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Field comparison of IEC 61400-11 Wind turbines - Part11: Acoustic noise measurement techniques: Edition 3.0 and Edition 2.1

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Summary

Following the release of Edition 3.0 (2012) of IEC 61400-11 Wind Turbines – Part 11: Acoustic noise measurement techniques, there has been a lot of interest as to how analysis results differ from methods stipulated in Edition 2.1 (2006).

This paper provides a detailed review of the differences between Edition 3.0 and Edition 2.1. An analysis is provided on differences in evaluation of the apparent sound power level and tonal audibility between both versions of the measurement standard.

1. Introduction

The IEC 61400-11 measurement standard provides a method for evaluating the acoustical emissions of wind turbines. The standard is broken down into two main parts: evaluation of apparent sound power level and tonal audibility. Guidance is also provided on how to evaluate measurement uncertainty.

Edition 2.0 [1] of the standard was released in 2002 and subsequently amended in 2006, Amendment #1, Edition 2.1 [2]. The differences between Edition 2.0 and Edition 2.1 were minimal and primarily focused on clarifications and minor improvements to the analysis method. Edition 2.1 was widely adopted within the industry and served as the industry standard for evaluating wind turbine noise emissions.

At the end of 2012, IEC released Edition 3.0 [3] of the measurement standard. Edition 3.0 is a major revision of the standard. Given the drastic changes between Edition 2.1 and Edition 3.0 there has been both industry and stakeholder interest in evaluating the specific differences and how they impact the evaluation of a wind turbines noise emission.

This paper focuses on the measurement of megawatt scale wind turbines that are horizontal axis and pitch controlled.

2. Key Differences between Edition 3.0 and Edition 2.1.

2.1 Purpose

Both versions of the standard intend to provide a method for evaluating the acoustical emissions of wind turbines and both evaluating sound power level and tonal audibility.

2.2 Instrumentation Requirements

There are limited changes to the instrumentation requirements for collection of the measurement data. Some updates have been made to reference instrumentation standards, which mainly account for updates of those respective standards from 2002 through to 2012.

The most significant instrumentation changes include:

1. 1/3 Octave Band centre frequencies were extended down to 20 Hz (Edition 3.0) from 50 Hz (Edition 2.1)
2. Narrowband measurements in Edition 2.1 for tonal audibility were based on a frequency resolution of 2 to 5 Hz for frequencies less than 2,000 Hz and 2 to 12.5 Hz resolution for frequencies between 2,000 and 5,000 Hz. Edition 3.0 specifies a resolution of 1 to 2 Hz for the entire frequency range (up to 11,200 Hz).
3. Edition 3.0 specifies rotor RPM as a mandatory turbine parameter that needs to be logged. It was optional in Edition 2.1
4. Where Edition 2.1 indicated that turbine parameters shall be arithmetically averaged, Edition 3.0 additionally stipulates a minimum sample rate of 1 Hz.

2.3 Instrumentation Setup

The microphone placement prescribed in Edition 3.0 remains unchanged from Edition 2.1. There is 1 main microphone position (Reference Position 1) located directly downwind of the wind turbine at a measurement distance based on the test turbines hub height plus rotor radius. Optional microphone locations remain prescribed at 3 other locations (directly downwind, +60º of downwind, and -60º of downwind). Both versions of the standard allow for a +/- 20% tolerance on the microphone position (distance to turbine); however, Edition 3.0 caps the adjustment to no more than +/- 30m.

For measurements of Background noise an anemometer located at least 10m above grade is required for both Edition 2.1 and Edition 3.0 (commonly referred to as the 10m anemometer).

The 10m anemometer placement differs significantly between the two editions, although both editions have the same purpose; provide a method for determining what wind speed a data point for Background was acquired at. A more detailed discussion is provided in Section 2.6.

In Edition 2.1, the 10m anemometer was placed 2 to 4 rotor diameters upwind of the turbine. In Edition 3.0, the 10m anemometer is placed at or behind the plane of the rotor, at least 1 rotor diameter away from the turbine and out of the downwind direction.

Figure 1 depicts the acceptable anemometer placement locations for both Edition 2.1 and Edition 3.0.

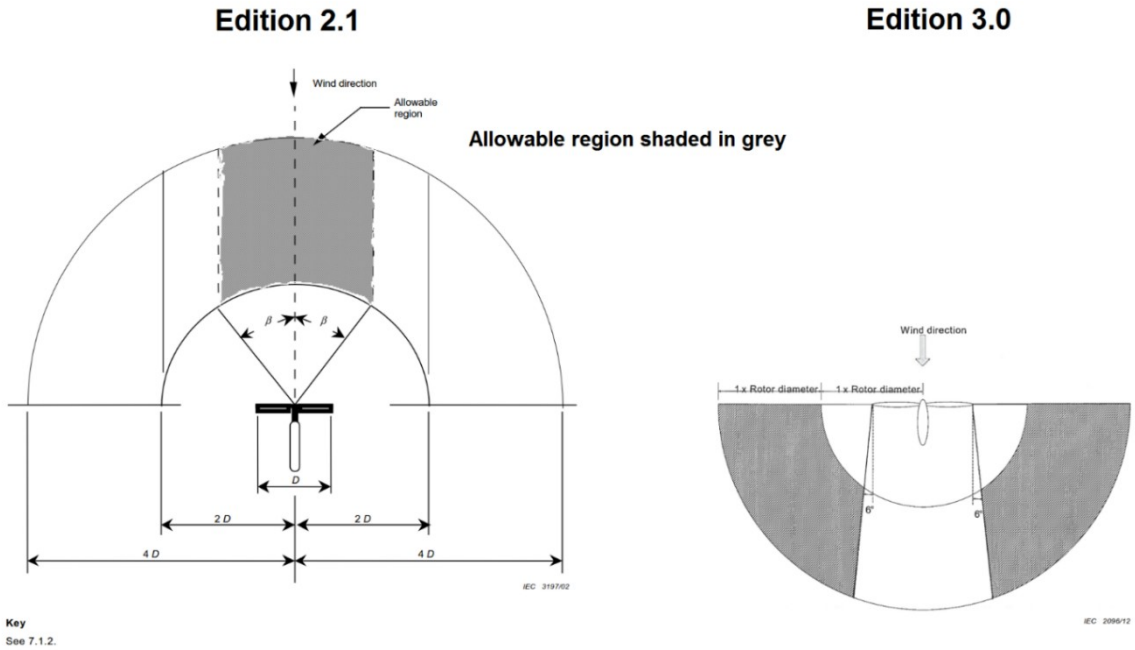

Figure 1 - 10m anemometer placement

2.4 Data Acquisition

Edition 2.1 and Edition 3.0 are based on acquisition of Turbine ON data and Background data. The Background data is used to evaluate ambient conditions at the test site and effectively calculate what the Turbine ONLY component is through subtraction from the Turbine ON data.

One of the more significant changes in Edition 3.0 was the implementation of 10 second averages for each interval (i.e. data point); whereas, Edition 2.1 implemented at least 60 second (1-minute) averages for each interval. As wind turbines become more advanced and efficient, they are able to take advantage of small wind bursts which allows the wind turbine to ramp up in power output at an increased rate (over older models).

Figure 2 depicts a 60 second time interval from a wind turbine installed and tested in 2014. Over the 60 second duration the wind turbines power output varied by almost 1400 kW and a large range of wind speeds (approximately 5 m/s based on the turbines power curve). Although modern wind turbines are capable of significant power output increases in less than 10 seconds (as depicted in Figure 2), a 10 second average provides much better resolution. The shorter averages strike a reasonable balance between capturing wind turbine operation while allowing sufficient time for the averaging of acoustic data.

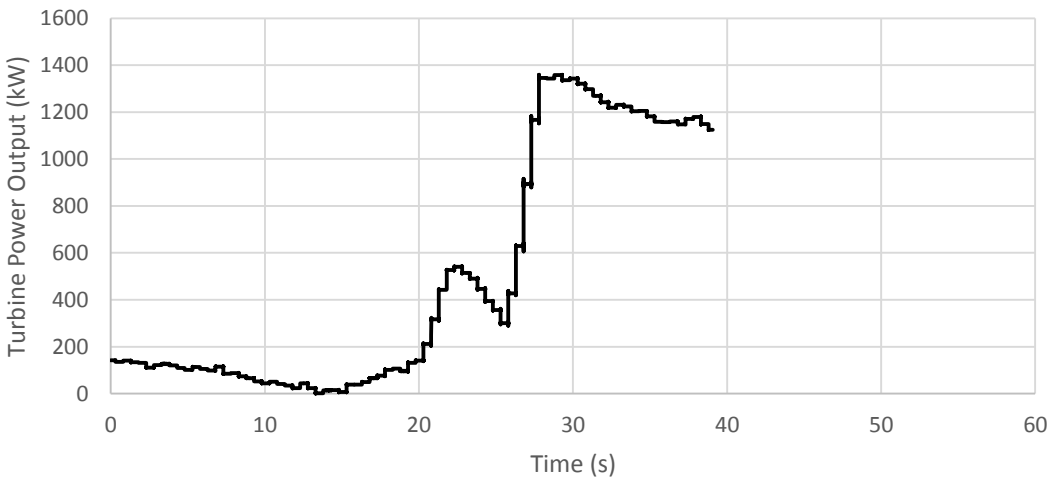

Figure 2 – Turbine power output level vs time (60 second interval)

For a 60 second segment of Turbine ON data processed as per Edition 2.1 the noise emission would be represented by a single value. Edition 3.0, on the other hand, would yield 6 separate points (10 seconds each), which provides a more representative and accurate indication of turbine emission.

Figure 3 depicts the direct correlation between power output and noise emission. The 10 second averaging in Edition 3.0 closely matches the trend of power output, while Edition 2.1 much less so. Further, for several 60 second averages that are represented by only 1 average for Edition 2.1, the Edition 3.0 analysis yields a range of almost 3 dB (see 480 to 530 seconds).

The close relationship between power output and the measured sound pressure level is valid until maximum power output is reached, at which point most pitch controlled turbines begin to furl out their blades and noise emission is typically maintained at a steady level or reduced.

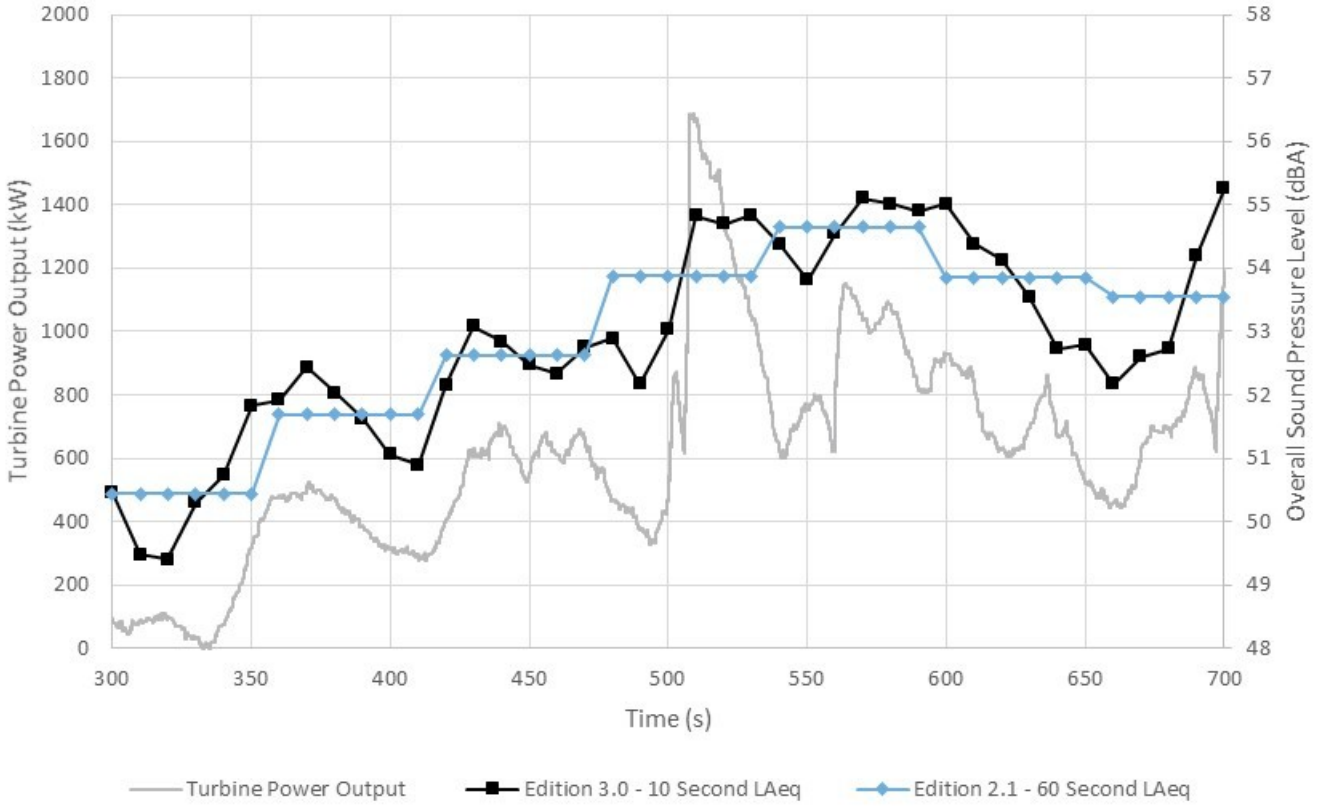

Figure 3 - Comparison of Edition 3.0 vs Edition 2.1 sound pressure level averaging

The change in time intervals has resulted in a revision in how many data points are required for a complete data set. Edition 2.1 required a minimum of 3 data points per each integer wind speed (5 bins, 6 m/s to 10 m/s) with at least 30 data points (total) for both Turbine ON and Background. Edition 3.0 requires at least 10 data points per wind speed at half integer increments (ex. 7.5 m/s, 8.0 m/s, 8.5 m/s….), with at least 180 data points for both Turbine ON and Background. A detailed discussion on changes in required wind speed ranges is discussed in the following section.

2.5 Wind speed – General

Sound power level analysis has shifted focus from evaluating the wind turbines noise emission with reference to wind speeds at 10m above grade (Edition 2.1) to wind speeds at hub height (Edition 3.0). Essentially, this only relates to how a data point is binned. Edition 2.1 evaluated the wind speed for Turbine ON data at hub height and then adjusted the wind speed down to the 10m reference height. The Background data would then be based off the ground anemometer (usually located at 10m above grade) with the actual values measured being used for binning of measurement data. Edition 3.0, on the other hand, leaves Turbine ON data at the hub height and adjusts Background measurement data to relative hub height wind speeds.

Where Edition 2.1 stipulated a fixed range of wind speeds required at integers of 6 m/s to 10 m/s, Edition 3.0 provides variability based on the performance of the wind turbine. Most megawatt scale wind turbines today are pitch controlled units whose maximum noise output is typically just before rated power output is achieved. That is the point where the turbine blades are closest to their aerodynamic limit and the likelihood of noise generating issues like flow separation (from the blade) are highest. As wind turbine efficiency increases, especially for low wind sites, the wind turbines are able to reach rated power output at lower wind speeds. This combination typically leads to much less information being gleaned from higher wind speed data (9 and 10 m/s bins for Edition 2.1).

Edition 3.0 focuses around the main area for noise emission by applying a multiplication factor of 0.8 (lower wind speed limit) and 1.3 (upper wind speed limit) to the wind speed at which 85% power occurs (from rated power output). This allows the noise emission test to effectively be tailored to focus on the key area of interest for noise emission based on the performance of each specific turbine.

A method to calculate the sound power level with reference to a 10m height is also provided in Edition 3.0; however, that is again based on the multiplication factors not necessarily a fixed 6 m/s to 10 m/s range. Also, the 10m reference height wind speed is reported based at integer wind speeds (similar to Edition 2.1), as opposed to half integer increments (Edition 3.0 at hub height).

2.6 Wind speed – Turbine ON

The standardized wind speed is the wind speed which is used to determine the wind bin associated with a given data point. For Turbine ON the most accurate way of determining the standardized wind speed is through calculation of the wind speed from the power curve. This is the preferred method for both Edition 2.1 and Edition 3.0. Although the majority of wind turbines contain an anemometer located at the nacelle, the readings can be inaccurate given their relative location and flow disruptions from close proximity to the rotor.

One of the main difficulties in evaluating wind turbine noise emission is determining which wind bin a given data point obtained at maximum power should fall under as the power curve cannot be used.

The nacelle anemometer method is preferred in Edition 2.1 for data points at or near maximum power. It relies on evaluating the difference between the nacelle anemometer wind speed and the calculated (standardized) wind speed for values between 5% and 95% power (from the power curve). This was accomplished through a linear regression of all data points between 5% and 95%, which would then be applied to data points above 95% power to determine an effective wind speed from the nacelle anemometer for a given data point. The calculated wind speed (at hub height) for values both above and below 95% power would then be scaled down to the reference 10m height using a roughness length (typically 0.05m).

Edition 3.0 follows a similar approach to Edition 2.1 by using a scaling factor, referred to as the k-factor method, to correct the wind speed at values near maximum power. Rather than defining 95% power as the cut-off point, Edition 3.0 relies on the slope of the power curve to determine to what wind speed calculation off the power curve is acceptable (while the slope is positive). For data points within the acceptable wind speed range the ratio between hub height wind speeds (from the power curve) and the nacelle anemometer is calculated and arithmetically averaged. The ratio (the k-factor) is then applied to the nacelle anemometer wind speed reading when above the acceptable wind speed range to establish a standardized wind speed. As evaluation of turbine noise emission is completed at hub height for Edition 3.0, no further adjustments are required.

2.7 Wind speed - Background

Determination of the wind speed for Background data points was fairly straight forward in Edition 2.1 with the 10m anemometer average providing the required value without any adjustments.

Edition 3.0 requires evaluation at wind speeds relative to hub height and a k-factor correction method is applied. This method is similar to that applied for data points near maximum power for Turbine ON where the power curve is no longer valid (also referred to as the k-factor method). During Turbine ON measurements, the ratio between hub height wind speeds and the 10m anemometer are logged with the arithmetic average serving as the scaling factor for adjustment of the 10m anemometer values acquired during Background measurements.

2.8 Sound Power Level Analysis

The majority of the changes between Edition 2.1 and Edition 3.0 lie within the way acquired data is processed.

Although the time interval of each data point varies between the two editions (10 seconds vs at least 60 seconds), the type of acoustic data acquired and reported between both versions of the standard are very similar (1/3 Octave Band, overall LAeq, etc.). However, the digestion of this data to evaluate the wind turbines apparent sound power level is drastically different.

Edition 2.1 focuses on utilizing the overall sound pressure level relationship to 10m wind speed to establish a line of best fit (4th order regression) which is used to determine the sound pressure level at each integer wind speed for both Turbine ON and Background. The Background correction for the Turbine ON measurement is also based on the overall level which is then being adjusted to provide an apparent sound power level. The 1/3 Octave band data is primarily used for informational purposes to provide additional detail about the wind turbine spectrum.

In instances where the correlation coefficient for the line of best fit is less than 0.8, Edition 2.1 permits the use of binned analysis (a method more similar to that specified in Edition 3.0).

Edition 3.0 utilizes the 1/3 Octave band data to evaluate the turbine noise emission. For each wind bin an energy averaged sound pressure level is calculated for both Turbine ON and Background. The average wind speed (which may not be at the bin centre wind speed) for each win bin is then adjusted using linear interpolation between the adjacent wind bin to adjust the average sound pressure level per 1/3 Octave Band to each wind bin centre. For example, if your data set for the 7m/s bin has a mean wind speed of 7.05 m/s a linear interpolation would be completed between the average value in the 6.5 m/s bin to determine the sound pressure level at exactly 7.00 m/s. The same process is applied to the Background data. The Turbine ON component is then Background adjusted per each 1/3 Octave Band. Lastly, the resultant sound pressure level is used to calculate the apparent sound power level and summed to provide an overall level.

As turbine technology has advanced, especially in control system and blade design, the region where pitch controlled wind turbines are most vulnerable to excess noise (right before hitting rated power output) has shifted. There has also been incentive for manufacturers to create what is commonly referred to as Noise Reduced Operating (NRO) modes for their turbine models to help facilitate the siting of wind farms to meet local noise regulations. For example, a 2 MW unit that has a noise emission rating of 105 dBA may also be operated at a rated power output of 1.9 MW but at 104 dBA (1 dB lower). These factors have resulted in a noise output that tends to remain almost constant after rated power output is reached and yields a noise emission profile that isn't very well suited to application of line of best fit curve.

Figure 4 contains a sample data set from one test analysed as per methods outlined in Edition 2.1 (both binned and line of best fit). Although, the correlation coefficient for the line of best fit (Edition 2.1) is near 1, the line of best fit tends to either over or under estimate compared to the energy averaged data in the main region of interest (7 and 8 m/s). The linear interpolation applied for the binned analysis matches very closely to the energy averaged sound pressured level for the same respective bins. Additional differences are discussed in Section 4.

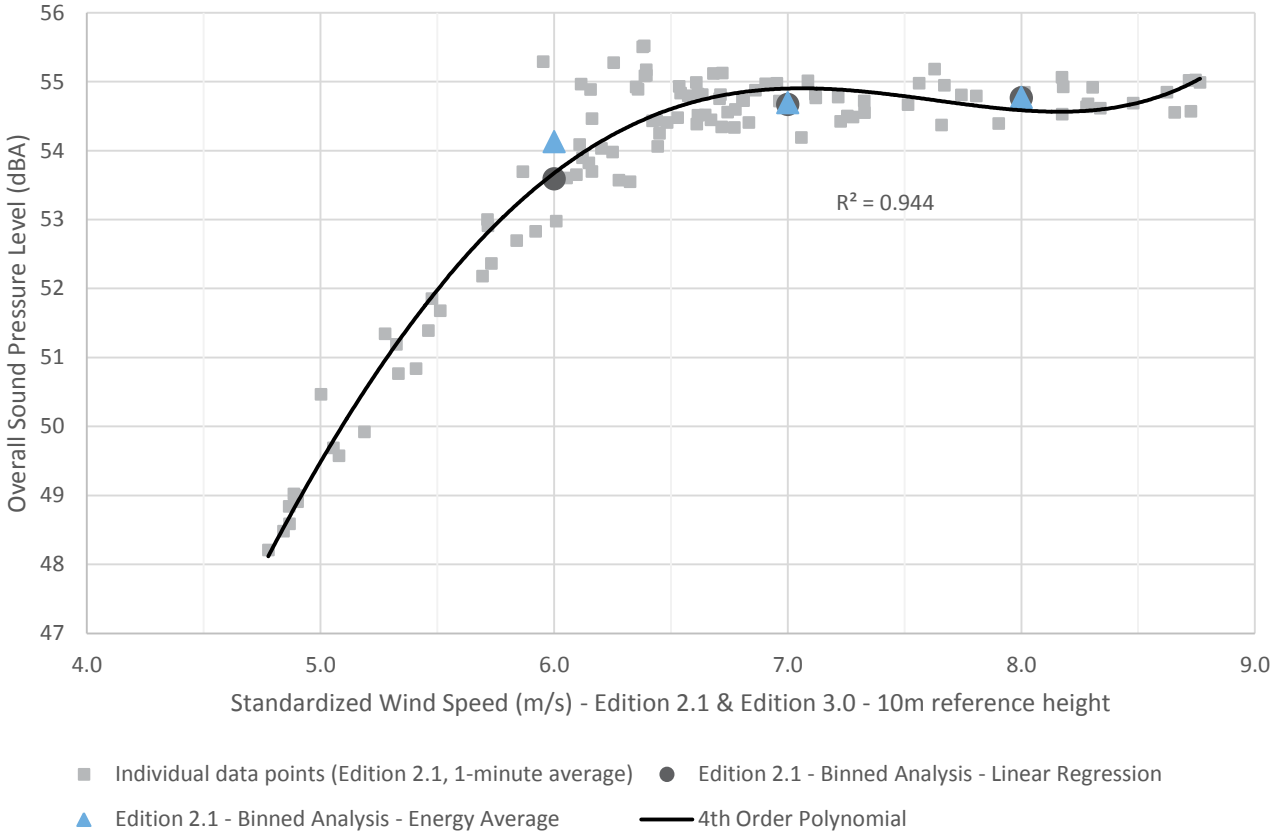

Figure 4 – Comparison of Edition 2.1 line of best fit analysis vs Edition 2.1 binned analysis for sample data set

2.9 Measurement Uncertainty

The measurement uncertainty in both editions is computed based on Type A (standard error of the estimated noise spectra) and Type B (site effects) uncertainties.

Edition 3.0 has significant changes to the uncertainty calculation. This is largely in part to the calculation of an apparent sound power level being based on linear interpolation between two adjacent wind bins. Edition 3.0 provides methods on computing measurement uncertainty per each 1/3 Octave Band and weights the overall measurement uncertainty for a wind bin based on the noise emission of the turbine. Frequencies which are dominant contributors to the overall level will carry more weight in determining the overall measurement uncertainty compared to ones who contribute less.

Calculations for measurement uncertainty in Edition 2.1 are based on the overall level and are based on a more simplistic approach of how the apparent sound power level is calculated in each respective wind bin.

2.10 Tonal Audibility Analysis

Tonal audibility analysis as per Edition 2.1 requires 12 data points per wind bin. The data is represented by 2, 1-minute intervals closest to a given integer wind speed and reprocessed into 10 second averages. Data for both Turbine ON and Background was required for the analysis.

The actual calculation method for each individual data point (i.e. 10 second sample) is similar between Edition 3.0 and Edition 2.1. The major difference being Edition 3.0 has removed the requirement for a Background adjustment in the tonal audibility calculation.

For reporting a tonal audibility, Edition 3.0 has increased the number of samples for the analysis to include the entire data set (if you have more than the 10 minimum stipulated per wind bin).

While the sound pressure level measured from a turbine remains relatively steady at a given standardized wind speed, tonal audibility can vary quite significantly. Figure 5 depicts the calculated tonal audibility (as per Edition 3.0) for a select wind turbine. The variation for a given wind speed easily exceeds 5 dB between the min and max values. Although only one sample set is depicted, the findings are fairly consistent for majority of tests completed and whether Edition 2.1 or Edition 3.0 is utilized.

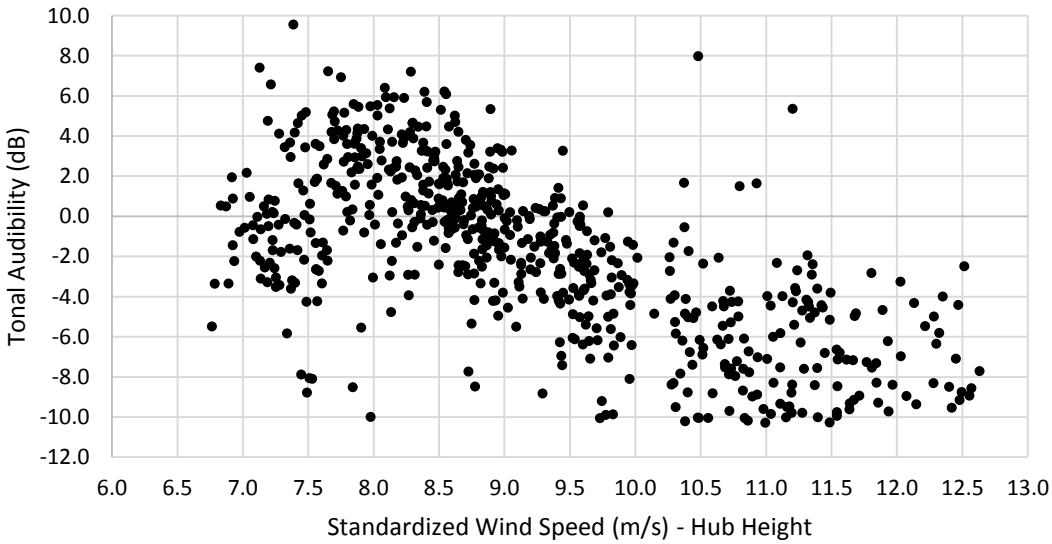

Figure 5 – Tonal audibility of all data points vs wind speed from a sample data set, as per Edition 3.0

The difference in minimum sample size between Edition 2.1 and Edition 3.0 is small, 12 vs 10 respectively. Edition 3.0, however, utilizes more representative wind speed data (as noted in Section 2.4) which ultimately provides a more accurate indication of the tonal audibility at a given wind speed.

Further, if the analysis is expanded to a larger sample set Edition 2.1 remains capped at 12 data points while Edition 3.0 accounts for the larger sampling. Given the variation typically observed in the tonal audibility results a larger sample set is likely to give a more consistent result with Edition 3.0, where Edition 2.1 is more akin to playing the lottery.

3. In-field Experience

3.1 Wind Speed Range

Most turbines tested required data for wind speeds between 7-13 m/s (at hub height), which equates to 5 to 9 m/s at a reference 10m height (using a roughness length of 0.05m).

3.2 Test Duration

Although both editions of the standard require at least 30 minutes of measurement data (for both Turbine ON and Background), our experience shows a full data set can be obtained faster with Edition 3.0. The observed efficiency primarily lies in the duration of each data point. Where for Edition 2.1 the turbine has to be at maximum power output for a whole minute, only 10 seconds are required for Edition 3.0. This is highly beneficial on days where moderate winds are present, but not strong enough to keep the turbine pinned at maximum power output.

3.3 Background Data

Acquisition of Background tended to be a difficult task with Edition 2.1 since wind speeds at the ground level (i.e. 10m anemometer) had to be between 6-10 m/s. This resulted in instances of having a full Turbine ON data set but only a partial Background set for days with moderate to high wind shear.

Edition 3.0, with use of the k-factor method, creates a more consistent relationship between the wind speed at ground level and hub height on the day of the test. This typically allows the test to be completed faster and Background to be more representative at a given wind speed.

One must, however, be cautious with Edition 3.0 as the k-factor is dependent on the Turbine ON data. After a certain duration you may have a full set of Background data, but after additional Turbine ON data and incorporation of it into your analysis you may find your Background data has shifted to a lower or higher wind speed bin. This is further complicated if measurements are completed over multiple days as the data is more subject to day-to-day vertical wind profiles.

Overall Edition 3.0 has showed an improvement in obtaining sufficient Background data more efficiently. Notably, obtaining Background still remains one of the main hindrances of the standard (both Edition 2.1 and Edition 3.0) due to the use of both ground level wind speeds and hub height wind speeds for both versions.

3.4 Measurement Uncertainty

Results from Edition 3.0 have typically yielded a lower overall measurement uncertainty compared with that of Edition 2.1. This is mainly attributed to different guidance provided by Edition 3.0 on the Type B component of the uncertainty calculation and the frequency weighting used by Edition 3.0 to calculate the overall measurement uncertainty.

Typical ranges for Edition 3.0 range between 0.7 to 1 dB, with corresponding Edition 2.1 results ranging between 1 to 1.3 dB. It is important to note that the values can be higher or lower depending on the test turbine and the measurement equipment used.

4. Comparative analysis (Edition 3.0 vs Edition 2.1)

4.1 Sample Set

To complete the comparative analysis between Edition 2.1 and Edition 3.0 a sample set of 20 separate IEC 61400-11 measurements was selected. All 20 data sets had sufficient signal-to-noise (above 6 dB) with over half with at least 10 dB.

The ground level anemometer was located at 10m for all tests, however, varied between the Edition 2.1 and Edition 3.0 location. This is considered to have minimal effect on the analysis given the signal to noise and that the purpose of the 10m anemometer between both Editions remained the same and consistent for each sample.

The data set represents a variety of turbine manufacturers, hub heights, and rotor diameters. All samples were of pitch controlled turbines with horizontal axis' and 3 blades.

4.2 Sound Power Level

Analysis of the sample data sets was completed as per Edition 3.0 and Edition 2.1. Edition 3.0 data was computed at both hub height and 10m reference height. Analysis as per Edition 2.1 was completed utilizing two methods at the 10 m reference height: line of best fit (prescribed method) and a binned analysis method (alternative method).

The maximum sound power level from each respective edition was used for analysis.

Edition 2.1 - Line of best fit analysis vs Edition 3.0

From the 20 data sets analysed, ten 10 samples contained correlation coefficients of less than 0.8 for the line of best fit method for Edition 2.1. As such analysis was completed with only 10 samples (those with correlation coefficients greater than 0.8). 5 of the sample sets had correlation coefficients above 0.7 (i.e. within 0.1 of the 0.8 cut-off).

Comparing Edition 2.1 line of best fit results with Edition 3.0 results (at hub height), 50% (5/10) of the line of best fit data was within +/-0.1 dB of Edition 3.0, while 80% came within +/- 0.5 dB. There was no clear trend of higher or lower sound power levels as an equal number of sample sets came above and below Edition 3.0.

When the Edition 2.1 line of best fit results are compared with Edition 3.0 results at the same reference 10m wind speeds the results are similar to those at hub height with 50% (5/10) samples coming within +/- 0.1 dB of Edition 3.0. Reference 10m height data was compared at integer wind speeds (as outlined in both standards). There was a slight decrease (70%, 7/10) of samples that fell within +/- 0.5 dB of Edition 3.0.

Edition 2.1 - Binned analysis vs Edition 3.0

As the binned analysis method is not reliant on a correlation coefficient, the sample set used included all 20 data sets.

Results from the Edition 2.1 binned analysis method indicated 40% (8/20) of the results were within +/-0.1 dB of Edition 3.0 (at hub height), while 90% (18/20) of the data came within +/- 0.5 dB.

There was a clear trend of the binned analysis method showing levels higher than Edition 3.0 (at hub height), with 80% (16/20) falling higher than that of Edition 3.0 by 0.1 dB or more. The majority however, 70% (14/20), were within 0.1 to 0.5 dB.

Comparison of Edition 2.1 binned data and Edition 3.0 data at 10m reference wind speeds shows 65% (13/20) of the data fails within +/-0.1 dB of Edition 3.0. 90% (18/20) did however fall within +/- 0.5 dB (same as comparison to Edition 3.0 hub height)

The following depicts the probability density function of the analysed data. Note that the distribution is provided in 0.2 dB increments where the above discussion was based on a resolution of 0.1 dB.

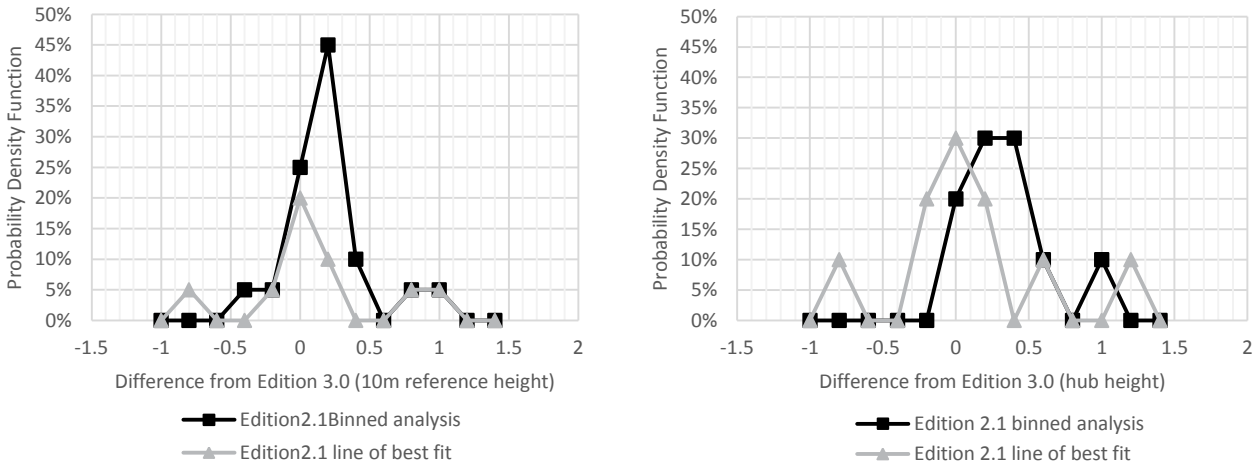

Figure 6 – Probability density function of Edition 2.1 data (line of best fit & binned analysis) vs Edition 3.0 (hub height and 10m reference height wind speeds)

4.3 Tonal Audibility

Tonal audibility analysis was carried out for all 20 data samples as per both Edition 2.1 and Edition 3.0. The comparative analysis discussed herein is based on the maximum reportable tonal audibility for each data set per each respective edition.

Of the 20 samples analysed 45% (9/20) of the data samples analysed as per Edition 2.1 fall within +/- 0.5 dB of results from Edition 3.0, with 60% (12/20) falling within +/- 1 dB. There is no clear distribution for either over or under evaluation compared to Edition 3.0. This is likely due to the wide variation that is observed in the tonal audibility results (irrespective whether Edition 3.0 or Edition 2.1 is used).

Figure 6, summarizes the tonal audibility comparative analysis results based on rounding of each tonal audibility result to the nearest half decibel

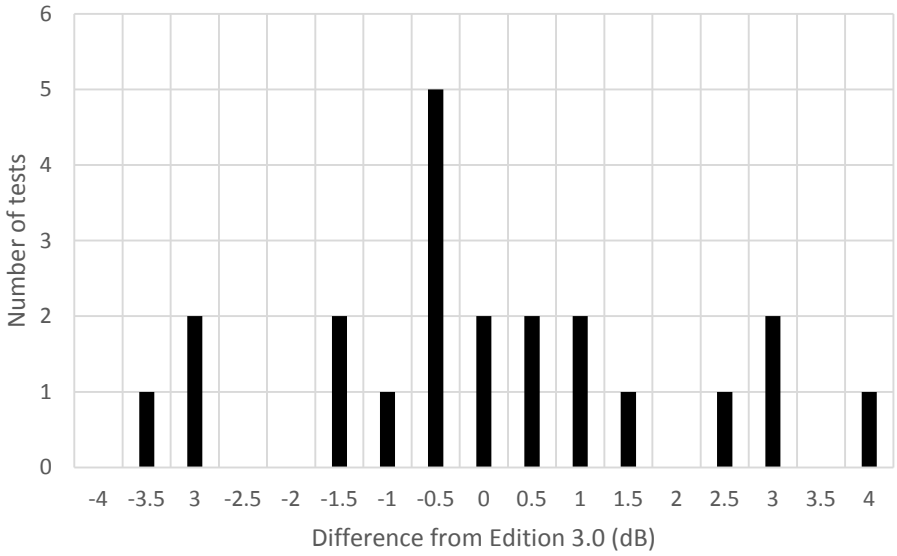

Figure 7 – Tonal Audibility comparison (Edition 2.1 vs Edition 3.0) for 20 data sample set

5. Conclusions

A comparative analysis of 20 samples indicates apparent sound power level results from Edition 2.1 are usually within 0.5 dB of Edition 3.0 but can be off by over 1 dB. The binned analysis method tends to overestimate the noise emission compared to Edition 3.0, while the line of best fit method shows a low degree of applicability. Only half of the sample data sets met the minimum 0.8 correlation coefficient requirement. This issue is primarily based on how modern turbines perform with better controls and more efficient blade design, and the limitation of using 1-minute averages to represent this performance.

Tonal audibility analysis in Edition 3.0 allows for use of a larger sample size and is more likely to yield a consistent result over methods prescribed in Edition 2.1.

Edition 3.0 provides a significant improvement in how the apparent sound power level and tonal audibility of a wind turbine is evaluated.

References

[1] IEC 61400-11:2002 edition 2.0 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques.
[2] IEC 61400-11:2006 edition 2.1 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques.
[3] IEC 61400-11:2012 edition 3.0 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques.