Danish Regulation of Low Frequency Noise from Wind Turbines

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SUMMARY
The Danish statutory order on wind turbine noise was revised in order to establish new rules for low frequency noise [1]. The new regulation entered into force January 1st, 2012, and it applies to wind turbines notified to the municipalities from this date. The new regulation complements the previous noise limits for wind turbines with a new mandatory limit for the low frequency noise, which is 20 dB A-weighted level of the calculated indoor sound level in the 1/3-octave bands 10 – 160 Hz. The purpose of the new regulation is to ensure that neither the usual noise nor the low frequency noise will annoy the neighbours when the wind turbines start to operate.

1. BACKGROUND

Noise from wind turbines in Denmark has been regulated by a Statutory Order since 1991 setting fixed limits for the total noise level from all wind turbines. The noise limit was 45 dB at dwellings in the open country and 40 dB in noise sensitive areas, such as residential areas. Both limits were to be kept at a reference wind speed of 8 m/s.

The Statutory Order was revised in 2006, where supplementary noise limits at weaker wind, 6 m/s, were introduced. At the same time the prescribed measurement method for noise emission from wind turbines was adapted to be more applicable to larger wind turbines, and the calculation method for noise levels in the surroundings was adjusted. Due to the adjustment, the noise limits at 8 m/s were reduced to 44 and 39 dB to ensure the same protection for the neighbours as previously. The noise limits at 6 m/s were 2 dB lower than the corresponding limits at 8 m/s.

Following public concern about possible low frequency noise from wind turbines, the Danish Minister for the Environment in January 2011 asked the Danish Environmental Protection Agency to draft a revision of the Statutory Order so fixed limits could be set also for this part of the noise. It was a basic assumption that wind turbines keeping the current mandatory noise limits would not cause particular problems due to the low frequency part of the noise, and it was not intended to change the existing noise limits.

A detailed analysis of the sketched regulation using new, unpublished noise emission data from wind turbine manufacturers showed that the planned noise limits could be challenging for some types of wind turbines in certain situations. For these turbines the proposed limits for low frequency noise could be the constraining factor determining the shortest possible distance to dwellings in the open country or the number of wind turbines it is possible to establish on a location with neighbouring dwellings in the open country.

The principles for the new regulation, including the calculation method, were subject to a preliminary technical consultation, where a number of organisations, acoustic experts, and wind turbine manufacturers took part. Later in 2011 a draft of the Statutory Order was subject to a public consultation, and after some changes had been made it was adopted by the Minister and put into force.

It should be emphasized that the regulation is based on the experience obtained with wind turbine noise in Denmark and both the sound propagation method and in particular the data for level difference due to transmission of noise into dwellings is based on prevailing conditions in Denmark.

2. DANISH LEGISLATION ON WIND TURBINES

Apart from the Statutory Order on wind turbine noise, wind turbines are regulated by several other rules. Actually, the Statutory Order on noise is the last link in a long chain of regulation. Below is given a brief description of the major noise-related topics.

One of the first issues is the municipal plans for establishment of wind turbines, where areas that can be appointed for wind turbines are localized and an investigation of possible contravention with regulations is done, including protection of nature and landscape. The legislation about Spatial Planning is the legal basis for a fixed minimum distance between wind turbines and neighbouring dwellings which is four times the total height of the turbine including the rotor [2].

After the municipal plan for wind turbine is approved, developers can show interest to set up wind turbines at one of the appointed areas for wind turbines. Then a local plan for the actual project and in most cases also an Environmental Impact Assessment must be made, including a mandatory public consultation. When all planning issues are solved, the developer can apply for a building permit and submit a notification according to the rules in the Statutory Order on noise, both to the municipalities. The wind turbine must be certified under the Danish Energy Agency's scheme for technical certification, regarding construction, manufacture, installation, maintenance and service of wind turbines [3].

In the notification from the applicant to the municipality documentation of the noise emission from the actual type of wind turbine, stated in a certified or accredited report, is mandatory together with calculations that show that the project comply with the noise limits. If the documentation is insufficient, the municipality has a four week period to object to the planned erection of wind turbines.

After the wind turbine is erected, the municipality is responsible for inspection and enforcement of the Statutory Order on noise from wind turbines. The main object is that the wind turbine does not emit excessive noise, compared to the information given in the notification. The owner of the wind turbine must supply the authorities with the information needed for the inspection and may be ordered to have noise measurements and calculations carried out at his own expense if the municipal council considers it necessary.

3. LIMITS FOR NOISE FROM WIND TURBINES

The noise limits apply to the total noise from all wind turbines. When notification of a planned wind turbine installation is made, the noise from existing turbines in the same area must be added to the contribution from the planned, new wind turbines. If the total noise level exceeds one or more of the noise limits the acoustical space is insufficient to contain the contribution from the planned new wind turbines.

The total noise level from wind turbines may not exceed the following limit values:

- At the most noise-exposed point in outdoor living area no more than 15 metres from dwellings in the open countryside:
    - (a) 44 dB(A) at a wind speed of 8 m/s.
    - (b) 42 dB(A) at a wind speed of 6 m/s.
- At the most noise-exposed point in areas with noise-sensitive land use:
    - (a) 39 dB(A) at a wind speed of 8 m/s.
    - (b) 37 dB(A) at a wind speed of 6 m/s.

The total low frequency noise from wind turbines at wind speeds of 6 and 8 m/s may not exceed 20 dB indoors in neither dwellings in the open countryside nor indoors in areas with noise-sensitive land use. The low frequency noise level is the A-weighted level of the noise in the frequency range defined by the 1/3-octave bands from 10 Hz to 160 Hz, including both.

4. CALCULATION OF NOISE FROM WIND TURBINES

It is impossible to make sufficiently precise measurements of wind turbine noise at neighbouring properties under the relevant wind conditions due to the background noise mainly from the wind in trees and bushes. Also noise from traffic and other sources may obstruct precise measurement of the relative low levels in question. With a view to the new regulation of low frequency noise, also noise sources inside or near the dwelling can seriously disturb a direct measurement. This is why the Danish regulation of noise from wind turbines is based upon the calculated noise level at neighbouring properties, which again is based on the noise emission from the wind turbine during reference conditions.

4.1. Measurement of noise emission from wind turbines

Noise emission is determined from noise level measurements relatively close to the wind turbine with the microphone mounted on a large plate placed directly on the ground. At the same time the wind speed is derived from the produced power, since this corresponds far better to the wind speed that actually acts on the blades than the wind speed measured at a lower height.

The noise is measured both at wind speeds about 8 m/s and about 6 m/s to reflect the two sets of noise limits. With the wind turbine parked the background noise is measured in the same intervals of wind speed to allow for a correction of the measurement results. The procedure for measurement of noise emission is described in an Annex to the Statutory Order. The procedure is in general agreement with the international standard IEC 61400-11, and measurements can be made in agreement with the standard as an alternative to the method prescribed in the Statutory Order.

It is a general observation that low frequency noise from wind turbines is rather weak so the measurements are often disturbed by background noise from the wind acting on the microphone unless a large secondary wind screen is used. This has a hemispherical shape, at least 40 cm diameter, and it is fixed concentrically with the primary wind screen on the measurement board. The secondary wind screen may attenuate the wind turbine sound at higher frequencies, so the measurement results will have to be corrected for this influence.

4.2. Calculation of the A-weighted noise level

The calculation of the noise levels in the surroundings of a wind turbine is fairly simple, because the noise is emitted from a significant height and the ground in Denmark is almost flat. The calculation is based on the measured noise emission in the downwind direction from the wind turbine, and corrections are made for sound absorption in the air and ground effect. Calculation of air absorption is based on ISO 9613 - 1 at 10°C air temperature and 80% relative humidity, which is a fair representation of the Danish climate. The absorption is given as a table with correction values in both 1/3- and 1/1-octave bands.

The correction for ground effect is simplified to a correction of + 1.5 dB for onshore wind turbines and + 3 dB for off shore turbines in every frequency band between 50 Hz and 10 kHz (if calculation is made in 1/1-octave bands: 63 – 8000 Hz). The ground correction is based on a simplification of the highly regarded and complicated general noise prediction method, Nord2000 [4], which is verified by measurement particularly for wind turbine noise [5].

Some very early attempts to apply the frequency dependent ground correction from ISO 9613 - 2 showed this method to be is less accurate when used for wind turbine noise than a simple, frequency independent correction [6]. The simplification of Nord2000 to a fixed correction of + 1.5 dB is described in a note [7], and the propagation from off shore wind turbines is treated in [8].

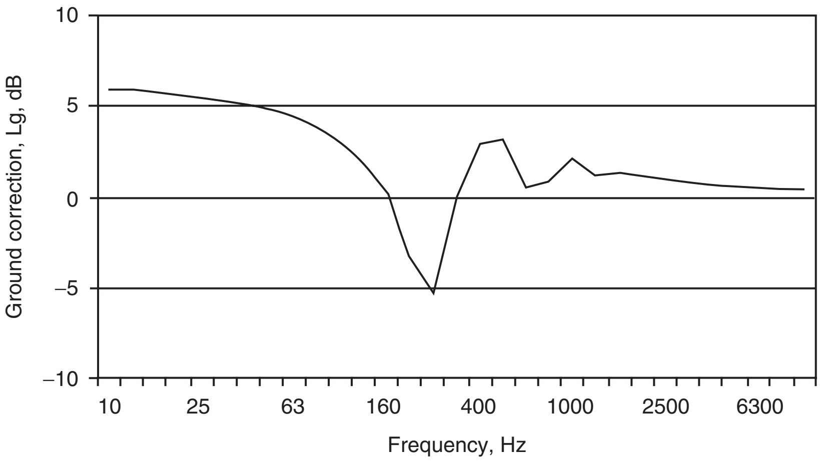

Figure 1. Illustration of ground correction. Source height 80 m, receiver height 1.5 m and 500 m distance; propagation over porous ground and 8 m/s wind speed.

The calculation method for the noise level L_{pA} in 1/3-octave bands is:

$$L_{pA} = L_{WA,ref} - 10 * \log(l^2 + h^2) - 11 \text{ dB} + \Delta L_g - \Delta L_a$$

where:

l = the distance from the base of the turbine to the calculation point and h is the height to the rotor axis of the wind turbine, both in meters

11 dB = correction for distance, 10 * log 4π

ΔL_g = correction for ground effect (1.5 dB for onshore turbines and 3 dB for offshore turbines)

ΔL_a = air absorption, $\left(\alpha_a * \sqrt{l^2 + h^2}\right)$ where the absorption coefficient α_a is shown in Table 1.

The calculations presuppose favourable weather conditions such as downwind sound propagation. Hence the calculated noise level is mostly higher than actual level experienced at neighbouring dwellings.

4.3. Calculation of the low frequency noise level

The calculation of the low frequency noise level is based fundamentally on the same assumptions as the calculation of the A-weighted level, but due to the increased coherence between direct and reflected sound the ground correction increases to + 6 dB at very low frequencies, so a more specific and detailed approach was chosen to avoid underestimation of the noise levels The ground corrections are given as a table in the frequency range from 10 to 160 Hz, independent of distance and height of the wind turbine.

Table 1.

Air absorption coefficients per 1/3 octave at a relative air humidity of 80% and an air temperature of 10°C

1/3 octave centre frequency in Hz	50	63	80	100	125	160	200	250	315
α_a in dB/km	0,07	0,11	0,17	0,26	0,38	0,55	0,77	1,02	1,3

1/3 octave centre frequency in Hz	400	500	630	800	1000	1250	1600	2000
α_a in dB/km	1,6	2,0	2,4	2,9	3,6	4,6	6,3	8,8

1/3 octave centre frequency in Hz	2500	3150	4000	5000	6300	8000	10000
α_a in dB/km	12,6	18,8	29,0	43,7	67,2	105	157

The given values for the ground corrections for on shore wind turbines were optimized for a range of distances between the Danish minimum distance (four times the total height of the wind turbine) and twice this distance, and the accuracy of the simplified method was checked in an interval up to four times the minimum distance. It was found that the simple corrections were rather accurate and resulted in an overestimation of about 1 dB at the largest distances checked.

For offshore wind turbines the corrections were optimized for a distance range between 1.4 and 8 times the minimum distance, and the accuracy was checked in the range 1 – 16 times the minimum distance. At the shortest distance the simple method overestimates the noise level with about 0.7 dB, and at the very largest distances the simple method overestimates the noise with about 1.7 dB.

A closer analysis showed that the simple calculation method for offshore wind turbines is inaccurate when calculation is made for receiver positions further inland from the coast than 200 m as seen in the direction towards the turbines. For positions further inland more precise results were obtained when the method for on shore wind turbines was used instead. This method will overestimate the actual noise level with about 1 dB at four times the minimum distance and up to 4 dB at the very largest distances checked, 16 times the minimum distance. For positions between the shoreline and 200 m inland from the shore, the appropriate ground correction is found by linear interpolation between the two values given for the ground correction, using the distance from shore as parameter.

The Danish EPA has published a report [9] describing the considerations and calculations made in connection with the simplification of Nord2000 for low frequency wind turbine noise.

The limit value for the low frequency wind turbine noise applies to the indoor noise level, so the noise level outdoors has to be converted to an indoor level by correction using the level difference. This is a measure of the sound insulation of the entire building, which is based on two series of measurements as is described in [10]. The indoor noise level and hence the level difference depends on the choice of measurement positions.

For the actual insulation measurements, the noise was emitted from a large loudspeaker situated outdoors at some distance from the façade and the measurement positions indoor were chosen in accordance with the recommendations in the Danish guideline [11]: One of the three measurement positions in a room is chosen near a corner, 0.5 to 1 m from the adjoining walls and 1 to 1.5 m above the floor, while the other two positions are chosen to represent normal use of the room, still at least 0.5 m from walls and large pieces of furniture and 1 to 1.5 m above the floor.

A total of 26 measurements were made in 14 different dwellings, representative of Danish buildings at the countryside and in suburban areas. For the use in the calculation method of the Statutory Order insulation values were chosen that were

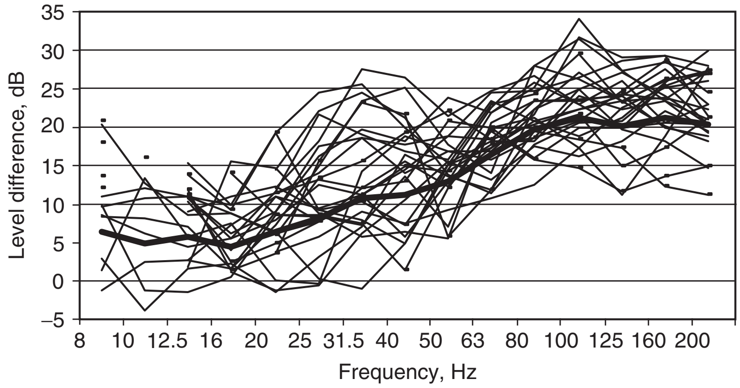

Figure 2. Results of all measurements of level difference and the selected 'level difference curve' that is exceeded by 67% of the measurements.

Table 2.
Ground correction for calculation of low-frequency noise for wind turbines on shore and offshore respectively, sound insulation (level difference) and air absorption coefficients per 1/3 octave at a relative air humidity of 80% and an air temperature of 10°C

1/3 octave centre frequency in Hz	10	12,5	16	20	25	31,5	40
ΔL_{gLF} : ground correction, on shore wind turbine (dB)	6,0	6,0	5,8	5,6	5,4	5,2	5,0
ΔL_{gLF} : ground correction, offshore wind turbine (dB)	6,0	6,0	6,0	6,0	6,0	5,9	5,9
ΔL_{σ}: sound insulation (level difference) (dB)	4,9	5,9	4,6	6,6	8,4	10,8	11,4
α_a in dB/km	0,0	0,0	0,0	0,0	0,02	0,03	0,05
1/3 octave centre frequency in Hz	**50**	**63**	**80**	**100**	**125**	**160**	
ΔL_{gLF} : ground correction, on shore wind turbine (dB)	4,7	4,3	3,7	3,0	1,8	0,0	
ΔL_{gLF} : ground correction, offshore wind turbine (dB)	5,8	5,7	5,5	5,2	4,7	4,0	
ΔL_{σ} : sound insulation (level difference) (dB)	13,0	16,6	19,7	21,2	20,2	21,2	
α_a in dB/km	0,07	0,11	0,17	0,26	0,38	0,55	

exceeded for 67% of the measured results, ΔL_{σ}, considering that the margin of safety for the sound insulation is additional to the margin of safety of the propagation calculations.

The calculation method for the indoor noise level L_{pALF} in 1/3-octave bands is:

$$L_{pALF} = L_{WA,ref} - 10 * \log(l^2 + h^2) - 11\text{ dB} + \Delta L_{gLF} - \Delta L_{\sigma} - \Delta L_a$$

where:

l = the distance from the base of the wind turbine to the calculation point and h is the height to the rotor axis of the wind turbine, both in meters
11 dB = correction for distance, 10 * log 4π
ΔL_{gLF} = correction for ground effect at low frequencies (Table 2)
ΔL_{σ} = sound insulation at low frequencies (Table 2)
ΔL_a = air absorption, $\left(\alpha_a * \sqrt{l^2 + h^2}\right)$ where the absorption coefficient α_a is shown in Table 2.

5. PERSPECTIVE – IS LOW FREQUENCY NOISE PARTICULAR FOR WIND TURBINES?

The major part of the noise from modern wind turbines is aerodynamic rotor noise which is broad band noise with a characteristic time pattern. This is not a particular low frequency noise. The machinery components generate tones, which according to constructive details may be radiated as tonal noise. This noise can occur both at low and higher frequencies, typically tones in wind turbine noise is seen in the range between 40 and 500 Hz.

Tonal noise is perceived as more annoying than noise without tones, and tonal noise is an unwanted side effect of wind turbines. Considerable effort has been made by the manufacturers during the years to control and reduce the tones, and in 2011. The Danish EPA published a report about the principles and possibilities for reduction of tones in wind turbine noise [12].

It has been suggested that wind turbines emit significant levels of infrasound. An investigation of this topic [13] concludes that infrasound noise emissions from wind turbines are well below the recognised perception threshold, and it is proposed that modulation of aerodynamic noise, which causes the characteristic time pattern of wind turbine noise, is sometimes mistaken for infrasound.

In a project sponsored by the Danish Energy Authority [14] it was investigated if modern large wind turbines emit significantly more low frequency noise than experienced from the smaller wind turbines. The project showed that the low frequency noise emission from large wind turbines was on the average slightly

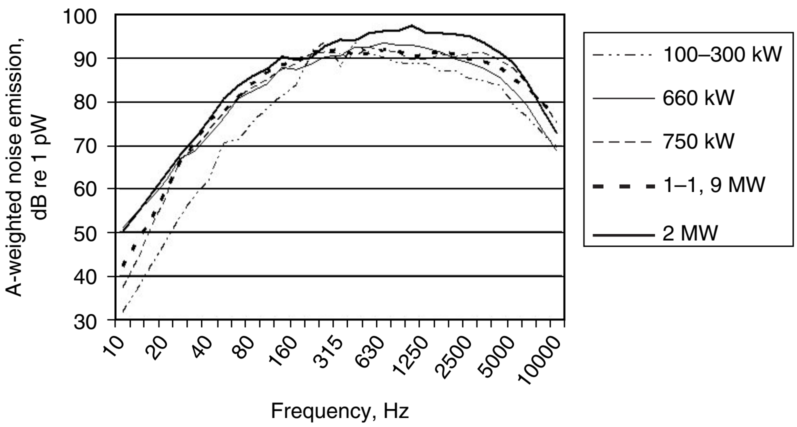

Figure 3. A-weighted spectra of wind turbine noise in 5 different classes of turbine nominal power. From [15]

higher than the emission from smaller wind turbines, but the observed difference between small and large wind turbines was much smaller than the differences between the individual wind turbines with regard to both total noise emission and the contribution of low frequency noise. Tones in the noise from large wind turbines was identified both at low and higher frequencies and both in four prototype wind turbines and to some extent also in new, series produced wind turbines. The project did not show that large wind turbines cause a special problem regarding low frequency noise impact at residences close to wind turbines, which was the actual hypothesis for the project.

The Danish EPA has published an investigation about typical data for noise emission from wind turbines of different size in Denmark [15]. The data are intended to be used when notification is made for a new wind turbine near existing wind turbines and the applicant has no access to sufficient measurement data for the noise emission from the existing turbines. Data from 170 measurement reports from the period 1992 – 2011 were treated statistically in nine groups of comparable wind turbine types and sizes from “less than 100 kW” to 2 MW. The results are given as typical worst case (90% confidence level) of noise emission in the frequency range 10 Hz – 10 kHz both at 6 and 8 m/s reference wind speeds. Apart from the groups with the smallest wind turbines, where the noise is dominated by middle frequency machinery tones, there is not any clear relation between turbine size and the share of low frequency noise as compared to the total noise. It is a general observation that the noise levels at frequencies below 25 Hz are influenced by background noise.

It would seem that noise from wind turbines is not particularly intense at low frequencies when compared to noise from other environmental noise sources such as road traffic and in particular to industrial noise. Tonal noise from wind turbines can be observed occasionally, with tones both at high and low frequencies regardless of the wind turbine size, but the general picture is that wind turbine noise contains no prominent tones and do not cause significant levels of low frequency noise. Thus the new Danish regulation for low frequency noise from wind turbines is not the response to a major, general problem. The rules have been established in response to the concern of the general public about low frequency noise as well as a tool for prevention of future low frequency noise problems and for handling of such problems when they occur.

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