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A New Method for Determining the Wind Turbine Noise based on the Constant Divergence of the Sound Pressure Level

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Summary

According to the IEC 61400-11 standard, the acoustic noise made by a wind turbine is calculated by subtracting the background noise from the sound pressure level measured in the field of the wind turbine at normal operation. The background noise measurements require stopping the wind turbine. In calculations it is assumed that the same level of background noise is present when the wind turbine is both in the *on* and *off* cycles. This paper discusses a new method for determining the wind turbine noise which does not require stopping the wind turbine for measuring the background noise, a costly and time consuming endeavor. The new method involves simultaneously measuring the sound pressure levels at two locations in the field of the wind turbine at normal operation. This data allows us to determine the noise produced by the wind turbine alone by using the constant divergence of sound pressure and assuming the same background noise level at the two locations chosen. The new method has two main advantages. Firstly, it seems to provide more accurate data due to the simultaneous measurement of sound pressure level at the two close locations. Also, eliminating the necessity to stop the wind turbine for the background noise measurements is an important logistical and ultimately financial advantage. The paper presents the theoretical approach for the new method and results from preliminary calculations and simulations.

1. Introduction

The international standard IEC 61400-11[1] gives guidance for determining the acoustic noise made by wind turbines (WT). With the recommended test setup, the operator should measure the noise L_{s+n} at the normal operation of the WT and the background noise L_n when the WT is stopped. Based on the acoustic power summation law, the noise L_s produced by the WT alone is determined with the equation:

$$L_s = 10\log(10^{0.1L_{s+n}} - 10^{0.1L_n}) \quad [\mathrm{dB}] \tag{1}$$

A basic test setup for such measurements on a horizontal axis WT is shown in Figure 1. The following standard requirements will be referred to in this paper:

- The horizontal distance R_0 from the WT tower vertical centerline to the microphone position shall be measured with an accuracy of ±2%.

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- The inclination angle ϕ of the slant line R_1 to the horizontal ground plane shall be between 25° and 40°.
- The acoustic measurements should be made with sound level meters of class 1 having microphones of diameter no greater than ½ inch. The 1/3 OB filters from 20 Hz to 10 kHz shall meet the requirements of IEC 61260 for class 1 filters.
- During the measurements, the periods with intruding background noise, as from aircraft, shall be omitted.
- The background noise shall be measured with the WT stopped immediately before or after each measurement series of WT noise.
- At least 180 measurements shall be made for both background and total noise.
- According to the data reduction procedures, the results shall not be reported if the difference between the total noise and background noise is less than 3 dB. If this difference is between 3 dB and 6 dB, the results shall be marked with an asterisk.

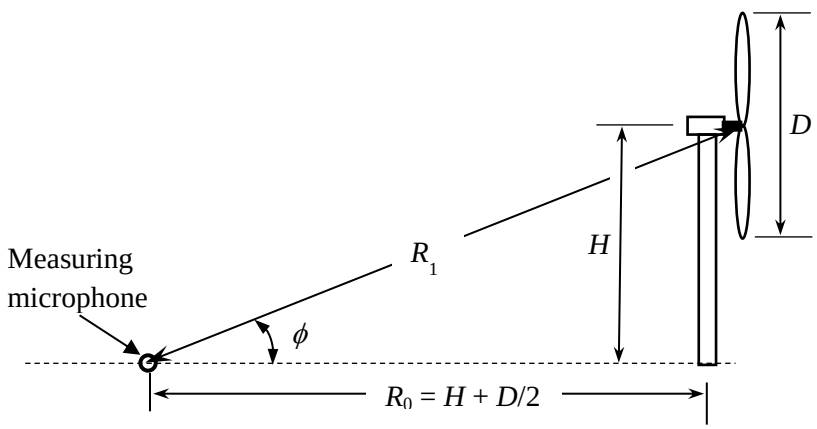

Figure 1: Test setup for acoustic measurements on WTs according to IEC 61400-11

2. Determining the noise from WTs by using the constant divergence of sound pressure

The principle of using the constant divergence of the sound pressure (CDP) for determining the acoustic noise from WTs was firstly shown at Inter-Noise 2013[2]. In the current paper we develop the theoretical approach for the CDP measurements on WTs and point out the advantages of the CDP method over the technique indicated in IEC61400-11. A test setup for the CDP measurement on a WT is shown in Figure 2. It is convenient to place the two measuring microphones on the same ground line also containing the WT tower, in the distance range recommended in IEC 61400-11. The distance from microphones to the WT hub, d_1 and d_2, will be used in calculations.

2.1 The divergence of the sound pressure produced by a WT

The sound pressure level (SPL) L_s produced by the WT at two locations as shown in Figure 2 can be expressed with the equation indicated for directive sources[3] (index 1, 2 holds for the location of Mic1, respectively Mic2):

$$L_{s1} = L_w + DI_{\theta 1} - 20\log d_1 - A_{e1} - 11 \quad [\mathrm{dB}], \tag{2}$$

$$L_{s2} = L_w + DI_{\theta 2} - 20\log d_2 - A_{e2} - 11 \quad [\mathrm{dB}], \tag{3}$$

where:

L_w = The sound power level of the source (WT hub center point), dB re 10^{-12} watt;
$DI_{\theta 1}, DI_{\theta 2}$ = Directivity index of the WT in the direction of the microphones, dB;
d_1, d_2 = Distance from the WT hub center point to Mic1, Mic2, in meters;
A_{e1}, A_{e2} = Excess attenuation due to environmental conditions (air absorption), dB.
The difference of the previous two equations produces:

$$L_{s2} - L_{s1} = DI_{\theta 2} - DI_{\theta 1} - (A_{e2} - A_{e1}) + 20 \log \frac{d_1}{d_2} \quad [\mathrm{dB}] \tag{4}$$

Equation (4) shows that the divergence of the SPL produced by WT at the two locations is constant: it does not depend on the acoustic power of the source.

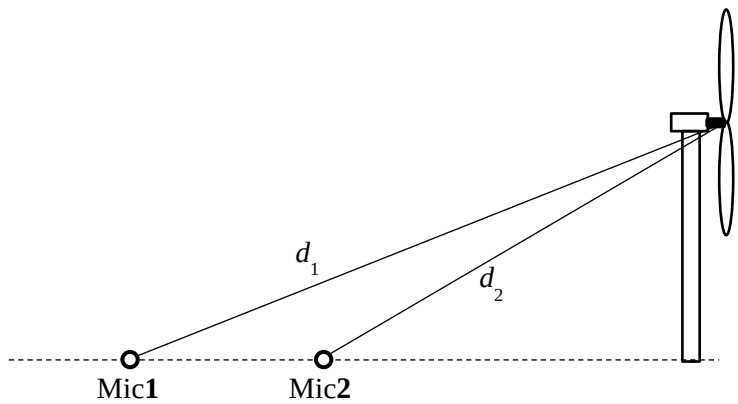

Figure 2: Test setup for acoustic measurements on WT by using the CDP method

The measurements reported in literature show that the WTs behave like circular plane sources[4]. Even if a WT has some directivity in the acoustic emission pattern, the angle between the slant lines d_1 and d_2 can be made smaller than 10° in real test setups and we can consider in a first approach $DI_{\theta 1} \cong DI_{\theta 2}$. Also, the difference $(d_1 - d_2)$ is generally less than 30 m for such CDP measurements and we can consider $A_{e1} \cong A_{e2}$. In these conditions, equation (4) reduces to:

$$L_{s2} - L_{s1} = 20 \log k \quad [\mathrm{dB}], \tag{5}$$

where $k = \frac{d_1}{d_2} > 1$.
However, equation (5) can include terms to count for the WT noise directivity pattern and/or for the air absorption, at least for some measuring frequencies.

2.2 Determining the noise produced by the WT alone by using the CDP

According to the acoustic power summation law, the SPL from a WT, L_s, combines with the background noise L_n at each measuring position as shown below (index 1, 2 holds for the SPL at the location of Mic1, respectively Mic2):

$$10^{0.1 L_{s,1}} + 10^{0.1 L_{n,1}} = 10^{0.1 L_{s+n,1}} \tag{6}$$

$$10^{0.1 L_{s,2}} + 10^{0.1 L_{n,2}} = 10^{0.1 L_{s+n,2}} \tag{7}$$

It is reasonable to consider the same background noise at two close locations during simultaneous measurements, $L_{n,1} = L_{n,2}$. In these conditions, by using the CDP rule expressed in (5), the difference of (6) and (7) produces:

$$L_{s1} = 10\log(10^{0.1L_{s+n,2}} - 10^{0.1L_{s+n,1}}) - 10\log(k^2 - 1) \quad [\mathrm{dB}] \tag{8}$$

Equation (8) shows that the SPL produced by the WT alone can be calculated from the SPL values recorded simultaneously with two microphones which are adequately placed in the field of the WT at normal operation. With this technique, stopping the WT for background noise measurements is not needed.

3. Example of practical test setup for CDP measurements on WTs

Figure 3 shows the proportions of a possible test setup for measuring the acoustical noise produced by WTs with the CDP method.

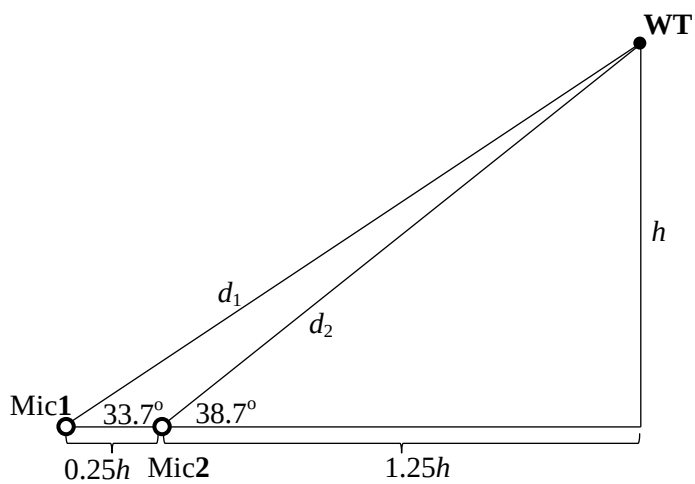

Figure 3: Example of test setup for CDP measurements on WTs

For a WT with the hub center at height *h*, the measuring microphones can be placed on the same ground line which includes the WT tower base, at 1.25*h* and respectively 1.5*h* from the WT vertical line (the distance between Mic1 and Mic2 is 0.25*h*). With these dimensions, the slant lines linked to Mic1 and Mic2 form angles of 33.7° and 38.7° with the ground plane, within the range of 25° … 40° recommended in IEC 61400-11.

The distances from Mic1, Mic2 to the WT hub center are $d_1 = \sqrt{h^2 + (1.5h)^2} = 1.803h$ and $d_2 = \sqrt{h^2 + (1.25h)^2} = 1.601h$, which produce the ratio $k = d_1/d_2 = 1.126$.

Equation (5) shows that the SPL produced by WT decreases between the locations of Mic2 and Mic1 with the amount $L_{s2} - L_{s1} = 20log1.126 = 1.03\ \mathrm{dB}$. For this particular test setup (that is $k = d_1/d_2 = 1.126$), the SPL produced by the WT alone at the location of Mic1 can be calculated with the following equation which is derived from (8):

$$L_{s1} = 10\log(10^{0.1L_{s+n,2}} - 10^{0.1L_{s+n,1}}) + 5.71 \quad [\mathrm{dB}] \tag{9}$$

3.1 The effect of the rotation of WT blades on the CDP calculations

The blades of WTs move around the axis and, as an example, for a horizontal axis WT having the blades length 30% of the hub height, the noise source moves up to the height of 1.3*h* and down to 0.7*h*. Simple calculations show that in this situation the ratio $k = d_1/d_2$ varies from $k_{\min} = 1.101$ (for the blade in the upper position) to $k_{\max} = 1.155$ (for the lower position). Accordingly, the term $-10\log(k^2 - 1)$ in equation (8) changes from 4.75 dB (for lower blade) to 6.75 dB (for upper blade). These results justify

modeling the WT as a point source located at the WT hub center and therefore using in calculations equation (9) which was derived for this position of the source. Then, an eventual effect of the rotating blades can be considered within the uncertainty of the results obtained with (9).

4. The place for the potential noise sources which would produce the same effect in the CDP test arrangement as the WT under test

The acoustic noise measurements on WTs described in IEC 61400-11 aim to determine the noise made by the WT alone at a given location, assuming that the WT is the dominant noise source at that location (at least 3 dB over the ambient). However, other sources in the ambient may become temporarily dominant at the measurement location and their noise can be erroneously attributed to the WT under test.

The standard measurements with a single microphone cannot make any distinction for the position of the source which produces a SPL value at the measuring location. The data filtering technique in IEC 61400-11 relies on the expertise of the operator who is asked to avoid the periods with intruding background noise, as from aircraft, during the tests. This adds a potential for human error which would adversely affect the results of the measurements.

Unlike the IEC 61400-11 procedure, the method described in this paper produces data which is linked to the position of the WT through equation (5). The SPL measured by Mic1 and Mic2 is the superposition of the WT noise with the ambient noise as shown in equations (6) and (7). The acoustic power of the WT may change during measurements and so will the SPL at the measurement locations, but the constant divergence of the noise from WT as ruled in (5) provides strong benefit for filtering the data. For evaluating the effectiveness of the CDP method in data filtering, two aspects must be clarified: 1) where should another noise source be located, if possible, in order to induce the same effect in a given CDP test setup, and 2) how significant would be the influence of other noise sources on the data from the CDP measurements on a WT.

4.1 A little math: the locus of the points where the ratio of the distances to two fixed points is constant

Let $\mathbf{M}_1(0,0)$ and $\mathbf{M}_2(a,0)$ be two points on the horizontal axis and $\mathbf{T}(x,y)$ an either point in the plane as shown in Figure 4. The distances **TM₁**, **TM₂** are written $d_1 = \sqrt{x^2+y^2}$, $d_2 = \sqrt{(x-a)^2+y^2}$. The condition for constant ratio of distances $\frac{d_1}{d_2} = k > 0$ leads to:

$$\left(x - \frac{ak^2}{k^2-1}\right)^2 + y^2 = \frac{a^2k^2}{(k^2-1)^2} \tag{10}$$

This is the equation of a circle with center coordinates $\left(\frac{ak^2}{k^2-1}, 0\right)$ and radius $r = \frac{ak}{k^2-1}$.

- For $k = 1$ the locus is the median line of $\mathbf{M_1M_2}$ (because $\frac{d_1}{d_2} = 1 \leftrightarrow d_1 = d_2$).
- For $k > 1$ the locus is a circle to the right of this median line.
- For $0 < k < 1$ the locus is a circle located to the left of the median line of $\mathbf{M_1M_2}$, as shown in Figure 4.

For the 3-D problem, due to circular symmetry around the horizontal axis, the locus is:

- For $k = 1$, the median plane of $\mathbf{M_1M_2}$.

- For $k > 1$, a spherical surface to the right of the median plane of **M_1M_2**, having the same radius and center point as the circle represented in Figure 4.
- For $0 < k < 1$, a spherical surface to the left of the median plane of **M_1M_2**, having the same radius and center point as the circle represented in Figure 4.

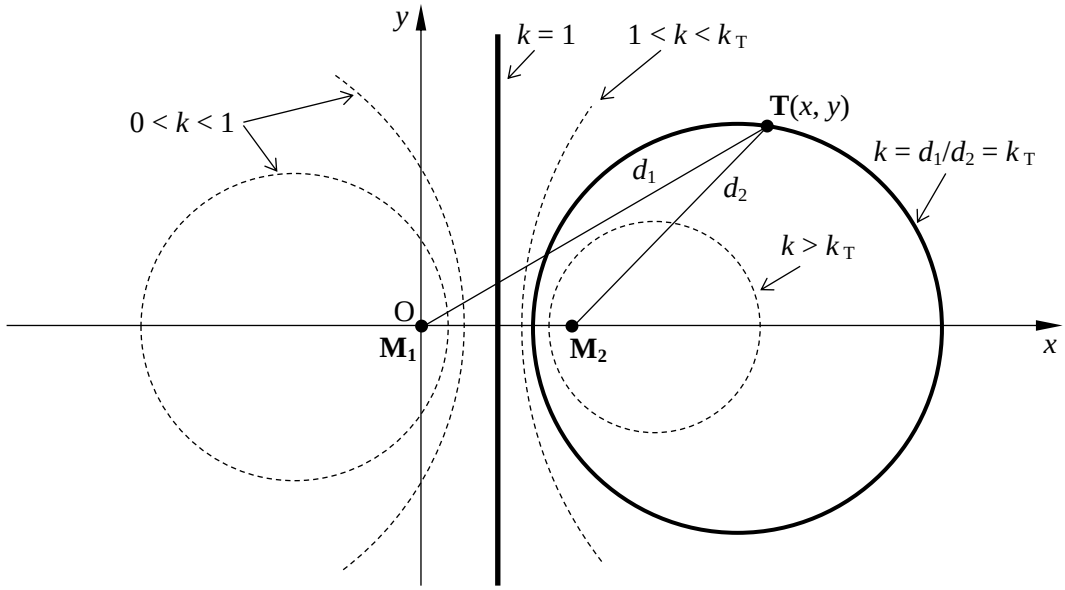

Figure 4: The locus of the points in the plane where the ratio of the distances to two fixed points, **M_1** and **M_2**, is constant

4.2 The position of a noise source which would produce the same divergence of SPL at the measuring locations as the WT under test

Based on the above discussion we can conclude that any noise source which is located on a hemisphere which contains the WT hub center point as shown in Figure 5 will induce the same divergence (5) in the CDP setup as the WT under test.

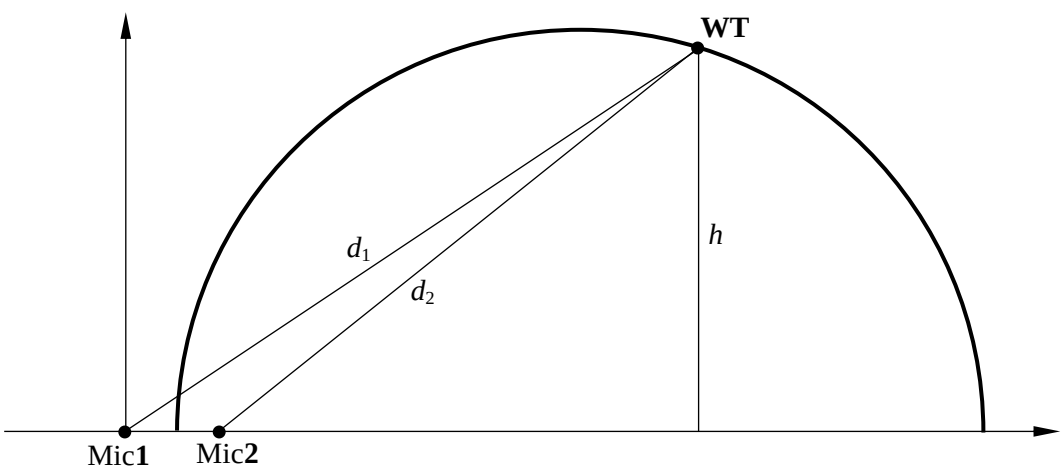

Figure 5: Cross-section through a hemispherical locus. Any noise source on this hemisphere will produce the same effect in the CDP setup as the WT under test

The hemispherical locus for the test setup example shown in Figure 3 ($a = 0.25h$, $k = 1.126$) has the center coordinates $(1.18h, 0)$ and radius $r = 1.05h$.
The discussion on this locus can be extended for the effect of the rotating blades as argued at 3.1.
The ratio $k_{\min} = 1.101$ (for upper blade) defines a hemisphere with radius $r = 1.30h$ and center at $1.43h$ from Mic1.
The ratio $k_{\max} = 1.155$ (for lower blade) produces a hemisphere of radius $r = 0.86h$ and center at distance $\cong h$ from Mic1.
We can conclude that any noise source which is located within the shell defined by these two non-concentric hemispheres will produce at the measurement locations the same divergence of SPL as the WT under test. A vertical cross-section through this shell and containing the measurement ground line is highlighted in Figure 6.

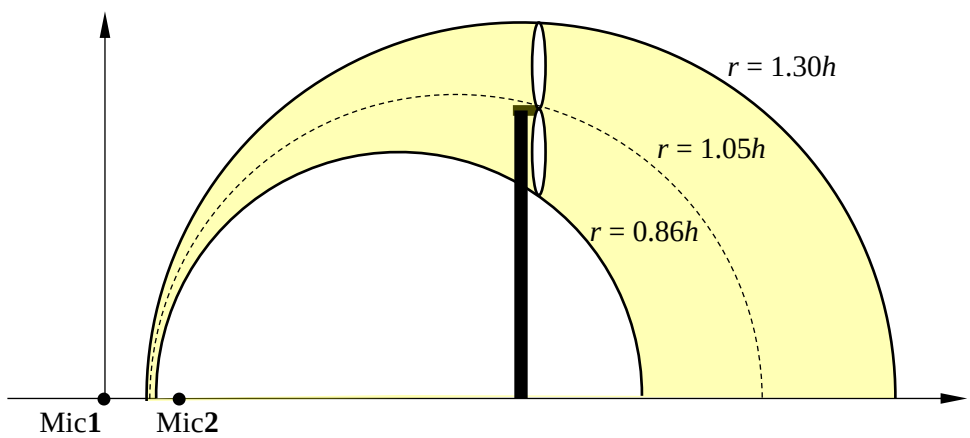

Figure 6: Cross-section through the region for position of noise sources which would produce the same CDP as the WT under test (the rotating blades effect included)

4.3 The effect of other noise sources on CDP data from WT noise measurements

For the purpose of this paper, we will name the region between the two hemispheres represented in Figure 6 ***<u>the CDP shell for the WT under test</u>***.
The CDP shell defines three distinct regions of interest for the measurements on a WT:

a) The region within the CDP shell. Any noise source located in this region has similar effect on the CDP data as the WT under test. If such disturbing source is dominant for a long enough time at the measurement locations, it will produce CDP data which can be erroneously attributed to the WT under test. However, this shell represents a small part of the space above ground where potential disturbing sources might exist and this shell can be visually controlled.
b) The region above the CDP shell. For any point in this region, the ratio $k = d_1/d_2$ is smaller than $k_{\min} = 1.101$ calculated at 3.1. A noise source from this region will produce in the test setup of Figure 3 a SPL divergence (5) lower than 0.84 dB and such data can be filtered as shown further on.
c) The region below the CDP shell. For any point in this region, the ratio $k = d_1/d_2$ is greater than $k_{\max} = 1.155$ calculated at 3.1. A noise source from this region will produce in the test setup of Figure 3 a SPL divergence (5) bigger than 1.25 dB and such data can be filtered as shown below.

5. Example of filtering the data from CDP measurements on WTs

The CDP data from the acoustic noise measurements on a WT can be filtered with an excel spreadsheet which is set for the calculations shown in equation (9). Such data samples, for a test setup as represented in Figure 3, are shown in Table 1.

The input value for Mic1 data ($L_{s+n,1}$) was chosen 44.0 dB, close to the value shown in Figure G.1 of IEC 61400-11 for the total noise at 1 kHz. The first column also lists two values which simulate possible aircraft (75 dB) and train (60 dB) noise levels.

The inputs for Mic 2 data ($L_{s+n,2}$) are "*possible*" values which allow making comments and decisions on accepting/rejecting the data. The following criteria and sample calculations help understanding the decisions and comments in Table 1 (recall the divergence of the WT noise in Figure 3 is $L_{s2} - L_{s1} = 1.03\ \mathrm{dB}$, as calculated before).

1) Due to the ambient noise, the SPL measured by Mic1 and Mic2 should surpass the noise from WT at those locations, that is $L_{s+n,1} > L_{s,1}$ and $L_{s+n,2} > L_{s,2}$.
2) Obey the IEC61400-11 rule: data is only reported if the WT noise exceeds the ambient noise by at least 3 dB: $L_{s,1} - L_{n,1} > 3\ \mathrm{dB}$ and $L_{s,2} - L_{n,2} > 3\ \mathrm{dB}$.
3) If $L_{s+n,1} \geq L_{s+n,2}$ the measurement result is rejected (the SPL measured by Mic2 should always exceed the SPL measured by Mic1 because the WT is the dominant noise source).

Sample calculations: The divergence of SPL from a noise source traveling at 1000 m height is no greater than $20\log(1020/1000) = 0.17\ \mathrm{dB}$. Similarly, the divergence of SPL from a noise source located at 500 m from Mic1 on the other side of WT is no greater than $20\log(500/470) = 0.54\ \mathrm{dB}$.

Table 1: Sample data treatment for CDP measurement results

$L_{s+n,1}$ [dB]	$L_{s+n,2}$ [dB]	$L_{s,1}$ [dB]	$L_{n,1}$ [dB]	$L_{s,1} - L_{n,1}$ [dB]	**Decision and Comments on data**
44.00	46.00	47.39	#NUM!	#NUM!	**Rejected data** ($L_{s+n,1} \leq L_{s,1}$, see criterion 1)
44.00	45.04	44.04	#NUM!	#NUM!	
44.00	**45.03**	**44.00**	**13.23**	30.77	**Accepted data** (The variation of WT noise values calculated from possible CDP data is less than 1 dB)
44.00	**45.00**	**43.85**	**29.24**	14.61	
44.00	**44.95**	**43.60**	**33.41**	10.20	
44.00	**44.85**	**43.07**	**36.85**	6.21	
44.00	44.70	42.15	39.40	2.74	**Data not reported** (see criterion 2)
44.00	44.60	41.43	40.50	0.93	
44.00	44.10	33.39	43.60	-10.21	
44.00	44.00	#NUM!	#NUM!	#NUM!	**Rejected data** ($L_{s+n,1} \geq L_{s+n,2}$, see criterion 3)
44.00	43.80	#NUM!	#NUM!	#NUM!	
75.00	75.20	67.45	74.16	-6.71	**Data not reported** (see criterion 2) **Aircraft** noise simulation
60.11	60.64	56.96	57.23	-0.27	**Data not reported** (see criterion 2) **Train** noise simulation

While the rejected data come out from excel spreadsheet calculations (undefined operations), the "not reported" data can be usually eliminated through "IF" conditions.

With a dual-channel analyzer having dedicated software for the CDP measurements on WTs, the data could be examined in real time. Thus, the measuring system could inform the operator during the tests about the steadiness of the measurement results, eventual unsuitable background conditions for the WT measurements, the number of acceptable measurements recorded, the average noise produced by the WT, etc.

6. Calibration of a CDP test setup for measurements on WTs

In addition to the IEC 61400-11 standard requirements for the calibration of the instruments used in acoustic noise measurements on WTs, it is useful to check the CDP test setup for the accuracy and steadiness of the data recorded. By using an acoustic source able to produce dominant noise in outdoor conditions, the operator can check easily the test setup given in Figure 3 at a convenient scale (the loudspeaker placed, for example, at 2m above the ground). Furthermore, in such scale-simulated conditions, the operator can check the response of the system to ad-hoc disturbing noise sources.

7. Conclusions

The currently used method in IEC 61400-11 for measuring WT noise requires stopping the WT, and makes a substantial assumption concerning the background noise at two potentially distant moments in time. The method proposed in this paper bypasses that requirement by simultaneously taking measurements at two different points on a line also including the WT. Calculations are shown to determine the noise produced by the WT using the measurements from the two appropriately placed microphones. The paper then goes on to analyze the effect of external noise sources based on their location and shows how such altered measurement results can be either automatically discarded or easily filtered out by the operator. The CDP measurements on various WTs in real conditions will allow optimizing the distance between the measurement locations and improving the details for this approach.

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