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An Efficient Algorithm for the Evaluation of Tonality and the Determination of the Tonal Frequency According to IEC 61400-11

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ABSTRACT

The terms of tonality and tonal audibility of the noise emitted by wind turbines are defined and described in the standard IEC 61400-11. The procedure for tonality assessment at different wind speeds based on the narrowband analysis is explained in section 9.5 of the standard. After sorting spectra into wind speed bins, the overall tonal audibility is determined if at least six of ten of the narrowband spectra have an identified tone with the same origin. The standard describes a procedure for tonality assessment by means of a flowchart. Tones of the same origin are treated and reported as one tone. However, the standard does not specify the final value of the frequency of the tone. An efficient algorithm has been developed to evaluate the tonality of the noise emitted by wind turbines. Likewise, different alternatives to specify the final frequency of the tone are discussed, based either on their frequency of appearance in the total of the number of measurements or on the tone levels produced by such frequency.

Keywords: Noise, Wind turbine, Tonality
I-INCE Classification of Subject Number: 81

1. INTRODUCTION

Part 11 of the IEC 61400 [1] presents measurement procedures that enable noise emissions of a wind turbine to be characterized. Two of the most important characteristics are the apparent sound power levels of the wind turbine and the tonal audibility both with reference to the different wind speeds. An objective method for the evaluation of the audibility of tones in noise (reference method) is described in Annex C of ISO 1996-2:2007 [2]. In the regulations of some countries, an addition of up to 5dB should be made to the measured noise level from a wind farm where tonality is shown to be a characteristic

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[3]. The edition 3.0 of the standard considers measurement periods of 10 s compared to the measurements of 60 s in the previous edition 2.1. Certainly, 60-second measurements could provide average wind speeds that can mask averaged speeds every 10 seconds falling within different speed ranges. When working with records of 60 s duration, the results of the tonality can be blurred and not always clear.

The algorithm proposed by the standard to determine both the tonality and the audibility of the noise emitted by wind turbines is quite clear except, perhaps, in two aspects. In the first place, the narrowband spectral resolution is not univocal, admitting resolutions between 1 and 2 Hz. A comparison between possible differences of such resolutions will be pointed out later. The second aspect is far more meaningful. The standard does not conclude what frequency has to be assigned to the identified tones. In the standard 'tones of the same origin' are defined as follows: Identified tones in different spectra are considered as tones of the same origin if there are within an interval of ±25 % of the critical band centered at the frequency. Tones of the same origin are treated and reported as one tone.

After showing and analyzing the results obtained with an algorithm that follows the procedure of the standard, it will discuss: a) the influence on the results of the spectral resolution, b) the assignment of a single frequency to characterize the representative tone of the 'tones' of the same origin and c) a new, more efficient algorithm for the search of tonality.

1. MEASUREMENTS

From the measurements carried out to determine the power and tonality of the wind turbine, the acoustic pressure signals were recorded continuously, along with multiple variables of the machine: power, rotation speed, orientation, etc. as well as wind speed, with averaging every 10 s. Subsequently, 10 measurements were selected for each wind speed range. The speed ranges vary every 0.5 m/s. Recordings with speeds in the range of ± 0.1 m/s around the central bin were taken. In our case, the sampling frequency was 25600 samples per second, so each matrix had 10x256000 cells (matrix M). Wind speeds ranged from 8 to 13 m/s.

There is an important difference with the procedure of the standard. Under this standard (point 7.2.5) 'narrowband spectra are measured synchronously with the sound pressure levels as the energy average over 10 s periods. Narrow band spectra shall be A-weighted. A Hanning window with an overlap of at least 50 % shall be used'. In our case, both the spectral analysis and the A-weighting are evaluated within the algorithm, from the 10 s time records.

2. ALGORITHM

On the input matrix M (pressure vs time, 10 s, for ten measurements of the same bin) the search and analysis of tones is carried out in the following way:

I. Spectral analysis of the signals.

First, the FFT of the 10 input signals is obtained. It is done by the *getFTcoef ()* function, which returns the coefficients of the FFT (*coef*).

II. Getting levels, energy and bandwidth for resolutions of 1 and 2 Hz.

Such parameters (*LP, ENE, BW*) are obtained through the *linesMatrix ()* function, which reads the previously calculated coefficients (*coef*), the resolution and the number of input signals (10 in our case). It is carried out for the two resolutions.

III. Determination of possible tones.

This is where tone's search begins. The local maximums of the signals are searched and only those meeting that their level exceeds the critical band average by more than 6 dB (except the maximum line and its two adjacent ones) are selected. It is performed by the *possibleTones ()* function, which has as inputs LP, ENE, BW, the resolution and the number of input signals. The function returns the variables *Tones* and *idxTones*. Tones is a matrix indicating on which lines there is a possible tone for each of the input signals. *idxTones* is a vector with the indexes of those lines where a tone appears in at least one of the signals.

IV. <u>Tone's localization.</u>

The *findTones ()* function locates the tones. First, the functions *L70criterion()* and *LPNcriterion()* classify the lines as 'masking', 'tones' or 'neither'. They are applied in a loop over each of the possible tones. Once a tone has been identified, its tonal parameters are obtained with the *toneParameters()* function.

- Tone frequency: frequency at which the maximum level line is located within the critical band. This frequency is found with the *getFreq()* function.
- Tone level: energetic sum of the lines classified as 'tones'.
- Masking noise level: the energy average of the spectral lines identified as 'masking' within the critical band plus the correction for the use of the Hanning window.
- Tonality: difference between the tone level and the masking noise level.
- Audibility: tonality plus a frequency dependent correction to compensate for the response of the human ear to tones of different frequency.

After obtaining the parameters of each tone identified in the 10 spectra, the results are ordered in a first matrix: *matrixRes1Hz* and *matrixRes2Hz* (one for each resolution). The function responsible for generating these matrices (plus others that simplify the final results later) is *convert2matrix()*.

The size of *matrixRes'X'Hz* is (i x 76), where *i* is the number of identified tones. The information contained in each of the columns is as follows:

(*i*, 1)	central frequency of the critical band of the tones (*fc*).
(*i*, 2:11)	identification of the spectra that have 'tone' in that line.
(*i*, 12:21)	frequency of the tone.
(*i*, 22:31)	level of the 'tone' line (centered on *fc*).
(*i*, 32:41)	tone level.
(*i*, 42:51)	masking noise level
(*i*, 52:61)	tonality.
(*i*, 62:71)	audibility.
(*i*, 72)	average tonality of tones of the same origin.
(*i*, 73)	average audibility of tones of the same origin.
(*i*, 74)	number of spectra in which tones of the same origin appear.
(*i*, 75)	number of spectra in which tones centered on *fc* appear.
(*i*, 76)	identification of relevant and non-relevant tones.

In the last column, only those tones that appear in at least 6 of the 10 analyzed spectra and whose average audibility is equal to or greater than -3 dB are shown. Figure 1 shows the flow diagram of the algorithm implemented.

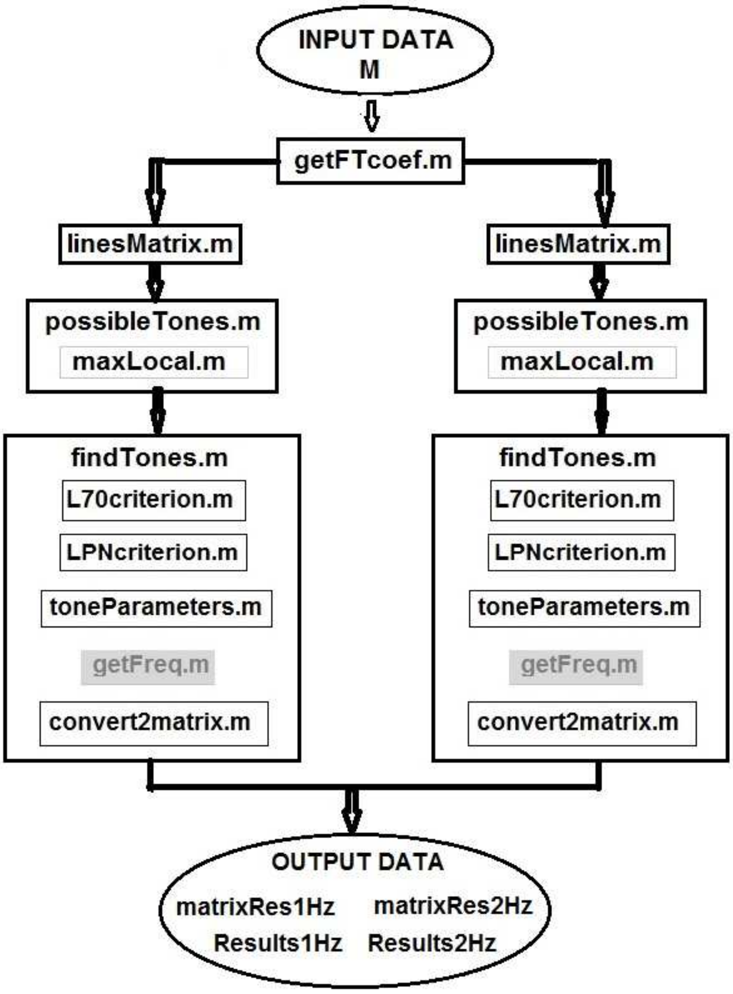
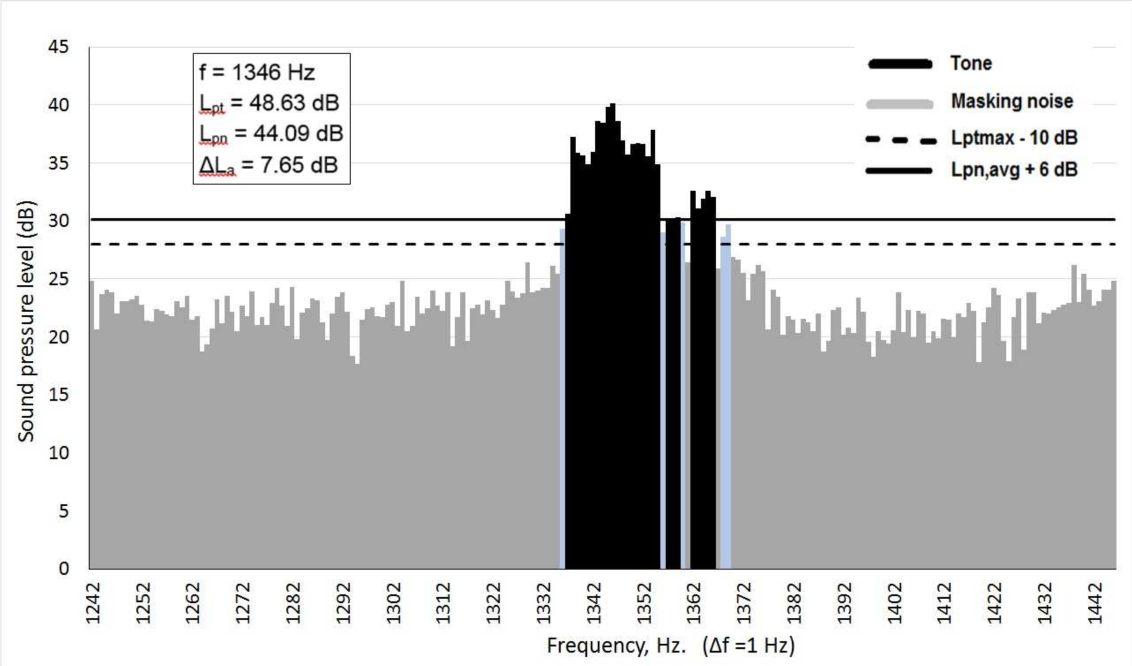


Figure 1. Flowchart of the program implemented in Matlab. The different functions are displayed, as well as the time and order of call

3. RESULTS AND ASSESSMENTS

3.1. Influence of the frequency resolution.

The frequency resolution must be between 1 and 2 Hz. The procedure used to identify possible tones requires identifying the spectral lines (within the critical band) in *masking*, *tones* and *neither* lines. Figure 2 shows the results for two resolutions (1 and 2 Hz) including tonal frequency, tone level (L_{pt}), masking noise level (L_{pn}) and audibility (ΔL_a) for a specific measurement. As can be seen the results for this measurement are practically identical.



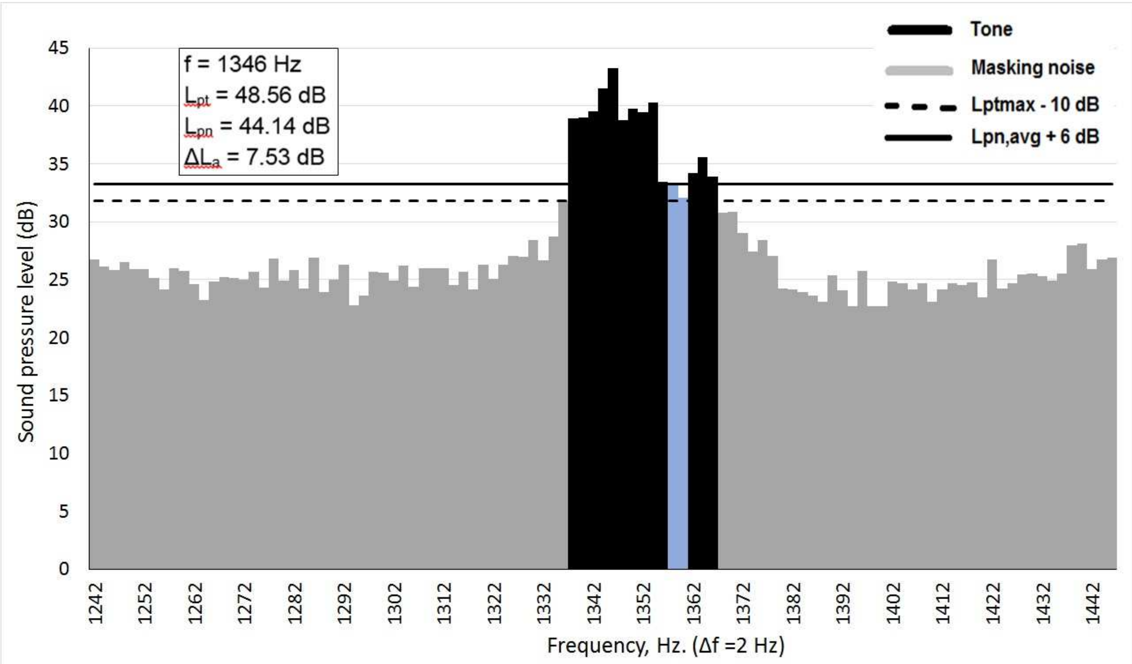


Figure 2. Illustration of the classification of the spectral lines in ‘masking’, ‘neither’ and ‘tones’ for two frequency resolutions, 1 (up) and 2 (down) Hz.

A comparison is made between tonal frequency, audibility and number of measurements (from 10) with an identified tone for all wind speed with the two frequency resolutions, 1 and 2 Hz. Table 1 shows the results. As can be seen, the results obtained with both resolutions are very similar.

Table 1. Results obtained with resolutions of 1 and 2 Hz

	1 Hz			2 Hz			Differences		
v. m/s	Freq, Hz	Audib, dB	N	Freq, Hz	Audib, dB	N	Δf	Δ(Aud)	ΔN
8	1352	5,88	9	1352	5,99	9	0	-0,11	0
8,5	1365	5,51	10	1366	5,77	10	-1	-0,26	0
9	1342	5,15	8	1342	5,43	8	0	-0,28	0
9,5	1342	5,94	10	1342	6,05	10	0	-0,10	0
10	1339	4,86	10	1340	4,91	10	-1	-0,05	0
10,5	1351	4,49	10	1350	4,77	10	1	-0,27	0
11	1351	3,82	10	1346	3,69	10	5	0,13	0
11,5	1350	4,73	10	1344	4,73	10	6	0,00	0
12	1346	4,59	10	1360	4,52	10	-14	0,06	0
12,5	1333	4,54	10	1364	4,47	10	-31	0,08	0
13	1343	4,99	10	1348	4,86	10	-5	0,13	0

3.2. Alternative tone search.

The search for local maxima is, in a way, an unnecessary work. After detection of the local maximum, the maximum of the critical band is selected as the frequency of the possible tone. An example is shown in Figure 3. There are 61 local maxima within the critical band. While it is very fast with the function 'max local' it implies a consumption of calculation time. Six of the 61 meet the following requirement of having a level 6 dB higher than the average level of the band excluding it and its neighbors. Finally, the standard requires taking only the maximum value of these six. In the example, 44.4 dB at 1341 Hz. Although the width of the critical band depends on the frequency, it is possible to search directly the maximums for bands with width 'similar' to the critical bands. This would have directly detected this last value. This process is much more efficient than that suggested by the standard. This strategy reduces the calculation time (for a bin with 10 measurements) by 10%. With an Intel 2.7 GHz processor and a 4 GB RAM, the search time for the tones for a speed bin (10 measurements of 10 s) is 1.5 s.

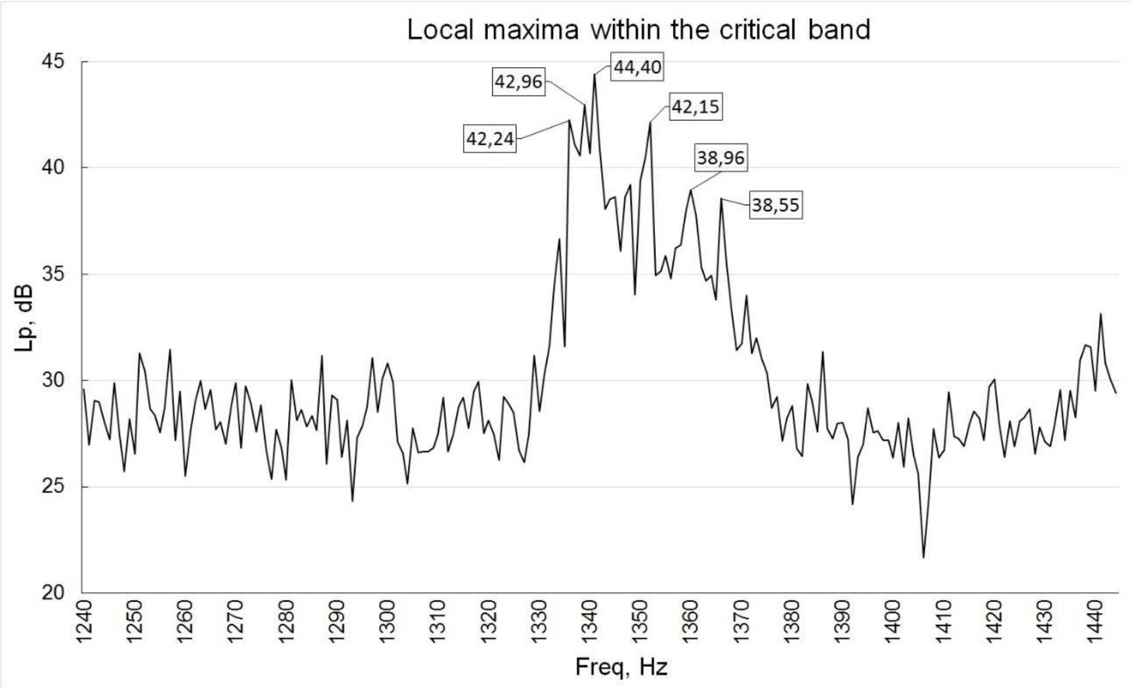


Figure 3. Local maximums and possible tones within the critical band.

3.3. Determination of the tone frequency.

There is no uncertainty in checking whether a single measurement has a tone or not and at what frequency it occurs. Indetermination occurs when averaging tones of the same origin in a series of measurements for a wind speed. The energy average of the audibility is made for all the tones of the same origin. This produces a common average audibility for all of them. However, such tones happen, in general, at different frequency. The standard does not establish what should be the frequency of the tone.

To assign a frequency to the tonal characteristic, several criteria can be used [4]. A first criterion can be the following. From the set of frequencies with tones of the same origin and with same average audibility, select the frequency with the higher modal value. That is, the frequency that (with the first criterion of the tonality) is most repeated in the ten measurements, columns 2 to 11 of the Matrix matrixRes'X'Hz. Using this criterion in multiple bins (10 measurements) figures obtained are 'centered' in the spectral maxima. Nevertheless, in many cases the mode takes the same value for several frequencies.

In our opinion, one criterion that improves the previous one is to select (again, from the set of frequencies with tones of the same origin and with same average audibility) the average value of the N frequencies that were the maximums of the selected critical bands. That is, the average value of the N frequencies that appear in columns 12 to 21 of the Matrix matrixRes'X'Hz. Remember that N must be a value equal to or greater than 6. In addition, the figure of this frequency is unique. With this criterion, a more 'centered' tone is obtained when graphing the spectral values of the ten measurements in the critical band of the tone.

4. CONCLUSIONS

A program has been implemented in Matlab to determine the tonality of wind turbines. The recommendations of the IEC 61400-11 standard have been basically followed with two slight differences. It start from temporary records and 10 records are used for each bin of wind speed. The 10 s of duration of each measurement is maintained. The program calculates the tonality for each wind speed in a very short time, around 1.5 s for a common processor. A tone search strategy is introduced that is much more efficient than that suggested by the standard. Finally, the program introduces a new criterion to assign a frequency value to the detected tones.

ACKNOWLEDGMENTS
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REFERENCES
1. IEC 61400-11 Wind turbines-Part 11 Acoustic noise measurements techniques. IEC, Geneva, Switzerland (2012)
2. ISO 1996-2 (2017), Description, measurement and assessment of environmental noise. Determination of sound pressure levels, ISO, Geneva, Switzerland (2017)
3.Wind farms environmental noise guidelines, (2009), Environment Protection Authority. Adelaide, Australia
4. Panu Lehto (2014), Signal analysis of wind turbine acoustic noise, Master Thesis, School of Electrical Engineering, Aalto University, Finland