Wind turbine sound power measurements

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This paper provides experimental validation of the sound power level data obtained from manufacturers for the ten wind turbine models examined in Health Canada's Community Noise and Health Study (CNHS). Within measurement uncertainty, the wind turbine sound power levels measured using IEC 61400-11 [(**2002**). (International Electrotechnical Commission, Geneva)] were consistent with the sound power level data provided by manufacturers. Based on measurements, the sound power level data were also extended to 16 Hz for calculation of C-weighted levels. The C-weighted levels were 11.5 dB higher than the A-weighted levels (standard deviation 1.7 dB). The simple relationship between A- and C- weighted levels suggests that there is unlikely to be any statistically significant difference between analysis based on either C- or A-weighted data. [http://dx.doi.org/10.1121/1.4942405]

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I. INTRODUCTION

The modelled outdoor A-weighted wind turbine sound pressure level (SPL) at a residence was used as the main measure of exposure to wind turbine noise (WTN) in the Community Noise and Health Study (CNHS) as it is consistent with current practice for wind turbine siting in Canada. To support the calculation of SPLs at dwellings this paper presents the results of field measurements made of wind turbine sound power levels, based on the 2nd edition of the International Electrotechnical Commission (IEC) 61400–11 wind turbine standard (IEC, 2002) with corrections so as to conform to the current edition of this standard (IEC, 2012). The results are used to validate the sound power level provided by the manufacturers. The field measurements also enabled the extension of the manufacturers' data to lower frequencies for the determination of C-weighted sound power levels.

II. METHOD

A. Site description

The CNHS took place in Southern Ontario (ON) and Prince Edward Island (PEI) Canada between July and November, 2013. In these areas there were 21 wind turbine installations and 10 turbine models from 6 manufacturers. All wind turbines were of modern design with three pitch controlled rotor blades upwind of the tower and with their rated electrical power from 660 kW to 3 MW [average 1.90 ± 0.61 MW standard deviation (SD)]. Ninety-six percent of the wind turbines in the CNHS had a hub height of between 78 and 80 m. The chosen areas consisted of flat agricultural land, 0.1–15 km from major bodies of water. Measurements were influenced by treed wind breaks between narrow rectangular fields (width typically 250–500 m), and small forested sections. The maximum tree height in ON and PEI is 30 to 40 m (Gaudet and Profitt, 1958; Sharma and Parton, 2007; Ontario Ministry of Natural Resources, 2014; Forests Ontario, 2015), although most trees in the study areas would typically be half this height.

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B. Sound power measurements

Sound power measurements were made according to IEC 61400-11 (IEC, 2002) on the ten wind turbine models to verify consistency with the manufacturer provided octave band sound power level data. Each measurement was unattended and lasted 3–4 days. Position relative to the wind turbine was estimated using a laser rangefinder (Bosch GLR825), and Global Positioning System (GPS) data (Samsung Galaxy Note 2). In most cases within a 1 m radius of the microphone position, the ground was cleared and leveled using a Stihl KM 110 R with BF-KM Mini-Cultivator. Microphones were located at ground-level on top of either (1) a 1 m diameter plywood ground disk with a secondary windscreen consisting of a 750 mm diameter hemisphere of polyester cloth (Microtech Gefell GFM920.1) or (2) a 1.1 m diameter plywood ground disk with a 600 mm diameter hemispherical secondary windscreen made of 25 mm thick foam (Aercoustics HSWS-100). In both cases, the primary windscreen was an 85 mm diameter foam hemisphere (Microtech Gefell GFM920.1). One third octave spectra and sound recordings were obtained using either Brüel & Kjær type 2270 or type 2250 portable sound analyzers, with Brüel & Kjær type 4189, $\frac{1}{2}$ in. pre-polarized microphones with preamplifiers type ZC0032. Field calibration checks at 1 kHz were performed before and after each period of measurements using a Brüel & Kjær type 4231 calibrator. By arrangement with wind turbine operators, the background noise was checked by turning off the nearest turbine in a single random 15 min period, with whatever wind speed that occurred in that period.

To reduce data storage and data analysis requirements, measurements were not collected at frequencies above the 3.15 kHz 1/3 octave band (8 kHz sampling frequency). In the CNHS measurements, in addition to verifying the manufacturer data, the intent was to extend the data to lower frequencies. To reduce contamination from low frequency pseudo sound, trees and tall grass were used as wind breaks at the potential expense of increased high frequency vegetation noise. Limiting measurements at and below 3.15 kHz also reduced complexities introduced by insects, birds, and atmospheric absorption (ISO, 1993; IEC, 2102). Large modern wind turbines do not normally produce high level, high frequency noise levels and what is produced is rapidly attenuated with distance. Based on the manufacturers' specifications, as well as for measurements near the base of typical wind turbines (Søndergaard and Henningsen, 2011) frequencies above the 3.15 kHz 1/3 octave band typically contribute less than 0.5 dB to the overall A-weighted sound power level.

C. Weatherproofing and characterization of wind screens

Weatherproofing measures included the treatment of the 85 mm primary wind screen with water repellent spray (Scotchgard$^{\text{TM}}$, 3M). Extending under and beyond the primary wind screen was a 30 cm × 25 cm rectangular piece of 10 μm thick low density polyethylene film (Glad$^{\text{TM}}$ wrap). This film loosely covered the microphone, preamplifier, and silica gel desiccant.

The wind screens and waterproofing measures were characterized following IEC 61400-11 (IEC, 2012) in wet and dry conditions in the Health Canada's 13 m × 9 m × 7 m hemi-anechoic chamber (see Keith *et al.*, 1994). For these measurements a speaker (Paradigm Signature S1 v3 P-Be) was mounted at 4 m height on a mast (Clark QTX10–6/HP) to reproduce pink noise from 50 Hz to 10 kHz. The ground board, which was equipped with vibration isolating rubber feet, was placed directly on the floor of the hemi-anechoic chamber.

D. Meteorological measurements

A weather station was set up 1.5 to 2 rotor diameters from the turbine base, as far away from trees and measuring microphones as possible. Conformance with IEC 61400-11 (IEC, 2002, 2012), was a challenge due to (i) space restrictions and (ii) the unavailability of wind direction information *a priori*. To compensate, the weather station measurements were corrected (Sec. II E) to make the results comparable to IEC 61400-11 (IEC, 2012).

Wind speed, direction (Sutron Windsonic ultrasonic sensors 5600-0215), and temperature (Sutron platinum probes with radiation shields 5600-0025) were recorded (Sutron 9210-ENC-B Xlite) at 2 and 10 m heights (Clark mast QTX10-6/HP) in 1 s intervals using a portable ground based weather station (per IEC, 2002). Barometric pressure (Sutron 5600-120), humidity (Sutron 5600-0312), and wetness (Sutron Decagon dielectric leaf wetness sensor) were also recorded at 2 m height. To complement these data, seven of the ten wind turbine models had nacelle level measurements of wind speed, yaw direction, electrical power output, and rotor rpm in 10 min intervals.

E. Post-analysis of spectral data

Analysis was restricted to the sound power associated with 8 m/s wind speed (standardized to 10 m height as per IEC, 2012).[1] All turbines in the study became operational on or before 2011 so measurements of wind turbine sound power conformed to IEC 61400-11 (IEC, 2002). The main difference from the requirements of IEC 61400-11 (IEC, 2012) was in wind speed measurements, and post analysis was used to make measurements consistent with the current standard.

Using the ground based weather station data, the wind speed was extrapolated to the turbine nacelle height every second using similarity or a log profile [as appropriate, based on L'Esperance *et al.* (1993) and our supplemental material[2]] and averaged over 10 s for use in IEC (2002) sound power calculations. For compatibility with the IEC (2012) standard these weather station data were further averaged over 10 min and the wind speed was adjusted to match the wind turbine nacelle anemometer data (when available). These weather station data were only used if the 10 min average of the nacelle height wind speed had less than 10% discrepancy from the turbine nacelle anemometer. Other inclusion criteria for data included: no rain (Sutron dielectric wetness sensor <0.3 arbitrary units and relative humidity $<85\%$); wind speed 8 m/s ± 0.5 m/s tolerance, gust strength <1 m/s. Due to the use of unattended measurements it was assumed that these criteria could exclude a significant amount of data. Therefore, the measurement protocol was to collect spectra for wind directions downwind of the turbine with a ± 30° tolerance, twice the angle specified by IEC 61400–11 (IEC, 2002, 2012). Wind turbine sound power measurements are not normally associated with significant directivity in the downwind direction (Friman, 2011). Compared to the SPL at 0° downwind of the wind turbine, at an angle offset of 15° the estimated SPL drops less than 0.2 dB, and at 30° the estimated SPL drops less than 0.6 dB (Okada *et al.*, 2015). Due to the inevitable scatter in the data, inclusion of more data points is assumed to be a cautious approach. This is supported by the fact that Møller and Pedersen (2011) examined data from three turbines and found variability in directivity but no general pattern.

The 10 s wind speed averages were used to select 1/3 octave band sound pressure levels obtained simultaneously in 10 s intervals (Brüel & Kjær PULSE REFLEX v.17). The spectra were audited aurally and excluded from analysis if there were any significant and clearly identifiable sources (i.e., birds, insects, trains, or vehicles). Unidentifiable mechanical noises were not exclusion criteria as the unidentifiable noises could potentially have originated from the wind turbines.

To prevent contamination from wind-induced pseudo-sound, narrow band FFT spectra (0.0625 Hz bandwidth, Brüel & Kjær PULSE REFLEX v.17) were examined for evidence of the first few harmonics of the blade passage frequency. When broadband wind-induced pseudo-sound prevented observation of these harmonics, the associated data were excluded from further analysis if the shape of the pseudo sound spectrum was judged to have the potential to significantly influence the overall A-weighted levels. Wind-induced pseudo-sound was not judged to be an issue in most measurements.

In summary, each turbine was evaluated using 3–4 days of unattended measurements, but only part of the data was accepted for further analysis. The conditions for acceptance, detailed above, can be summarized as follows.

1. Wind speed at 10 m height is close to 8 m/s.
2. Measurement position is downwind of the wind turbine.
3. Estimated wind speed at hub height matched the nacelle anemometer wind speed.
4. It is not raining.
5. No strong wind gusts.
6. No wind-induced noise in the sound signal.
7. No evidence that external noise sources, such as traffic, would have significant effect on the sound power level.

III. RESULTS AND DISCUSSION

A. Effect of wind screen and rain on measurements

As a result of testing, all of the wind turbine measurements were adjusted to account for a wet primary windscreen. Intermittent heavy rainfall occurred almost daily. Although the larger secondary windscreen would drain and dry, due to a lack of a drain hole, or wick, near the microphone there was usually pooled water under the primary windscreen. Figure 1 shows the effect on the wind screen insertion loss. When dry, the windscreens and waterproofing meet the requirements of IEC 61400-11 (IEC, 2012) at all frequencies. When the primary windscreen was wetted, the insertion loss at 400, 500 Hz was -1.3 dB, which was 0.3 dB outside the recommended range in IEC 61400-11 (IEC, 2012). Large deviations also occurred at 4 kHz and above, although as discussed in Sec. II B, these frequencies were not included in analysis.

B. Selection of spectra based on wind speed

After screening, approximately 38% of the ground based weather station 8 m/s wind speed data was within the wind speed acceptance criterion (Sec. II E, i.e., the extrapolated wind speed at hub height was within ±10% of the nacelle anemometer data). After correction to match the nacelle anemometer, the resulting wind speed had a 1.6% SD when compared to the wind speed derived from the electrical power output (the preferred method in IEC, 2012). Although the ground based wind speed estimates varied, the wind speed from the nacelle anemometer consistently tracked the wind speed derived from electrical power output. The ground based wind speed data that differed from the nacelle anemometer typically contained occasional notably large overestimates of wind speed which would have biased the wind speed to be 11% too high (with a 30% SD). For comparison, extrapolation of the weather station data using a log wind speed profile [according to IEC 61400-11 (IEC, 2002)], typically underestimated the hub height wind speed by 20%.

The wind speed screening procedure does not appear to have biased the sound power estimates. Analysis of the relevant sound power levels (averaged over 10 min) suggested that the data excluded by the wind speed screening criteria typically were within ±1 dB of the data that were retained.

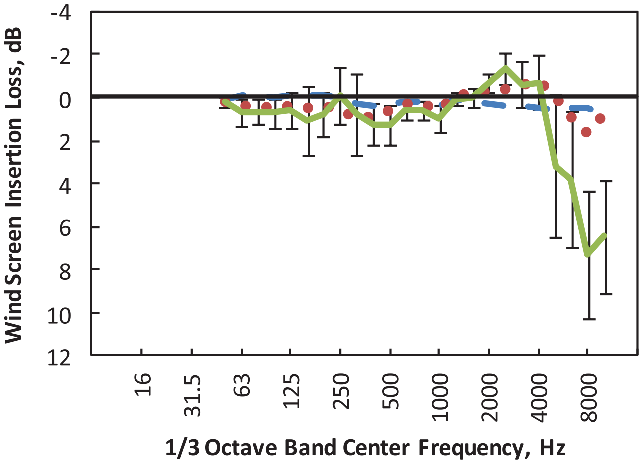

FIG. 1. Insertion loss of windscreens: the blue dashed line shows the insertion loss from a 750 mm diameter secondary windscreen, the red dotted line adds $10\,\mu$m plastic waterproofing film, the green line is the previous arrangement with a wet primary windscreen, and the error bars represent one SD. The baseline condition for these comparisons uses a 13 mm microphone on a ground board with a dry 85 mm primary foam windscreen.

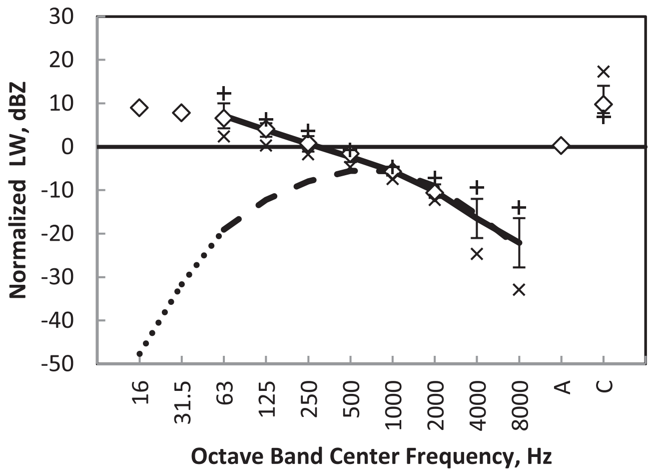

FIG. 2. Normalized sound power levels at 8 m/s wind speed (normalized meaning that the manufacturer's overall A-weighted level for an individual wind turbine has been subtracted from all of its octave band levels). The open diamonds are linear averages of the measured data (not shown, the SD ranges from 3.5 to 4.5 dB in part due to normalization). The solid line is the linear average of the unweighted octave band data from the manufacturers, its error bars represent 1 standard deviation of the ten data sets used to create the average, and the crosses are the maximum and minimum of the values used in the average. The dotted/dashed line shows the preceding averaged data with A-weighting applied.

C. Comparison of measured sound power levels to manufacturers' data for 8 m/s wind speed

Figure 2 shows averages of the data from all manufacturers compared to the averaged measured data. Results are observed to slope at approximately 3 dB per octave at frequencies below 2 kHz. From 63 Hz to 2 kHz, the difference between the average of the measured data and the average of the manufacturers' data is 0.00 dB ± 0.46 dB SD. Notably, manufacturer's data at 8 kHz spans a 20 dB range, which may be illustrative of measurement variability at high frequencies (see Sec. II B). For example, depending on temperature and humidity, at 125 m from the turbine base, atmospheric attenuation of the WTN can range from 3 to 13 dB at 4 kHz, and from 9 to 29 dB at 8 kHz (ISO, 1993). In addition, because IEC (2012) allows use of a 13 mm microphone on a reflecting ground board, the phase of the direct and reflected sound waves are only correctly in phase at frequencies below about 4 kHz [see Annex B of ISO 1996-2 (ISO, 2007)].

Figure 3 shows differences, A-weighted and in octave bands, between measured and manufacturers' sound power levels at a wind speed of 8 m/s for each wind turbine model. Comparing CNHS measurements and the manufacturers' data in individual frequency bands across ten turbines, the SD is typically 3 dB. The agreement in the overall A-weighted levels was within 2 dB for six model turbines. There do not appear to be any obvious trends in the deviations in Fig. 3. For example, there are 4 spectra (labeled A, E, F, and I) from one manufacturer (MA), which approximately span from the highest to the lowest differences observed in the measurements.

IEC 61400-11 (IEC, 2002) indicates that the standard deviation in sound power measurements can be as high as 3.7 dB. For the CNHS measurements, the sum of the uncertainty components for overall A-weighted measurements was 2 dB standard deviation. In addition to the components in IEC (2012), this includes 1 dB due to the windscreen

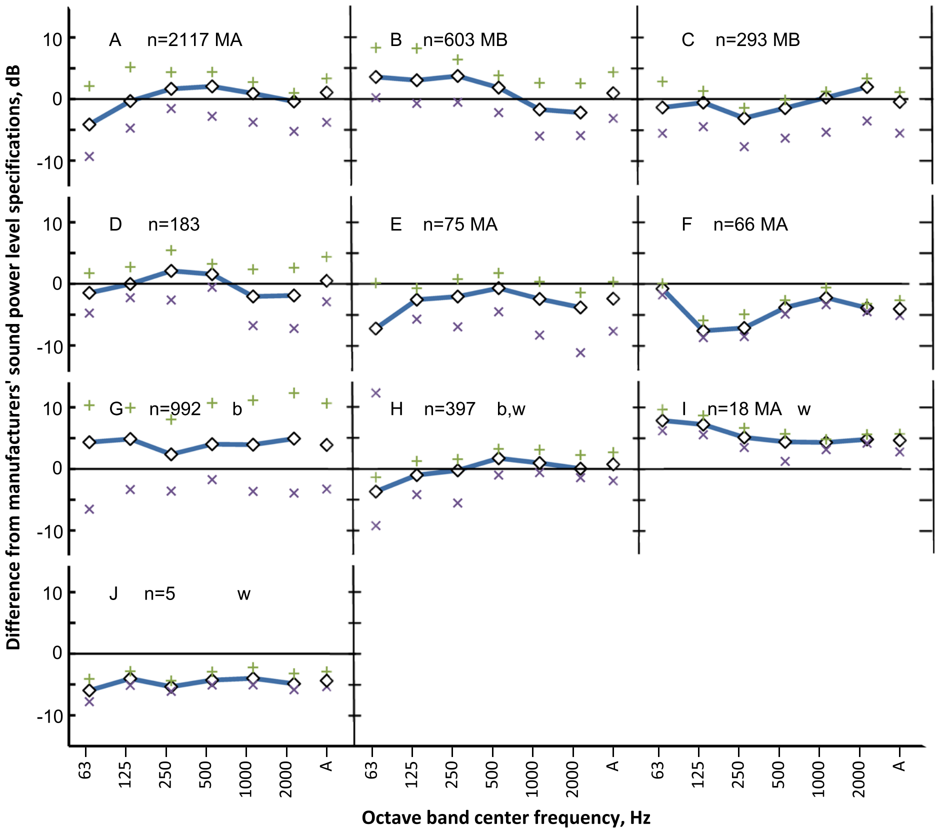

FIG. 3. (Color online) Measured sound power spectra minus manufacturers' data for 8 m/s wind speed. Values below the 0 line indicate the manufacturers' data is higher than the measured data. Crosses represent maximum and minimum values and the open diamonds are the energy average. Two manufacturers (labeled MA and MB) have multiple turbines represented in these data. The spectra are nominally sorted with the best quality data on the upper left. Indicators of reduced quality on the plots include: n, the number of measurements shown in each plot; w, the symbol indicating missing nacelle data for wind speed estimation for plots where it appears; and b, the symbol indicating unidentified ambient noise for plots where it appears.

(Fig. 1), and 0.8 dB for atmospheric attenuation (see, e.g., ISO, 1993). Covariance related to wind speed was ignored, because there is little effect of wind speed on sound power level at higher wind speeds.[1] Background noise was estimated to contribute less than 0.5 dB SD, due to the relatively quiet locations where the turbines were set up. The limited data available during shutdown periods is consistent with this estimate for background noise.

D. Estimated C-weighted levels based on extrapolation of manufacturer data using measurements

The results in Fig. 2 show a smooth curve, which, when extended to lower frequencies does not strongly influence the overall C-weighted levels. The measured frequencies below 63 Hz added on average 1.8 dB to the overall C-weighted levels (range 0.8 to 2.9 dB), when compared to the overall C-weighted values calculated using only the manufacturer's results at frequencies at and above 63 Hz. The overall C-weighted results were consistently 11.5 dB (SD 1.7 dB) higher than the overall A-weighted values. The uncertainty in the overall C-weighted values was estimated as 2.5 dB. The overall C-weighted uncertainty is slightly higher than the overall A-weighted uncertainty because there is larger uncertainty in the measurements at lower frequencies.

Due to the consistent difference between the overall C- and A-weighted values there is unlikely to be a statistical benefit to a separate analysis of C- and A-weighted results. Somewhat similar results were found by Tachibana *et al.* (2014) for the turbines in that study.

IV. CONCLUSIONS

The manufacturers' sound power levels were validated within measurement uncertainty for all ten installed wind turbine models. The standard deviation in the sound power levels was estimated at 2.0 dB.

Due to frequent rain, the microphone windscreens were almost always wet upon completion of measurements. The waterproofing methods employed changed results by up to 1.3 dB, which was marginally outside of the range in IEC 61400-11 (IEC, 2012).

The wind turbines in the CNHS are unlikely to give statistically different exposure response relationships regardless of whether A- or C- weighting is used. For there to be an added value in characterizing the low frequency noise in the CNHS, the wind turbine power spectra would have had to show larger differences at low frequencies.

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[1] Manufacturers provided sound power data as a function of wind speed for nine turbine models (for some, but not all wind speeds). Relative to the sound power values at 8 m/s, the sound level as a function of wind speed ranged from −11.0 dB ± 2.4 dB at 4 m/s (three models), −5.7 dB ± 1.6 dB at 5 m/s (five models), −1.4 dB ± 1.2 dB at 6 m/s (nine models), −0.13 dB ± 0.75 dB at 7 m/s (nine models), −0.07 dB ± 0.28 dB at 9 m/s (eight models), and −0.13 dB ± 0.28 dB at 10 m/s (seven models).

[2] See supplemental material at http://dx.doi.org/10.1121/1.4942405 for the wind speed calculations at the nacelle using ground-based weather station data.

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