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Noise annoyance of wind turbines

Authors: Denis Siponen

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Summary

A growing percentage of residents living in the vicinity of wind turbines perceive wind turbine noise annoying and hard to get used to. This is because of spectral and temporal characteristics of wind turbine noise. Low frequency noise and amplitude modulation are the main reasons for the annoyance.

The noise from wind turbines is being measured and described with A-weighted overall sound pressure level L_{Aeq}. Because of the characteristics of the wind turbine noise, it is not a sufficient noise indicator. It does not indicate how much temporal variations the measured signal contains. In L_{Aeq} the lowest frequencies are also heavily filtered out.

There has been discussion if some of the psychoacoustic descriptors should be used to quantify wind turbine noise. The most potential psychoacoustic descriptors would be loudness and fluctuation strength to quantify the perceived noise level and amplitude modulation of wind turbine noise. Based on the results of listening tests, it seems, however, that none of the psychoacoustic descriptors can explain the differences in annoyance response. Fluctuation strength is neither a valid measure for amplitude modulation since its designed scale is too large for noise which fluctuates 1 – 8 dB.

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Tampere

Written by	Reviewed by	Accepted by
Denis Siponen Research Scientist	Hannu Nykänen Senior Research Scientist	Johannes Hyrynen Deputy Technology Manager

VTT's contact address
P.O. Box 1000, 02044 VTT

Distribution (customer and VTT)
VTT

Preface

The work described in this report has been carried out at VTT Industrial Systems, in Smart Machines knowledge centre as a part of the VTT funded research project “Wind power plants - knowledge increase of noise and control issues” (WPPNoCo). The results of the report have been obtained mainly through a literary survey summarising results of recent studies and drawing conclusions adaptable to Finnish circumstances.

The work in this report is related to noise annoyance from wind turbines. According to the study low frequency noise and amplitude modulation are the main reasons for the noise annoyance.

The noise from wind turbines is being measured and described with A-weighted overall sound level L_{Aeq}. Because of temporal variations, and high low-frequency content, this is not sufficient enough as the only noise indicator.

There has been discussion if some of the psychoacoustic descriptors should be used to quantify the wind turbine noise. The most potential psychoacoustic descriptors are loudness and fluctuation strength to quantify the perceived noise level and amplitude modulation of wind turbine noise. Based on the results of listening tests, it seems, however, that none of the psychoacoustic descriptors can explain the differences in annoyance response. Fluctuation strength is neither a valid measure for amplitude modulation since its designed scale is too large for noise which fluctuates 1 – 8 dB.

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Denis Siponen

e-mail: denis.siponen@vtt.fi

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1 Introduction

This work is a part of the work done in the VTT funded project WPPNoCo (Wind power plants – knowledge increase of noise and control issues). The main goal of the project is to increase basic knowledge of the noise annoyance and control issues related to wind power plants.

2 Goal

There are two goals in this work. The first goal is to determine the nature of noise of wind turbines in terms of noise annoyance. The second goal is to increase the knowledge of noise annoyance of wind turbines.

3 The nature of noise of wind turbines

Noise of wind turbines is one of the main arguments against wind turbines. Residents living in the vicinity of wind turbines or wind farms claim that wind turbine noise is annoying and hard to get used to. Noise of wind turbines is being described with terms “swishing”, “thumping” and “low-frequency noise”. It is also described as “airplane that never leaves” or “train that never ends”. Numerous articles also indicate that noise of wind turbines exposes to adverse health effects, most commonly sleep deprivation and increased blood pressure [1, 14]. For example in Norway, while the typical distance between wind turbines and residential dwellings is 700 – 1000 m, there have been reports of mild and severe sleep deprivation when distance of wind turbine from the residential dwellings is 3 km and 300 m respectively [1, 2].

There are various noise limits concerning wind turbine noise throughout the world. Noise limits are mostly based on the use of the A-weighed apparent sound power level delivered by the manufacturer of wind turbines or measured A-weighed apparent sound power level of wind turbine in situ. Sound power level is used as the basis for immission level calclulation and assessment. The problem of the arrangement is that the A-weighted total sound power level does not describe the noise of wind turbines well enough. This is due to the spectral and temporal characteristics of wind turbine noise. There are publications where listening tests have shown that even if the sound level from a wind turbine is less than the ambient noise level, spectral and temporal characteristics of the sound make the noise often audible [3, 18]. In wind turbine noise the spectral and temporal characteristics are primarily low-frequency noise and noise from amplitude modulation.

3.1 Low frequency noise

Over the years there has been a wide discussion about infrasound and low frequency noise of wind turbines. The discussion is quite polarized as the residents living near wind turbines are complaining about low frequency noise and on the other hand professionals claim that low frequency noise and especially infrasound is not a problem with wind turbines [4]. It seems that in some countries low frequency content of noise of wind turbines and its adverse effects on nearby residents are underestimated or even ignored by the local authorities [11].

3.1.1 Infrasound

Infrasound is sound that occurs at a frequency below that is generally considered to be detectable by human hearing. As can be seen from Figure 1, sound is considered as infrasound, if the frequency is below 20 Hz. There are various ways to define the magnitude of infrasound. When the infrasound of wind turbines is being measured, ISO specified G-weighting is used [5]. G-weighted sound levels of 85 dBG and lower are not sufficient to create human perception. [7].

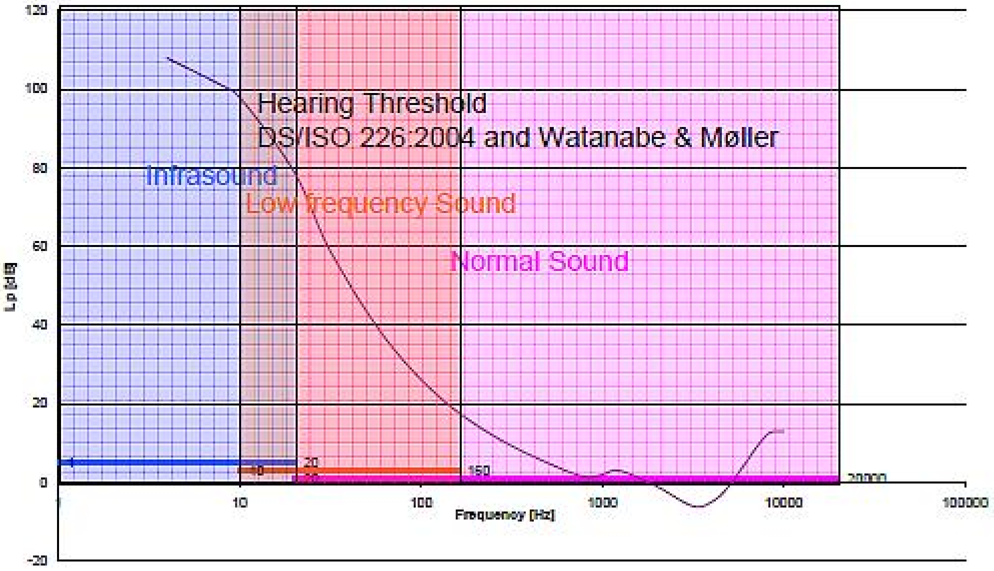


Figure 1. Hearing threshold and different frequency ranges of sound [6].

Infrasound becomes meaningful in terms of annoyance, when it is coupled with buildings and the effect is detected indoors. There have been publications of correlations found between measured infrasound inside residential dwellings and reported low frequency noise annoyance from the residents. Bakker et. al conducted continuous time series recording of seismic noise using a buried L4 geophone and acoustic surface microphone attached to a wall inside the house near wind farm in New Zealand during March 2009 [7]. In their analysis of 196 recorded seismic samples noise bursts lasting 10 seconds or more associated with easterly wind conditions with broad spectral power peaks centred on approximately 10 and 28 Hz. The audio records were played to the residents living near a wind farm being measured. The records were identified by the residents as similar to the noise they experienced. A conclusion was made that seismic energy from the wind turbines is coupled through the concrete foundations into the house. This coupling stimulates various vibrational modes, which produces the effect the residents experience. Also it was noted that these experiences were strongest when lying down, i.e. when best aurally coupled to the foundations. Further analysis of the measurement result also revealed that after eliminating all the unwanted artefacts from the signal, events were found with characteristics that appeared only when the wind was from a south-easterly direction, and reached maximum intensity on nights when the residents reported the loudest nuisance noise. These events were in order of ten seconds and with broad peaks at 28 Hz and 10 Hz. While 10 Hz is perceived as inaudible and 28 Hz being near the lower threshold of human hearing [8, 6], significant amount of energy was also in frequency range as high as 35 – 40 Hz. This would be perceived as a very low rumble similar to that described by the residents and would be amplified by mechanical coupling [7].

Møller has noted that at these low frequencies the dynamic range of human hearing is markedly decreased and with a spread of individual thresholds, which can lead to large differences in perceived loudness between individuals [9].

3.1.2 Low-frequency noise

Sound is considered as low-frequency sound, if the frequency range is from 20 Hz to 150 Hz (see Figure 1). Among with amplitude modulation low frequency noise is considered as the most important noise characteristic of wind turbines. This is mainly due to the high low-frequency content of sound of wind turbines, but also due to the fact that low-frequency sound is attenuated considerably less by the atmospheric conditions than high-frequency sound. The high low-frequency content of wind turbines can also be seen in Figure 2.

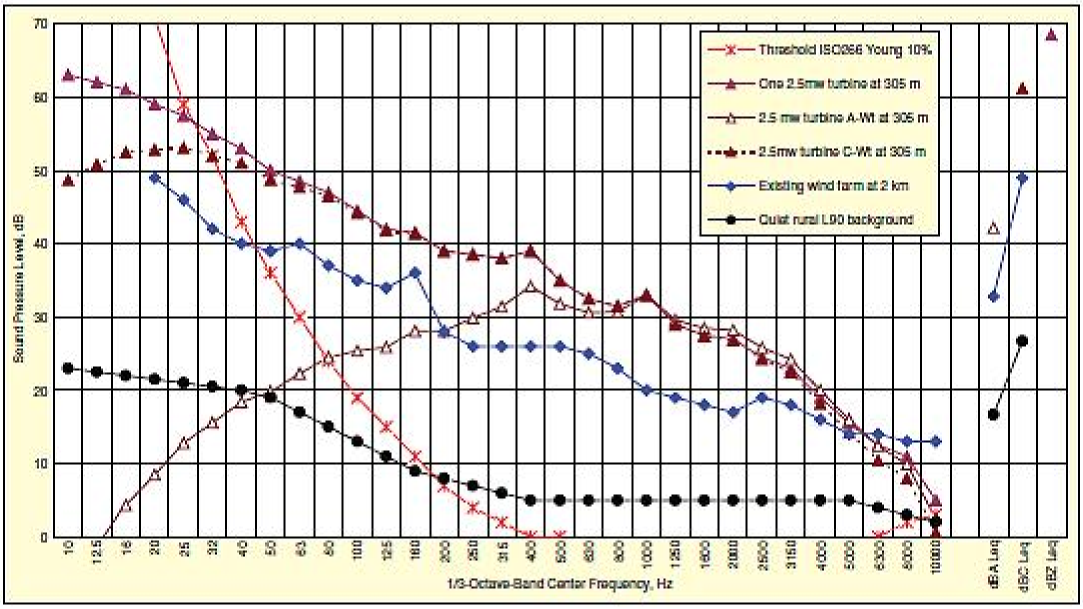


Figure 2. Generalized sound spectra vs. perception and rural community L_{90A} background, one-third-octave SPL [1].

It must be noted that while large wind turbines are somewhat quieter than smaller wind turbines, in terms of A-weighted noise emission per kW of generated power, the low frequency emission is somewhat higher than smaller wind turbines [6]. This is likely to increase the annoyance of wind turbine noise for various reasons. The most important fact is that present noise limits for wind turbines are misused when low frequency content is increasing in large wind turbines. It is simply not possible to describe the important characteristics of wind turbine noise by a single number. In addition the commonly used A-weighting is likely to be incorrectly informative on noise of large wind turbines, because in A-weighting the lowest frequencies are heavily filtered out [10].

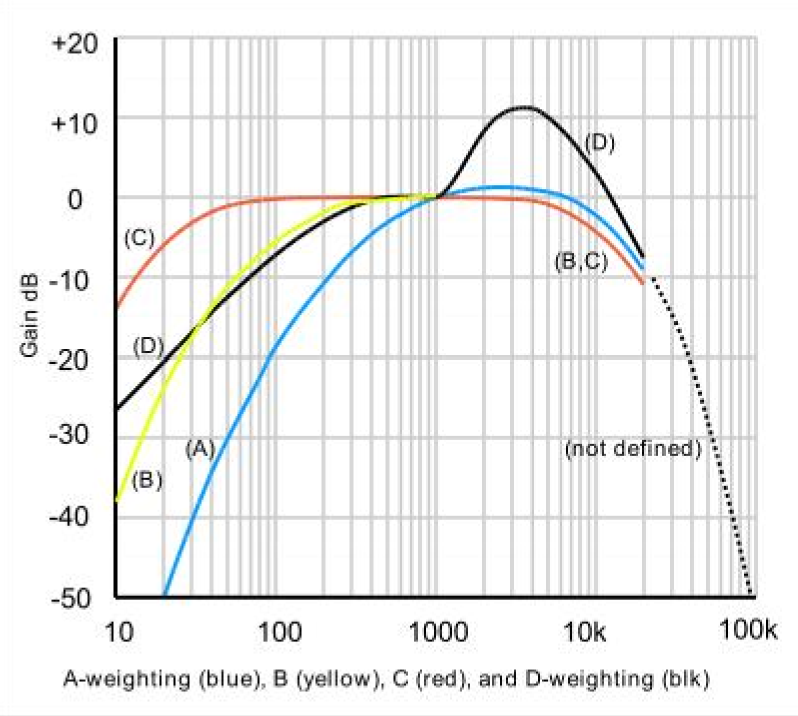
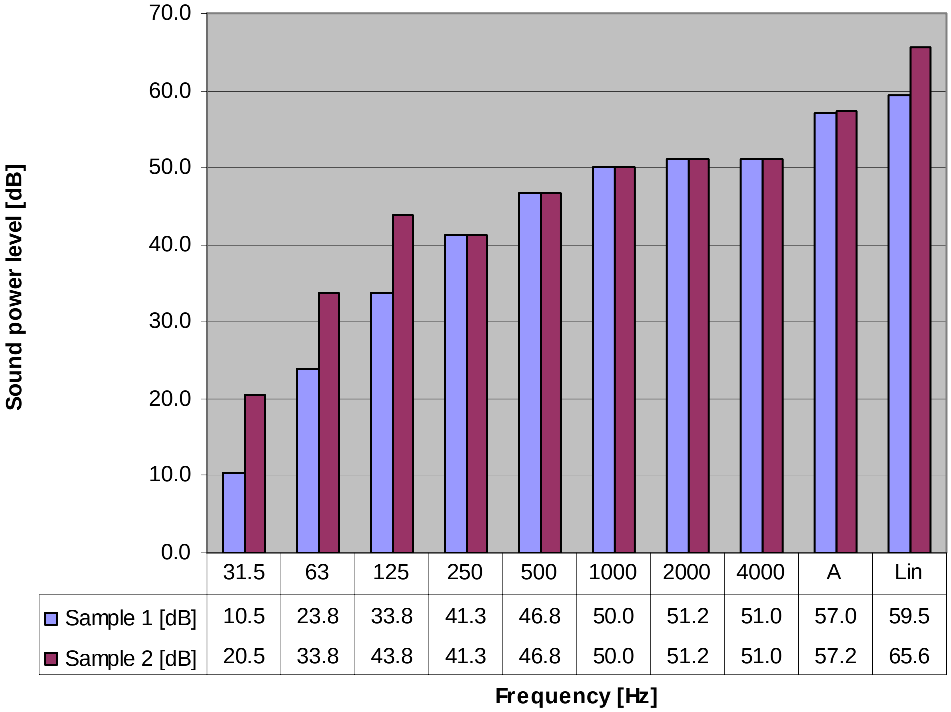


Figure 3. Different weightings over the frequency range of 10-20000 Hz [10]

An example of the weakness of using the A-weighted total sound level for evaluating low frequencies is displayed in Figure 4. Two samples are compared. The first sample has an unweighted sound level of 50 dB in each one-third octave bands and the second sample is the same apart from the one-third frequency bands of 31.5 to 125 Hz which are 10 dB louder. While the level difference in the lower frequencies is dramatic, the level difference between the A-weighted total sound levels is negligible (0.2 dB). The same analogy applies to wind turbines. Larger wind turbines may indeed be quieter in terms of A-weighted total sound level per kW produced but, their low noise emissions can be higher. This could at least partly explain the high number of complains of low frequency annoyance by the residents living in the vicinity of large wind turbines [7, 14, 11].



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

This phenomenon has a direct impact for residents living in the vicinity of large wind turbines. While wind turbines are located within the (A-weighted) noise immission level regulations, they emit higher levels at low frequencies exposing residents to high levels of low frequency noise. It is important to address this problem to environmental noise authorities. Otherwise increasing amount of complaints about low frequency noise of wind turbines are to be expected in the future.

A further concern related to the low frequency noise is the sound insulation of typical dwellings. As can be seen from Figure 5, the sound insulation is insufficient at low frequencies and therefore the increase of low frequency noise of large wind turbines is likely to increase noise annoyance also inside the dwellings. Many articles about the topic seem to support this [12].

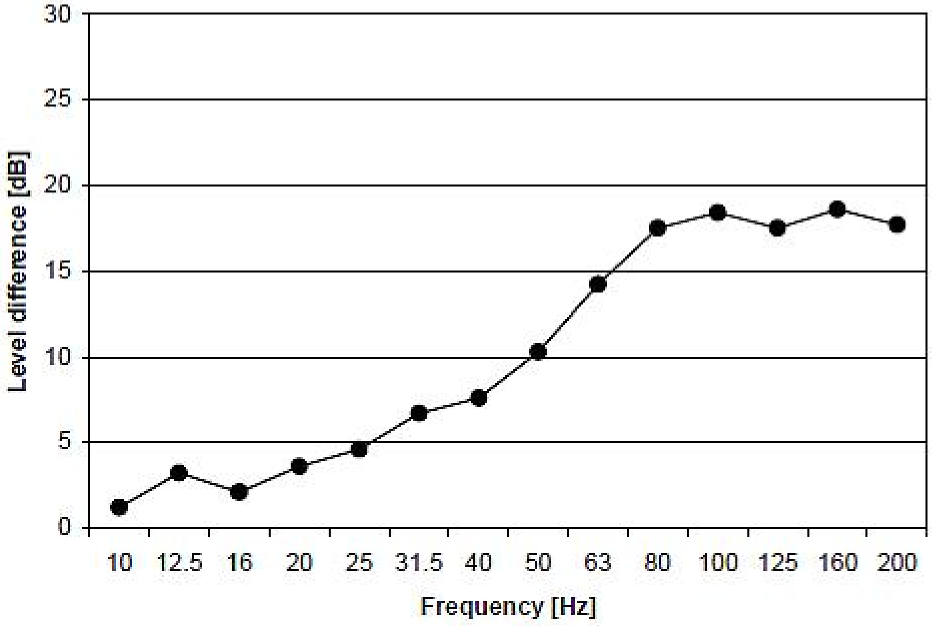


Figure 5. Sound insulation of typical Danish dwellings [4].

The nature of wind turbine noise should be considered when determining limit values of wind turbines. Because the A-weighted sound level does not describe the sound of a wind turbine well enough, especially in terms of low frequency noise, some improved noise limits have been proposed.

For audible sound, a noise limit of 5 dBA over the pre-constructed background sound level L_{90A} has been proposed [1]. The pre-constructed background level should be measured in contiguous 10-minute measurements in the quietest time of evening or night. L_{90A} results are valid when L_{10A} results are no more than 15 dBA above L_{90A} for the same time. For the low-frequency content of the wind turbine noise, either a limit of $L_{eqC} – L_{90A}$ of 20 dB or sound level of 50 dBC should not be exceeded. Also as a general clause, sound level of 35 dBA within 30 meter of any occupied structure should not be exceeded [1]. All measurements should be made when the ground level wind of measured site is 2 m/s or less.

3.2 Amplitude modulation

The explanation of the thumping sound of wind turbines can be found in the cyclical change of the sound level that occurs, particularly at night, as a stable atmosphere is created. The stable atmosphere creates the greatest change in the summed angle of attack considering the contribution of each blade taken together, as is heard by an observer [13]. The swish sound is broadband, audible portion being around 300 Hz and going as high as 5000 Hz. In addition, the rotating blades create energy at frequencies as low as 0.5–2 Hz (the blade-passage frequency), with overtones of up to about 20 Hz. Although some of this low-frequency energy is audible to some people with sensitive hearing, the energy is mostly vibratory to people who react negatively to it. Many people who live near the wind turbines find this condition very disturbing [14].

Some psychoacoustic descriptors have been proposed to characterise amplitude modulation of wind turbines. Intuitively, a suitable psychoacoustic descriptor for this could be fluctuation strength. Fluctuation strength describes the hearing sensation of sound at low modulation frequencies up to 20 Hz. At higher modulation frequencies, the hearing sensation is described by roughness [15]. A fixed point for fluctuation strength is defined for a 60 dB, 1 kHz tone 100 % amplitude modulated at 4 Hz, as producing 1 vacil. As seen in Figure 6, the maximum fluctuation strength is at 4 Hz for a modulation frequency but quickly decreases as modulation frequency decreases. For annoyance of amplitude modulation in wind turbines, this information is valuable. Generally, it means that the annoyance of amplitude modulation is likely to be diminished as wind turbines become larger and therefore rotational speeds lower.

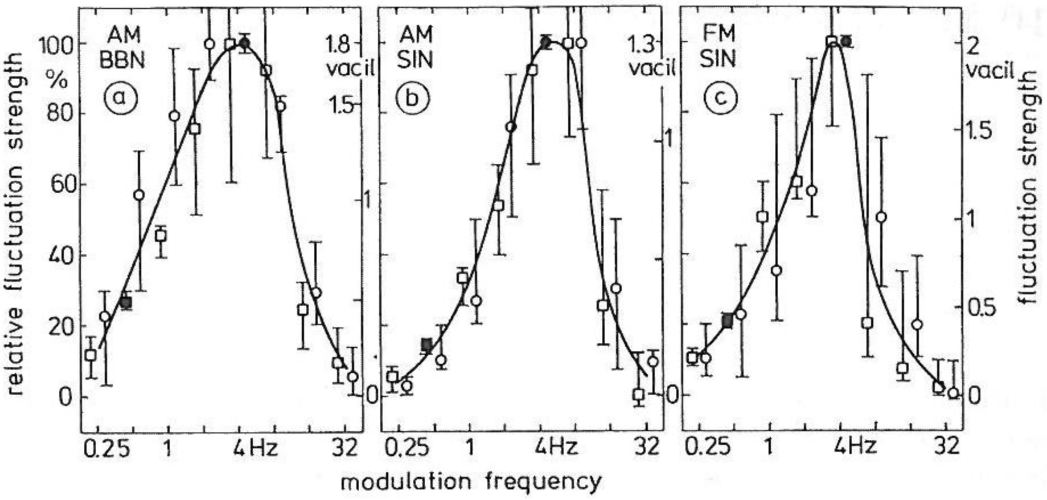


Figure 6 a-c. Fluctuation strength of three modulated sounds as a function of modulation frequency. (a) Amplitude-modulated broad-band noise of 60 dB SPL and 40 dB modulation depth; (b) amplitude-modulated 1 kHz tone of 70 dB SPL and 40 dB modulation depth; (c) frequency modulated pure tone of 70 dB SPL, 1500 Hz centre frequency and ± 700 Hz frequency deviation [15].

Legarth proposed that fluctuation strength could be a metric for amplitude modulation in wind turbine noise [16]. However, fluctuation strength may not be descriptive enough in relation to amplitude modulation of wind turbines [17]. This is because a model of fluctuation strength is based on temporal variation of a masking pattern [15], the scale of fluctuation strength is too large to measure amplitude modulation in wind turbine noise. This can be seen in Figure 7 (a), where the effect of modulation depth of amplitude-modulated broadband noise on fluctuation strength is displayed. The fluctuation strength is zero until a modulation depth of about 3 dB, after which it increases approximately linearly with the logarithm of the modulation depth. The modulation depth required to achieve maximum fluctuation strength is about 30 dB. For the amplitude modulation of wind turbines, the scale is too high as a typical amplitude modulation depth is about 3 dB and a strong modulation depth 7-8 dB.

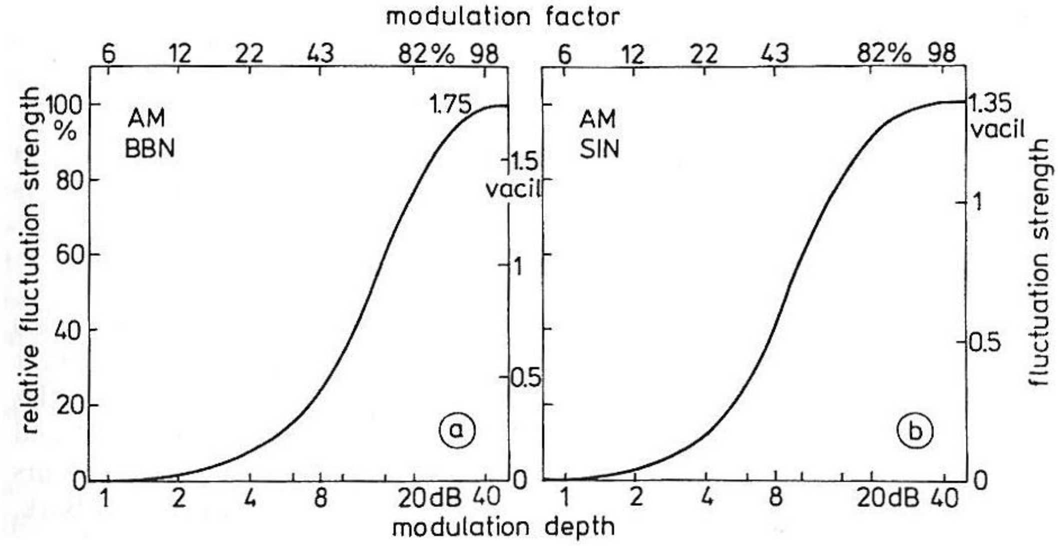


Figure 7 a-b. Fluctuation strength of two amplitude-modulated sounds as a function of modulation depth. (a) Amplitude-modulated broadband noise of 60 dB SPL and 4 Hz modulation frequency; (b) amplitude-modulated 1 kHz tone of 70 dB SPL and 4 Hz modulation frequency.[15]

3.3 Measuring amplitude modulation of wind turbines

In order to assess the community response, it is necessary to quantify amplitude modulation in wind turbine noise, which exposes residents. However, measurement methods in use today for amplitude modulation are not appropriate for proper community response assessment because none of the methods do measure amplitude modulation over a long period.

Amplitude modulation is commonly measured in three different ways. In the first method modulation depth is determined by the difference between L_{max} and L_{min} from a spectrogram [18]. The second method, also commonly used is the same as the first method, but level difference L_{max} and L_{min} is from the A-weighted sound pressure level with time weighting F [19]. The weakness of these methods is that they cannot be applied for long time measurements since the procedure has to be done manually. On the other hand, these methods are suitable where an occasional value for amplitude modulation has to be determined. One of these situations could be problematic with atmospheric conditions such as evening inversion, where amplitude modulation from wind turbines is likely to be strong. The third method employs percentile sound levels instead of L_{max} and L_{min} [20]. In this method the amplitude modulation is defined as the difference between L_5 and L_{95} from the one-third octave band spectra. It must be noticed that this method can be applied only when the overall sound level does not gradually increase or decrease.

In valid community response assessment, long time measurements for amplitude modulation need to be performed. Therefore none of the previous methods for measuring amplitude modulation is suitable for this purpose. Lee et. al. have proposed a simple and robust method to measure modulation depth of wind turbine noise for community response assessment [17]. In this method FFT to each time step of wind turbine noise is applied to get a spectrogram. Next, for each frequency band, the fast Fourier transform is applied again but this time along the time axis. If the signal is amplitude modulated at a blade passing frequency, two dominant peaks will be visible, as shown in Figure 8B. The peak at 0 Hz represents a steady root-mean-square value of the signal and another peak at the blade passing frequency represents sinusoidal amplitude modulation of the signal.

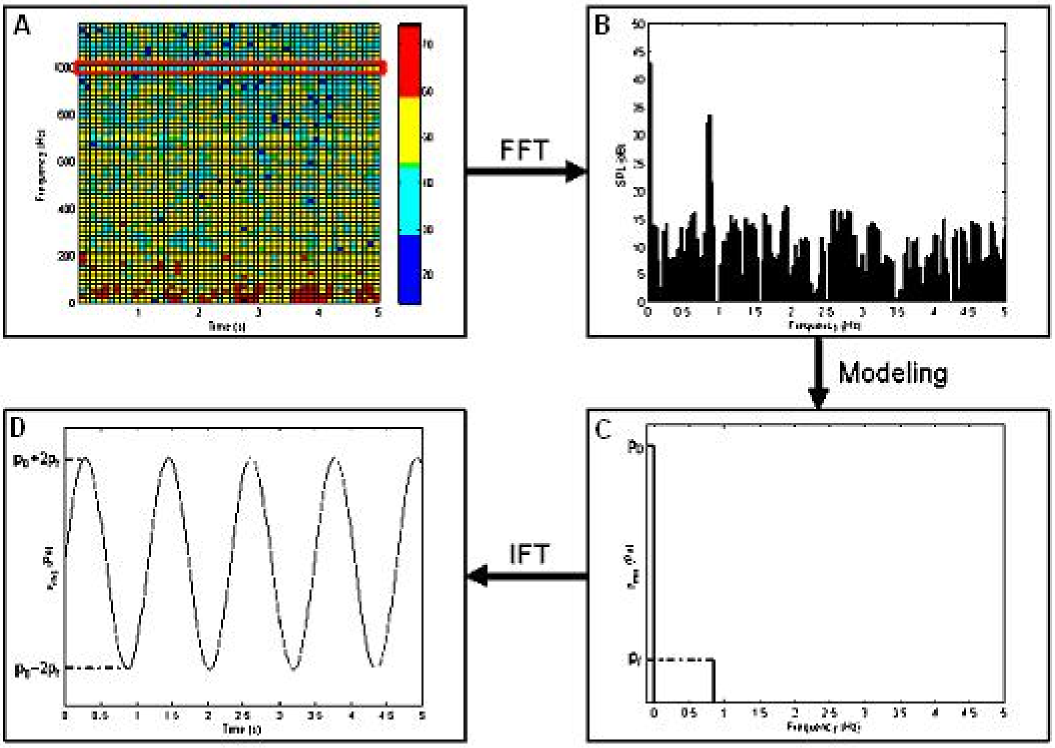


Figure 8A-D. The procedure for estimating amplitude modulation in wind turbine noise [17]

If the modulation depth at modal frequency bands is more than 1 dB, the values other than these two peaks can be neglected. If the two peaks are sufficiently narrow, the result of the FFT analysis in Figure 8B is also modelled as two tones, as shown in Figure 8C. Finally, the inverse Fourier transform is applied to the result in Figure 8D. The modulation depth (Equation 1) is defined as the difference between maximum and minimum value [17].

$$\Delta L = 20\log\frac{p_0 + 2p_f}{p_0 - 2p_f} \tag{1}$$

This method could be a valid tool for community response assessment because it automatically calculates the average amplitude modulation for a long time measurement. However, with this method it is not possible to calculate maximum values for amplitude modulation which could be important information in some cases. Therefore it is advised to use this method to a measurement signal, which is divided into hour or minute intervals.

Lee et. al. provide also an example of usage of this method. Two samples of 1.5 MW wind turbine noise were recorded at a distance of hub height; One (Sample I) at a wind speed of 4 – 6 m/s with opposite wind direction from the turbine. The other sample (Sample II) was recorded at a distance of hub height (62 m) from the turbine at a wind speed of 10 – 12 m/s from the right side of the turbine. The spectra of the samples in one-third octave bands are shown in Figure 9.

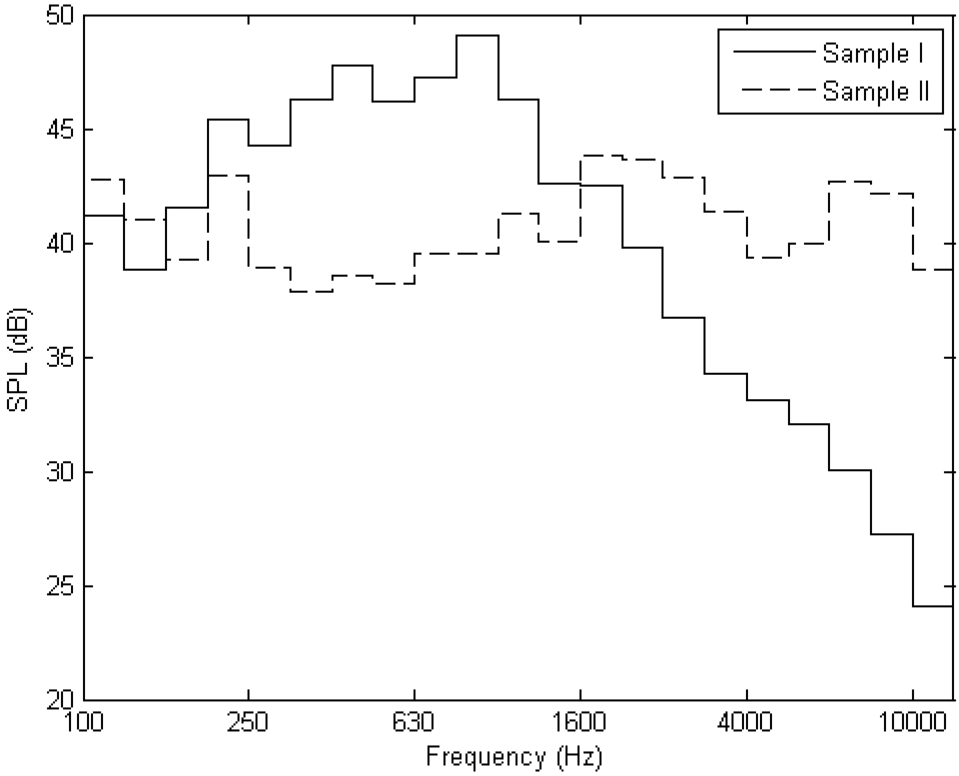


Figure 9. One-third octave band spectrum of Sample I and Sample II [17]

From these samples, an amplitude modulation spectrum was made using the proposed method. The frequency resolution of the modulation spectrum was set to 200 Hz. The amplitude modulation spectrum of the samples is displayed in Figure 10. As from Figure 10 can be seen, the maximum modulation depth of Sample I is approximately 5 dB at 1 kHz, while that of Sample II is approximately 12 dB at 8 kHz.

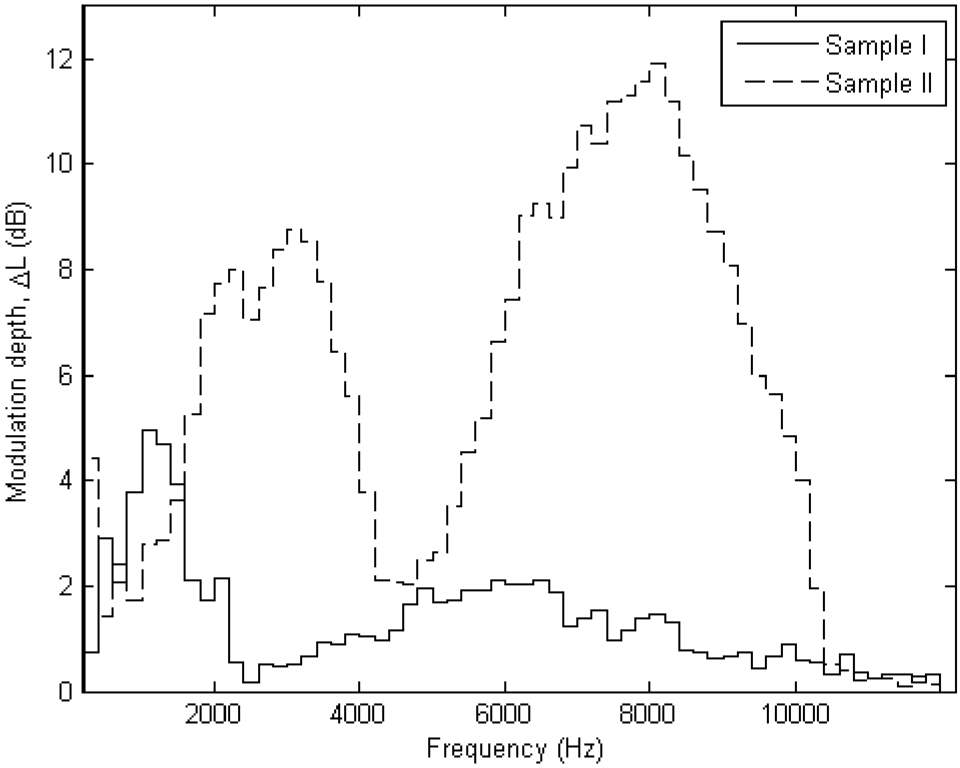


Figure 10. Spectral modulation depth of Sample I and Sample II [17].

3.4 Amplitude modulation and low frequencies

As stated in 3.1, there has been large amount of debate whether low-frequency noise is audible indoors of residents living near wind turbines. On one hand there are residents with complaints of low-frequency noise and on the other audio experts who try to measure the low-frequency noise indoors to conclude whether it is audible or not. Since a human perceives static noise less annoying than fluctuating noise [15], one potential explanation to this phenomenon is likely the amplitude modulation, which seems to extend to low frequencies [3]. This can be seen in Figure 11, where the spectrogram of measured wind turbine noise is displayed. It seems that amplitude modulation starts from as low as 40 Hz frequency. Frequencies this low penetrate average houses more easily than higher frequencies (see Figure 5), which seems to support the theory. However, more research and measurements have to be done to confirm the phenomenon.

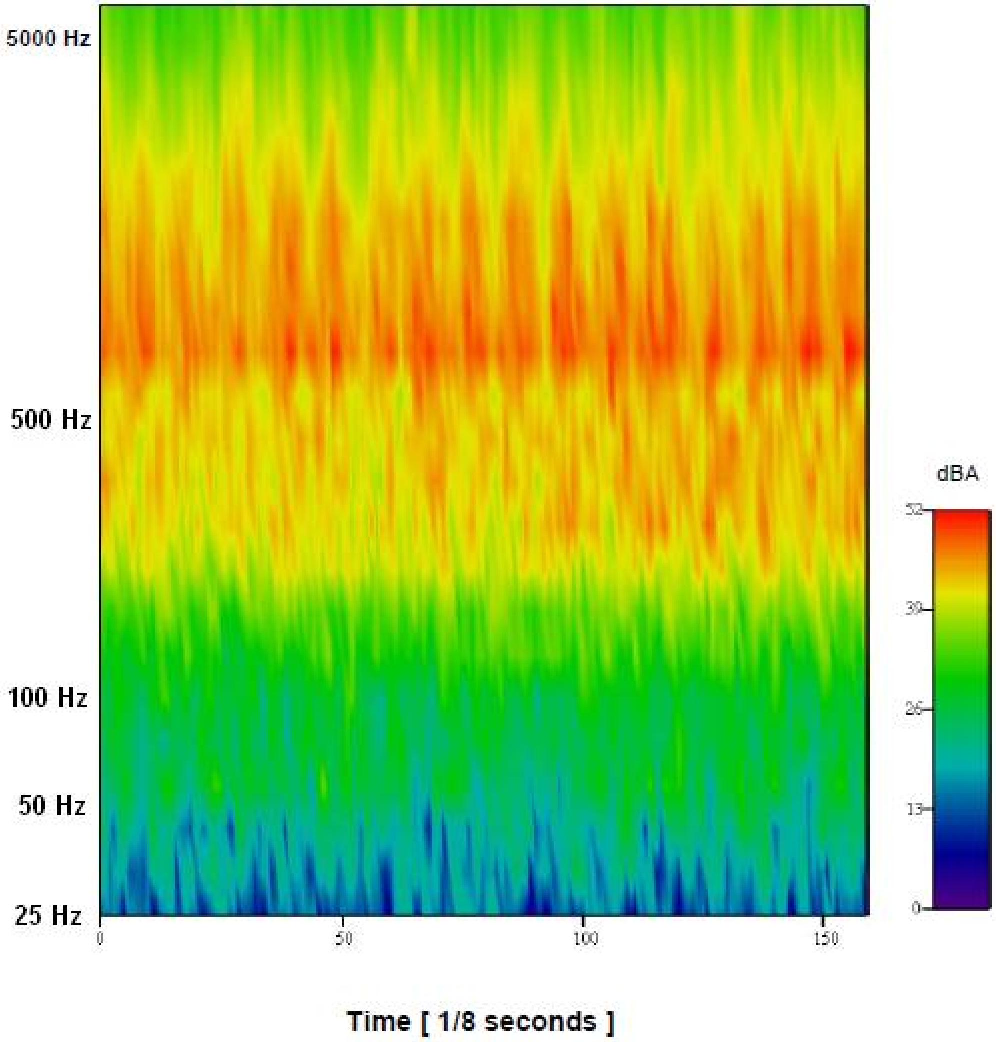


Figure 11. Spectrogram of wind turbine noise near the wind turbine [3].

4 Wind turbine noise and psychoacoustic criteria

4.1 Wind turbine noise and psychoacoustic descriptors

Annoyance from wind-turbine noise with the use of psychoacoustic criteria has been evaluated by Persson et. al [21]. In their research sound samples from five wind turbines common in Sweden (rated power 250 – 600kW) were recorded. The sound levels were normalized between samples to be 40 dB L_{AEq} to correspond to the Swedish recommendations for noise level from wind turbines that should not be exceeded at the nearest house. The samples were recorded at distance of 100 meter from wind turbines at a wind speed of 7 -10 m/s and with the wind direction from the wind turbine. Weather conditions during the measurements were not reported.

The samples were exposed to 25 subjects for 10 minutes to carry out subjective ratings of annoyance, relative annoyance and for how long they were aware of the noise. This was followed by 3 min exposures where perception and annoyance of 14 psycho-acoustic descriptors were evaluated. The results showed that the rating of annoyance, relative annoyance and awareness was different between the wind turbine noises, although they had the same equivalent noise level. A psychoacoustic profile was obtained for each noise, which subjectively described the most and the least annoying sound parameters. None of the psychoacoustic parameters, sharpness, loudness, roughness, fluctuation strength or modulation could explain the differences in annoyance response [21].

In Table 1 average values with standard deviations of annoyance, awareness and relative annoyance of measured wind turbines are listed. The scale (free scale) for annoyance seems to be 1-100 although in the paper the scale is described to be 1-10. The scale for awareness and relative annoyance is 1-5 (1 “not/nearly not/aware of it at all", 2 “only for a short time", 3 “often", 4 “nearly the whole time", 5 “the whole time". [21]

Table 1. Average values and (standard deviations) of annoyance, awareness and relative annoyance for the wind turbine noises.

	Bonus	Vestas	NWP	Zephyr	WW
Annoyance	26·6 (21·9)	28·6 (22·4)	32·3 (26·5)	33·4 (21·5)	37·0 (32·3)
Awareness	2·0 (0·79)	2·2 (0·64)	2·3 (0·80)	2·3 (0·69)	2·6 (1·04)
Relative annoyance	2·6	2·0	3·2	3·4	4·1

Average values for lapping, swishing and whistling are displayed in Figure 12 and for grinding and low frequency in Figure 13. In both figures, the scale for psychoacoustic descriptors is six-graded with the alternatives: 0 “do not notice", 1 “notice but not at all annoying", 2 “barely annoying", 3 “somewhat annoying", 4 “rather annoying" and 5 “very annoying".

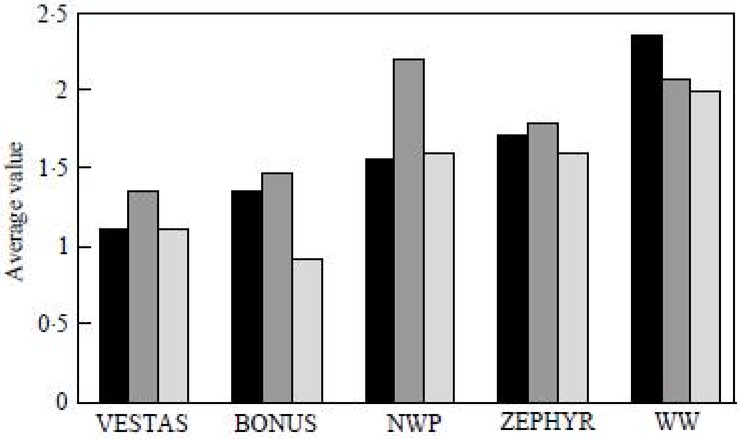


Figure 12. Average values of lapping, swishing and whistling for the different turbine noises. ,■ lapping; ▩ ,swishing; , ░ , whistling.[21]

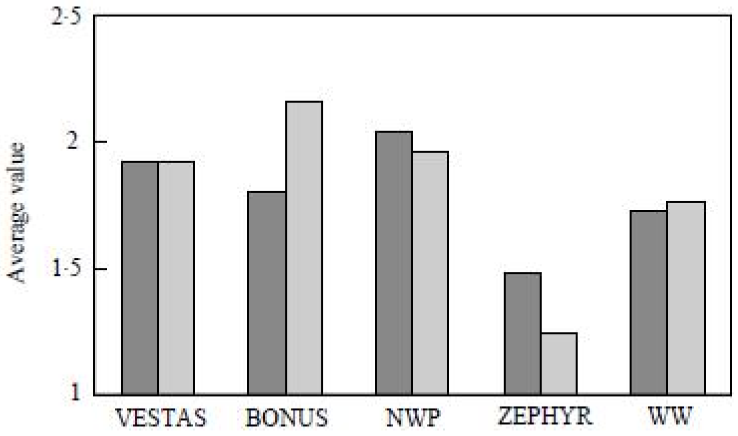


Figure 13. Average values of grinding and low frequency for the different wind turbine noises .■ ,grinding; □ , low frequency. [21]

The psychoacoustic parameters were analyzed from 30 s long sequences from DAT recordings taken in the exposure room, using a microphone B&K 4165 placed in the position of a subject's head. The calculations were carried out using Binaural Analysis System 4.3 software (Head Acoustics). The calculated psycho-acoustic parameters are shown in Table 2. It must, however, be realized, that this method is not fully valid, because a single microphone does not take into account the effect of the human head in psychoacoustical evaluation.

Table 2. Equivalent and (maximum) levels of the psycho-acoustical parameters for the five noises

	Bonus	Vestas	NWP	Zephyr	WW
L_{AEq} [dB]	40	40	40	40	40
Loudness [sone]	35.68 (44.30)	36.75 (42.65)	38.35 (42.65)	43.80 (55.20)	35.85 (45.06)
Sharpness [acum]	1.94 (2.29)	2.08 (2.51)	2.61 (3.18)	2.82 (3.25)	1.91 (2.21)
Tonality [tu]	0.03 (0.21)	0.04 (0.21)	0.05 (0.20)	0.04 (0.17)	0.03 (0.21)
Roughness [asper]	2.84 (3.78)	2.93 (3.74)	3.00 (3.61)	3.35 (4.18)	2.82 (3.60)
Fluctuation Strength [vacil]	3.32 (3.73)	3.14 (3.56)	3.38 (3.74)	3.56 (4.10)	3.38 (3.78)

4.2 Amplitude modulation and noise annoyance

Lee et. al has conducted some listening tests to find a relation between amplitude modulation and noise annoyance [17]. The test samples were made by weighting white noise with the frequency spectrum of sound samples. Amplitude modulation depth of these samples was done by varying the sound level of these samples. Listening tests were made with 30 participants of age of 20 – 30 years. 15 participants were women and 15 men. For the listening test, a total of 50 stimuli were produced. These combinations were made of two base samples, five different sound equivalent levels and five degrees of modulation. The equivalent sound level was varied in steps of 5 dB from 35 to 55 dBA. Modulation depth for stimuli originated from sample I varied from 1.7 to 5 dB (modulation factor 0.1 to 0.28) and for stimuli originated from sample II varied from 2 to 12 dB (modulation factor 0.12 to 0.6). Spectral modulation factors of stimuli of sample I at L_{Aeq} of 35 dBA is shown in Figure 14 and for stimuli of sample II in Figure 15.

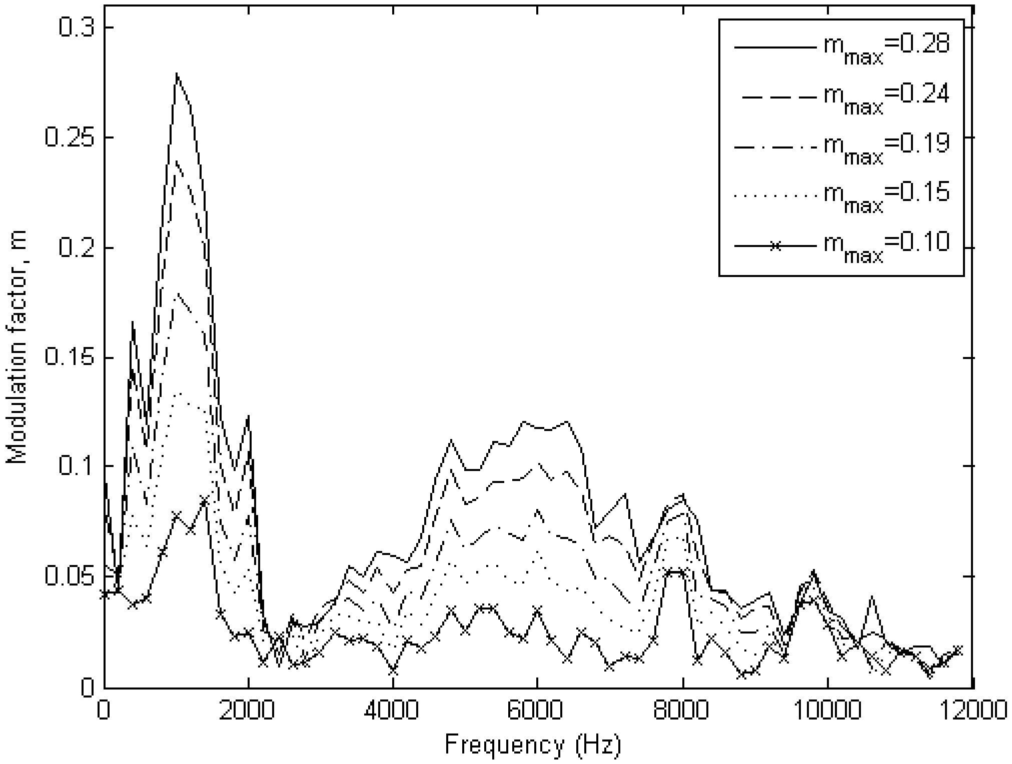


Figure 14. Spectral modulation factors of the stimuli at 35dB L_{Aeq} for sample I [17].

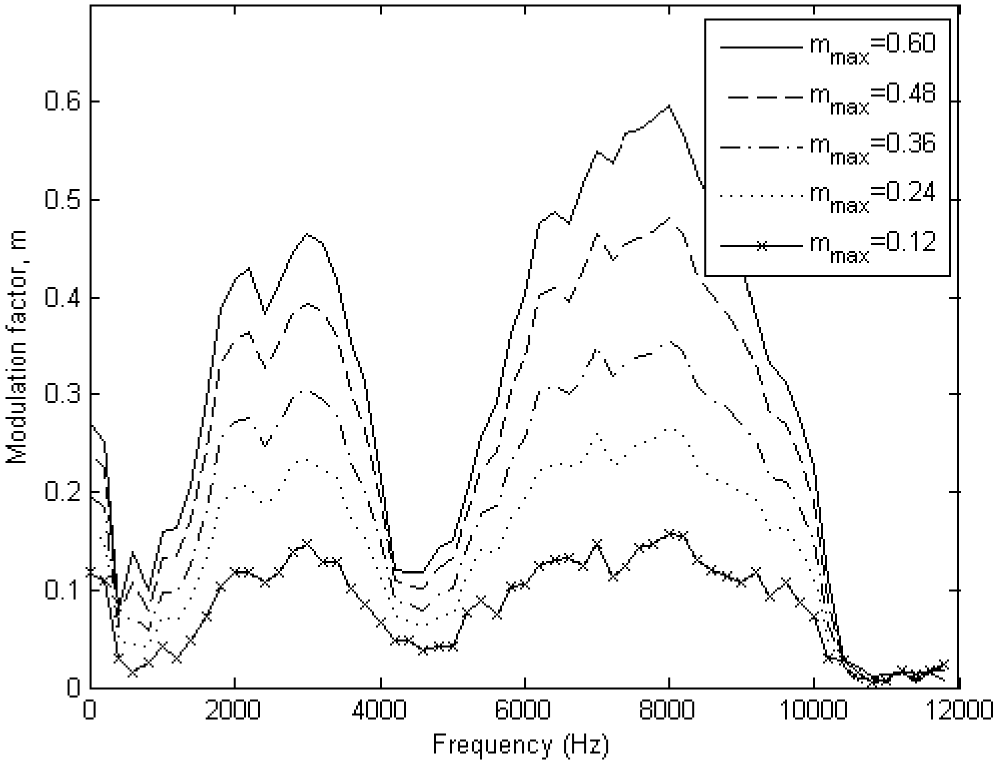


Figure 15. Spectral modulation factors of the stimuli at 35dB L_{Aeq} for sample II [17].

The listening tests were conducted in an anechoic chamber (3m x 3m x 2m) where the background noise level was between 20 and 25 dBA Participants were instructed to record the degree of annoyance after each stimulus. Response was recorded on an 11-point numerical scale according to ISO 15666 [22]. Statistical analysis was accomplished by a two-way analysis of variance (ANOVA) with factors of A-weighted equivalent sound level and modulation factor, followed by pair wise comparisons using Tukey’s HSD. A p-value of < 0.05 was regarded as statistically significant [17].

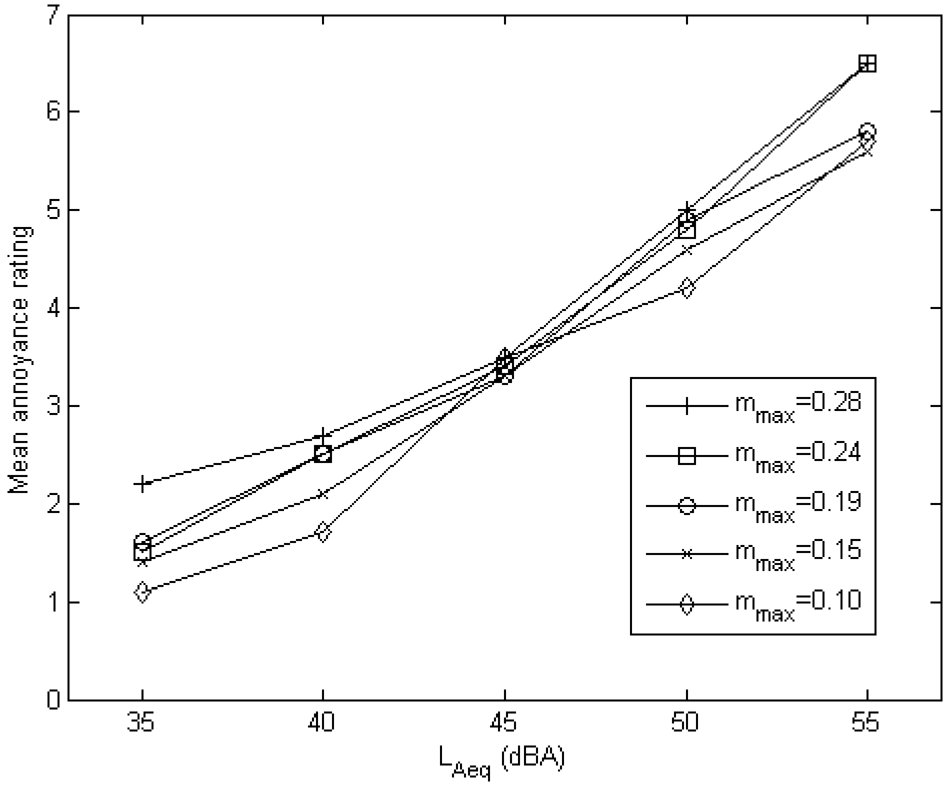


Figure 16. Mean annoyance rating for listening test of sample I [17].

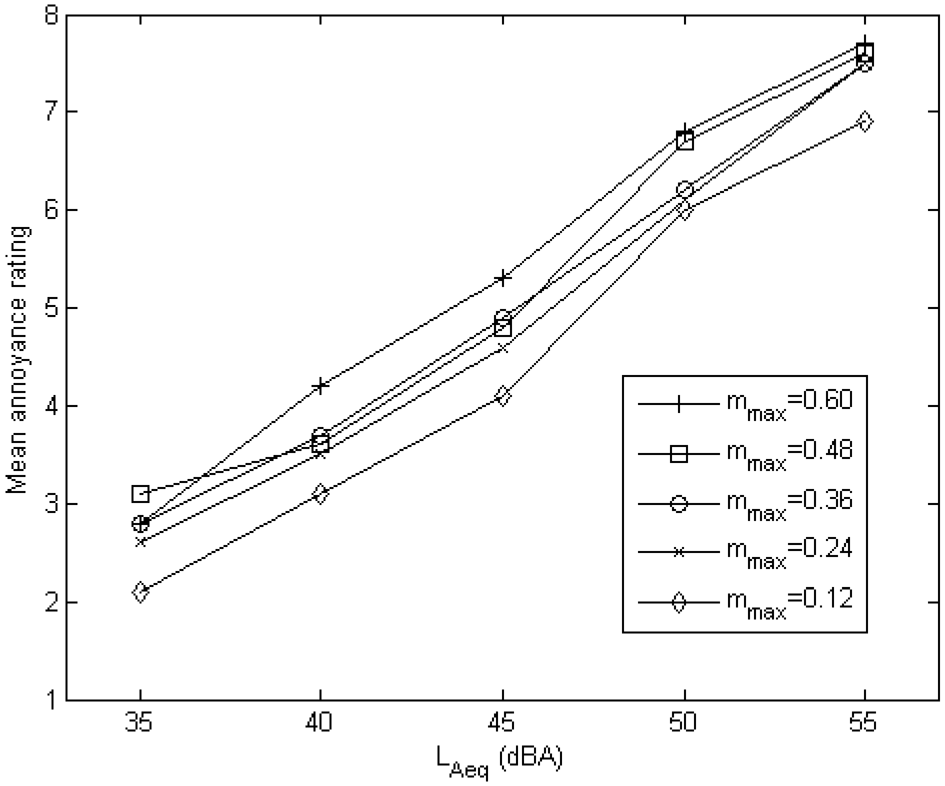


Figure 17. Mean annoyance rating for listening test of sample II [17].

From Figure 16 and Figure 17 can be seen that there is a relationship between the equivalent noise level and noise annoyance and also between amplitude modulation and noise annoyance. This can be one of the reasons why wind turbine noise is considered more annoying than other community noise at the same A-weighted equivalent sound level [23, 17]. In previous studies, there has been only a weak relationship between equivalent sound level and noise annoyance [24]. It has been proposed that other sound characters may influence on noise annoyance [21]. However, in the listening test made by Lee et. al. all other sound characters except modulation factor were unchanged.

5 Conclusions

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 into account low-frequency noise and consequently amplitude modulation of modern wind turbines would be the C-weighted total sound pressure level L_{Ceq}. However, since practically all noise immission regulations are based on the 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 an 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 at the immission point, not at the emission point.

Like the A-weighted apparent sound power level $L_{WA,k}$ of the wind turbine, also the level of low frequency noise and the amplitude modulation level of the noise should be mandatory values for the manufacturer to issue in the technical data sheets of the wind turbine. The most practical way to get an estimate of this value would be measuring the wind turbine in situ when the atmospheric conditions are suitable. This would be the case in the evening or night when wind speed at ground level is less than 2 m/s and sky is clear.

6 Summary

A growing percentage of the residents living in the vicinity of wind turbines perceives wind turbine noise as annoying and hard to get used to. This is because of the spectral and temporal characteristics of wind turbine noise. Low frequency noise and amplitude modulation are the main sources of these characteristics.

The noise from wind turbines is being measured and described with the A-weighted overall sound pressure level L_{Aeq}. Because of the characteristics of wind turbine noise, this is not a sufficient descriptor because it does not indicate how much temporal variations the measured signal contains. Also, in L_{Aeq} the lowest frequencies are heavily filtered out.

There has been discussion if some of the psychoacoustic descriptors could be used to quantify the sound characteristics of wind turbine noise. The most potential psychoacoustical characters for this would be loudness and fluctuation strength to quantify the perceived noise level and amplitude modulation of wind turbine noise. By the results of listening tests, it seems that none of the psycho-acoustic characters could explain the differences in annoyance response. Fluctuation strength is not a valid measure for amplitude modulation since its designed scale is too large.

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