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Methods for assessment of the characteristics of wind turbine noise

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Abstract

Wind turbine noise may due to special characteristics be heard through background noise eg. from traffic and wind in the vegetation. The main characteristics are tonal content from mechanical parts and aerodynamic swishing noise from the blades and to some extent low frequency (LF) noise.

An objective method for the prominence of tones in masking broad band noise is described in ISO 1996-2 Annex C. It is shown that the method correlates well with listening test (also at low frequencies) and proficiency tests for the objective method show that different laboratories are able to obtain similar results within acceptable tolerances.

If the swishing noise is regarded as amplitude modulation psycho-acoustic knowledge makes it possible to predict whether this phenomenon is masked by the background noise. A metric for the swishing characteristic is described.

It is often seen that a frequency analysis of the broad band noise is compared to the hearing threshold in an attempt to determine whether the noise is audible. Usually the bandwidth of the analyzer is disregarded even though use of different bandwidths may displace the spectrum up to 20-25 dB. A method based on psycho-acoustic principles makes it possible to compare the LF-broad band noise with the hearing threshold in a relevant manner that will give the same results irrespective of the analyzer bandwidth.

Measurement method for tones in noise

It is a general experience that the presence of audible tones in noise increases the annoyance relative to the same noise (level) without the audible tones. In the legislation of many countries a “penalty” of 3-6 dB is added to the measured noise levels (L_{Aeq}) to compensate for the extra annoyance due to the clearly audible tones in the noise.

An objective method for determining the audibility of tones based on psycho-acoustic principles is described in ISO 1996-2 [4]. The method determines the tonal audibility, ΔL_{ta} (the level above the masking threshold) and transforms it into an adjustment K_T of 0-6 dB to be added to the measured L_{Aeq}.

Although the ISO 1996-2 is intended for environmental noise the method is generally applicable for the declaration of the prominence of tones in noise.

The predecessor of the ISO 1996 method has been used in the Nordic countries since 1979 and a number of proficiency tests of this method have been made. From the results of these tests it can be concluded, that when a number of laboratories with different types of equipment analyze the same samples using the ISO 1996-2 Annex C method, standard deviations in the range 0.5-1 dB can be expected for the tone declaration value, ΔL_{ta} in normal cases.

Listening tests have been performed to –among other things- verify the method for low frequency tonal sounds from wind turbines, [2]. 19 persons (9 male, 10 female) participated. The mean age was 40 years, with a standard deviation of 14.6 years. The stimuli were presented to the participants over loudspeakers in a listening room with sub-hearing threshold background noise at Salford University. A careful equalisation of the sound field was made before the tests and all stimuli were measured at the position of the listeners head.

The test sounds comprised a tone and a broadband masking sound. The tone was played at one of six pre-determined frequencies. The masking sound was either a sound broadly representative of wind turbine sound at one of three pre-determined levels (outdoor: 39, 44 and 49 dB(A), indoor: 19-26 dB(A)) or this broadband wind turbine sound combined with surrounding garden noise. The wind turbine masking spectra were derived from third-octave sound power measurements of 45 wind turbines, each attenuated to simulate propagation to the minimum distance permitted to a dwelling by Danish legislation (4 total heights), scaled to the target A-weighted SPL, and finally averaged. Propagation attenuation was predicted in third octave bands by the Nord2000 model, [6] and [11], for a receiver 1.5 m above flat grassy terrain with a wind speed of 8m/s in the downwind direction.

The local garden noise was created to match a noise spectrum of 8 m/s wind through deciduous foliage. A similar process was followed for the stimuli for the indoor scenario, except that a third octave façade attenuation (see Table 3spectrum was applied to all spectra.

Some of the results are shown in Figure 1.

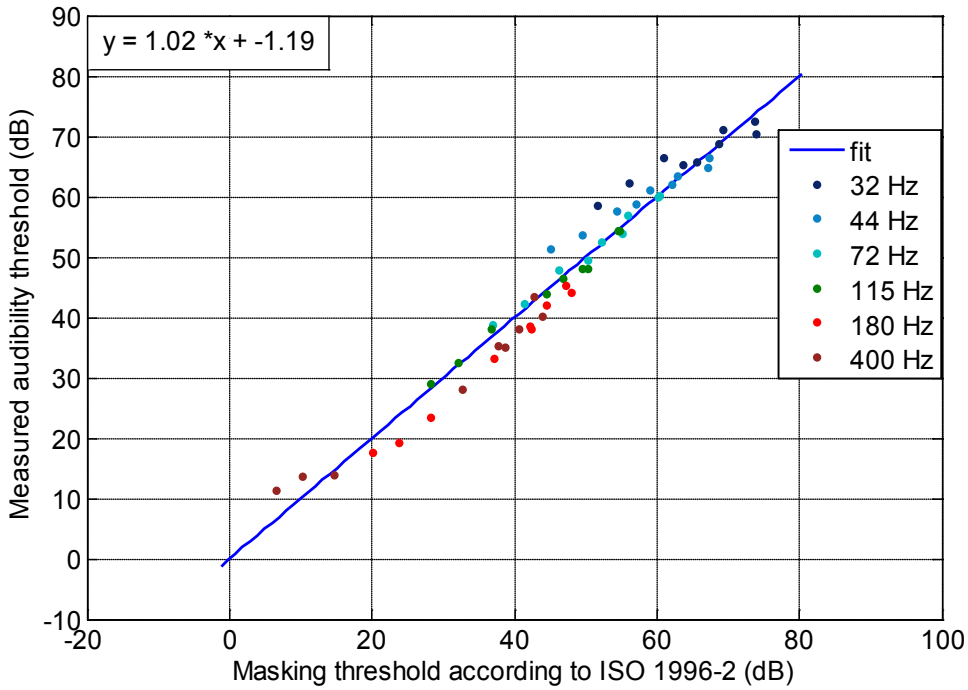

Figure 1
Correlation of audibility thresholds in masking noise found at the listening tests with masking threshold calculated in accordance with ISO1996-2. Linear regression shows a slope of 1 and R^2 = 0.96.

The figure contains data from both the indoor and the outdoor scenario. The 95% confidence intervals are approximately 5 dB wide and only single data points deviate by more than 6 dB from the regression line. The slope has a value of 1.02 which indicates excellent agreement between measured and calculated thresholds. If the values of the indoors scenario were left out of the regression because of concerns over the applicability of the masking threshold at the vey low levels then the correlation equation would change to y=1.09*x-6.38 with an R^2 value of 0.98. In conclusion, the calculations of the audibility defined by ISO 1996-2 are in good agreement with the listening test results also in the low frequency range.

A method for assessment of swishing noise

Listening tests

In the present study five different wind turbines were auralized at the distances of closest allowed residence according to Danish legislation, 4 total heights, (approximately 6 hub heights) and twice that distance. Perceptual attributes were evaluated for the auralized sounds by a group of 20 selected subjects (normal hearing for their age (average of 47 years) and the evaluations were correlated to physical metrics.

Five different wind turbines ranging in power from 225 kW to 2 MW were recorded with a a Brüel & Kjær Head and Torso Simulator (HATS) equipped with a special

designed Rycote fur wind cap at wind speeds around 5 m/s and at distances of 1.5 and 3 hub heights (HH) according to the procedures described in DS/EN 61400-11.

The Nordic sound propagation model Nord2000, [6] and [11], was employed for the spectral manipulation of the recorded sounds. The model accounts for wind speed, direction, -gradient, temperature, relative humidity, and terrain properties and calculates the attenuation in 1/3-octave bands.

Physical metric on swishing sound

The psychoacoustic metric “fluctuation strength” see [14] is the basis for the measurements performed with the Bruël & Kjær PULSE Sound Quality software. The fluctuation strength was measured for the 350 Hz – 700 Hz band pass filtered stimuli. Different cut-off frequencies and band widths were tested to verify that the maximum value on fluctuation strength was found. (In an earlier study [5] for smaller turbines the same effect was found to be most prominent in the 1 kHz range, but the 350-700 Hz range seems to be the optimum for large modern wind turbines). Figure 2 shows the results.

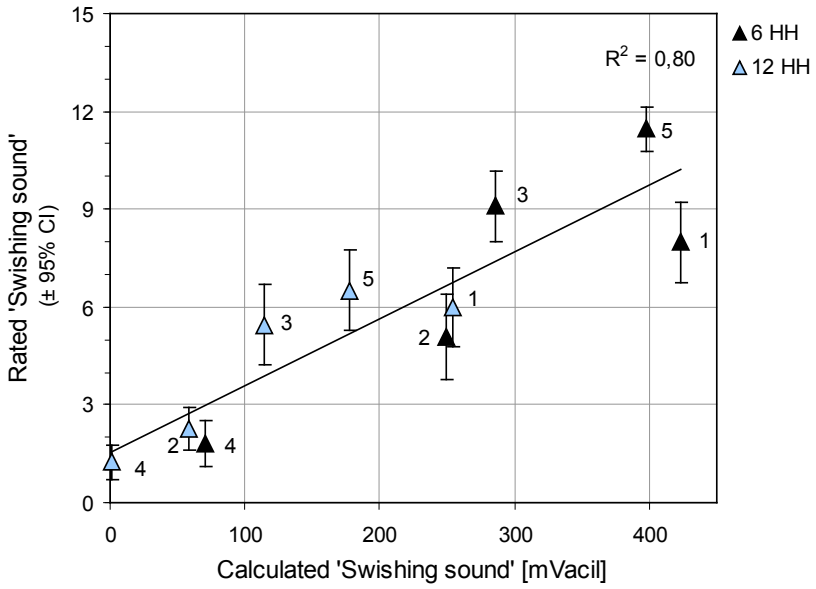

Figure 2

Rated ’Swishing sound’ from the listening tests versus the measured ‘Swishing sound’, ie. The fluctuation strength in the frequency band 350-700 Hz.

The metric on swishing sound correlated well (R^2 = 0.80) with the listening test results on ‘Swishing sound’.

Audibility of broad band noise near the hearing threshold

It is often seen that spectra of wind turbine noise are shown together with the hearing threshold and that conclusions are drawn on basis of a direct comparison of the spectra and the hearing threshold. In Figure 3 a number of spectra of the same wind turbine sound are shown with different resolution (analysis bandwidth).

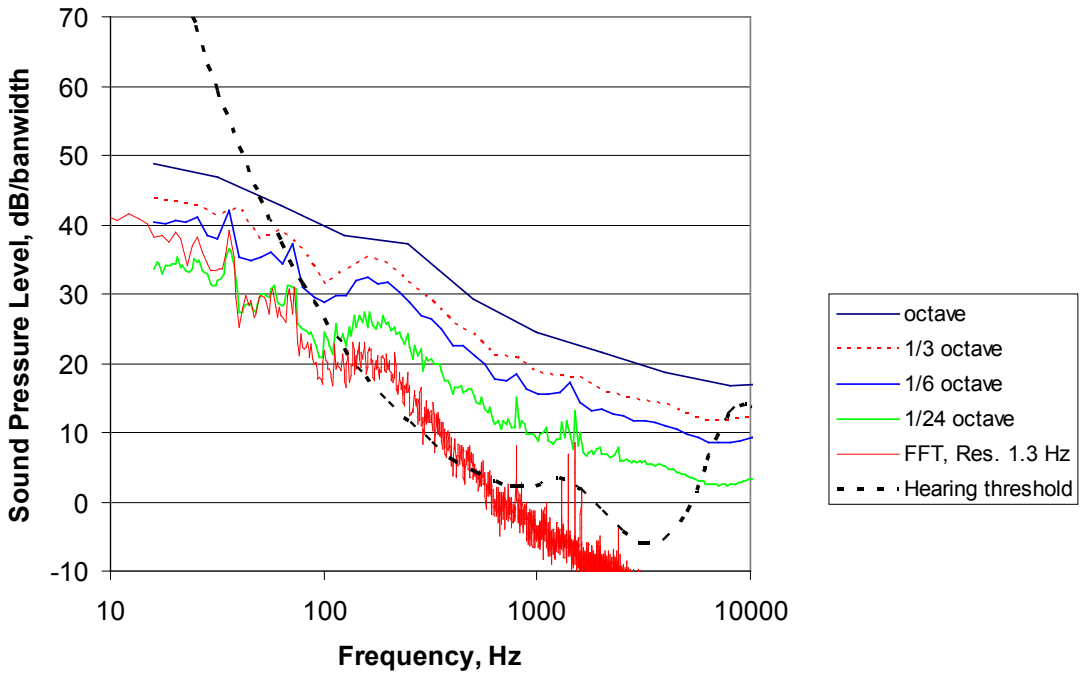

Figure 3
Spectra with different resolution of the noise from a 1.3 MW wind turbine, referred to a distance of 280 m (measured at 70 m). The abscissa is the level per effective analysis bandwidth. The hearing threshold is also shown at the graph. The A-weighted sound pressure level of the noise is 33 dB for all spectra.

As the curve with resolution 1.3 Hz is close to the hearing threshold the conclusion by comparison with that curve may be drawn that the turbine is hardly audible in general, and that the low frequencies are inaudible.

If we look at the 1/1 octave analysis other conclusions may be drawn.

From this example we can learn that a direct comparison of the hearing threshold and a spectrum of the wind turbine is not meaningful, so another approach is necessary.

Therefore a psychoacoustic “reasonable” procedure is proposed below.

A procedure for predicting the audibility of broad band sounds near the hearing threshold for frequencies below 500 Hz

Method A: Below or above the hearing threshold?

Even if you can't compare a spectrum and the hearing threshold directly, it is of course relevant to take the decrease sensitivity of the hearing at the low frequencies into account. For the method proposed here we need a specification of the hearing threshold as shown in Figure 4. Formulas for an accurate representation of the threshold curve are given in the Appendix.

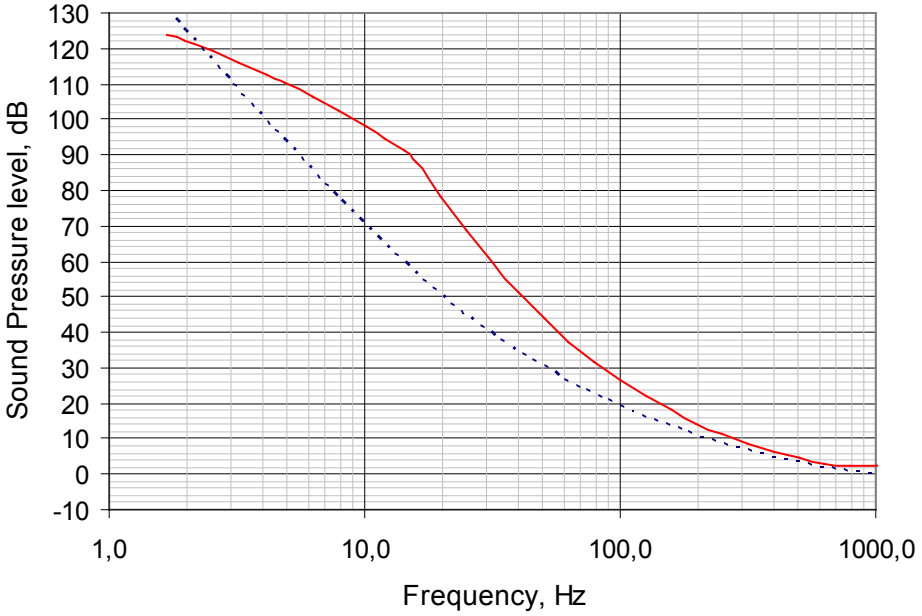

Figure 4
The average hearing threshold for pure tones in a free field (full line). The curve is constructed on basis of data from Møller & Pedersen, threshold proposal [9], (2-14 Hz), Watanabe & Møller [13], (16 Hz) and ISO 389-7, [3], (20-1000 Hz).The inverse A-curve is shown with a broken line.

As the perception of loudness and masking is based in the critical bands of the hearing the basic idea of the method is to calculate the energy in each critical band taking the hearing threshold into account. This is done in two steps:

First the lines/bands in the frequency spectrum are weighted (attenuated) according to the inverse hearing threshold; this is called HT-weighting. The attenuation in dB is specified in section the Appendix. The result of this frequency weighting is shown in Figure 5.

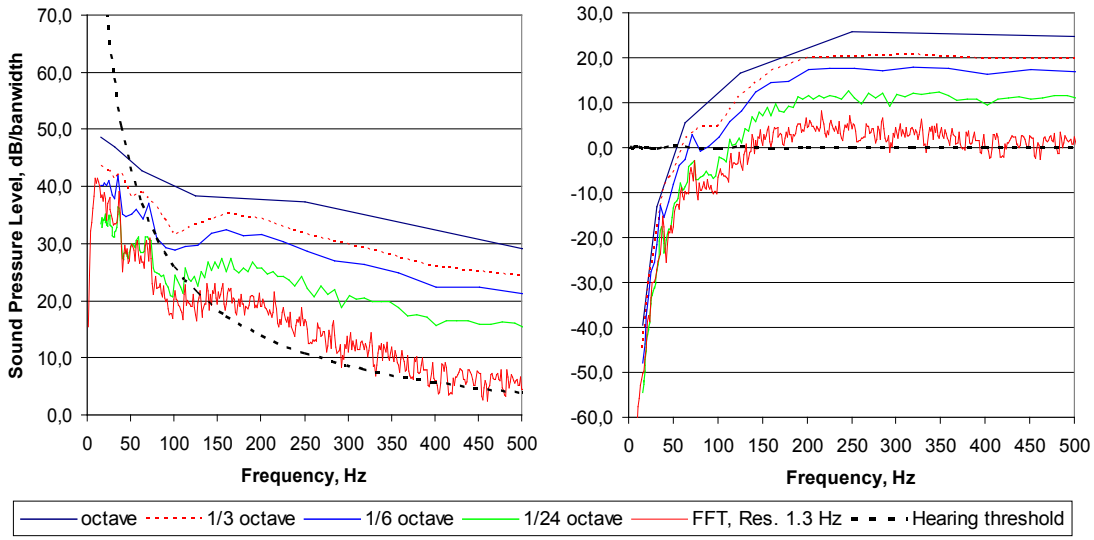

Figure 5
Same wind turbine noise spectra as shown in Figure 3 with linear abscissa axis. The right figure shows the HT-weighted spectra, from [10].

From the right part of Figure 5 we see that the spectra are still different, but it is possible to get an impression of which parts of the spectra that contributes most to the audibility of the noise.

Next step is to calculate the total HT weighted level per critical band. This can be done by adding the bands of the frequency analysis within each critical band as specified in Table 2.

Below 500 Hz the critical bands are approximated by 100 Hz wide bands. The lowest critical band includes both a low frequency and an infrasonic region.

A procedure that calculates the critical band level as a continuous function of frequency would be more in line with the fact that the critical bands of the hearing may be centred at any frequency, but the above mentioned procedure may be seen as a first attempt to get an overview of the matter.

After this calculation the resulting critical band spectra can be seen in Figure 6. Ideally all spectra from Figure 5 should result in the same critical band spectrum.

From Figure 6 it is seen that the 1/24 octave band analysis and the FFT analysis gives the most consistent results. Due to the fact that the limiting frequencies of the bands from the other types of analyses does not coincide with the critical bands inaccuracies occur. These depend on the spectrum shape. For the shown spectrum the inaccuracies for 1/3 band analysis are less than 2 dB while the errors for the 1/1 octave analysis are up to 5 dB. Therefore it is concluded that the 1/1 octave analysis is not appropriate for this type of calculation.

Apart from the mentioned inaccuracies the described method makes it possible to compare spectra measured with different bandwidth in a way that is meaningful in relation to perception, unlike the way the results are displayed in Figure 3.

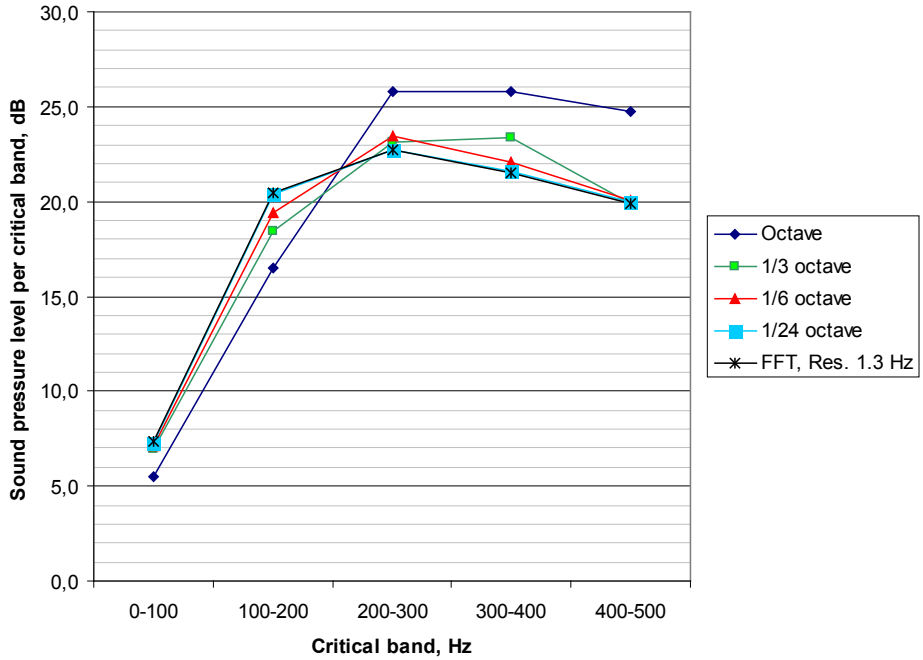

Figure 6
The critical band levels computed from HT weighted frequency analyses of the noise from the 1.3 MW reference wind turbine shown in Figure 3 and Figure 5. The different curves are the result of calculations based on analyses with different analysis bandwidths.

If the level per critical band is above the hearing threshold, the 0 dB line, it is anticipated that the sound is audible if it is not masked by other sounds. This anticipation definitely holds for sounds with dominating tones or narrow noise bands, because the results just give a direct comparison with the hearing threshold shown in Figure 4. For broad band sounds a check of this anticipation by listening tests would be desirable.

Verification of the method

No systematic threshold measurements have been conducted but the observations described below have been made during the listening tests in [2].

Figure 7 shows an example of broadband spectra. When the listening room for the listening tests reported in [2] was documented for the testing, the background noise in the room was measured in three different operational states: with all electronic systems off; with the loudspeakers on; and with the ventilation system on. Nothing could be heard by the researchers when everything was switched off and when the loudspeakers were on. But when the ventilation system was on this could be clearly heard. The results in are calculated according to the method A above. It can be seen that when all systems were off the level did not exceed -5 dB SPL per critical band. 0 dB denotes the hearing threshold. When the speakers were on all critical band

values were well below the hearing threshold except the band between 300 and 400 Hz that had a value very close to the hearing threshold. And still the loudspeakers could not be heard. The critical band levels of the inverse hearing threshold weighted spectra from the ventilation system exceeded the hearing threshold only by 2 dB in one critical band and by less than 1 dB in a second band and yet the vent could be heard clearly. These results indicate that the method worked well in this particular case.

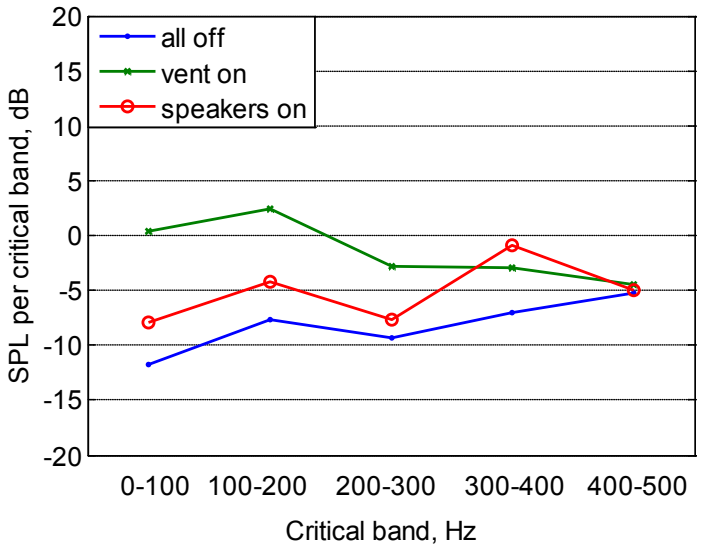

Figure 7
Audibility of background noise in listening room calculated according to method A above. 0 dB denotes the hearing threshold.

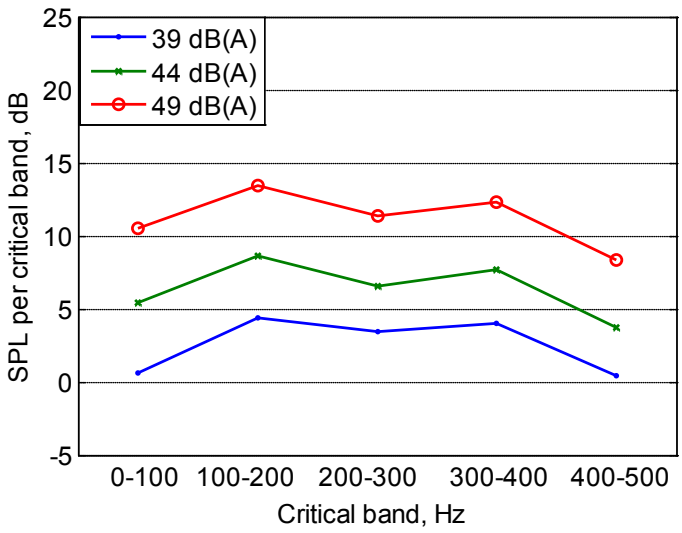

Figure 8
Audibility of masking noise in indoor scenario calculated according to method A above.

Another example is the audibility of masking noise in the indoor scenario in [2]. Participants reported that the masking noise was difficult to hear for the low masking

level of 39 dB(A) (see later). Figure 8 indicates why. All critical band levels are within 5 dB of the hearing threshold for this level whereas the other level exceeded the hearing threshold by more than 5 dB.

Although more systematic listening tests would be preferable, the two examples have indicated that the method A above for determining the audibility of broadband noise near the hearing threshold works as intended in the frequency bands between 0 and 500 Hz.

Method B: The audibility of broad band sounds partly masked by other sounds

In the preceding sections a method A for comparing the wind turbine noise in quiet surroundings with the hearing threshold was defined. If the result shows that the low frequency noise from a wind turbine is below the hearing threshold (in the relevant context: distance, indoor or outdoor conditions) the investigation can be concluded at that point.

In practice there is always some background noise, at least from wind in vegetation and buildings so the wind turbine noise may not be audible due to masking even if the HT-weighted critical band levels are above the hearing threshold.

In general both the wind turbine noise and the background noise is broadband noise types and the method for prominent tones in noise mentioned earlier will only give information about the audibility of tones and narrowband noise from the turbine.

We therefore need to look closer into the subject of the audibility of one broadband noise, the swishing noise from the turbine, masked by another, the background noise, [10].

In reference [12], listening tests for the audibility of wind turbine noise in the presence of natural urban/suburb background noise was investigated. It was fond that if white noise shaped to simulate a wind turbine spectrum was used as the primary noise no definite detection thresholds could be obtained. If recordings of wind turbine noise was used it was found that a signal to noise ratio of 0 dB in any 1/3 octave was sufficient for detection of the wind turbine.

From a psychoacoustic viewpoint it is obvious that it is difficult to determine a definite threshold for one stationary noise type masked by another. That requires that the test persons can distinguish between two slightly different noise spectres, which is a difficult task.

When detection thresholds are determined the test signal is often turned on and off at intervals of 250 ms as this frequency has the lowest detection threshold. The threshold does not change much for modulation frequencies in the range 1-10 Hz, [14]. The sensitivity for modulation increases with the bandwidth of the signal.

In reference [5] it was found that the swishing sound from wind turbines is best approximated by sine modulation. For a 75 kW wind turbine, the swishing sound from the rotor was most prominent (6-8 dB) in the frequency range 500-2000 Hz with a modulation frequency of 2.3 Hz. It was also found that the modulations at different 1/3 octave bands were slightly “mis-alined” in time, corresponding to a frequency modulation.

In reference [7] dealing with wind turbines of 600 kW to 1,3 MW, it was found that the level variations were most prominent in the frequency range 350-700 Hz (up to 10 dB variations) with modulation frequencies in the range 0,8-1,4 Hz. The measuring distances were 1.5-3 hub heights. (This effect decreases somewhat with the distance)

From [14] it is found that the modulation threshold for this kind of noise is corresponding to a level variation of approximately 3 dB. If a similar level variation occurs in the low frequency region (0-200 Hz) the detection is 3.5 dB (20%).

With basis in these data it can be calculated that an amplitude variation of 10 dB of the wind turbine noise will be masked by stationary background noise in the same frequency range when when L_{eq} of the wind turbine noise is approximately 0,6-1,6 dB below L_{eq} of the background noise. These figures corresponds well with the listening test results of masking of the wind turbine noise with background noise referred in [12].

The above mentioned findings can for stable wind conditions be concluded as follows. If both the wind turbine noise and the background noise are stationary it is difficult to define a detection threshold. The most sensitive detection of wind turbine noise in stationary background noise occurs when the noise is modulated (swishing noise). In this case the limit for detection is when L_{eq} of the wind turbine noise is approximately 1 dB below L_{eq} of the background noise.

The conclusion above applies in general and is not specific for the low frequency range. As the spectra of the wind turbine noise and the background noise may be different we have to take the change of the sensitivity of the hearing in the low frequency range into account when we compare the levels of the wind turbine noise with the levels of the background noise. The phenomenon's we are discussing in this section are well above the hearing threshold so the HT-weighting as discussed in earlier is not so relevant in this case.

The A-weighting is used when determining the audibility of tones and narrowband noise was demonstrated earlier to be appropriate for the purpose. Figure 4 shows that for frequencies and levels that are relevant for wind turbine noise the A-weighting does not underestimate the levels at low and infrasonic frequencies.

A reasonable and on "the safe side" way to compare a wind turbine spectrum with a background spectrum is therefore to compare the critical band levels of the A-weighted spectra. The critical band levels of the A-weighted spectra are calculated after the same principles as the HT weighted spectra mentioned earlier.

The wind turbine is most easily detected if amplitude modulation occurs. If we –to be on the safe side- assume that amplitude variations occur also at low frequencies, then the following rule can be formulated for the L_{eq} values of the critical band levels calculated from the A-weighted spectra:

- The low frequencies of the wind turbine noise are not audible if the A-weighted critical band levels are more than 1 dB below the critical band levels of the background noise.

As the main purpose here is to compare the total critical band levels of signals with somewhat similar spectral shapes, it is found that a more advanced procedure based on equal loudness curves would be to elaborate for this purpose.

Unstable wind conditions

For unstable wind conditions short term variations (gust of wind of duration less than 10-15 seconds) of the wind speed may cause variations of the levels of both the wind turbine noise and of the background noise. The variations of the A-weighted or the octave band levels measured with time weighting F are in the magnitude of 5-10 dB. Due to horizontal and vertical differences in location of the wind turbine rotor and the vegetation generating the natural background noise, these level variations are not synchronous in time. This means that the maximum values of the wind turbine noise may occur at times where the background noise is at minimum and visa versa.

If we want to find out if the low frequencies from the wind turbine is below the hearing and masking threshold at all times (for a specified average wind speed), then the maximum levels (with time weighting F) of the wind turbine noise should be compared to the minimum levels (expressed e.g. as the L_{95} with time weighting F) of the background noise after the same criteria as mentioned earlier.

Outdoor or Indoor conditions

Wind turbine noise is mainly perceived outdoors, but taken into consideration that the sound insulation of buildings is low at low frequencies and that the indoor background noise in some periods are lower than outdoors, then it is relevant to check if the low frequency noise from the turbines may cause an indoor problem.

The same principles as described above apply also for the indoor situation. Reference [1] gives values for sound insulation of dwellings at low frequencies.

Conclusions on audibility of low frequencies from wind turbines

Based on the thoughts and findings above a general method for assessment of the audibility of low frequency sounds is described in the Appendix.

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Appendix – Assessment of the audibility if low frequency sounds

This Appendix describes psychoacoustic reasonable procedures for predicting the audibility of sounds (tones, narrowband or broadband noise) below 500 Hz, may it be absolute thresholds or masking thresholds.

Furthermore the procedures make it possible to compare frequency analysis made with different bandwidths in a psychoacoustic meaningful way, by comparing the levels per critical band.

A: Audibility of sounds near the hearing threshold

Step 1: HT-weighting

The lines/bands in the frequency spectrum are weighted (attenuated) according to the inverse hearing threshold; this is called HT-weighting. The attenuation in dB is given by equations 1 to 3. These approximates the average hearing threshold with a deviation less than 0.4 dB.

2-20 Hz:

$$\mathrm{Att}_{2\text{-}20\mathrm{Hz}} = -1{,}0183 \cdot 10^{-2} \cdot f^{3} + 3{,}8537 \cdot 10^{-1} \cdot f^{2} - 6{,}3935 \cdot f + 133{,}48 \qquad \textit{Equation 1}$$

20-200 Hz:

$$\mathrm{Att}_{20\text{-}200\,\mathrm{Hz}} = 1{,}5948 \cdot 10^{-11} \cdot f^{6} - 1{,}3537 \cdot 10^{-8} \cdot f^{5} + 4{,}5945 \cdot 10^{-6} \cdot f^{4} - 8{,}0269 \cdot 10^{-4} \cdot f^{3} + 7{,}7761 \cdot 10^{-2} \cdot f^{2} - 4{,}2624 \cdot f + 137{,}99 \qquad \textit{Equation 2}$$

200-500 Hz:

$$\mathrm{Att}_{200\text{-}500\mathrm{Hz}} = -1{,}3635 \cdot 10^{-7} \cdot f^{3} + 2{,}2850 \cdot 10^{-4} \cdot f^{2} - 1{,}399 \cdot 10^{-1} \cdot f + 34{,}306 \qquad \textit{Equation 3}$$

The attenuations for a number of frequencies are shown in Table 1.

Freq. Hz	Att. dB	Freq. Hz	Att. dB	Freq. Hz	Att. dB
1.6	124.3	20.0	78.2	200	14.4
1.8	123.3	22.4	73.6	224	12.9
2.0	122.2	25.1	69.0	251	11.4
2.2	121.0	28.2	64.3	282	10.0
2.5	119.7	31.6	59.8	316	8.6
2.8	118.3	35.5	55.3	355	7.3
3.2	116.8	39.8	51.1	398	6.2
3.5	115.2	44.7	47.2	447	5.2
4.0	113.5	50.1	43.6	501	4.4
4.5	111.7	56.2	40.3		
5.0	109.8	63.1	37.3		
5.6	107.9	70.8	34.5		
6.3	105.9	79.4	31.9		
7.1	103.9	89.1	29.3		
7.9	101.9	100.0	26.7		
8.9	99.9	112.2	24.1		
10.0	97.9	125.9	21.7		
11.2	95.9	141.3	19.7		
12.6	93.7	158.5	18.1		
14.1	91.4	177.8	16.7		
15.8	88.4				
17.8	84.4				

Table 1
Attenuations for the hearing threshold weighting (HT-weighting) according to formulas 1-3.

Step 2: Energy addition of analysis bands into critical bands

The analysis bands within the ranges given in Table 2 should be “added” according to equation 4 to find the critical band levels. (the critical bands are approximated with a 100 Hz bandwidth in accordance with ISO 1996-2 Annex C, [4].

Critical band	0-100 Hz	100-200 Hz	200-300 Hz	300-400 Hz	400-500 Hz
Octaves	0-63	125	250	250	500
1/3 octaves	0-80	100-160	200-250	315-400	500
1/6 octaves	0-90	100-180	200-285	320-400	450-506
1/24 octaves	0-98	101-196	201-293	301-390	402-492
FFT analysis	0-99	100-199	200-299	300-399	400-499

Table 2
Centre frequencies in Hz for bands to be energy added from the HT weighted spectra to get the total HT-weighted level per critical band. Only analyses with a resolution of 1/3 octaves or better should be used.

Note
The “definite” placement in the frequency range of the critical bands, specified in Table 2, are for “pragmatic” reasons only. The critical bands of the hearing are not centred at any specific frequencies but can be placed at any frequency

The total HT-weighted level per critical band shall be calculated. For this purpose the energy in a number of bands according to Table 2 have to be added.

The energy addition is made according to the following formula:

$$L_{crit.band} = 10 \cdot \log\left(\sum_{i=1}^{n} 10^{\frac{L_{HT,i}}{10}}\right) \qquad \textit{Equation 4}$$

Where $L_{HT,\,i}$ is the HT-weighted level of the i’th analysis band.

Step 3: Below or above the hearing threshold?

The following rule applies:

The low frequencies will be regarded to be below the hearing threshold if the critical band levels found from the HT-weighted wind turbine spectrum are less than 0 dB.

Note
This anticipation definitely holds for sounds with dominating tones or narrow noise bands, because the results just give a direct comparison with the hearing threshold.

B: Audibility of sounds partly masked by other sounds

Even if the HT-weighted critical band levels are above the hearing threshold they may not be audible because they may be masked by other sounds e.g. the wind noise in the vegetation. In this section a method for finding the audibility of broad band sounds partly masked by other sounds is defined.

Simple cases

In simple cases where the entire wind turbine noise spectrum is below background noise spectrum the spectra can be compared directly independent of any frequency weighting (the spectra shall be measured or referred to the same frequency weighting and analysis bandwidth (1/3 octave bands or less):

The wind turbine noise will be masked if the levels in all analysis bands of the wind turbine noise is more than 2 dB below the levels of the background noise

Note: A 2 dB “limit” is chosen to take the audibility of any tones into account

Not simple cases

The wind turbine noise may be masked even if the levels of some analysis bands of the wind turbine exceed the levels of the background noise bands.

In this case the spectra shall be A-weighted and the critical band levels of the A-weighted spectra shall be calculated after the same principles as for the HT weighting described in step 2 in method A above.

The following rule applies for the audibility:

> *The wind turbine noise is masked if the levels of the critical bands of the A-weighted wind turbine noise are more than 2 dB below the levels of the critical bands of the A-weighted background noise.*

This rule takes into account any audible tones and/or amplitude modulation (swishing noise) and will also work for the simple situations.

Indoor situations

For indoor situations the outdoor spectra should be transformed to indoor spectra before methods A and B are applied. The level difference in Table 3 apply for Danish dwellings, [1]

Freq, Hz	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
ΔL_{10}	2,4	1,2	3,2	2,1	3,6	4,6	6,7	7,6	10,3	14,2	17,5	18,4	17,5	18,6	22,4

Table 3
Level difference in dB expected to be exceeded in 80-90% of typical Danish dwellings