the short duration of these tests, they are not a reliable method of quantifying the anemometers' altered response. Repeated calibration tests using the same sensors as well as the field comparisons conducted for this study indicate that affected anemometers drift in and out of DFW mode at different times and at different speeds.

The field tests conducted for this research reveal some general patterns in the performance of anemometers affected by DFW, including increased and often bimodal scatter. However, it is found that different anemometers can exhibit very different biases and dependences on wind speed and deployment time. Some anemometers demonstrate a consistent linear change in response over time, while others degrade at varying rates, and sometimes appear to improve for a time. All told, a significant correlation between the bias and the number of revolutions experienced by anemometers, as well as between the bias and wind speed, is observed.

The standard corrections described here are derived from the field comparisons of what is believed to be a representative sample of NRG #40 Type B anemometers. Standard Correction I is applied only to sensors that fail a post-deployment calibration test, whereas Standard Correction II is applied to all NRG #40 Type B sensors. Applying these corrections results in an increase in estimated mean wind speeds of 1.5% - 3.0% in most cases, depending on the wind speed frequency distribution and length of deployment. It is demonstrated that the proposed corrections effectively eliminate the mean biases in the sample of affected sensors and slightly reduce the scatter of the residuals relative to the paired IEC Class I anemometers. The uncertainty in the corrected mean speeds varies from less than 1% to close to 3% depending on the size of the adjustment.

The proposed Calibrated Correction is to be applied to sensors that are paired with an IEC Class I anemometer in the field. This correction eliminates the bias and is accompanied by a small additional uncertainty of 0.7%.

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FIGURE CAPTIONS

Figure 1. Scatter plot of wind speed ratio from paired NRG #40 sensors versus wind direction. The wide scatter and bimodal pattern indicate the likely occurrence of dry friction whip (DFW) in one or both sensors.

Figure 2. Weekly mean wind speed ratio from paired NRG #40 Type B sensors over a period of about 60 weeks of deployment, demonstrating that two sensors affected by DFW can pass the comparison tests shown in Table 1. Source: AWS Truepower.

Figure 3. Signal output for each wind speed interval in the OTECH calibration test of a single anemometer for five calibration tests. The arrows indicate wind speed intervals where one or more of the tests indicated the sensor was prone to DFW.

Figure 4. Frequency distribution of mean wind speed biases for 53 paired NRG #40 and IEC Class I sensors. Also shown are the results of Phase I comparing pre- and post-deployment calibration tests for 99 NRG #40 Type B anemometers at 10 Hz.

Figure 5. Scatter plots of the difference in 10-minute mean wind speeds reported by NRG #40 Type B and WindSensor P2546A anemometer pairs at three different sites. The patterns vary, indicating that DFW can manifest itself in different ways at different sites.

Figure 6. Scatter plot of the differences in 10-minute speeds recorded by a NRG #40 Type C (unaffected by DFW) and a WindSensor P2546A sensor.

Figure 7. Mean slope of the bias change with time (blue line) from 4 to 16 m/s for 47 NRG #40 Type B anemometers affected by DFW. The mean slope and variance are greatest around 6-9 m/s. Due to a small sample size in the 15 and 16 m/s speed bins, slopes for those bins were linearly extrapolated using the slopes from the 7 to 14 m/s speed bins.

Figure 8. Mean bias at each wind speed interval between 4 m/s and 16 m/s after removing the influence of deployment time. The magnitude of the speed bias is greatest in the 8-12 m/s wind speed bins. Using the 10 to 14 m/s bins, values in the 15 and 16 m/s bins are linearly extrapolated due to few samples.

Figure 9. Validation results for Standard Correction I. The adjustment removes the mean bias from measurements affected by DFW, with a small improvement to the standard deviation (normal distribution) of the biases.

Figure 10. Validation results for Standard Correction II, which are similar to those for Standard Correction I. Standard Correction II includes data from six properly functioning #40 anemometers.

Figure 11. Validation results for the Calibrated Correction. Compared to both standard corrections, the distribution of errors in the adjusted data is much narrower.

Figure 12. Five-point rolling standard deviation of adjusted mean wind speed errors for Standard Correction I and Standard Correction II as a function of the rolling average of the correction.

Figure 13. Five-point rolling standard deviation of adjusted mean wind speed errors for the Calibrated Correction as a function of the rolling average of the correction.

Table 1. Normal sensor performance thresholds for NRG #40 sensor pairs. Source: NRG Systems.

Statistic	Expected Normal Performance
Mean Bias	≤ ± 0.2 m/s
Ratio	0.98 – 1.02
Pearson’s Correlation Coefficient	≥ 0.995
Standard Deviation of the Wind Speed Ratio	≤ 0.02

Table 2. The number of NRG #40 anemometers failing expected performance criteria in post-deployment calibration tests out of 99 sensors manufactured between May 2006 and December 2008. The NRG and proposed criteria for standard error are both 0.12 m/s. The NRG criterion for calibration shift is 0.15 m/s in offset speed. The proposed criterion for calibration shift is a 1% decrease in wind speed reported at 10 Hz.

Test	NRG Criteria*	Proposed Criteria*
Standard Error	59 (59.6%)	59 (59.6%)
Calibration Shift	58 (58.6%)	80 (80.8%)
Combined	68 (68.7%)	86 (86.9%)

*Based on 99 anemometers tested.

Table 3. Summary of changes in pre- and post-deployment calibrations for the sample of 99 NRG #40 Type B anemometers.

Difference (Post - Initial Calibration)	Mean	Standard Deviation
Speed @ 10Hz	-2.2%	1.3%
Offset (m/s)	0.21	0.14
Slope (m/s/Hz)	-0.003	0.007

Table 4. Standard Correction I slope and offset adjustments.

Wind Speed (m/s)	Offset (m/s)	Slope [(m/s)/Total Hz^7]
4	0.087	0.144
5	0.092	0.785
6	0.098	1.790
7	0.120	2.470
8	0.159	2.140
9	0.179	1.714
10	0.185	1.383
11	0.179	1.022
12	0.162	0.906
13	0.145	0.910
14	0.136	0.746
15	0.132	0.286
16	0.132	0.036

Table 5. Standard Correction II slope and offset adjustments.

Wind Speed (m/s)	Offset (m/s)	Slope [(m/s)/Total Hz^7]
4	0.083	0.145
5	0.083	0.752
6	0.084	1.779
7	0.101	2.406
8	0.138	2.045
9	0.161	1.619
10	0.168	1.284
11	0.163	0.963
12	0.149	0.788
13	0.132	0.846
14	0.120	0.745
15	0.120	0.242
16	0.120	0.000

Table 6. Mean error and standard deviation of mean errors for the three corrections. The unadjusted statistics vary because of differences in the test data sample and time periods for each correction method.

Adjustment Parameter	Standard Correction I		Standard Correction II		Calibrated Correction	
	Mean Bias	Standard Deviation	Mean Bias	Standard Deviation	Mean Bias	Standard Deviation
Unadjusted	-2.2%	1.4%	-2.0%	1.5%	-2.3%	1.5%
Adjusted	0.0%	1.3%	0.0%	1.4%	0.0%	0.7%

Table 7. Recommended uncertainty functions for Standard Correction I, Standard Correction II, and the Calibrated Correction, in percent. *A* is the adjustment in percent.

Standard Correction I	Standard Correction II	Calibrated Correction
$\sigma = 1.876A - 3.0, A \geq 2.0$ $\sigma = 0.7, A < 2.0$	$\sigma = 1.707A - 2.3, A \geq 1.8$ $\sigma = 0.7, A < 1.8$	$\sigma = 0.7$