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Efficient Evaluation of Wind Turbine Noise

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ABSTRACT

Wind turbines and residential areas are continuously coming closer due to expanding cities, rising demands on regenerative energy and limited suitable turbine locations. Wind turbines create noise during operation, such as every rotating system, which obviously influences or disturbs the environment and people living nearby. Standards like the IEC61400-11 regulate the maximum noise emission as well as measurement and analysis methods. These are rather complex as both changing environmental conditions and the operational state of the turbine have to be considered during the measurement. Further, a significant amount of data, especially the number of elements in each wind bin, has to be acquired. While common systems usually determine whether the turbine fulfills the requirements for operation or not, it is better being able to capture data flexibly according to the current environmental conditions, microphone positioning and switching of the current power curves. The measurement effort is reduced significantly. In order to be able to correlate measurement results to the wind turbine state, it is recommended to acquire not only standard relevant data but also additional data, such as rotational speed and vibration. Hence it is possible to detect error sources during the development process and find suitable solutions easier.

1. INTRODUCTION

Wind energy is frequently considered as key factor for the transition from nuclear to regenerative energy sources. Due to the dependency on environmental conditions, turbines require wind for operation, possible inland positions are quite limited and often determined quite near to populated areas. Noise created by the turbine obviously influences the surrounding environment and disturbs residents nearby. Hence, the emitted noise has to be kept as low as possible, which is regulated by various ordinances, such as the IEC61400-11 [1] in Europe. These usually precisely describe the measurement method, including applied sensors, sensor positions, and the analysis that have to be computed. Currently the focus is set on sound power, 3^{rd} octaves and tonalities computed at different so called wind bins. The quite complex measurement task has to consider various environmental conditions, such as wind speed and direction, the topography and has to deal with challenges setting up the measurement system. As quite large distances have to be covered, the measurement setup can be quite costly and time-consuming. Unfortunately, the setup is also depending on environmental conditions, such as the wind direction and gondola position, which doesn't allow a fixed setup and requires frequent changes in the worst case. Further, the analyses require a sufficient amount of data for each wind bin and each possible operational mode. This requires a rather flexible system, allowing for rapid changes of the setup and a smart data organization supporting the user in finishing his task quite fast.

The present treatise is structured as follows: In section 2 we will give a brief overview of the measurement task according to IEC 61400, which precisely describes both the measurement procedure and the following analyses. Subsequently we will show the challenges during the measurement in section 3 and present a possible solution for the data acquisition task, allowing for fast and flexible measurements. While these are standard relevant topics, we will address the possible sound sources and their localization during the measurement in section 4. Section 5 will conclude this work with some remarks for future developments.

2. MESUREMENTS ACCORDING TO IEC64100

The IEC61400 require a quite strict measurement setup, regulating applied sensors, sensor positions, and the dedicated analysis. As the analysis usually requires measurements of the operating noise and is corrected by the according background noise at the same microphone position. Hence, only the operating noise is taken into account without disturbing environmental noises.

A. Measurement Setup and Method

The measurement setup is quite straight forward and is basically illustrated in **Figure 1**. Microphone and anemometer positions basically depend on the hub height *H* and the diameter of the rotor *D*. The optimum distance between tower and microphone is given by

$$R_0 = H + \frac{D}{2}, \pm 20\% , \tag{1}$$

where the microphone is positioned in a *15%* corridor behind the gondola. In case the wind direction and hence the gondola position changes, the microphone has to be rearranged and a new background noise has to be acquired. The anemometer is positioned in a distance in between *2D* and *4D* within the corridor

$$\beta = \frac{z - z_{ref}}{H - z_{ref}}(\beta_{max} - \beta_{min}) + \beta_{min} \tag{2}$$

in a height of apx. $z=10m$ if possible and $z_{ref}=10m$. Furthermore data monitored by the wind turbine itself, such as weather data at hub height, rotational speed, pitch, gondola position and produced electrical power have to be taken into account.

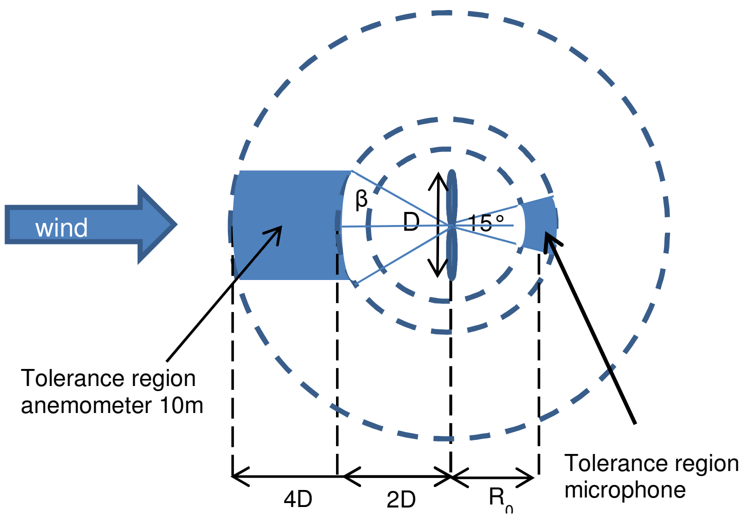


Figure 1: Top view of the basic measurement setup in accordance to IEC 64100. The possible locations for microphone and anemometer are indicated in blue.

While it seems obvious to record the noise during the operation of the turbine (ON – operation noise), an additional background noise BG, recorded at the same position while the turbine is turned off, is required in order to be able to eliminate environmental influences. These can be other turbines located nearby, streets, wind, rivers, etc. which must not be taken into account within the analysis step.

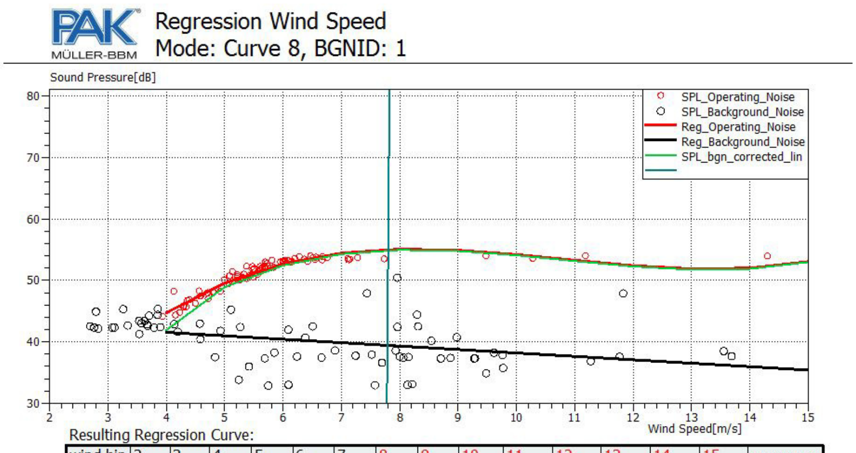
B. Required Analysis

Prior to the analysis with Müller-BBMs PAK software the so called normalized wind speed is computed, applying a regression curve with coefficients derived from the power curves. Hence, the normalized speed is based on the produced power. Nevertheless this is valid up to 95% of the maximum power, while larger values are computed using the measured wind speed and the factor κ, which is basically the ratio between measured and computed wind speed. The acquired sound pressure and the normalized wind speed are subsequently averaged with an averaging time of 60s and the sound pressure level is classified into so called wind bins, where the wind speed is divided into bins with 1m/s width and centered at integer values, according to the synchronously measured/computed wind speed. Subsequently, regression curves are computed for operating and background noise. The level of the recorded noise L_{s+n} is subsequently corrected by the level of the background noise L_n at the same microphone position, with

$$L_s = 10lg[10^{0.1L_{s+n}} - 10^{0.1L_n}], \tag{3}$$

resulting in the operating noise L_s for differences larger *6dB* between operating and background noise. Otherwise the correction is performed by subtracting *1.3dB*. The result is illustrated in **Figure 2**. Subsequently the resulting corrected sound pressure level can be used to compute the emitted sound power L_w with

$$L_w = L - 6 + 10lg\left[\frac{4\pi R_1^2}{1}\right], \tag{4}$$



Resulting Regression Curve:

wind bin [m/s]	2 1.5 - 2.5	3 2.5 - 3.5	4 3.5 - 4.5	5 4.5 - 5.5	6 5.5 - 6.5	7 6.5 - 7.5	8 7.5 - 8.5	9 8.5 - 9.5	10 9.5 - 10.5	11 10.5 - 11.5	12 11.5 - 12.5	13 12.5 - 13.5	14 13.5 - 14.5	15 14.5 - 15.5	WS@95%
(red)			44.7	49.5	52.7	54.4	55.1	54.9	54.2	53.3	52.4	51.9	52.0	53.0	7.78
(black)			41.5	41.0	40.4	39.9	39.3	38.7	38.2	37.6	37.1	36.5	35.9	35.4	
(green)			41.9	48.9	52.4	54.3	55.0	54.8	54.1	53.1	52.3	51.7	51.9	53.0	

Regression Function $y = a+b\cdot x+c\cdot x^2+d\cdot x^3$
Regression Coefficients a= 2.66, b= 16.03, c=-1.57, d= 0.05
Correlation Coefficient 0.96

Figure 2 Regression curves and resulting sound pressure levels for operating noise, background noise and the corrected sound pressure level depending on the current wind speed

Obviously only a selection of the collected data has been applied to compute the regression curves and will be used for further analyses. As both sound pressure and wind speed are already classified into wind bins, it is now possible to compute 3rd octaves and tonality, in contrast to DIN 45681 [2] a correction by the background noise is performed to eliminate frequencies from other sources, at selected time stamps, where the averaged wind speed is close to the wind bin center. In both cases multiple operating noises are used and corrected by the assigned background noise. Subsequently the sound power is computed based on the corrected 3rd octaves. Exemplary analyses are illustrated in **Figure 3**.

In order to receive reliable results these analyses should not be simply performed at time stamps with averaged wind speeds near the wind speed center. On the one hand extreme values are frequently represented by outliers, which would alter especially the resulting sound power. On the other hand the distance between operating and background noise should be at least 6dB, as the influence of the background noise should be limited if possible.

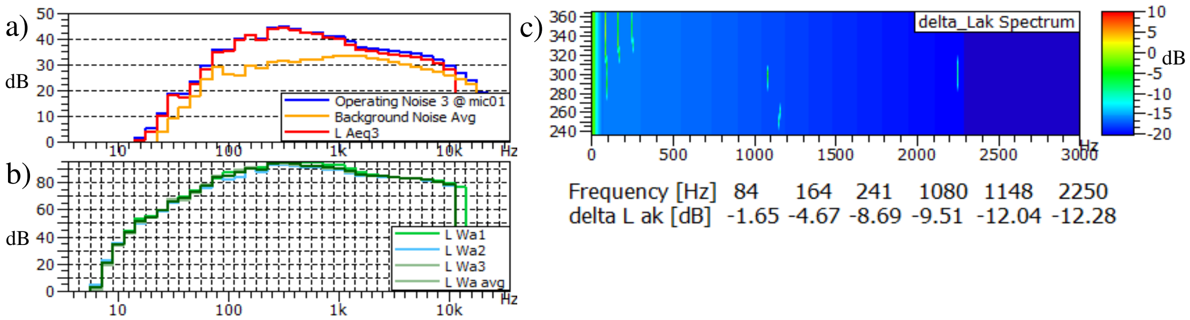


Figure 3 a) Shows 3rd octave levels for operating and background noise and the resulting correction L Leq b) Sound powers of all three required time stamps and the resulting average c) The tonality as spectrum over time for two minutes, averaged tones are illustrated in the table below.

3. CHALLENGES DURING THE MEASUREMENT

While the measurement task described in IEC61400 seems quite simple, it requires a costly setup and a cautious crew, as otherwise it is almost not possible to collect meaningful data.

A. The measurement setup

Both the large distances and the surrounding environment of a wind turbine are quite challenging for a simple and cost effective measurement setup. Applying a centralized data acquisition system is usually hard to handle, as distances that have to be covered are quite large, which requires costly and laborious cabling. Furthermore, cables frequently cannot be applied because of environmental conditions. As illustrated in **Figure 4** public roads, rivers, fences, agricultural areas or even fields for animals have to be passed, which is rather difficult. Additionally cables for sensors should be kept quite short in order to maintain a high SNR and avoid disturbing side effects. Hence, we employ a distributed measurement approach. Independent and battery powered PAK MKII frontends are installed near relevant measurement points, here anemometer, microphone and the tower base. All of these are connected via WLAN and data is centralized. As the ordinance usually applies averaged data and is not depending on phase synchrony, synchronization can be neglected. Nevertheless, phase synchronization has to be considered within the engineering process, where sound sources are addressed. A central and highly precise clock is commonly applied and the signal is distributed among the frontend with fiber optics. In order to overcome the cabling task, other approaches, such as GPS synchronization, have to be considered.

Figure 4: Exemplary location of wind turbines. Roads, fields and topology have to be taken into account during the measurement setup

B. Collecting a sufficient amount of data in a short time

The IEC 61400 describes the measurement procedure for one specified power curve and one microphone position. Multiple power curves and microphone positions are omitted. Both factors are obstacles to a fast, reliable and smooth data acquisition. For each of the wind bins, here the bins two to fifteen are used, at least three averaged points are required to fulfill the demands of the ordinance. In order to receive meaningful results, especially for the computation of the regression curves and the subsequent determination of the sound power, the acquisition of more data seems reasonable. While common approaches are acquiring data for quite a long time for one single power curve and hoping to collect both sufficient and meaningful data, we suggest a more flexible approach. An engineer obviously has no influence on the current wind speed and hence the emitted power. Therefore it is advantageous to monitor the amount of collected data for each bin and mode online, instead of a within subsequent post process. Consequently it is advisable to count the elements within each wind bin during the measurement. As soon as a bin is considered as filled, we suggest more than ten elements per wind bin, and the wind speed is considered as currently constant, the user can set another power curve for the wind turbine and the PAK system is automatically adjusting the data management to the selected power curve. The same procedure is performed in case the microphone position has to be adjusted. Further, this procedure uses only one background noise for each microphone position and all modes, which speed up the data collection task. As soon as the wind speed changes, the power curves can be once more adjusted, and data can be collected for other bins.

4. DETECTION OF SOUND SOURCES

While a certification measurement only decides whether a turbine complies with standards or not, engineers are usually interested in the detection and hence elimination of sound sources. This is essential during the development process, as later changes can be costly and exhausting. It is commonly agreed that disturbing noises obviously result from rotating and vibrating parts of the wind turbine. These include especially the blades, nacelle, gear box and generator. Applying a sound localization using microphone arrays, as suggested in [3], raises the acquired amount of data drastically and can provide information whether the noise is coming from the blade or nacelle. Nevertheless it is hardly possible to determine the sound location within the nacelle. Therefore it is advisable to collect further quantities within and on the wind turbine. These are commonly rotational speed of both rotor and gear box and vibrations of blades and nacelle. This procedure allows a by far more detailed analysis of suspicious points detected during the compliance measurement.

As for instance a quite vast amount of noise is created by the gear box, an additional microphone and a rotational sensor are additionally applied. Following, a frequency, as illustrated in **Figure 5**, or order spectrum are computed for relevant time stamps, where tones or high sound powers have been detected. This way it is possible to correlate unintended effects to a possible sound source. Further it is advisable to compute the FFT or order spectrum for accelerations measured during the certification measurement. Frequently vibrations find paths through complex structures and the source of sound creation and the location of perception are quite distant. Hence, it is required to compare emitted frequencies to find the source of creation.

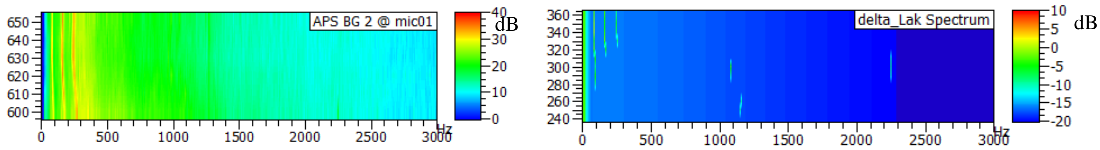


Figure 5: The diagram on the left hand side illustrates the spectrum of a microphone and the right hand side the tones detected in 150m distance.

7. CONCLUSION

While the description of the IEC61400-11 seems quite straight forward, the measurement procedure and subsequent analysis step are quite challenging. As it has been shown environmental conditions and large distances have to be considered during preparations. We suggest a distributed data acquisition approach, where multiple MKII Frontends are located near to the desired measurement points and data is transferred via WLAN. The data acquisition itself is designed as flexible as possible, in order to be able to complete measurements in a rather short time, where current wind speed is the limiting factor. Further, we propose to monitor additional quantities, which provide information on possible sound sources.

Currently the IEC61400-11 Ed.3.0 is discussed and being introduced slowly. Though the measurement setup remains almost unchanged, especially the analyses are changed quite drastically. Nevertheless practical limitations are not taken into account. Future work will show how to handle power curves with unsteadiness and the obviously more demanding data acquisition task. Furthermore, additional techniques, such as operational transfer path analysis [5], should be applied, in order to understand a complex system like a wind turbine and classify sources efficiently.

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