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Prominent tones in wind turbine noise - Round-robin test of the IEC 61400-11 and ISO/PAS 20065 methods for analysing tonality content

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Summary

Presently, IEC 61400-11[1] is the widely used method for analysing the tonality content in wind turbine noise for sound power level measurements (made close to the turbine). However, many different methods are used worldwide for analysing the tonality content in wind turbine noise at the receptor position. One of the most used methods at the receptor position is the ISO 1996-2 Annex C method[2]. However, in 2016 the new ISO/PAS 20065 method[3] was published, replacing the ISO 1996-2 Annex C method.

In 2018 a new standardization working group, PT-61400-11-2, was formed: “Wind energy generation systems - Part 11-2: Measurement of wind turbine noise characteristics in receptor position” [8]. The PT-61400-11-2 WG is interested in comparing the IEC 61400-11:2012 and ISO/PAS 20065:2016 for analysing tones in wind turbine noise. DELTA – a part of FORCE Technology, suggested and volunteered to set up a round-robin test distributed among parties working with wind turbine noise, hereafter referred to as “laboratories”.

Based on a prior project[4] 31 samples were constructed based on real wind turbine noise recordings and distributed these to participating laboratories. The tonality of the 31 samples have also been subjectively analysed in formal listening test by a panel.

This paper gives examples of analysis results of the round-robin tests and shows the uncertainties when a number of laboratories with different experience and different types of equipment analyse the same samples and identifies areas for additional research.

1. Introduction

It is critical to understand the differences between the two tone methods and understand any cases where there might be significant differences.

2. Working group TC 88/PT 61400-11-2

In 2018 the working group TC 88/PT 61400-11-2 was established, with 29 members from Europe, North America and Asia.

2.1 Scope

The scope of the working group is as follows:
"To establish standardized techniques and methods applicable for measurement of noise immission. The technical specification focuses on compiling methods for quantification of wind turbine noise in one or a set of documents in order to ensure a common reference taking the characteristics of wind turbine operational parameters into account.
Quantification of the acoustics phenomena at the receiver position includes the following topics:
• amplitude modulation;
• low frequency noise;
• impulsivity;
• tonality;
• sound pressure levels;
• rating level, which includes adjustments for the above-mentioned phenomena, should be suggested if possible."

2.2 Tonality

Presently IEC 61400-11 is the widely used method for analysing tones in wind turbine noise for sound power level measurements (i.e. measurements close to the turbine) whereas one version of the ISO tonality method (the old ISO 1996-2 or the new ISO/PAS 20065) is typically used for analysing tones in wind turbine noise at receptor position. Other methods are used as well.

As part of the work the group would like to compare the following two methods for analysing tones in wind turbine noise:

1. The tonality method described in IEC 61400-11:2012
2. ISO/PAS 20065:2016

Both methods can be described as a two-step method, where the first step evaluates the tonal audibility for each critical band of each spectra. The second step combines the tonal audibility to an overall tonal audibility.

One of the members of PT 61400-11-2 is performing an in-depth study of the two methods. In addition, the group has desired a round-robin comparison of the first step of the two methods, to ensure that differences between the two methods are found for more than one participant.

3. Round-robin comparison

3.1 Scope of the round-robin

Factors tested in the round-robin:

- Computation of the audibility of tones in each critical band.
- The correctness of the implementation of the standard
- The correct understanding of the algorithms used by each participant *
- The correct understanding of the use of the tone analysis algorithm.

*: An example of the correct understanding of the algorithms used by each participant could be the placement of the Critical Band centred around the tone. The ISO standard specifies this with a formula based square root of the product of the upper and lower frequencies of the critical band. This is different from the method implied by the IEC standard where the lower and upper frequencies of the critical band are placed symmetrically around the tone.

Factors not tested in the round-robin:

- Differences between the two standards due to
    - Data Recording
    - FFT Line Spacing: For IEC: must be from 1 to 2 Hz. ISO: from 1.9 to 4 Hz.
    - Averaging time for FFT: For IEC: 10 seconds, for ISO: about 3 seconds.
    - Impact of FFT overlap: IEC: at least 50%. ISO: Not specified
    - Differences due to frequency shifts of the wind turbine tones as related to the above parameters
- Uncertainty calculations.
- Combinations of multiple tones in a critical band.

3.2 Invitation

It was initially assumed that not many have implemented both methods, so additional participants outside the working group have been invited to ensure enough participants.
The invitation has been sent to:

- Members of IEC/TC88/MT 11
- Members of ISO/TC43/SC1/WG45
- Persons working with wind turbine noise and tonality known from for example the Wind Turbine noise conference in Rotterdam in 2017

Additionally, some of the invitees has been so kind to extend the invitation even further.
In total more than 100 persons/laboratories have been invited.

3.3 Stimuli

From a number of original recordings of wind turbines (recorded with Class 1 equipment) 24 samples of 20 second periods were selected. If several 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 tone analysis. In additional, seven samples of stationary industrial noise with tones were added.
The samples - each mono recording 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).

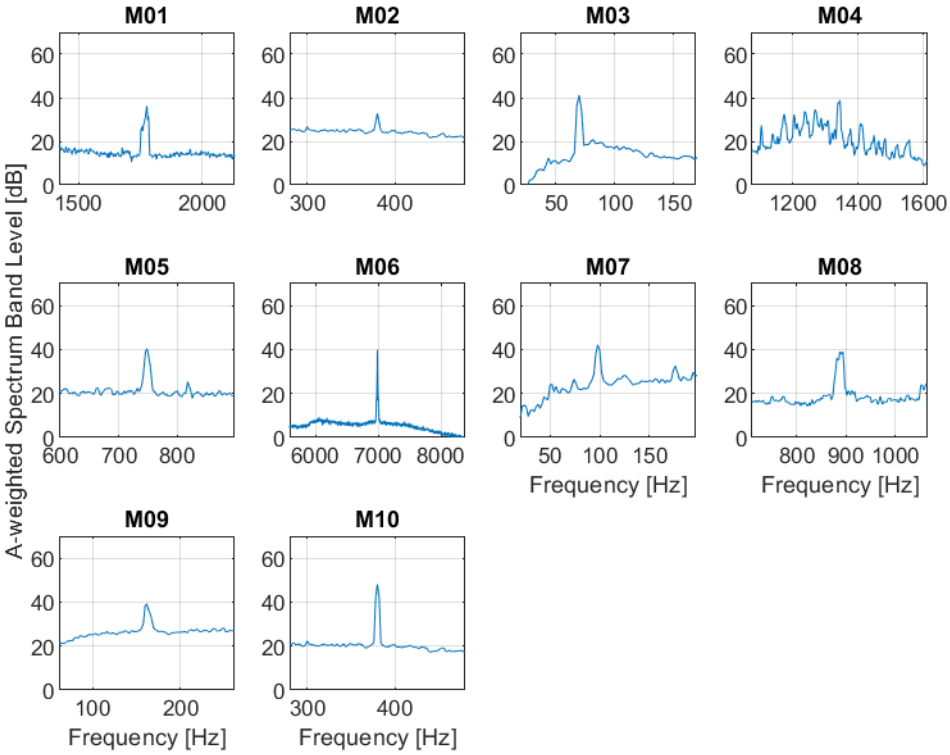

Figure 1. The 10 mandatory A-weighted spectra, M01-M10. The X axis is zoomed to only show the frequencies of interest.

The 31 spectra were randomized, numbered and grouped in ten mandatory (M01-M10) and 21 optional spectra (O01-O21). The A-weighted spectra are shown in the following three figures, Figure 1 - Figure 3 (where only 2 times the critical bandwidth surrounding the “true” tone is shown).

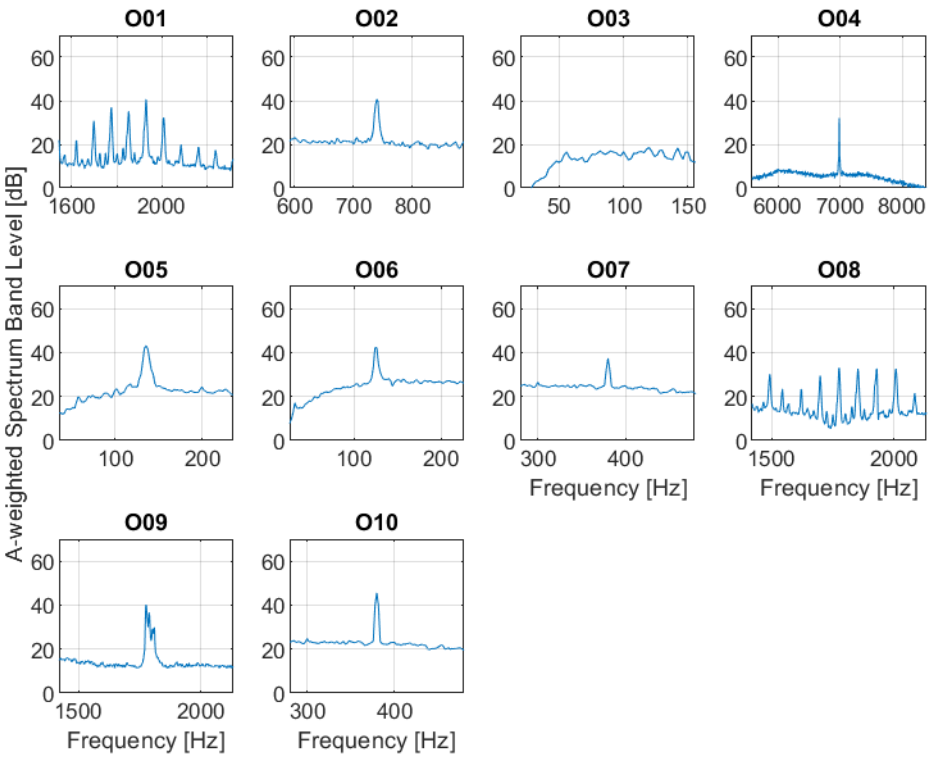

Figure 2. The first 10 optional A-weighted spectra, O01-O10. The X axis is zoomed to only show the frequencies of interest.

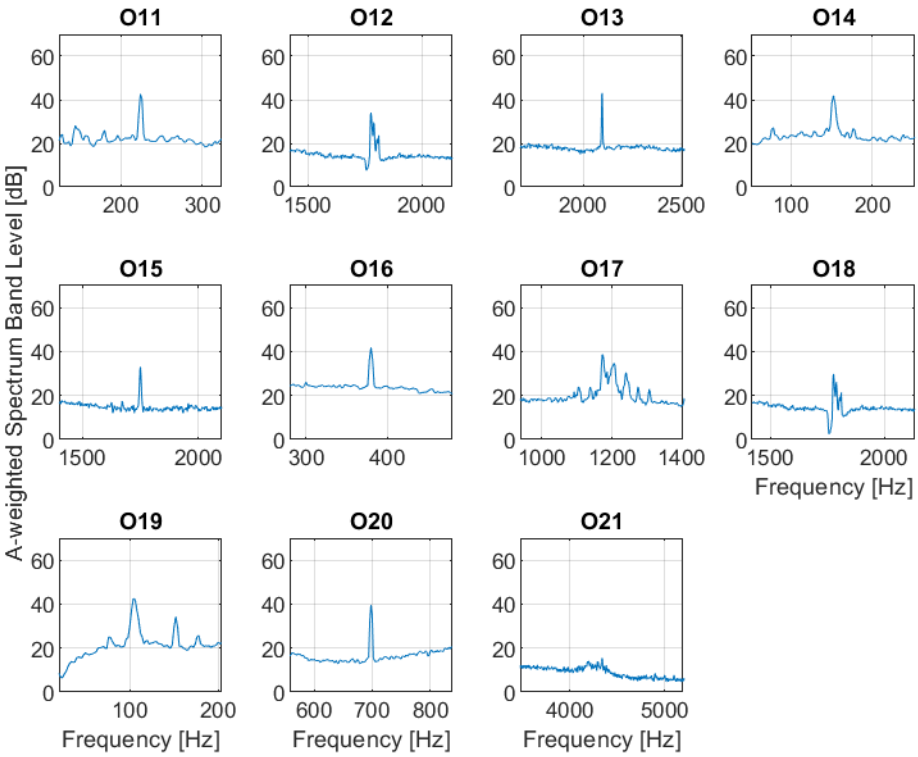

Figure 3. The last 11 optional A-weighted spectra, O11-O21. The X axis is zoomed to only show the frequencies of interest.

3.4 Instructions

The participants were given the following instructions (only relevant sections are shown):

"It is MANDATORY as a minimum to analyse the 10 spectra marked with an M with at least one of the above-mentioned methods. Preferable all 31 spectra should be analysed with both methods."

"To prevent too many variations, I hope everyone or as many as possible will be able to do the analysis based on the spectra. I will also provide a link to the wav files. You're of course very welcome to provide the results with both the spectra and the sound files. Please indicate whether you used the sound files or the enclosed spectra."

"You might find more than one tone in the spectra. You should report the most prominent/audible of the tones."

"The frequency resolution of the provided spectra is 2 Hz. If you analyse on the recordings, it is recommended to use the same frequency resolution, to compare results. You're of course very welcome to supply additional results with other frequency resolutions, where you document which settings you have used."

"The provided spectra are A-weighted, which should be used for the analysis. I however also attach the linear spectra in case your software applies the A-weighting itself. Please mark which spectra you have used."

"The sound files are 20 seconds long. If you use the sound files for analysis, please perform the analysis on the full 20 second data in order to compare it to the analysis with the spectra."

A pre-formatted xls sheet was supplied to be used when submitting the results. The submitted results will be anonymised, so no result can be tracked back to a participant.

3.5 Participation

29 persons/laboratories accepted the invitation, where 23 of those submitted results. 20 of the participants analysed using the IEC method and 15 of the participants used the ISO method. 12 participants submitted results with both methods. Two participants also submitted results using the old ISO standard, ISO 1996-2 Annex C, the results are not included in this analysis. The table below shows whether the analysis was performed based on A-weighted spectra, unweighted spectra or sound files.

	IEC 61400 -11	ISO/PAS 20065
A-weighted spectra	16	14
Un-weighted spectra Z weight)	3	1
Sound files	5	2

Table 1. Overview of number of results which each method and stimuli

4. Methods and parameters

4.1 IEC 61400-11

The analysis should be performed according to IEC 61400-11:2013/A1:2018 however notice that in section 9.5.5 the sentence "This corresponds to subtracting 10 log (1/1.5) or 1.8 dB

(1.76 dB) from the tone level." should have been "This corresponds to subtracting -10 log (1/1.5) or 1.8 dB (1,76 dB) from the tone level."
Earlier versions of the method can be followed as well, it is however then important to state which version is used. The method used, if for large turbines, and not the method in Annex F for small turbines.

For the analysis according to IEC 61400-11 the following parameters shall be stated:

- Frequency of the tone, F_c
- The sound pressure level of the tone $L_{pt,j,k}$
- The sound pressure level of the masking noise $L_{pn,j,k}$ in the critical band around the tone
- The tonality $\Delta L_{tn,j,k}$, the difference between the sound pressure level of the tone and the masking noise level
- The tonal audibility $\Delta L_{a,j,k}$, the difference between the tonality and the audibility criterion of the tone

4.2 ISO PAS 20065

For the analysis according to PAS 20065 the following parameters shall be stated:

- f_T, is the frequency of the maximum narrow-band level, in Hertz (Hz)
- L_T, is the tone level, in decibels (dB)
- L_G, is the masking noise, in decibels (dB)
- a_v, is the masking index, in decibels (dB)
- ΔL, the audibility, in decibels (dB)

5. Results

Each participant reported results in the pre-formatted xls sheet. Numerous good comments were also received and will be distributed to the respective maintenance standardization group. Unless marked otherwise, the comments will be anonymized before the distribution.

5.1 Tone frequency

For most of the spectra there was good agreement between the participants of the result of the tone frequency. Figure 4 and Figure 5 show the detection rate in % of the "true" tone frequency, where the "true" tone frequency will be referred to as the tone frequency the majority of the participants report. See also Table 2.

There are three examples of significant differences in the ability to find the "true" frequency.

- M02 (380 Hz): The ISO method only finds these in 2 of 15 instances and also identifies it as "no tone" in 11 out of 15 instances. Which method is "correct" for this type of barely audible tone may require more research. However, for this spectrum it will have no consequence, since the average tonal audibility is low (about -5 dB).
- O07 (380 Hz): This spectrum is the same as M02, but with a 5 dB higher tone level. However, the differences between the two methods in the ability to detect the tone, is virtually the same for M02 and O07. Further research may be required.
- O08 (1776 Hz): This is a complex, multi-tone spectrum. The ISO method finds the "true frequency" 67% of the time, while the IEC method finds it 25% of the time.

The above examples of the most extreme differences should be the basis for additional research to determine if the differences are reproducible, if they are "correct", and perhaps most important, if they have any significant impact on the final tonality. This research may also have high relevance to document the credibility of the respective standards.

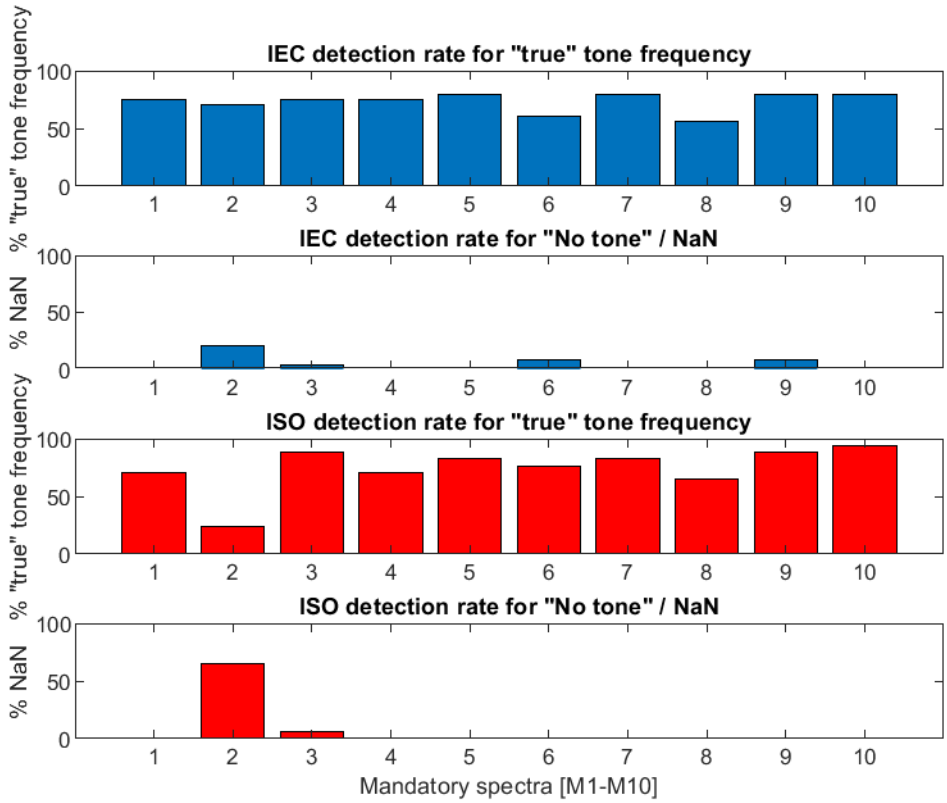

Figure 4. Detection rate for "true" tone frequency and "no tone" for mandatory spectra

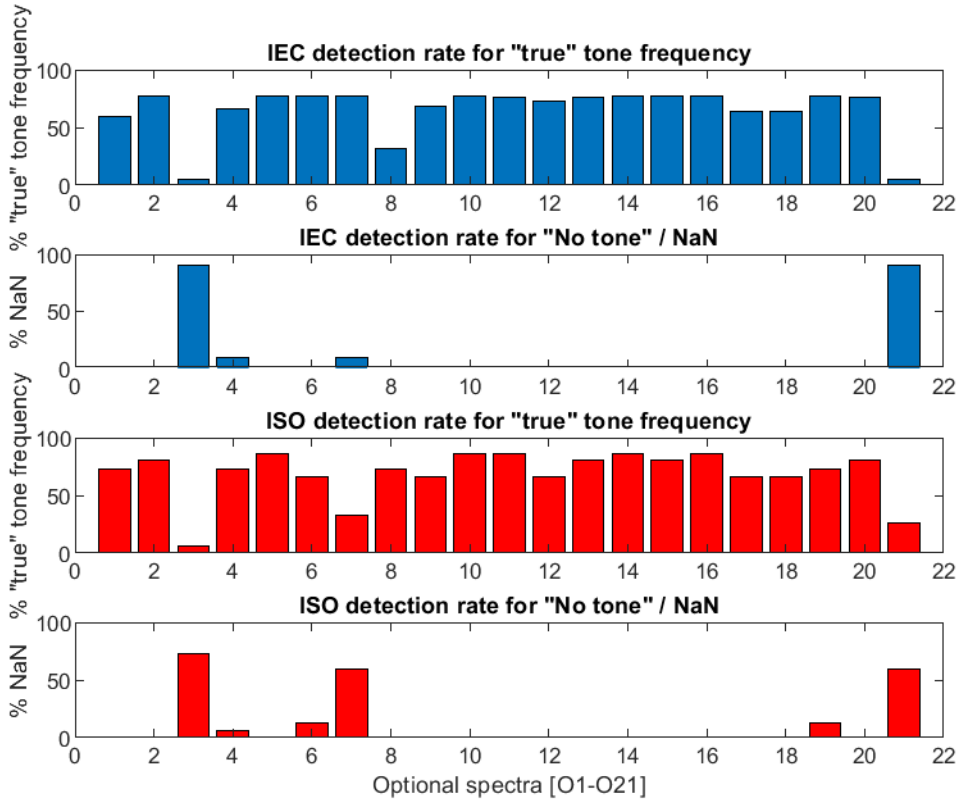

Figure 5. Detection rate for "true" tone frequency and "no tone" for optional spectra

5.2 No tone

Two spectra were included with no tones, O03 and O21. The detection rate for “no tone” or NaN are also shown in Figure 4 and Figure 5. The detection rate for “no tone” is high both for participants using the IEC and for participants using the ISO method. Apparently, the detection rate for “no tone” is higher for the ISO method than for the IEC method for spectra intended to contain a tone, for example M02 and O07. See also Table 2. It should be remarked that participants were not informed that spectra without a tone was included as well.

5.3 Tonal audibility

The average tonal audibility together with the standard deviation for each method is shown in Figure 6 calculated with all results. As it can be seen the deviation is quite large.
When closer examined (not shown) some quite large deviations/outliers are found.

When outliers are removed, the average tonal audibility and the standard deviation for each method is shown in Figure 7. Compared with Figure 6 the deviation is significantly smaller now.

As described above the majority of the participants detected the same tone frequency. If the results are filtered so only those with the “true” tone frequency (regarding “true” tone frequency see section 5.1) are analysed (i.e. removed a second set of outliers), the average audibility and standard deviation are shown in Figure 8. Compared to Figure 6 and Figure 7 it is seen that the deviation is even smaller.

Figure 9 shows the standard deviation as a function of “true” tone frequency. It can be seen that variation is clearly largest in the 1-2 kHz frequency range, for spectra with multiple tones in the critical band. The reason for this has not been determined.

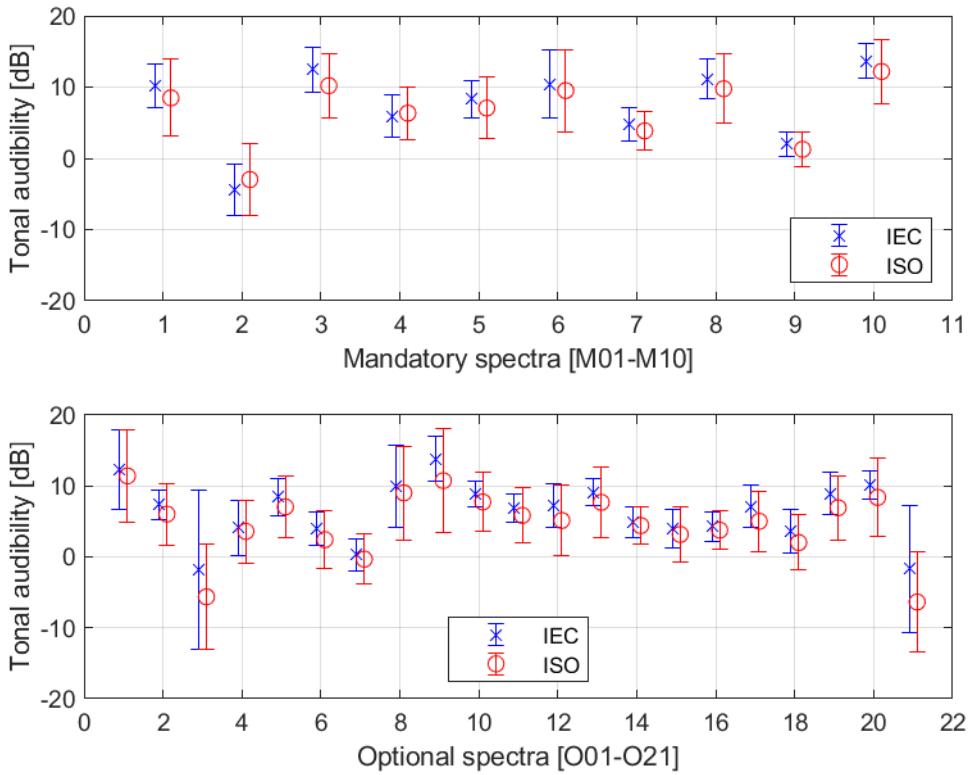

Figure 6 Average tonal audibility and standard deviation calculated with all results

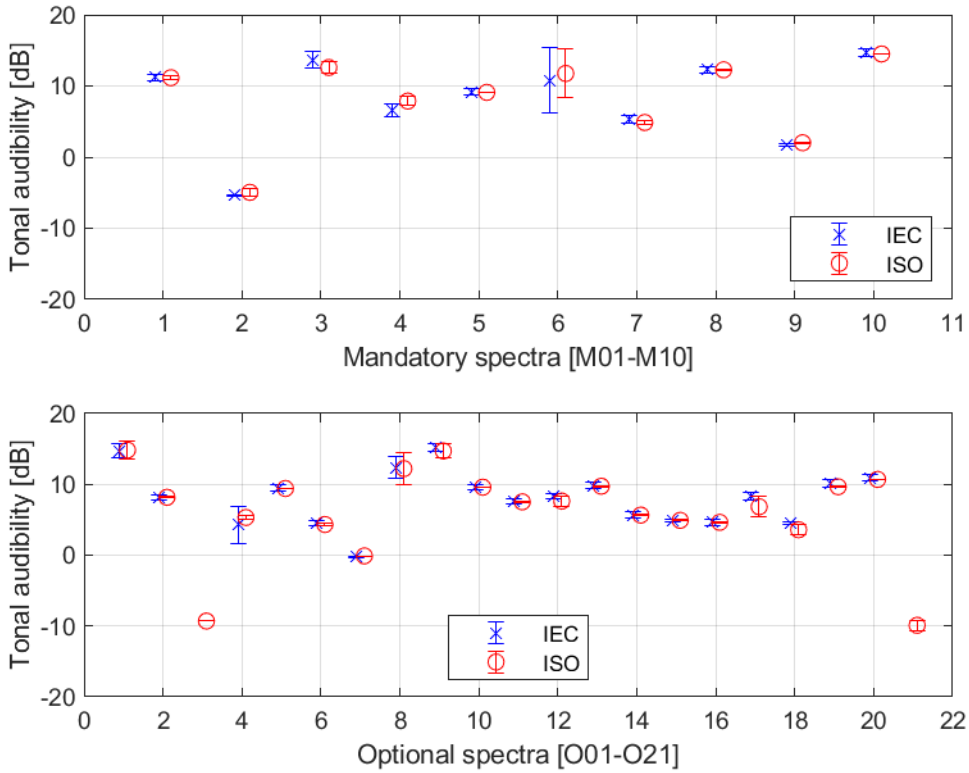

Figure 7 Average tonal audibility and standard deviation calculated without outliers

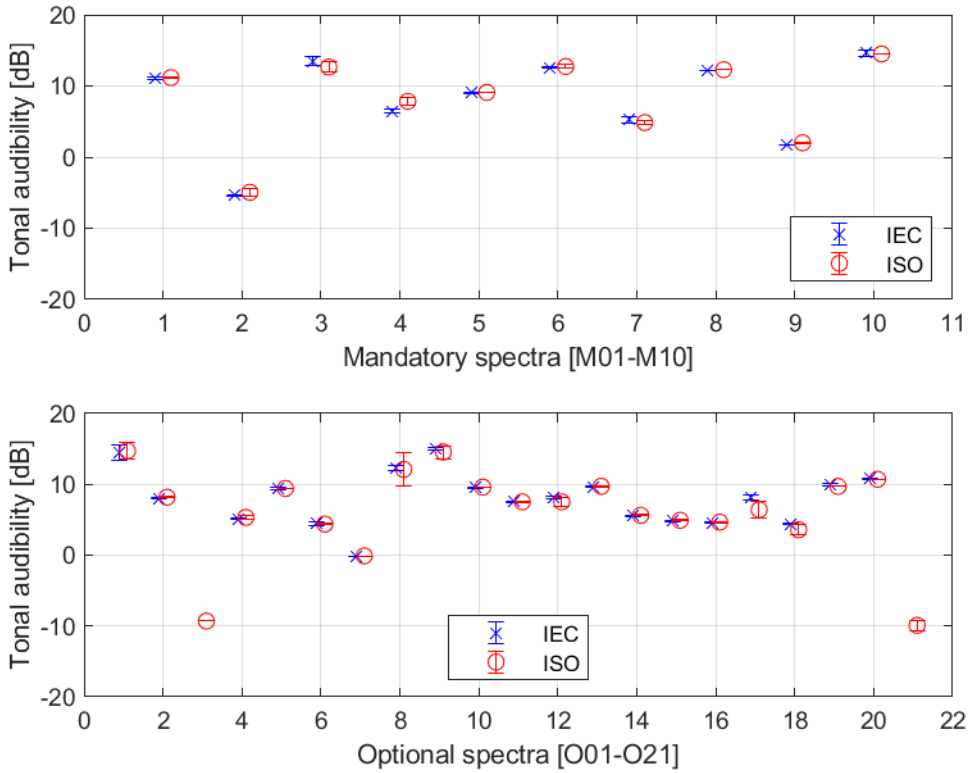

Figure 8 Average tonal audibility and standard deviation calculated only for "true" tone frequency

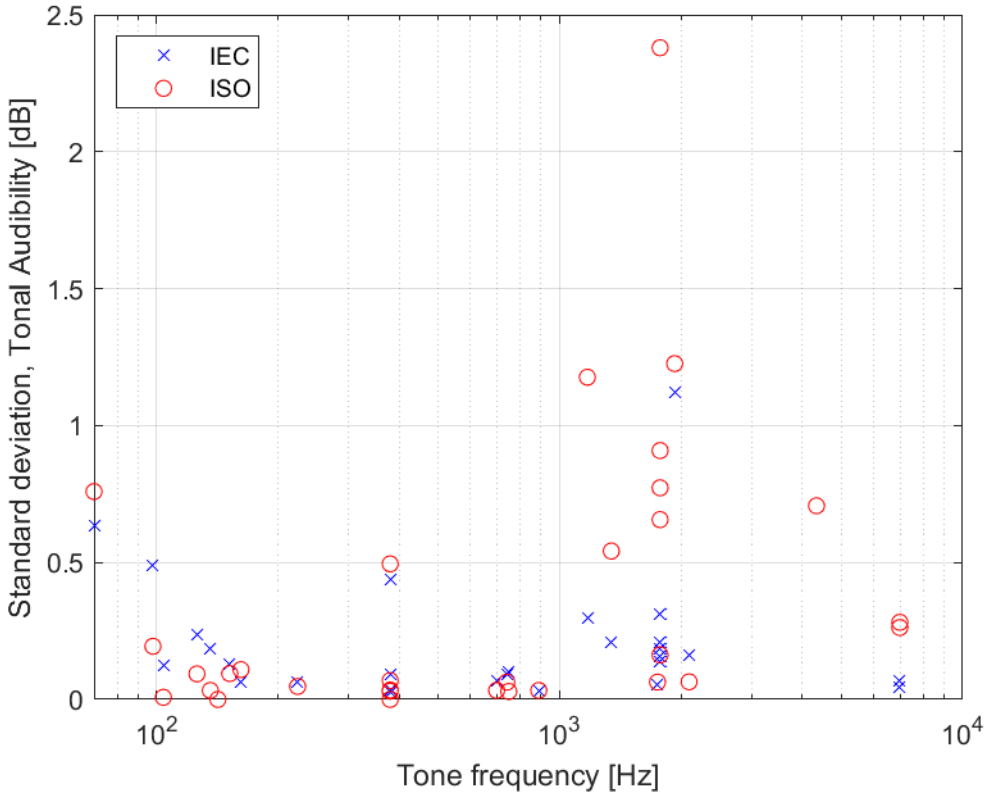

Figure 9 Standard deviation versus "true" tone frequency. Data from Figure 8.

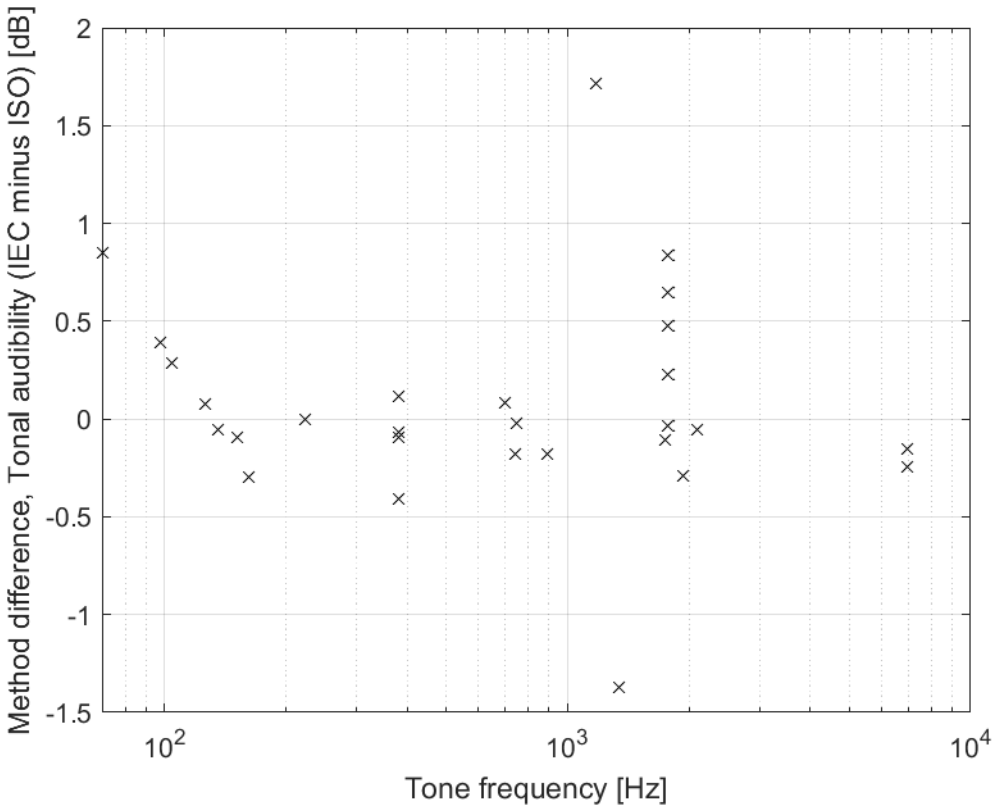

Figure 10 Difference between average tonal audibility (IEC minus ISO) calculated only for "true" tone frequency, shown versus "true" tone frequency

Figure 10 shows the difference between the average tonal audibility with the two methods. For most spectra the difference is small and below 0.5 dB, however in the 1-2 kHz area the difference is larger, which should be seen in comparison with the large deviation in standard deviation shown in Figure 9, and the spectra shown in Figure 1 - Figure 3.

If we choose an acceptable error of ± 0.5 dB, we note four outliers:

- M03 (70 Hz): The difference of 0.8 dB is in an area of the spectrum with a fairly steep downward slope below the 70 as well as very asymmetric skirts for the tone. Whether this is an inherent difference in the two methods has not been studied or determined.
- M04 (1344): This is a very complex multi-tone spectrum. The difference of 0.7 dB should be investigated as to whether it is related to this type of spectrum, and if it is a bias or random error.
- O17 (1172 Hz): This spectrum also contains multiple tones in the critical bands. This difference of 1.7 dB is significant. It should also be investigated if this a bias error or random error for this type of spectra.
- 018 (1776 Hz): This main tone has is surrounded by an asymmetrical spectrum, with a dip on the lower frequency side. The difference of 0.8 dB can be significant, and it should also be investigated if this a bias error or random error for this type of spectra.

In Figure 11 is shown an example of the distribution of results for different participants, shown as the difference to the calculated average Tonal Audibility.

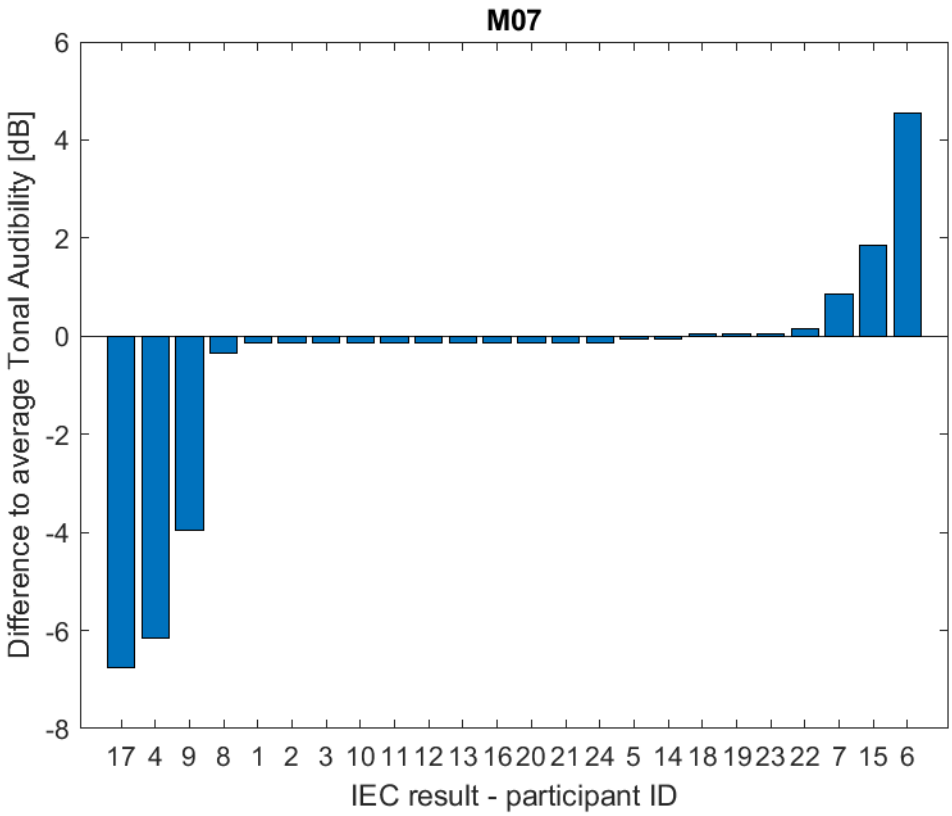

Figure 11. Example of Distributions of Results for different participants (all results included, also outliers)

The main results are shown in Table 2.

	(all participants)		Detection rate (all participants)				Tonal audibility (selected data)			
	"True" tone frequency		Tone frequency		"No tone"		Average		Standard deviation	
	IEC	ISO	IEC	ISO	IEC	ISO	IEC	ISO	IEC	ISO
	[Hz]	[Hz]	[Number (%)]				[dB]	[dB]	[dB]	[dB]
M01	1776	1776	18 (75 %)	12 (71 %)	0 (0 %)	0 (0 %)	11.1	11.2	0.2	0.2
M02	380	380	17 (71 %)	4 (24 %)	5 (21 %)	11 (65 %)	-5.4	-5.0	0.1	0.5
M03	70	70	18 (75 %)	15 (88 %)	1 (4 %)	1 (6 %)	13.5	12.7	0.6	0.8
M04	1344	1344	18 (75 %)	12 (71 %)	0 (0 %)	0 (0 %)	6.5	7.8	0.2	0.5
M05	748	748	19 (79 %)	14 (82 %)	0 (0 %)	0 (0 %)	9.1	9.1	0.1	0.0
M06	6986	6986	14 (61 %)	13 (76 %)	2 (9 %)	0 (0 %)	12.6	12.7	0.0	0.3
M07	98	98	19 (79 %)	14 (82 %)	0 (0 %)	0 (0 %)	5.2	4.9	0.5	0.2
M08	888	888	13 (57 %)	11 (65 %)	0 (0 %)	0 (0 %)	12.1	12.3	0.0	0.0
M09	162	162	19 (79 %)	15 (88 %)	2 (8 %)	0 (0 %)	1.7	2.0	0.1	0.1
M10	380	380	19 (79 %)	16 (94 %)	0 (0 %)	0 (0 %)	14.6	14.5	0.4	0.0
O01	1930	1930	13 (59 %)	11 (73 %)	0 (0 %)	0 (0 %)	14.5	14.7	1.1	1.2
O02	740	740	17 (77 %)	12 (80 %)	0 (0 %)	0 (0 %)	8.0	8.2	0.1	0.1
O03	976	142	1 (5 %)	1 (7 %)	20 (91 %)	11 (73 %)	-	-9.3	-	0.0
O04	6984	6984	14 (67 %)	11 (73 %)	2 (10 %)	1 (7 %)	5.1	5.3	0.1	0.3
O05	136	136	17 (77 %)	13 (87 %)	0 (0 %)	0 (0 %)	9.4	9.4	0.2	0.0
O06	126	126	17 (77 %)	10 (67 %)	0 (0 %)	2 (13 %)	4.5	4.4	0.2	0.1
O07	380	380	17 (77 %)	5 (33 %)	2 (9 %)	9 (60 %)	-0.2	-0.1	0.0	0.0
O08	1776	1776	7 (32 %)	11 (73 %)	0 (0 %)	0 (0 %)	12.3	12.1	0.3	2.4
O09	1776	1776	15 (68 %)	10 (67 %)	0 (0 %)	0 (0 %)	15.0	14.6	0.2	0.9
O10	380	380	17 (77 %)	13 (87 %)	0 (0 %)	0 (0 %)	9.5	9.6	0.0	0.0
O11	224	224	16 (76 %)	13 (87 %)	0 (0 %)	0 (0 %)	7.5	7.5	0.1	0.0
O12	1776	1776	16 (73 %)	10 (67 %)	0 (0 %)	0 (0 %)	8.2	7.5	0.2	0.7
O13	2096	2096	16 (76 %)	12 (80 %)	0 (0 %)	0 (0 %)	9.7	9.7	0.2	0.1
O14	152	152	17 (77 %)	13 (87 %)	0 (0 %)	0 (0 %)	5.5	5.6	0.1	0.1
O15	1750	1750	17 (77 %)	12 (80 %)	0 (0 %)	0 (0 %)	4.8	4.9	0.1	0.1
O16	380	380	17 (77 %)	13 (87 %)	0 (0 %)	0 (0 %)	4.6	4.7	0.0	0.1
O17	1172	1172	14 (64 %)	10 (67 %)	0 (0 %)	0 (0 %)	8.1	6.4	0.3	1.2
O18	1776	1776	14 (64 %)	10 (67 %)	0 (0 %)	0 (0 %)	4.4	3.6	0.1	0.8
O19	104	104	17 (77 %)	11 (73 %)	0 (0 %)	2 (13 %)	10.0	9.7	0.1	0.0
O20	698	698	16 (76 %)	12 (80 %)	0 (0 %)	0 (0 %)	10.8	10.7	0.1	0.0
O21	150	4340	1 (5 %)	4 (27 %)	20 (91 %)	9 (60 %)	-	-9.9	-	0.7

Table 2. The "true" tone frequency is found on the basis on the results for all participants.
The detection rate columns show the number of participants submitting a result and is also calculated as a percentage of all participants for each particular spectrum. Notice that the number of results is not the same for all spectra.
The average and standard deviation for tonal audibility is only calculated with outliers removed and filtered for "true" tone frequency.

6. Listening tests

Formal listening tests were performed to assess the perceived tonality compared to the computed tonality.

6.1 Methodology and procedures

The SenseLabOnline Internet-based listening test software from DELTA – a part of FORCE Technology [5] 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 expert listening panel (ages 22-52, mean 32 years) all with normal hearing and four 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 [6] and five assessors with poor replication, discrimination or panel agreement were excluded before the final statistical analysis of the results. The methods used for these formal listening tests are based on best practice as described in "Sensory Evaluation of Sound" [7].

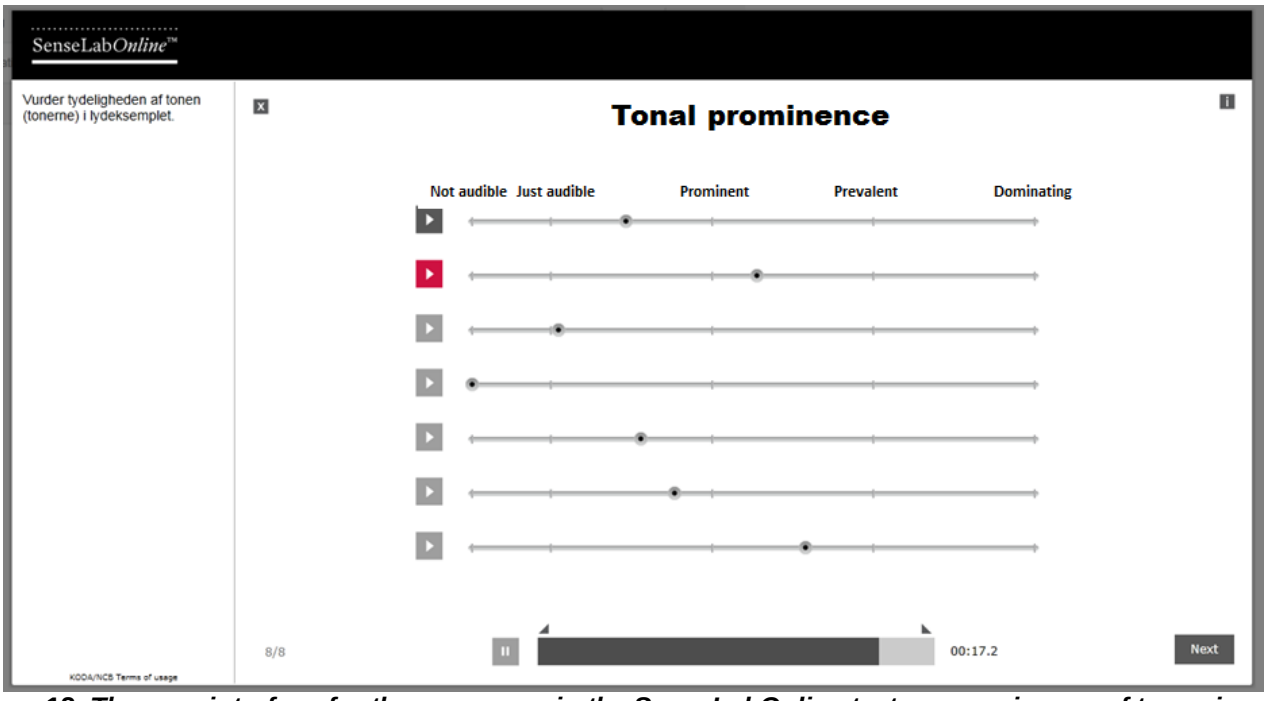

Figure 12. ***The user interface for the assessors in the SenseLabOnline test on prominence of tones in noise.***

The sliders shown in Figure 12 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.

6.2 Level calibration

Each assessor started the listening test by adjusting the playback 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 3.

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

Table 3. ***Mean values, standard deviation and 95% confidence intervals (CI) for the level adjustment of male speech at 1 m distance made by 24 persons.***

6.3 Comparing the results from the round-robin with the listening test

The average tonal audibility from the round-robin are then compared with the results of the listening test, and the comparison is shown in Figure 13 and Figure 14.

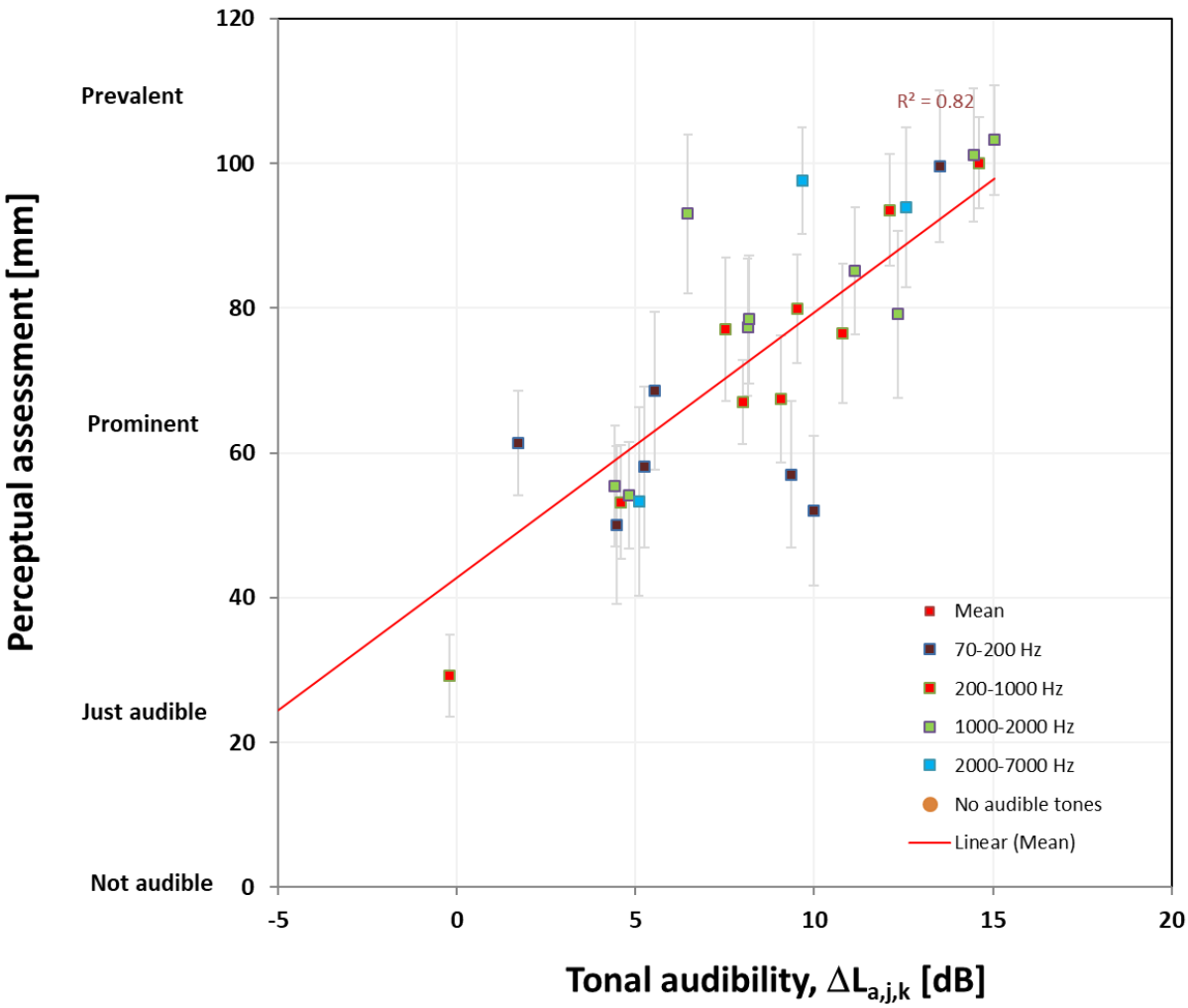

Figure 13. ***Tonal audibility according to IEC 61400-11 method versus the results of the listening test on an answering scale calibrated in mm. The vertical bars indicate the 95% confidence intervals. The percentage of explained variance of the linear regression is R^2 = 82 %.***

Figure 13 shows that the percentage of explained variance of the linear regression for the IEC 61400-11 is good (R^2 = 82%). The equivalent results for ISO PAS 20065 are essentially the same, where Figure 14 shows R^2 = 83 %.

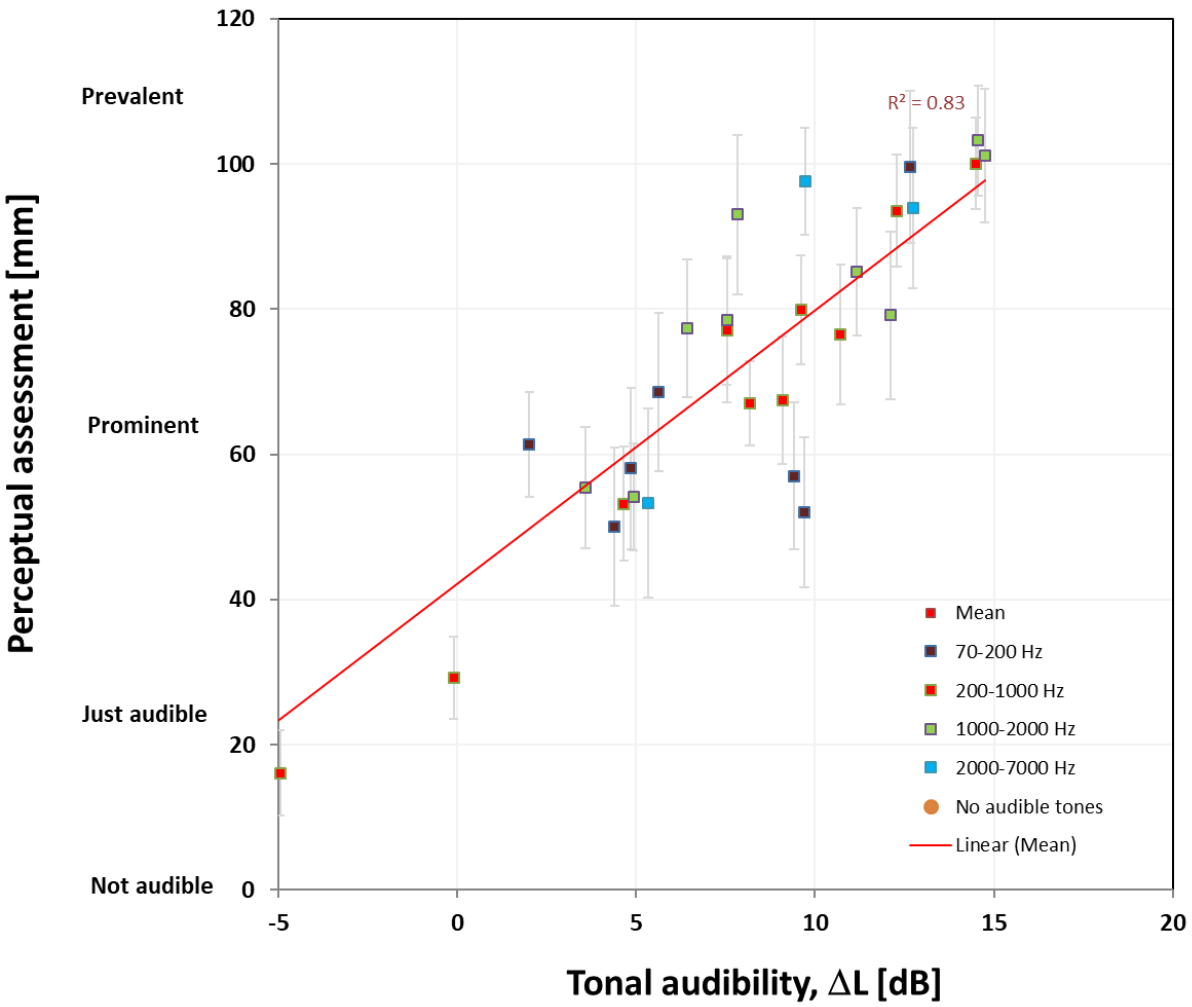

Figure 14. ***Tonal audibility according to ISO PAS 20065 method versus the results of the listening test on an answering scale calibrated in mm. The vertical bar indicates the 95% confidence intervals. The percentage of explained variance of the linear regression is R^2 = 83 %.***

7. Conclusions

A round-robin test has been performed comparing objective tone analysis with two methods, the method described in IEC 61400-11 and the new ISO PAS 20065 method.
Results were received from 23 different persons/laboratories, most submitting results with both methods.

This round-robin has focused on the first step of both tonality methods, investigating only the most significant tonal audibility for each spectrum. With this in mind, when comparing the results with the two methods, very similar results were obtained.

For both methods the clear majority of participants has determined the exact same tone frequency (except for the two spectra without a tone), and this tone frequency (here referred to as the “true” tone frequency) are the same for both methods.
When outliers have been removed and only results with the “true” tone frequency the average tonal audibility for each spectrum are very similar for the two methods, and where the difference is only larger than 0.5 dB for a few cases.

When the average tonal audibility is compared with a listening test the percentage of explained variance of the linear regression is R^2 = 82 % and 83 % for the IEC and ISO method respectively.

For both methods the majority of the participants clearly detected “no tone” for the spectra with no tone. However, where the majority of the participants with the IEC method detected a tone for the spectra with tones, the majority of the participants with the ISO method detects “no tone” for the two spectra with a 380 Hz tone.
However, additional research is recommended in the areas where significant differences have been found in this round-robin test (Section 5.1, 5.2 and 5.3). This research should attempt to determine if the differences are random or systematic errors, their root cause, and also investigate their potential impact on the final tonal audibility for the different spectrum types. In addition, it is important to recall that the scope of the round-robin is limited as described in Section 3.1, and hence is not a comprehensive comparison between the two standards.

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- Petri Välisuo **University of Vaasa**, Finland
- **Vestas**, Denmark
- **WG 45 Japan members**, Japan
- **Xi Engineering**, Scotland

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