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Wind turbine noise prediction

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Abstract

Renewable energy sources, however green they may be, have inherent negative concerns. One such source, a multi-bladed wind turbine, generates noise levels that can adversely affect residences that surround a given wind farm. Regulatory agencies require wind farm developers to submit an acoustic assessment report before approving the wind farm. The main focus of the assessment is to evaluate the potential noise levels that can exist at all nearby receptors. Earlier studies applied different prediction models to evaluate the receptor noise levels. However, all of the current available prediction methods assume the wind turbine to be a point source located at the hub height. But, the wind turbine is a multi-bladed rotating source interacting with the mast during its rotation. The main aim of the current investigation is to research the point source assumption. A small 5 turbine wind farm in southwest Ontario, Canada will be used for the study. A few locations, including some very close to two turbines, will be used to conduct acoustic measurements. Three different prediction models will be used to evaluate the noise levels at the different locations. Comparison of prediction and site measurements will shed light on the point source approximation. The results of the study are presented in this paper.

Keywords: Turbine noise, weather profiles, parabolic equations, prediction
Wind turbine noise prediction

1 Introduction

Wind energy plays a vital role in the transition from fossil fuels to renewable energy sources. The presence of abundant wind energy in our environment has led to the development of wind turbines. Wind-farm projects has been on the rise ever since. As the turbines require wind for operation, possible locations in densely populated areas are limited; hence most projects of wind turbines are introduced near the coast or within farmland. Nearly 500 wind turbines were installed in Southwestern Ontario, Canada by 2013, whereas approximately 6500 wind turbines applications were approved by October 2013.

A wind turbine emits noise into the environment from mechanical components and the turbine blades. The noise emissions from the operation of the turbine have been the biggest concern for the residents near wind farm projects. And hence, prediction and/or measurement of noise levels from wind farms have been one of the main influencing factors for wind farm developers and various regulatory agencies.

Outdoor sound levels, calculated by following the procedures outlined in ISO 9613- Part 2, has been the conventional norm in Ontario [1]. It must be noted that sound waves propagating in the environment are affected by intervening meteorology and atmospheric factors. Simple ISO 9613 Part 2 procedures do not consider atmospheric influences, except with simple empirical adjustment factors. And hence, it must be recognized that prediction models must properly include atmospheric factors. The determination of the feasibility, accuracy and efficiency of different acoustic models must be determined before using them in prediction schemes.

The propagation of sound from wind farms was the focus of a research study undertaken by Sehrawat and Ramakrishnan for a health unit in Southwestern Ontario [2]. The assessment of three sound prediction schemes was presented in the 22nd International Congress on Sound and Vibration, held in Florence, Italy in July 2015 [3]. The research study also investigated the assumptions applied by the prediction schemes, in particular meteorological effects and point source approximation. The results of the above concerns are discussed in this paper.

2 Background

The current practice for the approval of wind farm development in many jurisdictions around the world is for the developers to prepare and submit an acoustic assessment report to the respective regulatory agencies such as the Ministry of the Environment and Climate Change in Ontario, Canada. The acoustic assessment is usually conducted by using the sound power levels, PWL, (apparent) submitted by the turbine manufacturers following the procedures outlined in the IEC Standard 61400 [4]. The consultants apply the apparent PWLs and assume the entire turbine can be replaced by a single point source at the hub height. It must be noted, however, that the scope of the IEC Standard 61400 is to provide a standard comparison scale between different turbine manufacturers. The standard does not make any reference as to the type of the source or to its actual location in the rotating plane. It can be seen that the acoustic assessment reports make ‘a leap of faith’ and apply two untested assumptions to predict the far-field noise.
levels – a) the turbine can be treated as a point source; and b) that the point source is located at
the rotor hub. Unfortunately, the regulatory agencies accept the above two untested
assumptions.

A wind turbine is usually a-three-bladed rotor that revolves around a horizontal axis. Rotor and
propeller noise has been studied extensively since the mid-1940s, starting within Gutin in late
1940s [5] and Hosier and Ramakrishnan in early 1970s [6]. Gutin formulated the basic frame
work for the prediction of far-field noise from a rotating propeller. Reference 6 measured the
fluctuating forces of a single rotating blade and evaluated, successfully, the rotational noise in the
far-field. Reference 6 also contains an extensive list of references that researched the rotor
noise from 1940s till mid-1975. Viterna developed a computer code to predict the noise levels
from a wind turbine, using the measured values of fluctuating forces on the rotating blade [7],
similar to the work of Reference 6. Shepherd et.al. at Nasa Langley Research Center conducted
a detailed measurement program of noise levels from a 4.2 mW wind turbine and spent
considerable effort to provide a comparative analysis [8]. The results of Reference 8 clearly
shows a dipole behavior of the sound spectrum. It can be inferred, clearly, from the cited
references, the turbine is definitely not a point source and the source directivity is also important.

Recently, Oerlemans and Lopez [9], and Hadad and Benoit [10] applied beam-forming
techniques with multiple microphone arrays and conducted source localization programs of wind
turbines. Reference 9 used a 152-microphone array and Reference 10 applied a 121-
microphone array. Their results clearly indicated that dominant source of noise of a wind turbine
is not located at the hub. A sample result from Reference 9 is reproduced in Figure 1 below.

![Location of wind turbines noise sources](Source: Oerlemans and Lopez [9])

It can been seen from Figure 1 that the dominant source is near the tip of the blade and
extends, in the rotor plane, from about 40° to about 160° (0° is due up). A small source, but with
diminished power, can also be seen at the rotor hub. One can only conclude that the current
practice of placing a point source at the rotor hub with measured PWLs using the IEC Standard
is, at best, questionable.

Further results, at the appropriateness of the above assumptions, will be presented in later
sections. The current study has used a small wind farm with five 1.8 mW turbines to conduct a
comparison analysis of site measurements with far-field noise predictions. The details of the
wind farm and comparison results are described in the next section.

3 West Lincoln wind farm

The wind farm under investigation is located in the Town of West Lincoln, near Hamilton, Ontario. The layout in West Lincoln is shown in Figure 1. The wind farm project consists of five (5) wind turbines (Vestas v100) each rated at 1.8 MW with a hub height of 95 m and rotor diameter of 100 m. In total, the project will generate 9 MW and approximately 26 million kWh per year. All the turbines were installed on top of a tubular tower with all the mechanical components, including the transformer, mounted inside the nacelle at the top of the tower. The project site is an open farmland with sparse human population. The wind farm and the five turbines became operational in May of 2014.

Figure 2: Location of wind turbines and receptors

The distances from each turbine to each of the six receptors are shown in Table 1. The four residential receptors were chosen for noise evaluations, since sleep disturbance tests were conducted on these residents by other researchers. Receptors 5 and 6 were chosen to evaluate the propagation through attended noise monitoring.

<table>
<thead>
<tr>
<th>Location</th>
<th>WT1</th>
<th>WT2</th>
<th>WT3</th>
<th>WT4</th>
<th>WT5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>1768.0</td>
<td>1394.1</td>
<td>566.3</td>
<td>1693.1</td>
<td>1003.5</td>
</tr>
<tr>
<td>Location 2</td>
<td>2021.0</td>
<td>2420.9</td>
<td>3201.1</td>
<td>3259.7</td>
<td>4487.8</td>
</tr>
<tr>
<td>Location 3</td>
<td>3068.4</td>
<td>2842.7</td>
<td>1440.1</td>
<td>3438.0</td>
<td>2175.7</td>
</tr>
<tr>
<td>Location 4</td>
<td>3091.6</td>
<td>2987.8</td>
<td>4100.3</td>
<td>2088.5</td>
<td>3765.1</td>
</tr>
<tr>
<td>Location 5</td>
<td>569.3</td>
<td>244.6</td>
<td>1544.3</td>
<td>796.3</td>
<td>2162.6</td>
</tr>
<tr>
<td>Location 6</td>
<td>2041.8</td>
<td>1667.6</td>
<td>676.5</td>
<td>1909.6</td>
<td>821.5</td>
</tr>
</tbody>
</table>

The main aim of the original investigation was to determine a suitable prediction scheme that
can calculate realistic wind turbine sound levels at sensitive receptors around wind farms. Site measurements were conducted at a few locations close to wind turbines so as to provide field data that can be compared to prediction results from the three simulation platforms to be described in Section 3.1. The measurements were conducted over short durations on different days in 2014 and 2015: a) 28 August 2014; b) 11 June 2015; and c) 6 July 2015.

### 3.1 Simulation results

A brief summary of the results of three simulation platforms is presented in this section to highlight the complexities and uncertainties that accompany the efforts to evaluate the far-field noise levels from a wind farm with many wind turbines. Complete details of the three platforms and the results were presented in References 2 and 3. The three platforms were: a) Cadna_A, by Datakustik, that uses procedures from Reference 1 and applies simple empirical adjustment factors for meteorological effects based on wind speed, wind direction and stability class of the weather; b) exSound 2000+ which is a two-dimensional subset of NORD2000 developed by Delta Acoustics [12]; and c) INPM code developed by JASCO Associates of Victoria, BC, Canada that uses parabolic equation solver and the exact weather profiles. The results of the three platforms and their comparisons to the measured value at Location 5 are presented in Table 2 below.

| Table 2: Comparison of measured and calculated sound levels at Location 5, dBA |
|-------------------------------------------------|-------------------|-------------------|-------------------|
| Cadna_A (NO CONCAWE)                            | 45.1              | 40.7              | 35.6              |
| Cadna_A (CONCAWE)                               | 48.3              | 40.4              | 43.7              |
| Cadna_A (CONCAWE)                               | -                 | 43.9              | 40.7              |
| exSOUND 2000+                                   | 48.6              | 51.4              | 51.2              |
| INPM Code                                       | 45.5              | 41.3              | 42.0              |

The main observations of Table 2 results are:

i) CADNA_A is simple to implement and easy to use. The main module of the platform does not include the weather data such as wind speed and temperature profiles. If one wants to include CONCAWE procedures, the information on the stability class of the weather data is an important input parameter. Because of these deficiencies, the results of CADNA_A evaluation can be consistently different from actual levels at the sensitive receptors.

ii) The basic sound module exSound2000+ of the full NORD2000 platform was unable to resolve sound levels generated at the receptor location accurately. The sound levels at the receptor locations, evaluated with exSound2000+, were well beyond the acceptable error band (engineering accuracy) of ± 2dB. In addition, Reference 12 applies geometrical acoustics (ray-theory) to evaluate noise levels. Ray theory is applicable only for high frequency regions. And hence, the application of 2-D geometrical acoustic modelling did not provide reliable results.

iii) Platforms that use ISO9613 – Part II procedures to evaluate receptor noise levels use receptor locations that are further away than the recommended distance limitations prescribed in the standard.

iv) Finally, INPM seems to be the most accurate of the three platforms used in the current study. The main reason is the application of actual profiles from weather data.
One can therefore conclude that reliable representation of weather profile, such as wind variation with altitude, temperature variation with altitude, and relative humidity variation with altitude, is a necessary component of far-field prediction of wind farm noise levels at all sensitive receptor locations. Further analysis of the impact of weather data is presented in Section 4.

4 Turbine noise predictions

Two questions, the impact of weather profiles and the point source approximation, were the main aims of the current investigation. A brief summary of the findings are presented below.

4.1 Impact of weather profiles

The INPM code was used for the evaluations as it can use exact weather profiles. The weather data variation with altitude is shown in Table 3 for two periods in 2015. The maximum PWLs, supplied by the manufacturer, were used and the source was assumed to be a point source at the hub height of 95 m. The results are presented in Table 3 below.

Table 3. Calculated sound levels at Location 5 using INPM Code, dBA

<table>
<thead>
<tr>
<th>Turbine Number</th>
<th>Distance to Location 5, m</th>
<th>11 June 2015</th>
<th>20 August 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT # 1</td>
<td>593</td>
<td>42.0</td>
<td>42.2</td>
</tr>
<tr>
<td>WT # 2</td>
<td>264</td>
<td>38.2</td>
<td>40.8</td>
</tr>
<tr>
<td>WT # 3</td>
<td>1545</td>
<td>33.1</td>
<td>39.8</td>
</tr>
<tr>
<td>WT # 4</td>
<td>775</td>
<td>38.5</td>
<td>38.7</td>
</tr>
<tr>
<td>WT # 5</td>
<td>2146</td>
<td>27.2</td>
<td>31.9</td>
</tr>
</tbody>
</table>
| Weather data   | (from 2.5 m to 200 m height) | -          | T: from 21°C to 19°C
|                |                           |              | Speed: from 4.1 to 7.3 m/sec and 135° from north |

The main concerns can be gleaned from the results of Table 3. The predicted results for June 2015 show that the noise from WT#2 is smaller than the noise from WT#1 even though WT#2 is closer to Location 5 (264 m as compared to 593 m). Similarly, the noise level from WT#4 is similar to or slightly more than the noise from WT#2 and the two distances are 775 m and 264 m. Same behavior can be seen for the results for August 2015 simulation. In addition, the noise from WT#3 is only one dB less than the noise from WT#2 even though WT#3 is nearly seven times further away from Location 5 as compared to WT#2.

Discussion with Dr. Roberto Rocca produced the following response [13] and we quote, “the results of the modelling are in fact consistent with sound propagation properties in the specified atmospheric conditions. In particular, the lower received level at Location 5 for the sound from WT2 (at 250m range) compared to WT1 (at 570m) is due to the sound being refracted toward the ground in such a way that it is louder from the farther location than from the nearer…..

“The results, presented as broadband sound intensity maps synthetized from the octave-band modelling run results between 31.5 and 4000 Hz centre frequencies, are shown in Figure 3. It
can be seen from the lower panel (propagation from WT1 toward R5), the sound from the elevated turbine with hub at 95 m remains mostly aloft in a relatively “collimated” beam up to about 300m from the source, then because of refraction effects it fans out toward the ground so that points around 600m range are subjected to higher exposure. It is not a very strong effect but it easily accounts for the 4 dB difference in the results. In the case of propagation from WT2 toward R5 (top panel) the higher sound density in a sense “flies overhead” the receiver at the closer range. This result is clearly dependent on the atmospheric properties and may not occur for a different meteorological profile, but appears quite reasonable” [13].

Figure 3: Propagation of sound from WT#1 and WT#2 to Location 5 (Source: Reference 13)

It is obvious that weather data is a critical input parameter for the reliable evaluation of far-field noise levels from a wind farm, from the results of Table 3 and Figure 3 and from explanations provided by Dr. Roberto Rocca.
The importance of weather profiles can also be gleaned from Kaliski et.al., who investigated methods to improve wind turbine noise predictions [14]. Their results showed that ISO9613 procedures can both under-predict or over-predict depending on the stability classes of weather and the severity of wind and temperature inversions.

### 4.2 Point source approximations

The second concern raised by the current investigation is the assumption of representing the turbine by a single point source at the rotor hub. The INPM code was used, as before, and the source was placed at three different heights. The resulting predicted sound levels at Location 5 are presented in Table 4 below. The predicted noise levels of Table 4 include the weather profile data shown in Table 3.

<table>
<thead>
<tr>
<th>Source Height</th>
<th>11 June 2015</th>
<th>20 August 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 m (Rotor Hub)</td>
<td>46.0</td>
<td>46.4</td>
</tr>
<tr>
<td>75 m (along the mast)</td>
<td>57.7</td>
<td>57.7</td>
</tr>
<tr>
<td>55 m (along the mast)</td>
<td>59.0</td>
<td>59.7</td>
</tr>
</tbody>
</table>

The results clearly indicate that the location of the turbine source representation is a critical input to any predictive methods of far-field noise. As Reference 14 clearly points out, the wind turbine is more than a simple point source. The sound power changes in the rotor plane as the blades revolve around due to many contributing factors. And hence, Reference 14 suggests that one should represent the rotor as a series of point sources with random phases along a vertical axis. The relative sound power variation in the vertical axis can be assumed as that shown in Figure 4 below (Figure 4 is Figure 7(a) of Reference 14).

![Figure 5: Relative sound power along horizontal slices of the rotor plane. (Source: Figure 7a of Reference 14)](source: Figure 7a of Reference 14)

One can then surmise that the two concerns raised in this paper are valid and one should look at alternate methods to evaluate the noise levels at far-field receptors from a wind farm with
multiple wind turbines. In addition, Reference 14 concluded that the directivity of the distributed sound sources can have significant impact on receptors who are not in the up-wind or down-wind directions.

4.3 An alternate proposal

Earlier sections showed that acoustic assessment procedure, used currently, can have significant drawbacks. An alternate method of evaluating receptor noise levels is proposed and may involve the following steps:

i) The turbine manufacturer provides the apparent PWLs of the rated turbine at selected wind speeds measured as per the IEC Standard [4];

ii) Using source localizations techniques, similar to that of References 9 and 10, the manufacturer also provides a relative variation of the PWLs in the rotor plane, similar to that of Figure 4 [Figure 7a of Reference 14];

iii) The turbine manufacturer also provides the directivity factor of the source distribution in horizontal slices at different heights;

iv) The wind farm developer would have collected weather data with a few met stations with sensors at different heights. The collected weather data can be used to validate weather prediction models such as that developed by Radonjic et. al. [15]. The weather prediction models can then be used to generate a few worst case scenario weather profiles at the wind farm site. The realistic weather data variation with altitude can thus be generated;

v) The information from Steps i) through iv) can then be used as input in a program such as INPM that uses parabolic equation solver routines to predict the far-field noise levels.

Finally, the only uncertainty in the proposed method is the influence of the wake from one turbine on all other wind turbines that are located downwind.

5 Conclusions

Complex issues that control the evaluation of far-field noise levels from a wind farm with multiple turbines were highlighted in this study. The impact of weather data such as variation of wind speed with altitude, were investigated through on-site measurements and through computer simulations. The results showed that simulation procedures that do not account for the atmospheric factors were unable to realistically evaluate the noise levels. The point source approximation were shown to be erroneous by citing the research of other investigators. The location of the point source at the rotor hub was compared to the location at different heights. The main conclusion of the study was that the point source approximation was not valid. An alternate method of evaluating the far-field noise levels was proposed in this study.

Acknowledgments

The assistance provided by Dr. Roberto Rocca of JASCO Associates is duly acknowledged. We would like to express our thanks to JASCO Associates for providing us with the INPM code for far-field noise prediction.
References


