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Tonality in wind turbine noise. IEC 61400-11 ver. 2.1 and 3.0 and the Danish/Joint Nordic method compared with listening tests

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Summary

The International Standard on acoustic noise measurement techniques for wind turbines IEC 61400-11 has recently been revised where the current version is edition 3.0. Regarding tonality the basic idea is the same for the two methods. However where the methodology in edition 2.1 analyses few samples for each wind speed bin, the new version analyses all samples for each wind speed bin. A number of typical wind turbine noise sequences are analysed and compared for the two methods together with the tonality analysis method used in Danish regulation. The Danish tone analysis algorithm is now part of the ISO 1996-2 standard. The data will be analysed with 10 m height wind speeds to be comparable. Furthermore the results for all three methods will be compared with the results of listening tests.

1. Introduction

Wind turbine noise primarily consists of aerodynamic noise but often also includes more or less audible tones. If the tones are clearly audible often a penalty is given, since it is a general experience that presence of audible tones in noise increases the annoyance relative to the same noise level without the audible tones. It is important to have precise and objective tonality analysis methods to best asses the tones. For this paper implementation of two different tonality analysis methods are used to analyse wind turbine noise and the results are compared to listening tests of the same wind turbine noise.

2. Tonality methods

2.1 IEC 61400-11 Wind turbines – Part 11: Acoustic noise measurement techniques

This part of IEC 61400 defines the procedures to be used in the measurement, analysis and reporting of acoustic emissions of a wind turbine. Regarding tonal audibility the method consists of two parts: the first part is a tonality analysis procedure for each spectrum and the second part describes how this is averaged to give a single number tonal audibility for each wind bin. The IEC 61400-11 has recently been revised where the current version is edition 3.0 and the previous version is edition 2.1. Part 1 is identical for the two versions, where the methodology in part 2 is updated for the new version.

For IEC 61400-11 ed. 2.1 [6] tonality analysis will be performed for the two 1-minute periods closest to each integer wind speed. In detail this implies that a tonal audibility value will be found for each wind speed by an energy average of the tonal audibilities found for each of the twelve spectra (1 spectre for each 10 second period in the 2 x 1 minute). Only tones with same frequency origin will be averaged.

For IEC 61400-11 ed. 3.0 [7] tonality analysis will be performed on all data. For each wind speed an energy average of the tonal audibility will be found for all spectra within that wind speed. Only tones with the same frequency origin will be averaged.

2.2 The ISO 1996-2 Annex C method / Joint Nordic method version 2

For assessment of tonality from wind turbines in Denmark the Environmental Protection Agency's guideline from 1984 is referred to [5]. The Danish method for assessment of objective tonality analysis is also referred to as the Joint Nordic method version 2 (JNM2). The method has been updated and adapted for implementation in software and is described in ISO 1996-2 Annex C [3]. For the purpose of assessment of wind turbine noise the two methods are almost identical.
For assessment of clearly audible tones in Denmark the highest tonality (1 minute average time or longer) is located for wind speeds between 6 and 8 m/s.

3 Listening tests

3.1 Methodology and procedures

The SenseLabOnline Internet based listening test software from DELTA [1] was used for the tests. 31 sound samples mainly representing wind turbine noise with tones of different prominence and frequencies were prepared for presentation to the assessors. The samples were uploaded to SenseLabOnline which arranged the files in a random order in a double blind paradigm for each assessor.
23 assessors from DELTA's listening expert panel (ages 22-52, mean 32 years) all with normal hearing and 4 acoustic experts (ages 33-64) with normal hearing for their age participated in the listening test. The assessors made the test as a "home test" via their own PC with soundcards and headphones (Sennheiser type HD 449) supplied from DELTA. The assessors were instructed to make the test in a silent room and time at home. The experts made the tests in DELTA's listening rooms with calibrated headphones (Sennheiser HD 650).
The participants had no prior information about the test signals. The total duration of the listening test was estimated to approximately 1 hour, including one repetition of all sound samples and including a training session where the assessors were trained in assessing tones in noise and scale usage with 38 other sound samples.
After the test, the assessor performance was checked with DELTA's eGauge tool [2] and 5 assessors with poor replication, discrimination or panel agreement were excluded before the final statistical analysis of the results.

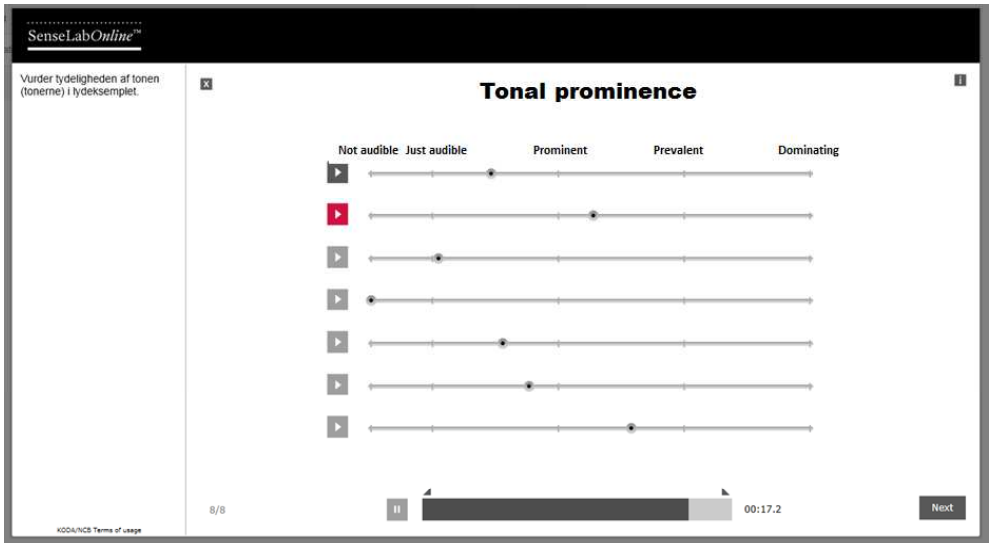

Figure 1
The user interface for the assessors in the SenseLabOnline test on prominence of tones in noise.

The sliders shown in Figure 1 are used for the assessment of the stimuli. Beside the sliders are play buttons for the samples (sounds). The assessor is allowed to switch forth and back at will between any of the sounds during the test.

3.2 Level calibration

Each assessor started the listening test by adjusting the play-back volume of an audio reference file with male speech, so the voice had a natural volume of a man talking at 1 m distance (nominal sound pressure level 64 dB(A)). From previous tests we have found out that the mean levels and deviations are within acceptable limits for this kind of test, see Table 1.

	L_{Aeq}, dB
Mean	63.9
Stand. Dev.	4.5
CI 95 %	1.8
Maximal difference	15.0

Table 1
Mean values, standard deviation and 95% confidence intervals (CI) for the level adjustment of male speech at 1 m distance made by 24 persons.

3.3 Stimuli

From a number of original recordings of wind turbines 24 samples of 20 second periods were selected for the listening tests. If more equally prominent tones in different critical bands were present in a sample, the least prominent were attenuated to facilitate an unambiguous and comparable assessment in the listening test and in the tone analysis. Supplementary 7 samples of stationary industrial noise with tones were added.
The samples - each mono recordings and of duration of 20 seconds - were level aligned so that the A-weighted levels were the same for all samples. The intended presentation level after the level calibration was 50 dB(A).

3.3 Results

The results for the objective tone analysis according to ISO 1996-2 Annex C [3] in this clause is made by the DELTA noiseLab software [4]. The equivalent results according to IEC 61400-11 are made by MATLAB implementation of the algorithm described in the standard.

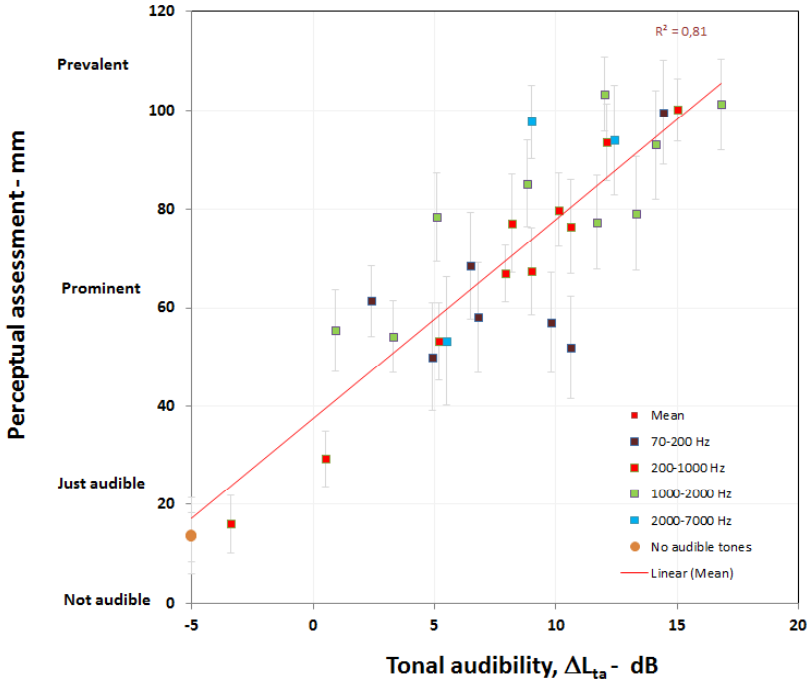

Figure 2
Tonal audibility according to ISO 1996-2 Annex C (the whole 20 sec. sound sample) versus the results of the listening test on an answering scale calibrated in mm. The vertical bar indicates the 95% confidence intervals. The percentage of explained variance of the linear regression is R^2 = 81 %.

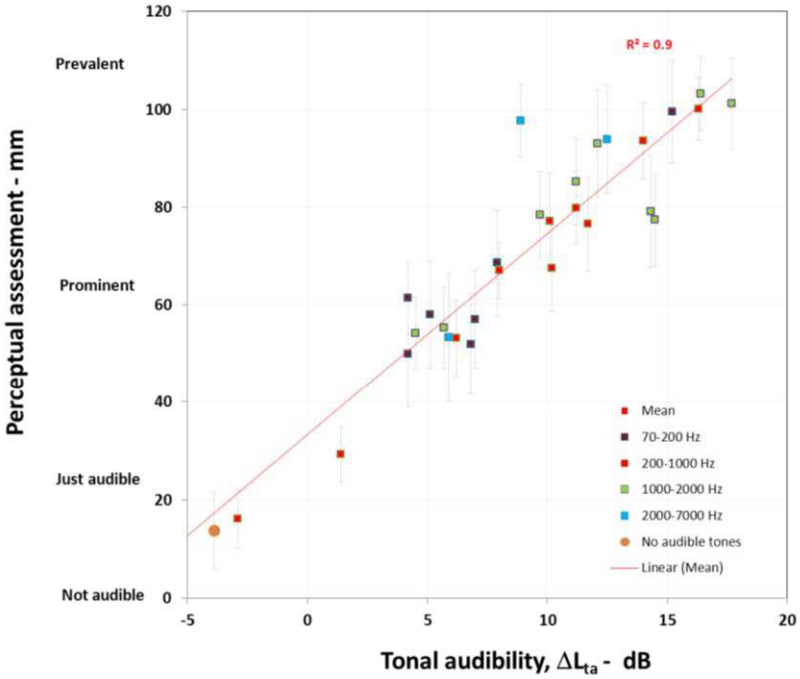

Figure 3
Tonal audibility according to ISO 1996-2 Annex C (the first 5 sec. of the sound samples) versus the results of the listening test on an answering scale calibrated in mm. The vertical bars indicate the 95% confidence intervals. The percentage of explained variance of the linear regression is R^2 = 90 %.

It is seen from Figure 2 that the percentage of explained variance of the linear regression for the ISO 1996-Annex C method is good for the 20 sec. average analysis (R^2 = 81%) but even higher for the averages of the first 5 seconds (R^2 = 90%), which is a satisfying result. The reason for this difference is assumed to be an assessor listening strategy that focusses on the first part of the sound samples, despite they were instructed to listen to the whole sample before they made their assessment.

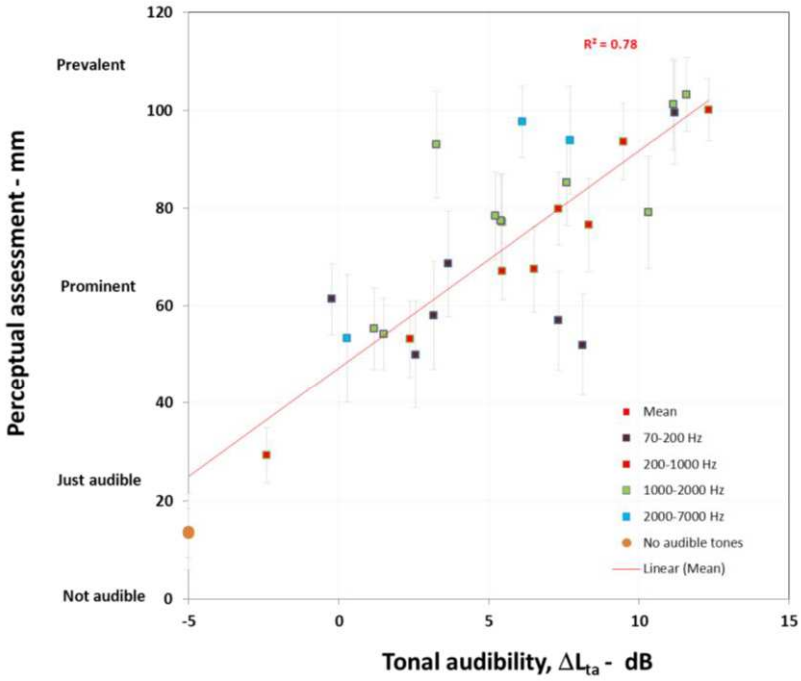

Figure 4
Tonal audibility according to IEC 61400-11 (the whole 20 sec. of the sound samples) versus the results of the listening test on an answering scale calibrated in mm. The vertical bars indicate the 95% confidence intervals. The percentage of explained variance of the linear regression is R^2 = 78 %.

The equivalent results for IEC 61400-11 have the same tendency, where Figure 4 shows a good average analysis (R^2 = 78 %) for the 20 sec. average analysis, but again the percentage of explained variance of the linear regression for the first 5 seconds (R^2 = 85 %) is even higher in Figure 5.

The reasons the ISO 1996-2 Annex C method achieves a higher explained variance of the linear regression than IEC 61400-11 could be that several differences exist between the two methods. For example the data is A-weighted with ISO 1996-2 Annex C which they are not in IEC 61400-11. This should however only have influence on low frequencies.
More important is that the implementation of the IEC 61400-11 employs the same "setup" for all files, where regression and slope has been adjusted for some of the samples for the ISO 1996-2 Annex C analysis (according to the method).

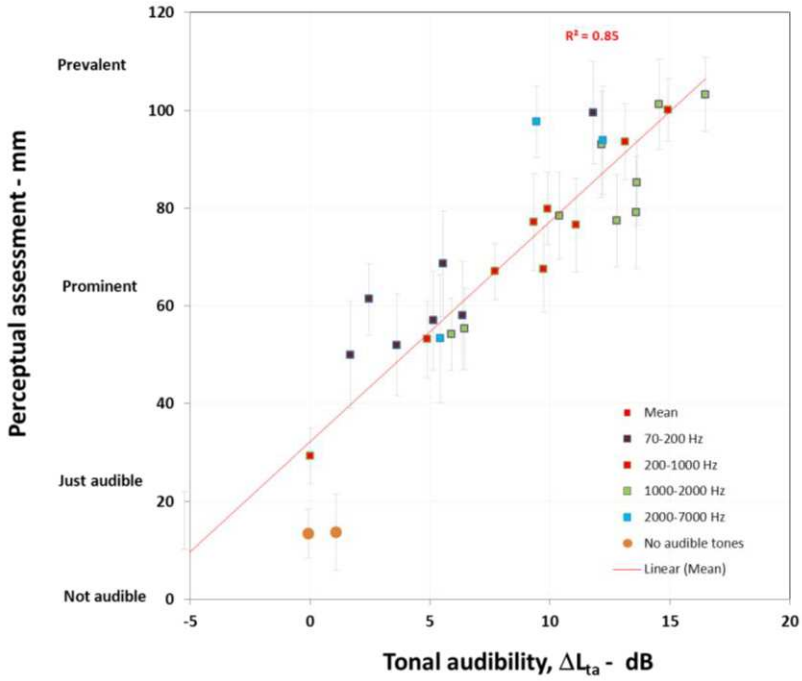

Figure 5
Tonal audibility according to IEC 61400-11 (the first 5 sec. of the sound samples) versus the results of the listening test on an answering scale calibrated in mm. The vertical bars indicate the 95% confidence intervals. The percentage of explained variance of the linear regression is R^2 = 85 %.

4 Tonality assessment of noise from a wind turbine

4.1 Methodology and procedures

Subjected to short signals the two methods have above proved to match the results from the listening test. A wind turbine measurement however lasts between half an hour and up to maybe several days depending on the scope of the measurement. For a tonality assessment of the noise from a wind turbine the methods are used to analyse all the data and combining the data to a few single numbers describing how audible the tones in the noise from the wind turbine were.
As a case study data from a wind turbine measurement will be analysed in the following section. The data will be analysed with both editions of IEC 61400-11 together with the Danish method (ISO 1996-2 Annex C). The three methods are different and cannot be directly compared.
The data used for the comparison consists of wind speeds in the range of 4 to 7.5 m/s. Figure 6 shows the variation of wind speed over time for the chosen data. The acoustic data has been captured in a vertical distance from the wind turbine equal to the total height of the wind turbine. Data has been chosen to have a high tonal audibility.

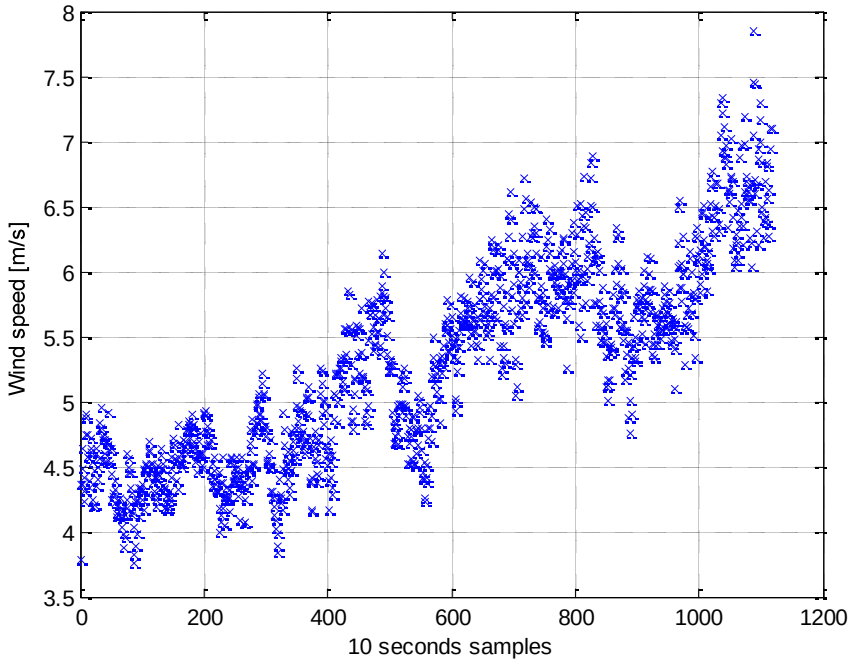

Figure 6
Wind speeds in the used dataset - here shown for 10 seconds samples.

4.2 IEC 61400-11 ed. 2.1

For the previous version of IEC 61400-11 the data average time is 1 minute. As described earlier the method only analyses 2 x 1 minute for each wind speed. As a consequence of this the tonality assessment with this method can be quite random if the tones are not stationary – an effect which can be increased with turbulence.
For the dataset the following tonal audibility is found:

Wind speed	[m/s]	4	5	6	7
Tonal audibility, ΔL_{ta}	[dB]	7.4	4.0	8.0	12.6

Each of the wind speeds, however, consists of more than 2 x 1 minutes of data. If the tonality for some of the other combinations of data is investigated different tonality levels occur. Examples of achievable tonality levels using the same data set are shown in figure 7 for up to 30 x 1 minute data for each wind speed. The data is spread in the following intervals:

Wind speed	[m/s]	4	5	6	7
Minimum tonal audibility, ΔL_{ta}	[dB]	≈ 5	≈ 3	≈ 5	≈ 12
Maximum tonal audibility, ΔL_{ta}	[dB]	≈ 11	≈ 8	≈ 14	≈ 14

The size of the intervals above is from approximately 2 dB to approximately 9 dB, meaning that for example at wind speed 6 m/s instead of a tonal audibility of 8 dB the result can be 14 dB.

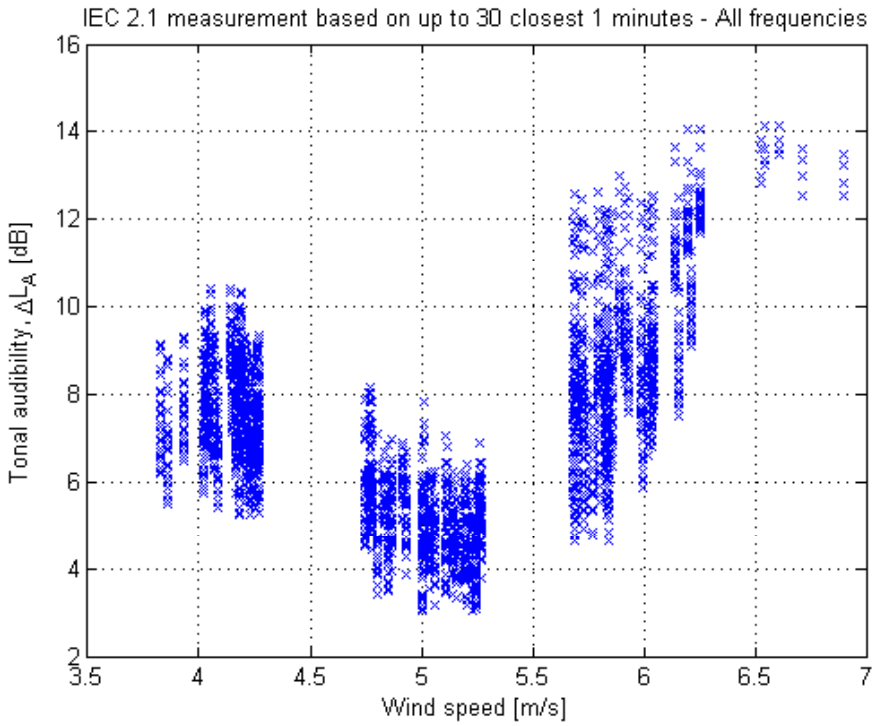

Figure 7
Possible tonal audibilities for wind speed 4-7 m/s with IEC 61400-11 ed. 2.1 if not necessarily the 2 x 1 minute closest to integer wind speed are analysed.

4.3 IEC 61400-11 ed. 3

For the newest version of IEC 61400-11 the average time is 10 seconds and the width of wind speeds are 0.5 m/s. With this method all data for each wind speed is analysed.
The results for this wind speed are as follows:

Wind speed	[m/s]	4	4.5	5	5.5	6	6.5	7
Tonal audibility, ΔL_{ta}	[dB]	7.9	9.1	8.1	4.3	9.7	13.3	16.7

4.4 Danish Method (Statutory Order 1284 / 1518) / ISO 1996-2 Annex C

According to the Danish Statutory Order 1284 [8] (and 1518 [9]) an assessment of the tonality shall be performed at the nearest neighbour with the highest noise level. The assessment shall be performed in downwind with wind speeds between 6 and 8 m/s. An average time of at least 1 minute shall be used. If there are no clearly audible tones at the reference distance (vertical distance to the wind turbine equals the total height of the turbine) there will be no clearly audible tones at receiver position. If there are clearly audible tones at receiver position a 5 dB penalty will be given.
In other words the minute with highest tonality for wind speeds in the range 6-8 m/s (5.5 to 8.5 m/s) shall be located. For the Danish method, however, ΔL_{ts} is used instead of ΔL_{ta}. For comparison reasons in this paper ΔL_{ta} will be used. Below ΔL_{ts} and ΔL_{ta} is defined:

$$\Delta L_{ts} = L_{pt} - L_{pn}$$

$$\Delta L_{ta} = L_{pt} - L_{pn} + 2 + \log\left(1 + \left(\frac{f_c}{502}\right)^{2,5}\right)$$

Resultantly the highest tonal audibility (ΔL_{ta}) for wind speeds in the range 6-8 m/s is found to be 12.3 dB for this case study.

4.4 Summary

In Figure 8 the results for the different analyses have been put together for comparison. There seems to be an overall tendency but the variation is very large.

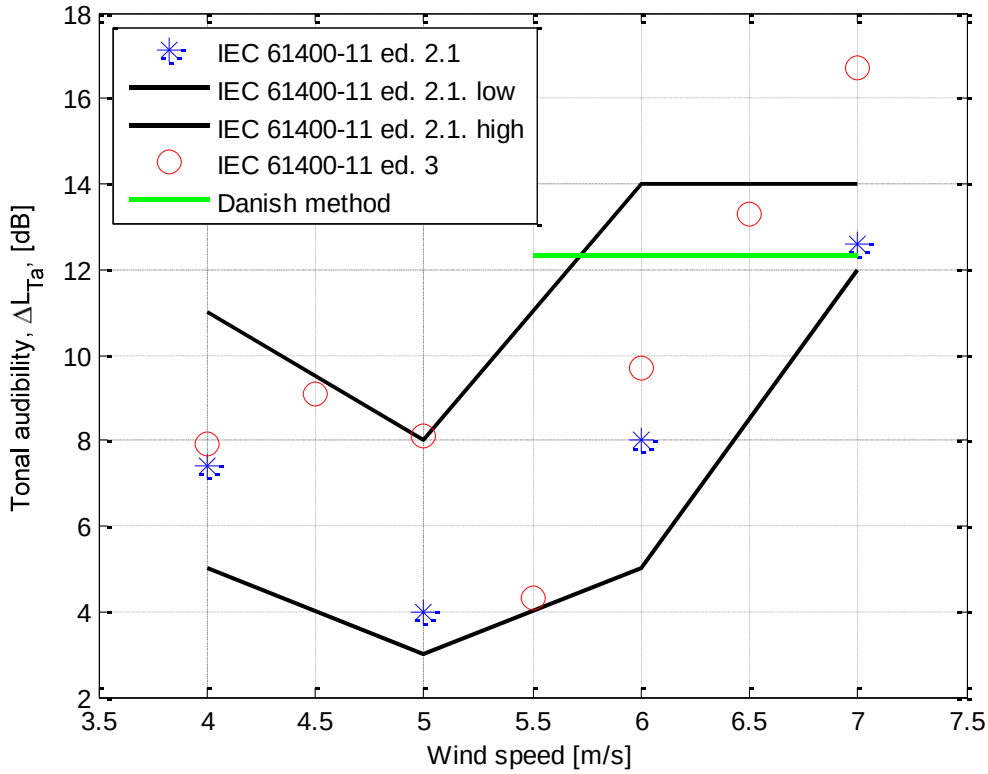

Figure 8
The results from the different analyses on the same figure for comparison.

5 Conclusions

The linear regression between the listening test and the objective analysis methods of IEC 61400-11 or ISO 1996-2 shows a large explained variance, even that the percentage of explained variance drops for non-stationary signals. This means that the two methods work well when used for assessment of tonality level for wind turbine noise (short signals).

When comparing assessment of tonality for wind turbine noise (longer measurement) the observed methods seem to follow the same overall trend but with large differences. This has, however, only been a case study with one set of data and more data sets should be studied.

Comparing the two versions of IEC 61400-11 the newer version seems to be more robust to non-stationary signals and turbulence – for very long measurements data may be averaged too much and short periods with high tonality may not be detected. There is however no insurance that the older version of IEC 61400-11 will detect short periods with high tonality either.

References

[1] www.senselabonline.com

[2] Lorho, G., Le Ray, G,. Zacharov, N. (2010). eGauge - *A Measure of Assessor Expertise in Audio Quality Evaluations*. AES 38th (Piteå, Sweden).

[3] ISO 1996-2 Acoustics – Description, assessment and measurement of environmental noise. Annex C: *Objective method for assessing the audibility of tones in noise*. February 2011.

[4] DELTA. noiseLAB, a software recording and analysis package, see www.noiselab.dk

[5] Danish Environmental Protection Agency, *Guidelines for Measurements of Environmental Noise*, 6/1984 (in Danish), Nov. 1984.

[6] IEC 61400-11:2002 edition 2.1 Wind turbine generator systems – Part 11: *Acoustic noise measurement techniques*.

[7] IEC 61400-11:2002 edition 3.0 Wind turbine generator systems – Part 11: *Acoustic noise measurement techniques.*

[8] *Statutory Order on Noise from Wind Turbines*; Statutory Order no. 1284 of 15. December 2011 (in Danish. English translation can be seen at http://www.mst.dk/NR/rdonlyres/E8562E10-2B2D-4BF3-BAE0-A265C5A0B86E/0/engelsk_vindmoellebekendtgoerelse.pdf).

[9] *Statutory Order on Noise from Wind Turbines*; Statutory Order no. 1518 of 14. December 2006 (in Danish).