Fourth International Meeting

on

Wind Turbine Noise

Rome, Italy, 12 – 14 April 2011

The assessment of low frequency noise and amplitude modulation of wind turbines

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Abstract

As wind turbines are getting larger and their rated power higher, more concern should be allocated on low frequency noise and amplitude modulation of wind turbine noise. So far these noise components of wind turbines and their adverse effects on nearby residents are underestimated or even ignored by local authorities. However, reports of residents living in the vicinity of wind turbines suggest that low frequency noise along with amplitude modulation are perceived as the most annoying noise emitting from wind turbines.

By this day, almost all existing regulations of noise measurements of wind turbines use the A-weighted noise level in sound power estimates. This leads to underestimation of noise annoyance of large modern wind turbines. Additional noise indicators are needed for measuring the noise of wind turbines to minimize the problem. The same indicators should be used for assessing the noise at immission points near wind turbines.

In this paper, a short overview of low-frequency noise and amplitude modulation of wind turbines is presented. The use of A-weighting as a wind turbine noise indicator is analyzed and evaluated. Finally, improved noise indicators for assessment of low-frequency noise and amplitude modulation of wind turbine noise are suggested and evaluated.

Introduction

While the trend of modern wind turbines is towards larger and more powerful facilities, more complaints about low-frequency noise and amplitude modulation is emerging from residents living in the vicinity of modern wind turbines [1,2]. The complaints often describe wind turbine noise as “swishing”, “thumping” or “low-frequency hum”. These descriptions are a result of spectral and temporal characteristics of wind turbine noise. Low frequency noise and amplitude modulation are the main sources of these characteristics.

Amplitude modulation

Amplitude modulation, also described as “swooshing” or “thumping” sound is the most recognizable sound character of wind turbine noise. It is also perceived as most annoying.

The angle of attack of wind plays an important role in the action of wind turbine noise generation. This occurs especially at atmospheric inversion situations, where the wind speed gradient increases upwards from the ground level. This is illustrated in Figure 2, where wind speed and air temperature gradient of neutral and stable atmospheres are displayed.

Recent research work suggests that the varying angle of attack of incoming wind caused by the wind shear is the main source of amplitude modulation of wind turbine noise [3]. Depending on the blade profile, the angle of attack has an optimal value related to the generated lift of the blade, as illustrated in Figure 1. If the angle is differed from its optimal value, the turbulent boundary layer on the low pressure side of the blade grows, decreasing power performance and increasing sound level.

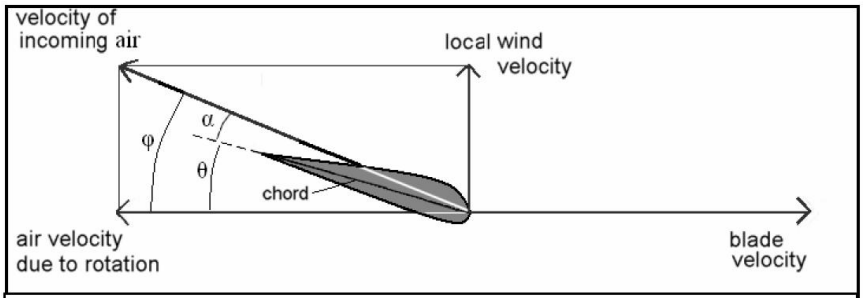


Figure 1. Flow impinging on a turbine blade with flow angle φ, blade pitch angle θ and angle of attack $\alpha = \varphi - \theta$ [3].

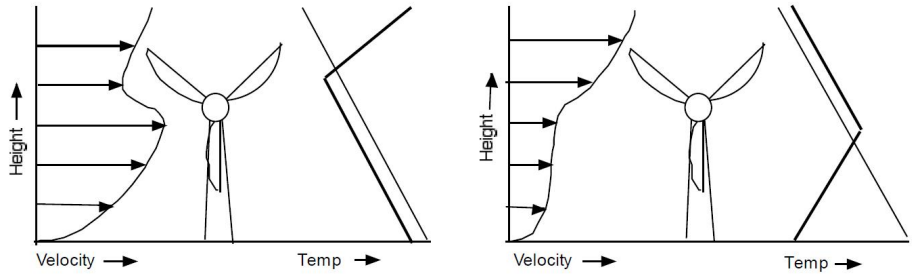


Figure 2. Neutral atmosphere near the ground with stable atmosphere above (left); stable atmosphere near the ground with neutral atmosphere above (right.) Wind velocity and temperature distributions indicated. [3].

Because the blade length of modern wind turbines can be more than 60 meters, the difference in wind speed at different blade positions can be several meters per second. As wind speed varies in different blade positions, also the angle of attack varies resulting periodic fluctuation in the generated sound level. Therefore growing the size of wind turbines and the diameter of their blades may yield increasing problems with amplitude modulation.

Low-frequency noise

Sound is considered as low-frequency sound, when the frequency range varies from 20 Hz to 150 Hz. The sound properties of wind turbines are given as the apparent sound power levels. The spectrum of the apparent sound power level of a modern 2 MW wind turbine is shown in Figure 3. The level difference between unweighted and A-weighted apparent sound power level is more than 14 dB. Typically, the noise is considered to be low-frequency noise if the level difference between the C- and A-weighed level exceeds 20 dB [4]. Although the criterion is not met in the example, it gives indication of the frequency content of modern wind turbines.

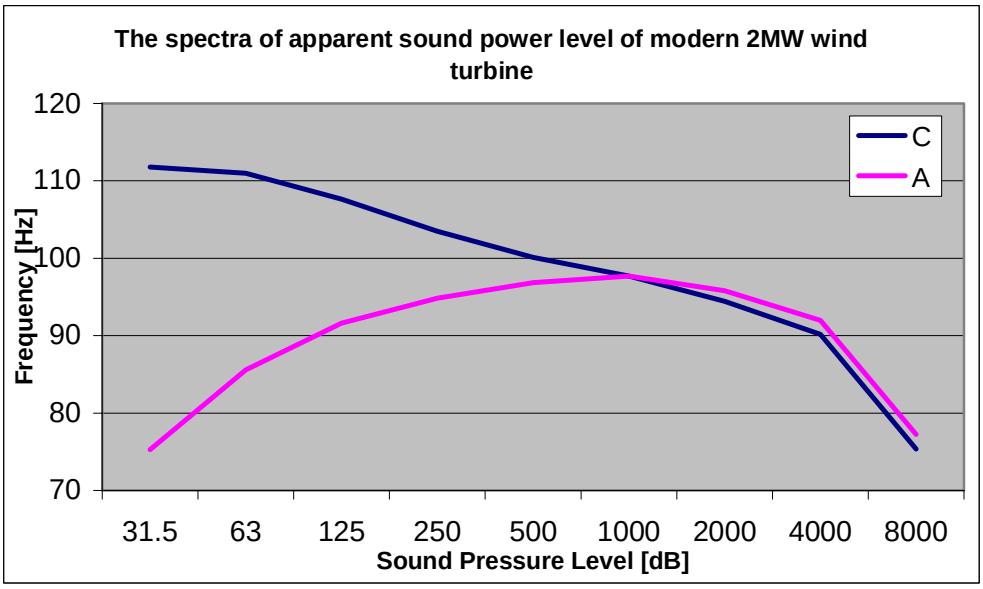


Figure 3. The spectra of apparent sound power level of modern 2MW wind turbine.

The noise annoyance concerning the low-frequency noise of the wind turbines mainly consists of two factors. These are atmospheric sound absorption and noise insulation of residential dwellings [5]. Due to the atmospheric conditions, the low-frequency sound is attenuated considerably less than high-frequency sound while the sound propagates in the air. For example the theoretical atmospheric sound absorption at 2000Hz at one kilometer distance is 9 dB, but at 100Hz the attenuation is negligible [6]. Practically this means that in typical distance between the wind turbine and residential dwelling, the spectra of the wind turbine emitted noise increases towards low-frequencies. Also these low-frequencies are penetrated more easily into residential dwellings, because sound insulation of the dwellings is limited in the low-frequencies. This can be seen from Figure 5, where the sound insulation of typical Danish dwelling is displayed.

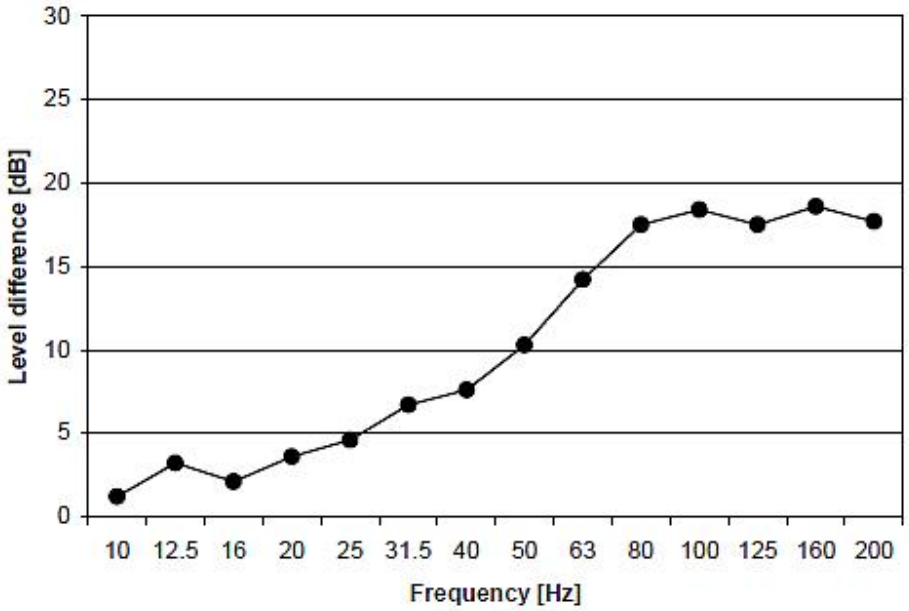


Figure 4. Sound insulation of typical Danish dwellings [10].

Amplitude modulation of low-frequency noise

There has been some debate whether low-frequency noise is audible indoors near wind turbines. There are residents living in the vicinity of wind turbines who complain of low-frequency noise whereas audio experts try to measure the low-frequency noise indoors to conclude whether it is audible or not. Since humans perceive static noise as less annoying than fluctuating noise [7], a potential explanation to annoyance of low-frequency noise could be amplitude modulation which seems to extend to low frequencies [8]. This can be seen in Figure 5, where the spectrogram of the measured noise of a wind turbine is displayed. It seems that amplitude modulation starts from as low as 40 Hz. Frequencies this low penetrate average houses more easily than higher frequencies (see Figure 4), which seems to support this theory. However, more research and measurements have to be done to confirm this. Note that in Figure 5, the sound level in the spectrogram is A-weighted, which gives a false impression of the sound level of amplitude modulation at lower frequencies. Despite of that the low frequency amplitude modulation can be observed in this picture.

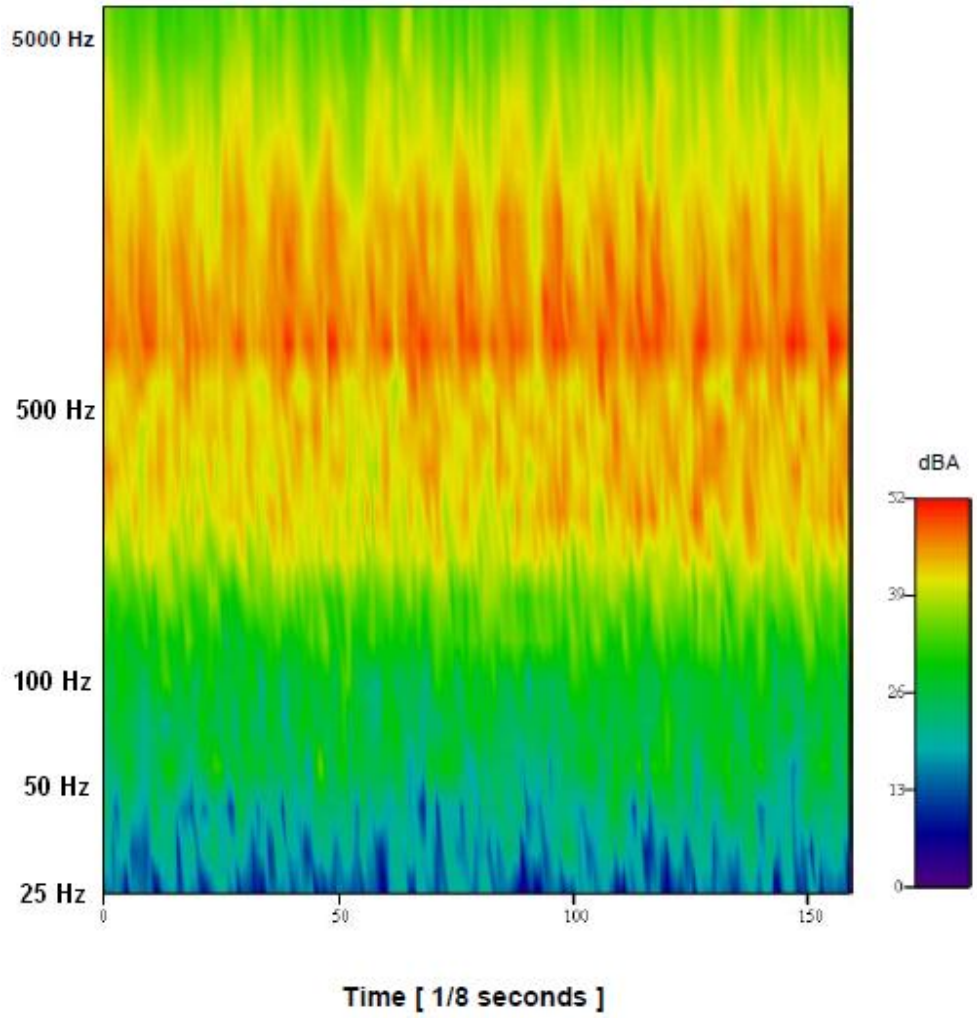


Figure 5. The spectrogram of wind turbine noise near the wind turbine [8]

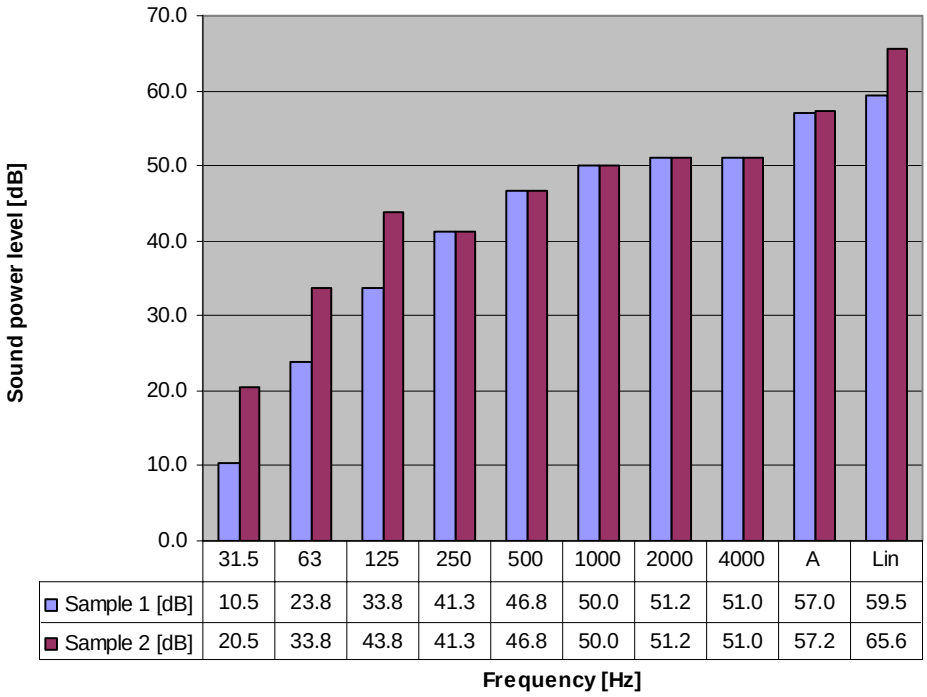
Wind turbine noise and A-weighted sound level

There are various immission regulations concerning wind turbine noise throughout the world. In practice the compliance with the noise limits is calculated by either the use of A-weighted sound power level delivered by the manufacturers of wind turbines or measured A-weighed apparent sound power level of wind turbine in situ. The problem of the arrangement is that the A-weighted sound power level nor the A-weighted sound immission level are not descriptive enough to assess the noise of wind turbines. As pointed out in the previous clause, this is because of the spectral and temporal characteristics of wind turbine noise. Some listening tests have indicated that spectral and temporal characteristics of a sound source can be audible, even if the sound level from the wind turbine is lower than the ambient noise level, [8, 9].

It must also be noted that when comparing small and large wind turbines, the relative increase of low-frequency noise with large wind turbines is somewhat

higher than the increase of A-weighted sound level [10]. This is likely to increase the annoyance of wind turbine noise. Also, because in A-weighting the lowest frequencies are heavily filtered out, the present noise limits for wind turbines are misused when low frequency content is increasing in large wind turbines [11].

A simple example of low-frequency filtering using the A-weighted total sound level is displayed in Figure 4, where sample noise spectrums are compared. The first sample has an unweighted sound level of 50 dB in each one-third octave bands and the second sample is similar to the first sample but the level at one-third frequency bands of 31.5 to 125 Hz is 10 dB higher. While the sound level difference in lower frequencies is dramatic, the level difference between A-weighted total sound levels is negligible.



	31.5	63	125	250	500	1000	2000	4000	A	Lin
Sample 1 [dB]	10.5	23.8	33.8	41.3	46.8	50.0	51.2	51.0	57.0	59.5
Sample 2 [dB]	20.5	33.8	43.8	41.3	46.8	50.0	51.2	51.0	57.2	65.6

Figure 6. Example of the effect of A-weighted overall level difference of two samples where other sample is 10 dB louder on frequency range of 31.5 – 125 Hz.

This fact has a direct impact on residents living in the vicinity of large wind turbines because these wind turbines are located within the noise immission level regulations. Since larger wind turbines emit higher noise levels at low frequencies while their A-weighted overall level remains the same relative to their size, residents are exposed to higher levels of low frequency noise. Therefore it is important to pay attention to this, or increasing amount of complaints about low frequency noise of wind turbines are to be expected in the future.

For better understanding of the problem at hand, an imaginary situation of the effect of increasing low-frequency noise of immission limits is presented: By

using the measured apparent sound power level of a modern wind turbine (See Figure 3) and 40 dB noise immission limit it is possible to calculate the theoretical minimum distance of 443m between the wind turbine and a residential dwelling. By increasing the level of the octave band levels 31.5, 63 and 125Hz of the wind turbine by 3 dB, the A-weighted sound pressure level at the immission point is only increased by approximately 1 dB, thus increasing the minimum distance only by 27 meters (6% more). But if the same immission level assessment is performed using C-weighted levels, the minimum distance is increased by 170 meters (38% more).

Low-frequency noise, amplitude modulation and noise immission limits

If using only A-weighting in immission level calculations, both low-frequency noise and amplitude modulation at the immission point are neglected. In fact, the annoyance and possible adverse health effects of low-frequency noise and amplitude modulation are likely to increase in the future even more. This is because the increase of the calculated minimum distance between the wind turbine and the residential dwelling is relatively smaller. If low-frequency noise and consequently amplitude modulation of modern wind turbines is taken into account in noise immission calculations, the minimum distance between the wind turbine and the residential dwelling should be relatively larger than the increase of A-weighted noise emission per kW of generated power. The use of C-weighting as an improved noise indicator for wind turbine noise would solve this inconsistency.

Conclusions and discussion

The noise from wind turbines is perceived as annoying by the residents living in the vicinity of wind turbines. This is because of spectral and temporal characteristics of wind turbine noise. Amplitude modulation and low frequency noise are the main sources for these characteristics.

The noise from wind turbines is being measured and described with A-weighted overall sound level L_{Aeq}. Because of the characteristics of wind turbine noise, this is not a sufficient indicator because it does not indicate how much temporal variations and low frequency noise the measured signal contains.

As wind turbines are still getting larger and their rated power higher, the number of complaints of wind turbine noise is also quite likely to be increased. This is because the used apparent sound power level $L_{WA,k}$ is emphasized for large wind turbines. In wind turbine noise for community response assessment, the sound levels at immission points are calculated with modern noise propagation models using the apparent sound power level $L_{WA,k}$ of the wind turbine as a basis. No estimation of low-frequency noise or amplitude modulation is being made in immission point, thus greatly increasing the risk of noise annoyance and adverse health effects from noise on residents living near wind turbines.

This inconsistency could be solved using improved noise indicators. However, the noise indicator should be chosen carefully because it has to meet three important requirements:

- Simple enough that it can be calculated with existing sound level meters and therefore does not require any hardware upgrading.
- Cannot be misused in a way that some of the harmful noise aspects could be neglected.
- The existing noise immission level regulations in countries would not need to be dramatically modified.

A noise indicator which takes account low-frequency noise and consequently amplitude modulation of modern wind turbines would be C-weighted total sound pressure level L_{Ceq}. However, since practically all noise immission regulations are based on A-weighted total sound pressure level L_{Aeq}, this noise indicator may not be the optimal for this purpose.

Perhaps the most potential noise indicator which fulfills all the requirements would be additional correction level on wind turbine noise which is based on the difference between C- and A-weighting, $L_{Ceq\text{-}Aeq} = L_{Ceq} - L_{Aeq}$. However, it must be noticed that this noise indicator must be calculated in the immission point, not in emission point.

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