Infrasound Emission from Wind Turbines

Jørgen Jakobsen
Danish Environmental Protection Agency
Strandgade 29, DK- 1401 Copenhagen K, DENMARK
Email:jj@mst.dk

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ABSTRACT

A critical survey of all known published measurement results of infrasound from wind turbines has been made. The survey indicates that wind turbines of contemporary design with an upwind rotor generate very faint infrasound with a level far below the threshold of perception even at a rather short distance. From considerations on propagation and transmission of infrasound it is concluded that infrasound from such upwind turbines can be neglected when evaluating the environment effects of wind turbines. Turbines with downwind rotors produce 10 - 30 dB higher infrasound levels, and these may exceed relevant assessment criteria for dwellings in the immediate neighbourhood. When longer distances are considered, neither downwind nor upwind turbines are capable of violating assessment criteria for infrasound. This paper considers whether other aspects of the noise than the infrasound can explain the indicated adverse public reactions to large downwind turbines.

1.INTRODUCTION

1.1 Noise from wind turbines

Wind turbines constitute a very distinctive group of noise-producing devices. During the last 20 years or so a considerable insight has been gained into the noise mechanics of wind turbines, mainly for the purpose of making quieter turbines to enable a better exploitation of wind energy. An excellent overview of the noise sources of wind turbines can be found in [1] . They may be split into two groups, machinery noise and aerodynamic rotor noise.

1.2 Machinery noise

The machinery that transforms the rotation of the rotor blades into electricity chiefly generates the machinery noise: the gear box and the generator. The noise from these components frequently contains more or less prominent tones, whose amplitude and sometimes also frequency fluctuates slightly in rhythm with the blade passing frequency of the rotor. Additional sources of machinery noise are ventilation equipment for the machinery compartment, hydraulic pumps, and yawing machinery. It is common to all these sources that the mechanisms responsible both for the noise generation and the radiation are known from other fields of application, and they are well described. Also the means of controlling machinery noise have been known for some time, [2], though it is not to say that it can be easily obtained.

1.3 Aerodynamic rotor noise

The aerodynamic noise from the rotor is less well-known, though a better understanding has been gained both through development of theories for the aerodynamic noise sources of a wind turbine [3, 4] and through experiments [5, 6]. Design rules for quiet rotor blades exist in most manufacturing companies, and it is rare nowadays to listen to the bleating, squeaking, whining, or whistling sounds that were characteristic for the earlier types of wind turbines. The rotor noise from a well designed wind turbine would have a broadband character and a characteristic amplitude modulated pattern in rhythm with the blade passing frequency, giving the typical "swishing" sound. At larger distances from the turbine the amplitude modulation decreases and the sound gains a more stationary character. Some observations indicate that the modulation can be strong, even at rather large distances, in a stable atmosphere which can occur at night time when the wind is not too strong.

1.4 Infrasound from wind turbines

The rotor also generates infrasound, due to the varying aerodynamic loading of the rotor blade as it passes through the wake behind the tower of the wind turbine, or through the pressure gradient that builds up in front of the tower [7, 8] Here the orientation of the wind is defined, such that 'front' means the upwind side of the turbine, and 'behind' is downwind. The noise has a discrete frequency character, consisting of the blade passing frequency, and a number of harmonics. In cases where the wind turbine emits strong infrasound, the noise is sometimes described to subjectively have a "thumping" character.

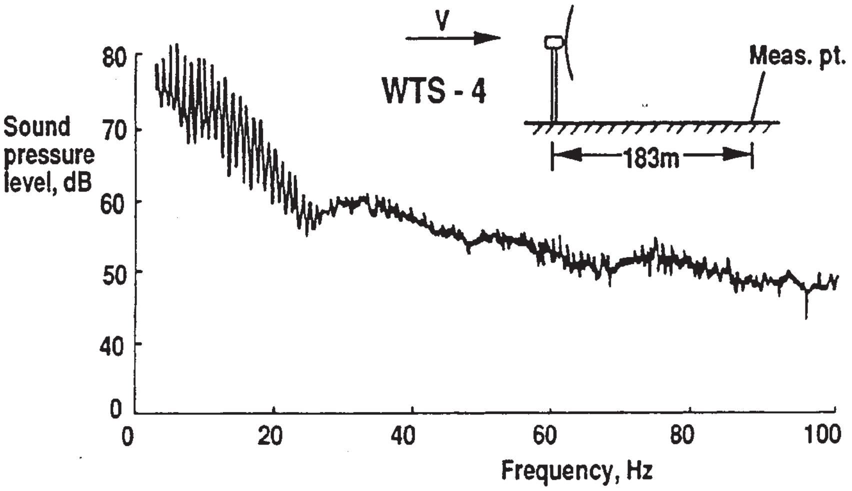


Figure I. FFT-spectrum of the noise from a wind turbine, showing the discrete frequency noise in the infrasound region (from Hubbard and Shepherd [7]).

Many of the earlier types of wind turbine had the rotor placed behind the tower. It was regularly observed that they caused high levels of infrasound and low frequency sound, and neighbours out to quite large distances blamed them for severe annoyance. Present day wind turbines almost exclusively have their rotor in front of the tower.

2. MEASUREMENTS OF INFRASOUND FROM WIND TURBINES

In a small number of reports and papers measurements of infrasound emission from wind turbines have been described. In this section all the measurements known by this author are described briefly, and the results are extracted and are made comparable.

Generally the measurement conditions and the operating conditions of the wind turbine have not been described in detail in the reports, and even fewer specifications are given in the papers. In the infrasound range the influence of placement of the measurement microphone can be neglected. Because of the very long wavelength of infrasound all practically applied microphone placements are estimated to be in the region of coherent ground reflection, such that the recorded sound pressure level is 6 dB higher than it would be in an ideal free field. Typically the measurement results are given as examples of narrow band spectra or as third octave spectra with unknown integration time period. From a visual inspection of the narrow band spectra it is estimated that integration has been made over several minutes in most of the
cases.

2.1 Betke et al.

The group of applied physics at the University of Oldenburg [9 - 13] has carried out several series of measurements of infrasound. A specially developed measurement method has been used, where the measurement microphone was protected from wind noise that would otherwise mask the infrasound signal from the wind turbine. The microphone was placed in a hole, dug in the ground and covered with an acoustically transparent material, as is illustrated in Figure 2. This procedure would not be valid at higher frequencies, where it is important that the microphone is placed close to a sufficiently large reflecting surface such as described in the standard for measurement of noise emission form wind turbines, [14], but at the lowest frequencies it is a valid way of reducing the wind-induced microphone noise and still obtaining a coherent ground reflection. In the earliest measurement sessions [9 and partially 10] two microphones were used and the cross correlation technique was applied to further suppress the wind noise, which is not correlated between the two microphones placed several metres apart. In later sessions only one microphone and autocorrelation was applied.

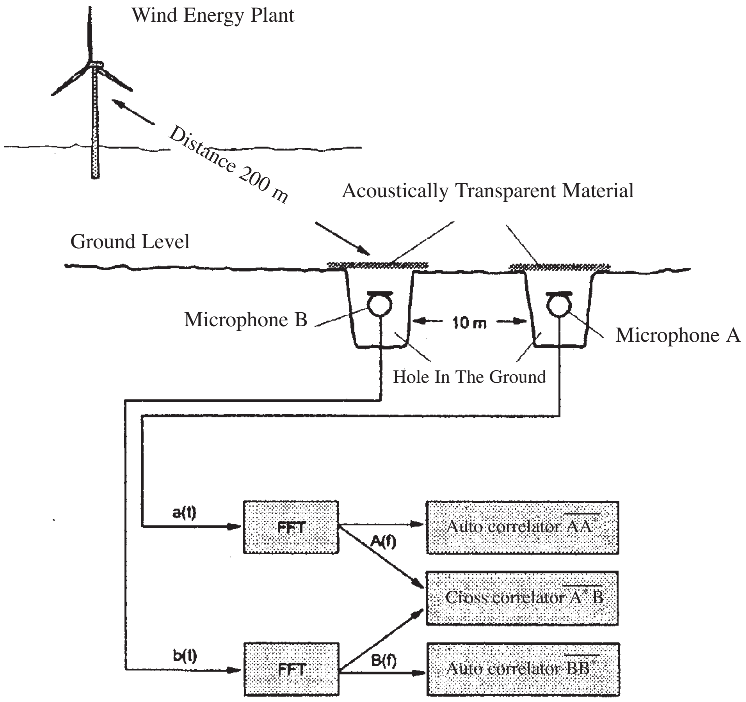


Figure 2. Illustration of measurement technique with two 'buried ' microphones and cross correlation technique, from Betke & Remmers [11].

The first measurements [9] dealt with both a traditional 500kW three-bladed upwind wind turbine (Vestas V39) and a one-bladed downwind machine with 640kW rated power and 56m rotor diameter (MBB Monopteros 50). It appears that the measurement results in the thesis are not consistent with later findings, especially the levels reported for the three-bladed turbine are considerably higher than expected at all frequencies, so it is suggested that an error can have been made in the analysis or data treatment [13]. In a following paper [10], measurements of the Monopteros 50 are shown together with measurements from another three-bladed upwind machine, an Enercon E-40. In [10] both measurements where the cross correlation technique had been used and measurements with only one microphone and autocorrelation technique are shown, and it is seen that there is no significant improvement from the cross correlation technique at the harmonics of the blade passing frequency. Another paper [11] shows slightly different measurement results from the Enercon E-40 and compares these to other noisy environments such as inside a car or in an office.

Finally, [12] briefly mentions a measurement of a 1,65MW Vestas V66, where more details have been informed by [13], who also has mentioned a recent series of measurements of an anonymous 2MW turbine.

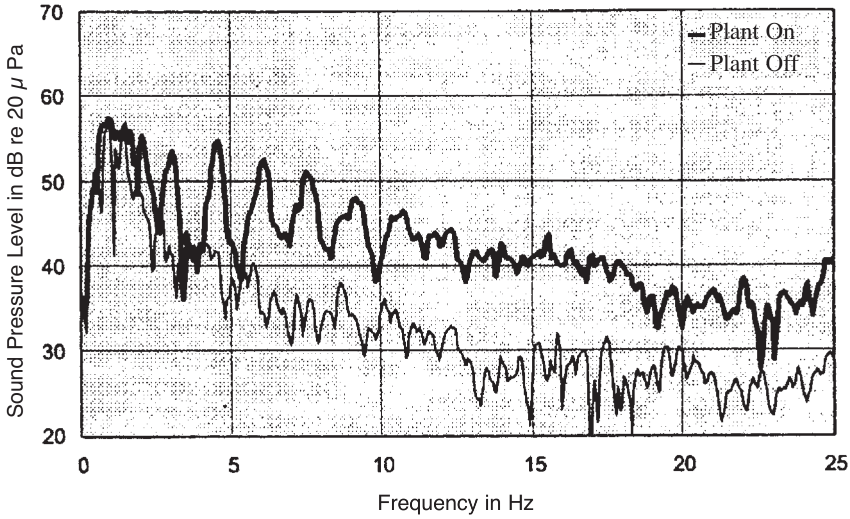


Figure 3. FFT-spectrum of the sound pressure level 200m from an Enercon E-40. The thin line indicates the background level, measured with the wind turbine turned off: From Betke & Remmers, [11].

2.2 Snow, on a contract for ETSU

A comprehensive series of vibration and low frequency noise measurements was carried out in the neighbourhood of a modern wind farm in the UK, [15 - 17]. The noise measurements took place with traditional measuring equipment, where a correction of the frequency response allowed for measurements down to 0.7 Hz. It proved necessary in order to reduce the wind-induced background noise in the microphones to locate the microphone so that it was sheltered from the wind by vegetation, wind breaks etc, and to reduce the microphone height to 0,5 - 1m above ground level. The measurements were averaged over 2 minutes each and were analysed in 1/24-octave bands, which clearly revealed several of the harmonics of the blade passing frequency.

In the report [15] measurements in four positions are described. N1 was located in the middle of a cluster of four turbines with a distance of 100 - 200m to each of them, N2 was outside the cluster about 80m from the nearest turbine and 250 - 500m from the other three, while N3 and N4 were 400 - 800m and 1000 - 1200m respectively from the four turbines. The wind farm consisted of still more turbines placed further away. Various combinations of the turbines were turned on and off to allow for, among others, correction for background level, however the report gives no consistent data of background noise level in the four positions. The wind turbines were of the make Bonus with a rated power of 450kW and 35m rotor diameter. A paper [16] gives a summary of the observations form the report. Here it is mentioned that the tones - the harmonics of the blade passing frequency in the infrasound region - were subjectively audible in the measurement positions, on occasions, out to 800m. One of the authors has stated that this was not actually the case; rather it was the modulated rotor sound at higher frequencies and not the infrasound that could be heard [17] .

2.3 Paper by Shepherd and Hubbard

In [8] a number of measurement results from various American wind turbines are shown. The measurement conditions are not mentioned in the paper, and the background noise is not specified for any of the measurements. The results are given in the form of either a typical narrowband spectrum measured near a turbine, or a range of third octave band spectra measured at (or calculated for) distant locations. The third octave band spectra are shown from 100 Hz down to between 5 and 12,5Hz, but in the comparison here mostly measurements with data down to 5 or 6,3Hz are considered.

There are measurements from, among others, the following wind turbines:

- General Electric MOD-l, 1500 - 2000kW, 61m rotor diameter, 2 blades downwind
- Hamilton Standard WTS-4, 4200kW, 79m rotor diameter, 2 blades downwind
- Boeing MOD-5B, 3200kW, 98m rotor diameter, 2 blades upwind
- US Wind Power USWP-50, 50kW, 18m rotor diameter, 3 blades downwind
- WTS-3, 3000kW, 78m rotor diameter, 2 blades downwind.

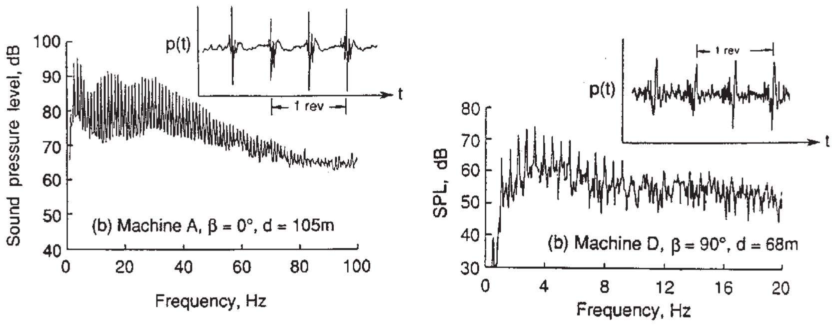


Figure 4. Example spectra and time traces of the sound pressure for MOD-I (left, a downwind turbine) and MOD-5B (right, an upwind turbine), from Shepherd & Hubbard, [8].

3. COMPARISON

To allow easier comparison between the different findings on infrasound emission the G-weighted infrasound level [18] has been calculated on the basis of the various reported or published measurement results. None of the measurement sessions mentioned here has reported consistent data for the background sound level, so it has not been possible to correct for the background noise in a comparable manner. Where the narrowband spectra were given, the harmonics of the blade passing frequency could be discriminated form the broadband background noise. Here the infrasound level was calculated by weighting and summing only the levels of the harmonics - this procedure was used in most of the examples. It is expected that the error due to background noise is not severe in these cases. In the remaining examples, where the third octave bands were used for the calculations, the infrasound levels are probably overestimated to some degree due to wind-induced background noise.

Table I below gives the main results of these calculations.

The operating conditions of the different wind turbines are not immediately comparable, and for the measurements in [8] no specifications are given at all, though it can safely be assumed that the wind speed would have been in the interval between cut-in and power limitation.

At higher frequencies, it is a frequent observation that the A-weighted noise level from a stall- regulated wind turbine, operated below power limitation, varies by about 1 dB per 1 m/s wind speed change. Pitch-regulated turbines may show less wind speed dependence, and turbines with variable RPM have a higher wind speed dependence. The wind speed dependence of low frequency wind turbine noise or infrasound is not known, but from simple considerations of the noise-producing mechanisms it would be expected to be less than at higher frequencies. On the other hand, the measurement results given by [13] show exactly a dependence of 1 dB (G) per 1 m/s.

In comparing the different measurement results, some regard must be paid to the uncertainty due to (at least) the following causes: background noise mainly due to wind, where the results from [8] are possibly overestimated by several dB and the

Table I. Summary of infrasound measurements on wind turbines

Wind Turbine	Rated power	Distance	Infrasound level	Conditions	Ref.
Monopteros 50	640kW	200m	84 dB (G)	11 m/s	[10]
Enercon E-40	500kW	200m	56 – 64 dB (G)	8 m/s	[10, 11]
Vestas V66	1650kW	100m	70 dB (G)	(723 kW)	[12, 13]
(Anonymous)	2000kW	200m	59 dB (G)	6 m/s	[13]
-	-	200m	65 dB (G)	12 m/s	-
Bonus	450kW	80m	65 dB (G)	9 m/s (4 turb.)	[15]
-	-	100m	71 dB (G)	8 m/s (1 turb.)	-
-	-	200m	63 dB (G)	10 m/s (1 turb.)	-
-	-	100 – 200m	70 dB (G)	9 m/s (4 turb.)	-
-	-	(n.a.)	67 dB (G)	Background, 9 m/s	-
MOD-1	2000kW	105m	107 dB (G)		[8]
-	-	1000m	73 - 75 dB (G)		-
WTS-4	4200kW	150m	92 dB (G)		-
-	-	250m	83 - 85 dB (G)		-
MOD-5B	3200kW	68m	71 dB (G)		-
USWP-50	50kW	500m	67 - 79 dB (G)	(14 turbines)	-
WTS-3	3000kW	750m	68 dB (G)		-
-	-	2100m	60 dB (G)		-

remaining results may be expected to have an uncertainty of some dB; and operating conditions, where a general uncertainty of some dB is likely.

It seems fair to summarize the findings for the infrasound level as a rough estimate, that the level from an upwind turbine of contemporary design at 100m distance would be about 70 dB (G) or lower, while the level from a downwind machine can be 10 - 30 dB higher. It is evident that these figures can be subject to change due both to design parameters and operating conditions of the wind turbine, and they also depend on the measurement conditions.

4. EVALUATION AND ASSESSMENT OF INFRASOUND FROM WIND TURBINES

4.1 Basis for assessment

Usually the noise from wind turbines is assessed based on the A-weighted noise level that is measured or predicted in positions representative of the nearest dwellings or other noise sensitive areas. Several countries have national procedures and directions for assessment of wind turbine noise. Sometimes the C-weighted level, or the difference between the A- weighted and the C-weighted level, is used as an indicator of low frequency noise both for wind turbine noise and for other types of noise. It is debatable if this use of the C-weighting correction would have any relation to the way low level low frequency noise is subjectively perceived or heard, since it is well known that there is no similarity between the (inverted) C-weighting curve and the hearing threshold or the equal loudness contours at low levels in the low frequency range. Furthermore, the tolerances upon the C-weighting network in sound level meters extend to -4 dB below 20 Hz, as is also the case for the A-weighting network, so the C-weighting filter is not well defined in the infrasound region.

In this connection, however, only the infrasonic frequency range below 20 Hz is considered, and here the G-weighted infrasound level would be used as an obvious basis for assessment. It is a particular quality of infrasound that there is a very narrow dynamic range between a level that is just audible (about 100 dB (G)) and one that is very loud (120 dB (G)). Furthermore it appears that the spread between individual hearing thresholds in the infrasound region is of the same size as at higher frequencies, corresponding to an s. d. of about 5 dB. Thus it cannot be excluded that an infrasound which is inaudible to one person is loud and annoying to another. The recommended limit for environmental infrasound in dwellings in Denmark is 85 dB (G), this is about 10 dB below the average hearing threshold. The limit applies to the indoor level, measured according to a procedure designed to ensure that local minima due to standing waves do not excessively affect the results, [19] .

All the measurements of infrasound from wind turbines that are mentioned in the previous section are measured outdoors. For a comparison between the measurement results and the criterion mentioned, first the measurement results have to be converted or corrected from the measurement distance to a distance that can represent the nearest dwellings. Secondly the converted noise levels must be corrected so they represent indoor levels.

4.2 Propagation of infrasound

From a basic point of view, infrasound propagates like sound at higher frequencies. The level decreases with distance due to spherical divergence with 6 dB per distance doubling. It is mentioned in some references, including [8], that the distance attenuation at very low frequencies would not be 6 dB but only 3 dB per distance doubling due to atmospheric refraction and channelling of sound in the lower atmosphere. This phenomenon is described in other works, including presentations on propagation of wind turbine noise such as [20], and is not particular to low frequencies but rather to the atmospheric conditions that may cause channelling of sound, such as temperature inversion or special conditions related to sound propagation over water.

The propagation phenomena that are known to change the spectral balance at higher frequencies are generally not in play in the infrasound range:

- The atmospheric absorption causes a pronounced extra attenuation at the highest frequencies, but has a negligible influence on the attenuation below a few hundred Hertz
- The ground effect causes a characteristic ‘dip’ typically in the frequency range between some hundred Hertz and up to almost 1 kHz due to partial cancelling between the direct and the reflected sound path. This effect is not relevant at lower frequencies since the impedance of all normal ground surfaces below 20 Hz corresponds to that of an acoustically hard terrain. Besides, the ground effect is not very pronounced for tall noise sources such as wind turbines, [21].
- Screening by obstacles between the sound source and the receiver is largely proportional to the detour caused by the obstacle, measured in wavelengths. Since the wavelength in the infrasound region is extremely long, screening has hardly any effect in this frequency range.

In conclusion it can be said for certain that the sound level decreases with increasing distance. Also it is expected that the spectral balance in the infrasound range will not change much due to propagation phenomena, which at higher frequencies would cause some parts of the frequency range to be attenuated more than others.

4.3 Indoor noise level

Traditionally building and room acoustics deal with the frequency range between 100 Hz and a few kHz. Little is known about transmission of sound through building elements and the properties of building materials at very low frequencies, and it is not conceivable that the usual room acoustics models would apply in the infrasonic range.

Some attempts have been made to establish a relation between an outdoor and the corresponding indoor sound level based on purely empirical observations. Reference [22] describes a method for assessment of low frequency noise from high speed ferries, where first the outdoor noise level is calculated and next the indoor noise level is found by use of a standardised outdoor-to-indoor correction term. The latter was based on a series of measurements in buildings estimated to be typical Danish suburban dwellings with a sea view. The measurements and hence the corrections are based on octave bands and are shown in Table II.

Some later measurements in typical town centre houses have shown larger outdoor-to-indoor corrections, also at the lowest frequency bands.

In [8] some measurements of the difference between outdoor and indoor noise

Table II. Outdoor-to-indoor correction in typical Danish suburan dwellings with a sea view. From [22]

Octave band	16 Hz	31,5 Hz	63 Hz	125 Hz
Level difference	3 dB	3 dB	12 dB	18 dB

levels are mentioned. Here it is stated in broad terms that there exists a minimum around 10 Hz, where the sound level difference is very small, and above which the level difference increases by 6 dB per octave (the sound reduction is controlled by the mass per unit area of the walls). As the frequency decreases below the minimum, the level difference increases again. In conclusion it can be said that the outdoor-to-indoor correction may be quite small in a part of the infrasound range, but it is unlikely to become negative, which would imply a higher level indoors than out of doors. Assuming an outdoor-to-indoor correction in the infrasound region of 0 dB thus would appear to be on the safe side.

4.4 Assessment of infrasound

The rough summary of the data from Table I can be combined with the observations made above on propagation of infrasound and its transmission into buildings. It can then be seen that even in positions very close to an upwind turbine, the indoor infrasound level is expected to be far below the Danish recommended limit for environmental infrasound, 85 dB (G). On the other hand it can be noted that the infrasound from downwind turbines may be expected to violate this assessment criterion in buildings in a distance out to several hundred metres. With the size of the wind turbines in question, it is not likely that people would live much closer to the turbines than some hundred meters. From Table I it is noted, however, that the infrasound level from even the most powerful of the infrasound generators, MOD-l, is reduced well below the criterion at lkm distance.

5. DISCUSSION, OTHER POSSIBLE ASPECTS OF WIND TURBINE NOISE

It would appear from the explanations given above that infrasound alone is hardly responsible for the complaints that are mentioned in [8] from people living up to two km from the large downwind turbines. In this section some other explanations of the adverse public reactions are discussed.

5.1 Vibration

In [8] two different means for the assessment of low frequency noise from wind turbines are described. One is a comparison between the sound spectrum (of the outdoors sound level) and the average perception threshold, which is given down to 16Hz. This reveals which part of the frequency range can be heard by an average person. The other is an evaluation of whether the acoustically induced vibrations of wall elements or window panes exceed the threshold for tactile perception of vibration. In many of the cases shown the vibration threshold is exceeded at the very lowest frequencies, while the threshold of audibility in every case is exceeded at the higher end of the frequency range considered. It is debatable if tactile perception of vibrations of walls or windows would be regarded as a cause for major annoyance or dissatisfaction since people do not normally touch or rest on these surfaces. However the vibrations can cause windows and decorative artefacts on walls and shelves to rattle, and the rattle may disturb or annoy the inhabitants.

It is an established practice in the assessment of blast sounds from artillery ranges to consider not only the strength or the loudness of the blast but also the possibility that the impulsive low frequency sounds cause rattling, [23]. It is mentioned that the sounds exceed a certain level to evoke rattling. This is given as an explanation why the annoyance from blast sounds increases more rapidly with level than the annoyance from sounds with higher frequencies, such as sounds from hand weapons, which are not capable of producing rattle. It is not possible to conclude from the data in [8] if the sound levels were so high that they might evoke rattling, but it is estimated rather unlikely.

5.2 Low frequency sound

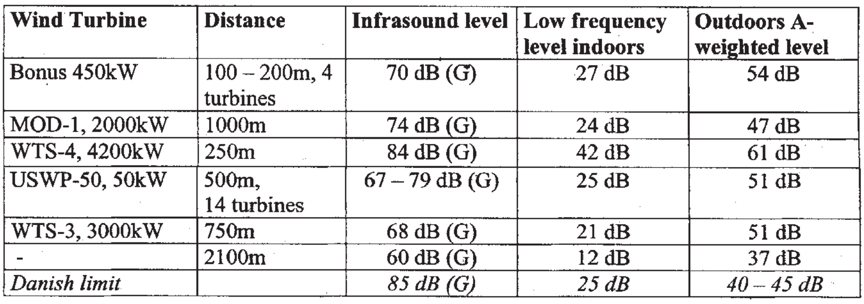
Another possible explanation of the public reaction would focus on the low frequency noise, in the range 10 - 160 Hz. The papers surveyed here give no consistent information about the noise from the turbines in this frequency range, and again the data on background noise levels are missing. The reason for the interest in the slightly higher frequencies is the observation that the upwind turbines exhibit a limited number of harmonics of the blade passing frequency in their acoustic signature, while the downwind turbines show a long line of harmonics, reaching out above infrasound range.

The G-weighting function is not suited for assessment of low frequency sounds outside the infrasound range, since it rolls off steeply from 16 Hz. In Denmark the A-weighted level of the sound in the frequency range 10 - 160 Hz indoors is used to assess low frequency noise [19, 22]. The indoor A-weighted low-frequency sound level has been estimated for some of the measurements described here by first estimating the noise levels in the frequency range mentioned and secondly applying the corrections from Table II. Considerable care must be taken with these figures since neither the measurement nor the propagation conditions are known in sufficient detail, and since the influence from microphone placement cannot be neglected in this frequency range. It is still believed that the estimates for the indoor low frequency level shown in Table III below would suggest at least an order of magnitude. The levels are compared to the Danish recommended limit for dwellings in the evening and the night, which is 25 dB, and it can be seen that this limit is severely violated by the WTS-4 turbine (2-bladed downwind machine), and is just violated by the four Bonus turbines measured at close range.

5.3 Usual A-weighted sound level

One final thought relates to the usual A-weighted sound levels from these turbines. Some information on the A-weighted level is directly given in [8, 15] and this is also shown in Table III below. The A-weighted levels are expected to be rather reliable, and the uncertainty can be assumed less than the uncertainty on the infrasound levels. When the A-weighted levels are compared to the Danish noise limits for wind turbines, which are 40 dB(A) for dwelling areas and 45 dB(A) for single dwellings in the countryside, both measured out of doors, it is seen that both the criteria are violated in most of the cases. Consequently, a simple assessment of the "normal" wind turbine noise suggests a fair explanation of the adverse public reaction mentioned in [8].

Table III. Comparison between the infrasound level (in dB (G) measured or calculated outdoors), the low frequency sound level (in dB (A) for the frequency range 10- 160 Hz, estimated indoors level), and the outdoors A-weighted level to the corresponding recommended Danish noise limits.



Wind Turbine	Distance	Infrasound level	Low frequency level indoors	Outdoors A-weighted level
Bonus 450kW	100 – 200m, 4 turbines	70 dB (G)	27 dB	54 dB
MOD-1, 2000kW	1000m	74 dB (G)	24 dB	47 dB
WTS-4, 4200kW	250m	84 dB (G)	42 dB	61 dB
USWP-50, 50kW	500m, 14 turbines	67 – 79 dB (G)	25 dB	51 dB
WTS-3, 3000kW	750m	68 dB (G)	21 dB	51 dB
-	2100m	60 dB (G)	12 dB	37 dB
Danish limit		*85 dB (G)*	*25 dB*	*40 – 45 dB*

6. CONCLUSION

From a critical survey of all known published measurement results of infrasound from wind turbines it is found that wind turbines of contemporary design with the rotor placed upwind produce very low levels of infrasound. Even quite close to these turbines the infrasound level is far below relevant assessment criteria, including the limit of perception. Such low infrasound levels are unimportant for the evaluation of the environmental effects of wind turbines.

Wind turbines with a downwind rotor generate considerably higher infrasound levels, which may violate relevant assessment criteria in distances up to several hundred metres. At longer distances the level drops below these criteria, and it is questioned if the infrasound can be the objective cause of negative public reactions to large downwind turbines.

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