Noise and Low frequency noise from Wind Turbines

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ABSTRACT

Noise is a key issue when planning wind farms. The presentation will look into details in noise from wind turbines, noise measurements, noise assessment, including the Danish noise limits for low frequency wind turbine noise, and noise propagation. Development of noise and low frequency noise with the size of the turbines will be discussed. Questions like how far does low frequency noise propagate will be addressed.

Keywords: Wind Turbine Noise, Low frequency Noise. I-INCE Classification of Subjects Number(s): *14.5.4.*

1. INTRODUCTION

Around 2004 – 2005 low frequency noise from wind turbines became a major concern in the public in Denmark. There was a worry that larger wind turbines would emit substantially more low frequency noise than the wind turbines people knew already. As this had consequences for the development of on-shore wind energy, the Danish energy authorities initiated an investigation into the topic. The results were reported by Søndergaard (1) and Madsen (2) and an alternative interpretation were reported by Møller (3), (4) and (5). In December 2011 the Danish regulations on wind turbine noise were revised and noise criteria was introduced for the in-door low frequency noise (6). Details on the regulations and the background can be seen in (7) by Jakobsen. Sørensen presented some of the consequences for the planning process in (8).

In short the Danish regulation introduces a set of noise criteria as well as a method for assessing the criteria through measurements and predictions. The noise limits are described in the Statutory order 1284 of 15 December 2011 from the Danish ministry of the environment (6) as follows:

The total noise impact from wind turbines may not exceed the following limit values:
1) At the most noise-exposed point in outdoor living area no more than 15 metres from dwellings in 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.
2) 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 must not exceed 20 dB at a wind speed of 8 m/s and 6 m/s indoors in dwellings in open countryside or indoors in areas with noise sensitive land use respectively.

2. NOISE AND LOW FREQUENCY NOISE FROM WIND TURBINES

2.1 Investigations

The question now is; do the new regulations have any impact on low frequency noise from wind turbines and how can it be checked. As the neighbours are the main objective for the new regulations, a set of wind farm projects, where Grontmij has been involved in the post construction documentation of noise were reviewed. Another parameter which has been used as an indicator is the sound power level and specially the sound power spectra of the wind turbines. An analysis based on Grontmij's database on wind turbines has been made to see if there is a development.

The database consists of the original data from (1) except for the specific prototype wind turbines. Measurement reports from the archives of Grontmij, Acoustica ranging back to 1988 are included and supplemented with new measurements from 2010 to 2013. Gnerel information on noise from wind turbines can be found in Wagner (9) and Bowdler ang Leventhall (10)

2.1.1 Noise from wind farms.

As an independent consultancy Grontmij is often involved in post construction documentation of noise from wind farms. In Denmark this includes determination of the sound power level of individual wind turbines and prediction of the noise in the surroundings. In Figure 1 the noise contours, representing the noise limits, around a wind farm is shown. The blue line is 39 dB(A), the red line is 44 dB(A) and the pink line is 20 dB(A) indoor low frequency noise, all at 8 m/s. Typically for the projects Grontmij has seen, the pink curve for low frequency noise is enclosed by the other curves indicating that low frequency noise is not the decisive parameter on whether the noise requirements are met or not.

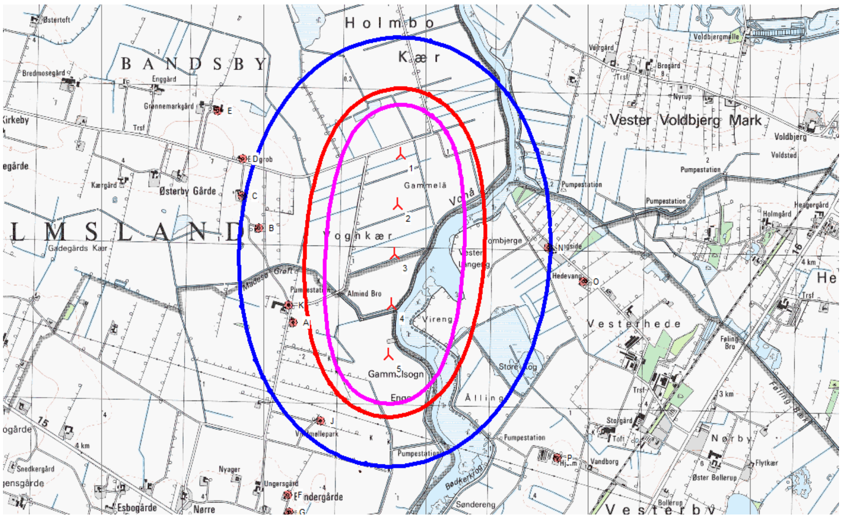

Figure 1. Typical noise contours for a Danish wind farm at 8 m/s. The blue line is 39 dB(A), the red line is 44 dB(A) and the pink line is 20 dB(A) indoor low frequency noise.

Table 1 - Main results from typical wind farm projects in Denmark. The numbers in parenthesis show the margin to the noise criteria. For project 4 at 6 m/s the noise is above the noise criteria. It is allowed for owners and part owners to exceed the noise criteria at their own residence. Note that the neighbour with the highest noise level is not always the neighbour with the shortest distance. For some of the projects the nearest neighbour are at a shorter distance with lower noise levels.

Project	**Wind Turbines**	**Neighbour with highest noise level**				
		Distance [m]	L_{pA} (6 m/s) [dB]	$L_{pA,LF}$ (6 m/s) [dB]	L_{pA} (8 m/s) [dB]	$L_{pA,LF}$ (8 m/s) [dB]
1	6 V90-3MW	656	39,9 (2,1)	14,8 (5,2)	42,6 (1,4)	17,3 (2,7)
2	6 SWT 2,3-93	700	41,1 (0,9)	14,4 (5,6)	43,3 (0,7)	16,8 (3,2)
3	3 600 kW WTG	304	41,2 (0,8)	12,7 (7,3)	42,7 (1,3)	14,4 (5,6)
4	5 SWT 3.0-101	587	42,6 (-0,6)	13,7 (6,3)	43,5 (0,5)	16,1 (3,9)
5	3 V112-3MW	810	36,3 (0,7)	11,0 (9,0)	37,9 (1,1)	12,7 (7,3)
6	3 SWT 3.0-101	574	41,4 (0,6)	12,5 (7,5)	42,1 (1,9)	14,9 (5,1)
	Noise criteria		42/37	20	44/39	20

In **Error! Reference source not found.** results from noise predictions for 6 wind farms according to the Danish regulations are shown. The first three projects are planned and erected before the regulations on low frequency noise were introduced. The last three were planned with the new regulations as a design criteria. Project no. 3 is actually a much older project with new measurements made in 2013, allowing for a comparison with the new criteria. The numbers in the parenthesis show the margin to the noise criteria. For the normal noise the margin is typically up to 2 dB, while it is in the range of 3 to 7 dB for low frequency noise. This again indicates that it is the “normal” noise which is the decisive parameter and not the low frequency noise. From these limited data it is difficult to conclude on the difference between older and newer projects, but it looks like low frequency noise from new and old projects is of the same order at the neighbours.

2.1.2 Noise emission from wind turbines.

Much of the discussion so far has been based on sound power levels of the wind turbines and whether the wind turbines generate more low frequency noise when the size increases. For this review an analysis based on 213 measurement reports is made. All the original data from the project in (1) are included, except for the 4 prototype wind turbines. Data are supplemented with older measurement reports from the archives at Grontmij, where 1/3-octave band data were available, and new measurement reports. The reports represent wind turbines ranging from a few kW to the newest version of MW turbines and give the sound power spectrum at 8 m/s at 10 m height.

The analysis is based on the same principles as in (1) to (5) but on a much better statistical basis with 213 measurement reports, against only 65 measurement reports in the previous analyses. As the new data also includes older types of stall regulated wind turbines with a nominal power between 2000 kW and 3000 kW sorting of data is a little different. The data are sorted into 4 groups: ≤ 200 kW,]200 kW – 1000 kW],]1000 – 2000 kW], >2000 kW, >2000 kW old types and >2000 kW new types. This makes it possible to evaluate new large wind turbines compared to wind turbines designed and erected before the investigation in (1) and (2) was published. For comparison with previous investigations the group]200 kW – 2000 kW] is included The spectra are normalised to LWA of the individual wind turbine before averaging. A comparison of the averaged spectra for each class can be seen in Figure 2 and the number of spectra in each class can be seen in Table 2.

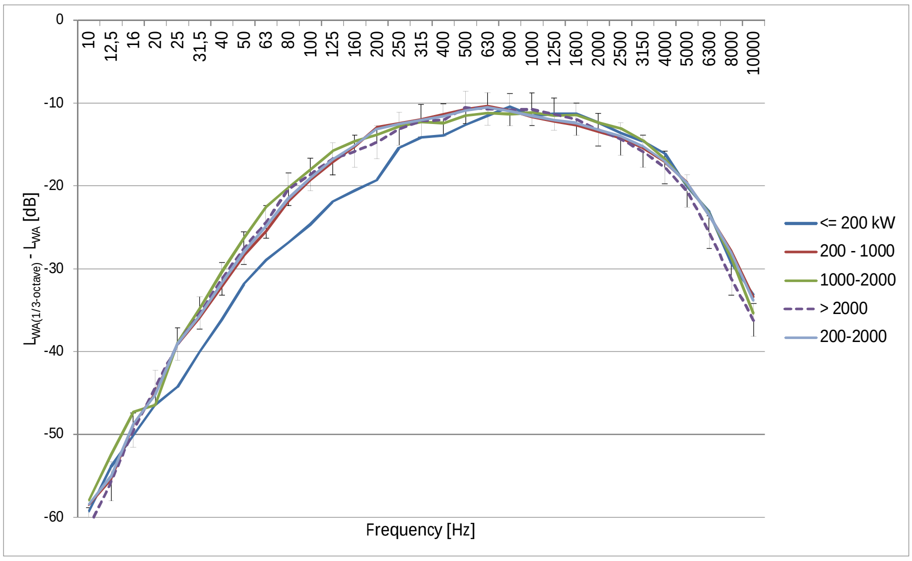

Figure 2. Normalized apparent sound power levels in one- third-octave bands. Mean of groups of wind turbines. Error bars show ± 95 % confidence interval around the mean in every 1/3-octaveband for the group > 2000 kW.

Table 2 - Number of spectra in each group. As not all measurements are covering the entire frequency range the count of spectra, including the 10 Hz 1/3-octave band is shown as well.

Group	Number of spectra	Number of spectra at 10 Hz
≤ 200 kW	16	5
]200 kW – 1000 kW]	108	5
]1000 kW – 2000 kW]	27	1
> 2000 kW	62	27
]200 kW – 2000 kW]	135	6
> 2000 kW new	34	23
> 2000 kW old	28	4

All spectra are measured down to at least 50 Hz and for the new large turbines down to at least 16 Hz.

The spectra representing the different groups do not deviate much in the low frequency region from 10 Hz to 160 Hz, except for the group of wind turbines below 200 kW. These turbines are relatively rare these days and due to the early design are dominated by machinery noise and tonal noise. Small wind turbines are represented by the group]200 – 2000 kW] which is consistent with the previous analyses in (1) to (5). In Figure 3-left a comparison of the group]200 – 2000 kW] and the group > 2000 kW wind turbines is shown. The differences in the low frequency range are small, which can be seen in more detail in Figure 3-Right, where the spectrum for the group > 2000 kW is subtracted from the spectrum of group]200 – 2000 kW]. It is clear that the group of turbines above 2000 kW deviates very little from the group]200 – 2000 kW] wind turbine spectrum and positive deviations are less than 1 dB. In the low frequency range the difference is significant at 10 Hz [t=2,3301 d.f=7,8 p=0,0263], 80 Hz [t=2,3249 d.f=474,2 p=0,00101], 160 Hz [t=2,0044 d.f=894,1 p=0,0227], and 200 Hz [t=4,5449 d.f=896,5 p<0,0001] from a Students t-test comparison of the two groups. To illustrate the variation within the groups examples of spectra with high and low level of low frequency noise for the 2 groups are shown in Figure 4. The spectra for the groups]200 kW- 2000 kW] are both from 600 kW wind turbines.

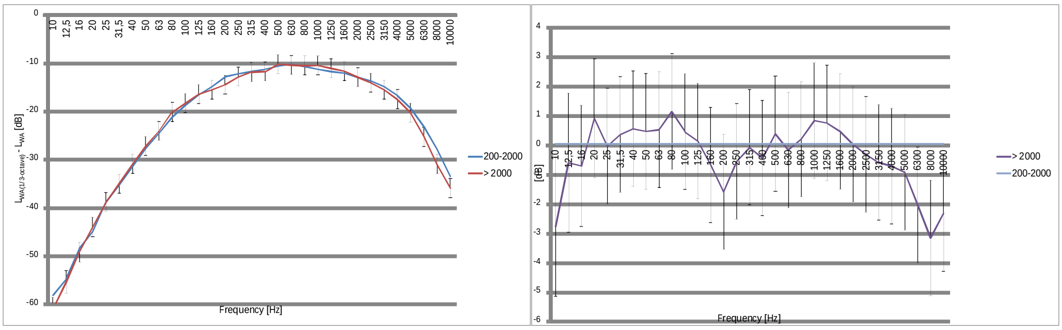

Figure 3, Normalized apparent sound power levels in one- third-octave bands. Mean for two groups of turbines:]200 kW- 2000 kW] and > 2 000 kW-Left. Spectrum of the group > 2000 kW wind turbines relative to the spectrum for the group]200 – 2000 kW] wind turbines - Right

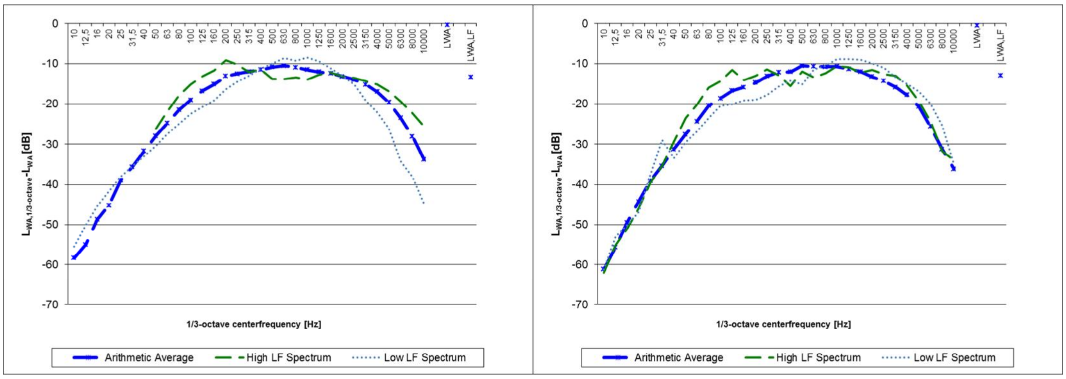

Figure 4 Average spectrum and examples of spectra with high and a low level of low frequency noise from the groups]200 kW- 2000 kW] Left and > 2000 kW Right

Møller suggested (3), (4) that the development in low frequency noise with size corresponds to a shift by one 1/3-octave in the spectrum. In Figure 5 a comparison is made where the spectrum for the group of wind turbines]200 kW- 2000 kW] wind turbines is shifted one third of an octave down. It is obvious that the original presentation in Figure 3, also shown in Figure 4, gives a better match between the two groups and the assumption can be rejected as can the consequences of this assumption when extrapolated to 5 MW and 10 MW wind turbines.

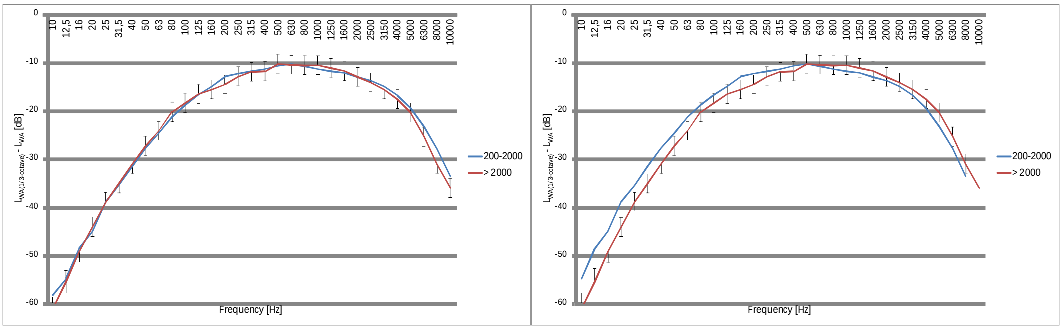

Figure 5 Normalized apparent sound power levels in one- third-octave bands. Mean of two groups of turbines:]200 kW- 2000 kW] and > 2000kW. To the right the group of turbines]200 kW- 2000 kW] are shifted one third of an octave down in frequency as suggested by Møller in (3) and (4).

In order to investigate the results from Figure 3 further a comparison between new (after the regulation) and old (before the regulation) wind turbines from group >2000 kW is made in Figure 6. The definition of new and old is a little diffuse, but measurement reports from before 2010 are considered to be old and after 2010 as new. Around 2010 it was obvious to the industry that regulations on low frequency noise would be introduced and possible measures would be introduced. There is a statistically significant difference in the frequency range from 125 Hz to 400 Hz [$p<0,001$], where the relative amount of noise is lower for the new wind turbines than for the old wind turbines in this group. In the frequency range from 630 Hz to 1600 Hz [$p< 0,01$], the relative amount of noise from the new wind turbines are higher than for the old wind turbines. This suggests that there is a development towards less low frequency noise, possibly because tonality in this frequency range is an area of focus for the developers. Also aerodynamic and aero acoustic optimization of the blades tends to shift the aero acoustically generated noise towards higher frequencies.

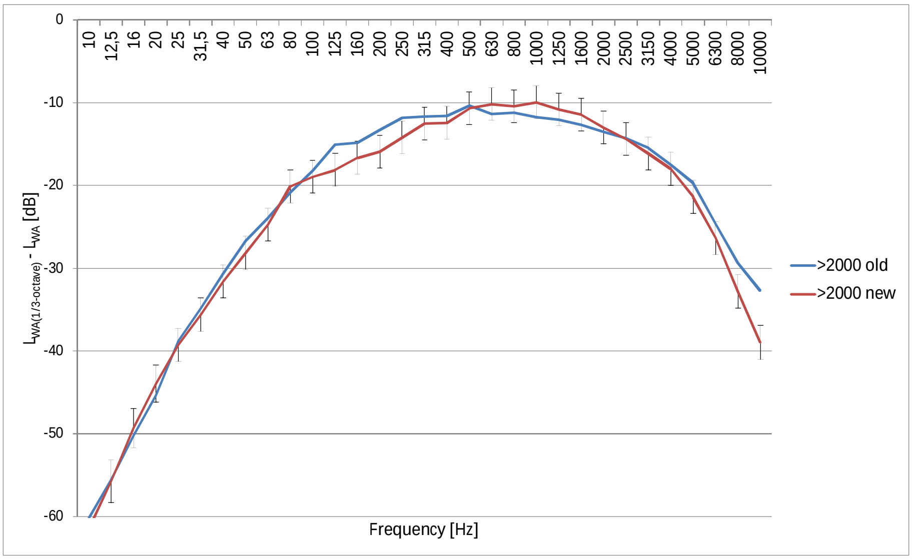

Figure 6 Normalized apparent sound power levels in one- third-octave bands. Comparison of new and old wind turbines > 2000 kW. Error bars show 95% confidence interval around the mean in every 1/3-octaveband for new wind turbines above 2000 kW

The apparent sound power level from the measurement reports is shown as a function of nominal power in Figure 7 both as the total level, L_{WA} and the low frequency part of the level, calculated as the sum of all 1/3-octave bands from 10 Hz to 160 Hz, $L_{WA,LF}$. The figure shows that the low frequency part of the level increases at a higher rate than the total level. From a regression analysis based on wind turbines with a nominal power above 200 kW the rate is 0,43 dB for each doubling of the nominal power in MW. This is a modest development compared to previous analyses of this and suggests that low frequency noise emission can be reduced. The slopes of the lines are not statistically significant different from each other [90 % confidence interval 7.2 to 10.5 for L_{WA} and 8.6 to 11.3 for $L_{WA,LF}$]. If the tendency seen in section 2.2 continues and more new wind turbines are included in the analysis, the difference is likely to be reduced even more.

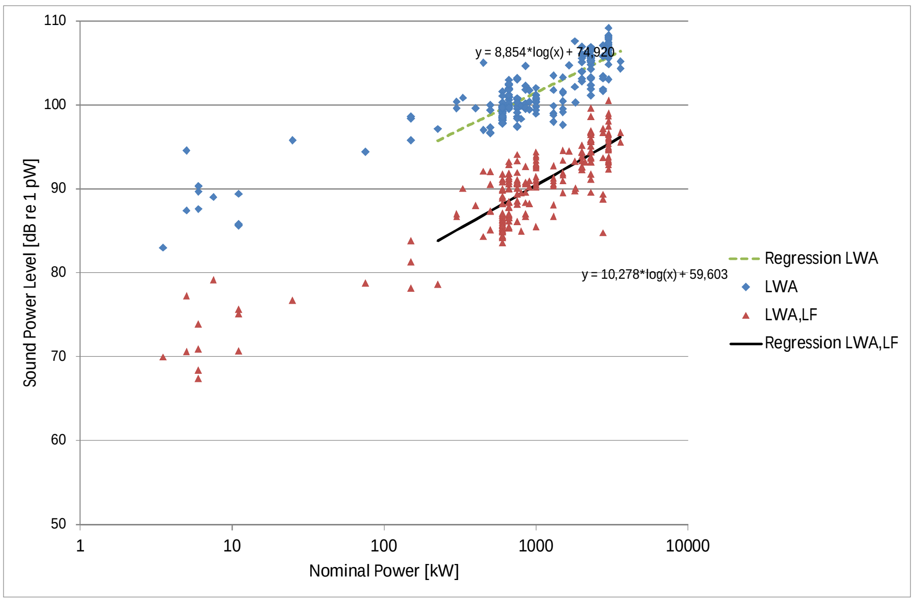

Figure 7 L_{WA} and $L_{WA,LF}$ as a function of nominal power at 8 m/s.

2.2 Type of regulation

In this article as well as in most other reviews and presentations the basis has been the sound power level at 8 m/s. This wind speed has been the reference wind speed during the period where noise from wind turbines has been measured. This is a good parameter for the new type of turbines where pitch-RPM control has taken over from stall and active stall regulation of wind turbines. Measurements where a wider wind speed range has been covered show that the pitch-RPM regulated wind turbines from group > 2000 kW, have the maximal noise emission around 8 m/s. Older wind turbines especially stall and active stall regulated wind turbines have the maximum noise emission at higher wind speeds. Sometimes the maximum may be 5 dB or more higher than the value at 8 m/s. This can be seen in Figure 8, where the noise as a function of wind speed is shown for the three types of regulation. For comparison the curves are normalized to 0 dB at 8 m/s.

Experience from measurements show that the low frequency noise increases at approximately the same rate as the "normal" noise and older wind turbines may actually produce more low frequency noise at wind speeds above 8 m/s than the modern large pitch controlled wind turbines. It is possible that neighbours to wind farms have been exposed to more noise and low frequency noise from the old turbines than they are from the present generation of turbines.

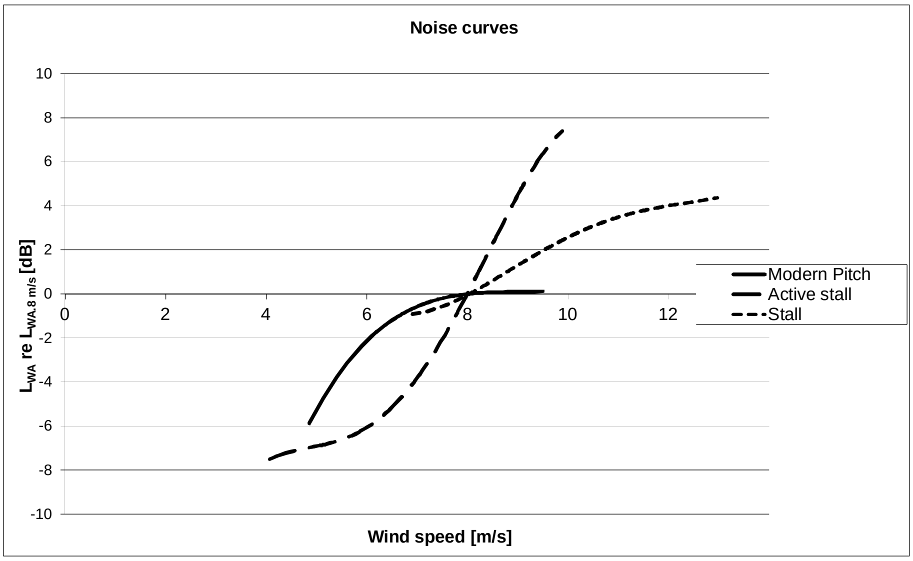

Figure 8. Noise curves for 3 types of wind turbines. The curves are normalised to 0 dB at 8 m/s for comparison, but are from actual measurements and are examples only.

In Figure 9 this is illustrated with a comparison of the spectra for a stall regulated wind turbine from group]200 kW – 1000 kW] and a pitch-RPM regulated wind turbine from group >2000 kW at 8 m/s and 10 m/s are shown. The wind turbines are selected to have comparable spectra and levels at 8 m/s. It is obvious that the noise and the low frequency noise has increased significantly for the stall regulated wind turbine compared to the pitch-RPM regulated wind turbine at 10 m/s. This is a direct consequence of the noise curves in Figure 8 and is a general trend.

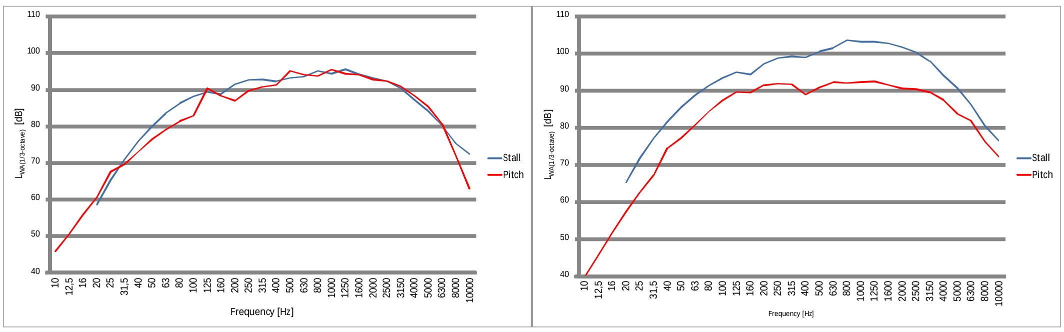

Figure 9. Sound power spectra for a stall regulated wind turbine from group]200 kW – 1000 kW] and a pitch-RPM regulated wind turbine from the group > 2000 kW at 8 m/s (left) and at 10 m/s (right).

2.3 Noise and low frequency noise as a function of wind speed

From the previous section it is clear that the type of regulation of the wind turbine is important for the emission of noise at different wind speeds. In this section an analysis of the development of noise and low frequency noise with wind speed for different types of wind turbines is made. Since almost all commercial measurements are designed to give the level and frequency distribution at 8 m/s or 10 m/s, only few measurements cover a wide range of wind speeds. A number of measurements have been analyzed in more detail. The measurements cover stall regulated wind turbines, active stall regulated wind turbines and modern pitch-RPM controlled wind turbines. In Figure 10 the wind speed dependency of the sound power levels L_{WA} and $L_{WA,LF}$ is shown for different wind turbines. The sound power levels are shown relative to the level at 8 m/s. It is clear from the curves that the sound power level does not increase above 8 m/s for the pitch-RPM regulated wind turbines while there is a significant increase in the sound power level for the stall and active stall regulated wind turbines. What is interesting is that the curves for low frequency part of the noise are similar to the curves for L_{WA}. For pitch-RPM regulated wind turbines the low frequency noise does not increase above 8 m/s but a significant increase occurs for the other types of wind turbines. Note that for all the wind turbines 95% of rated power is reached around 8 m/s to 9 m/s.

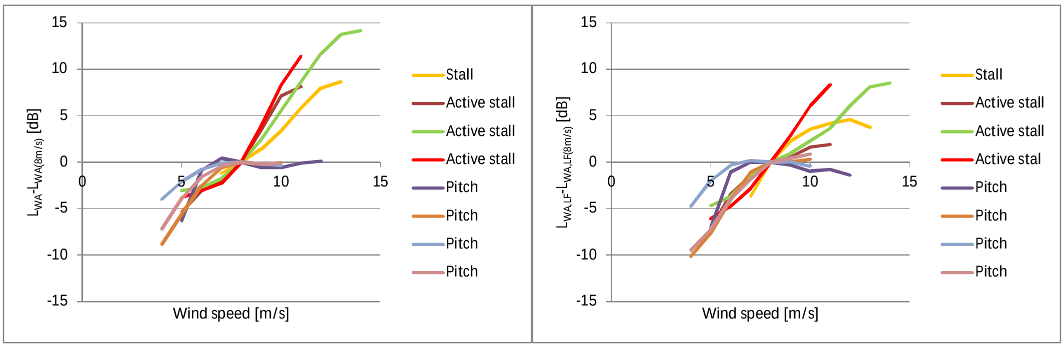

Figure 10. Noise curves L_{WA} and $L_{WA,LF}$ for different wind turbines. The curves are normalized to L_{WA}= 0 dB at 8 m/s for comparison.

In Figure 11 the curves from Figure 10 are averaged according to type of regulation to make the comparison clearer. Note that the curve for stall regulated wind turbines is from a single measurement.

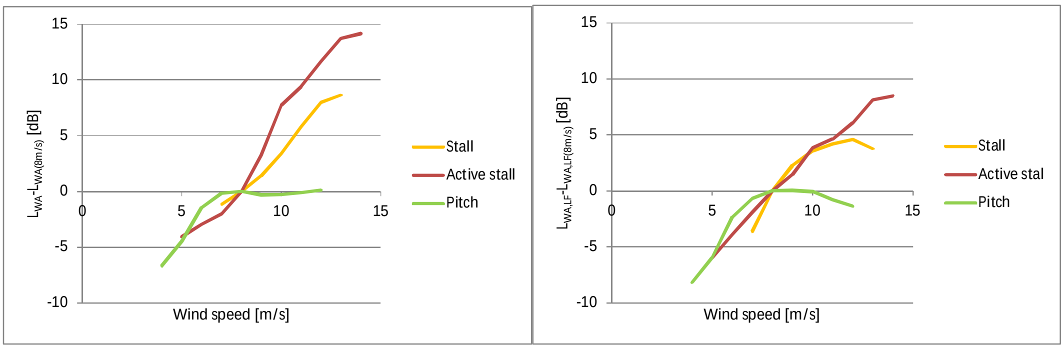

Figure 11. Noise curves L_{WA} and $L_{WA,LF}$ for different wind turbines. Average of the curves in Figure 10.

It is clear from Figure 10 that the development of low frequency noise with wind speed follows the development of the noise in general with wind speed. To be able to see which parts of the spectrum that are the dominant part at different wind speeds an analysis of three of the wind turbines have been made. The results are given in Figure 12 as 1/3-octave band sound power spectra at different wind speeds relative to the sound power spectrum at 8 m/s. It looks like the development of low frequency noise with wind speed is slower for all types of wind turbines than the noise at frequencies above 200 Hz. The corresponding sound power spectra at 8 m/s are shown in Figure 13.

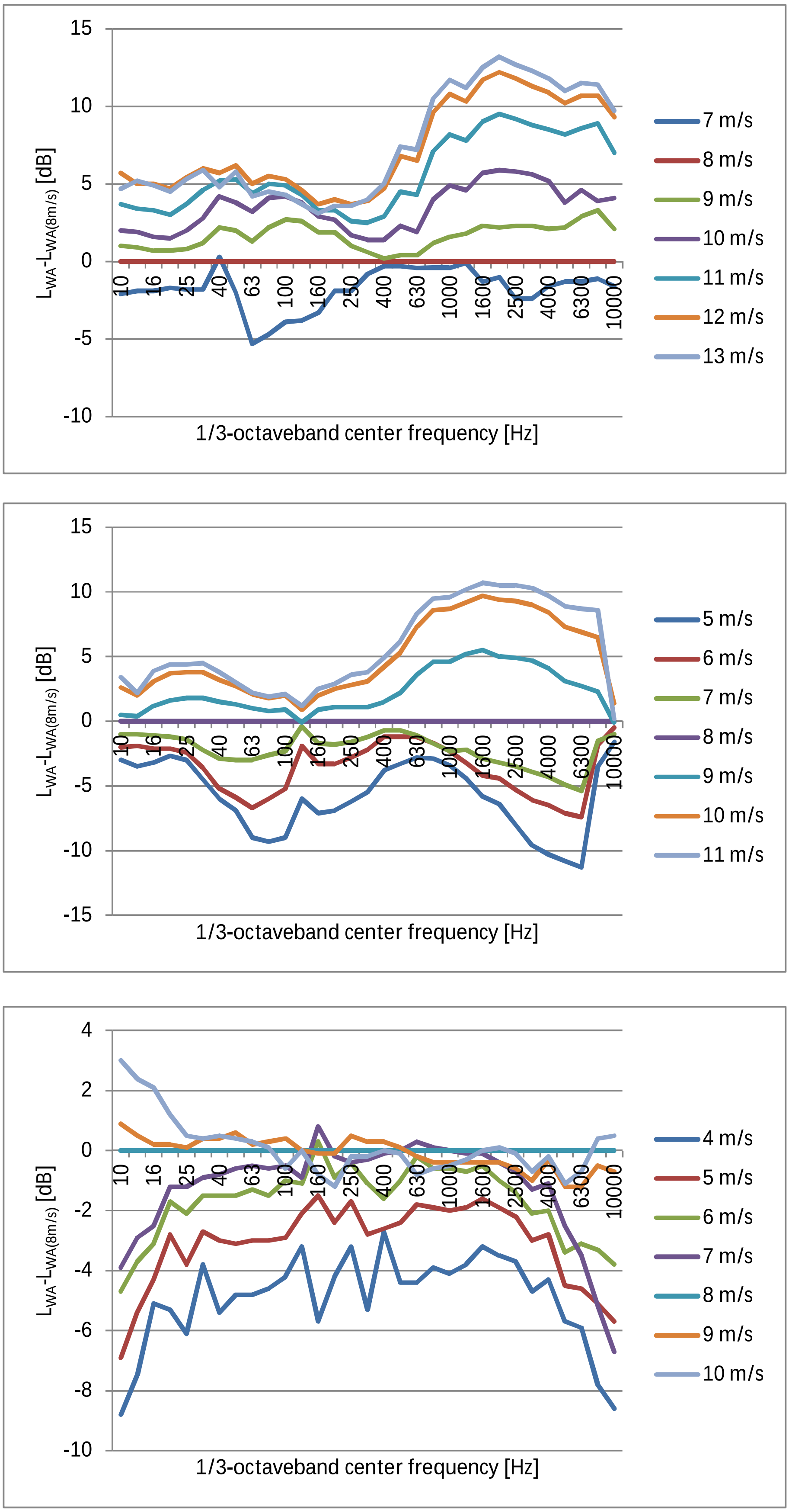

Figure 12. Spectral distribution of the sound power level for a stall (top), active stall (mid) and Pitch-RPM (bottom) regulated wind turbine at different wind speeds. The spectra are relative to the spectrum at 8 m/s.

Above 8 m/s there is no increase in the low frequency part of the noise for the pitch-RPM regulated wind turbine. The increase below 25 Hz in Figure 12 (bottom) is due to an increase in background noise at these wind speeds and do not represent the wind turbine.

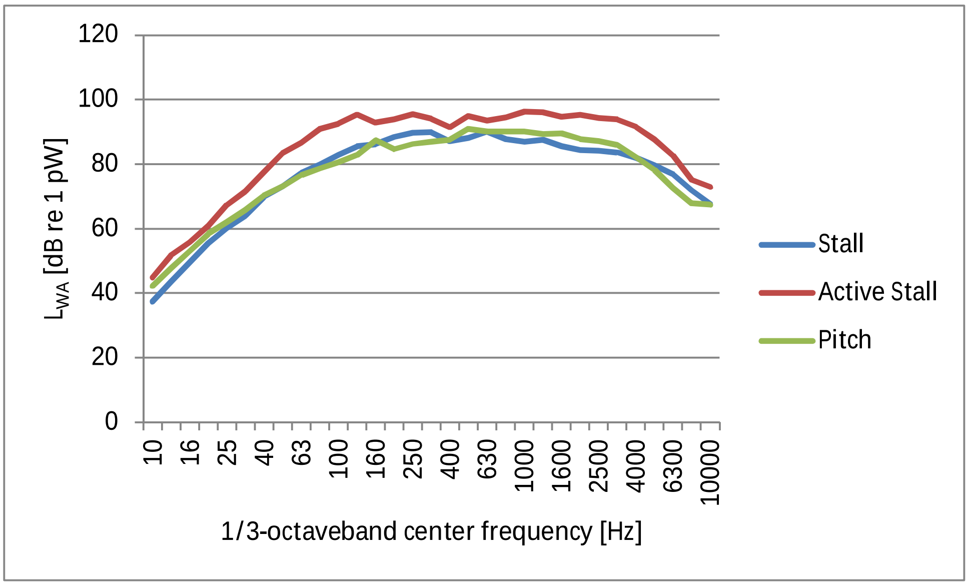

Figure 13. Sound power spectra L_{WA} [dB re 1pW] at 8 m/s for the three different wind turbines.

2.4 Noise as a function of distance

In Denmark the required distance from a wind turbine to nearest neighbour is at least 4 times the total height of the wind turbine. Low frequency noise is reduced less with the distance than higher frequencies. In Table 3 predicted values of noise and low frequency noise are presented for the groups]200 kW to 2000 kW] and > 2000 kW wind turbines with different total heights. Mean spectra from each group are used in the predictions. The results are scaled to a noise level at the neighbour of 44 dB(A) corresponding to the Danish noise limit at 8 m/s. In the predictions the total height for group]200 kW to 2000 kW] is 75 m (50 m hub height and 50 m rotor diameter) and 150 m for the rest of the turbines. Differences in in-door low frequency noise level is within 1.6 dB. New wind turbines > 2000 kW are 0.6 dB higher than small wind turbines. For wind farms the predicted levels can change with different layouts, but most often the noise is dominated by the nearest wind turbines and as the noise is reduced by 6 dB from spherical spreading at all frequencies the contribution from wind turbines at larger distances will often be small. At least for typical Danish wind farms with 2 to 5 wind turbines. It is possible to design wind farm layouts that give different results, but it is chosen to use a simple example for clarity. The results in Table 3 are in line with the results from existing wind farms in Table 3.

Table 3 - Predicted in-door low frequency noise $L_{pA,LF}$ at 8 m/s for different groups of wind turbines assuming the noise level is 44 dB(A).

Wind Turbine	**]200 kW – 2000 kW]**	**>2000 kW**	**>2000 kW New**	**>2000 kW Old**
Distance [m]	300	600	600	600
$L_{pA,LF}$ [dB re 20 μ Pa	16.3	17.4	16.9	17.9

To test if these levels of low frequency noise is audible a comparison with the hearing threshold is given in Figure 14. The comparison shows that below 100 Hz, the spectra are below the hearing threshold and above 100 Hz, the levels are above the hearing threshold. The lower frequencies including the infrasound range is well below the hearing threshold and the part of the noise that is audible is in the normal audible frequency range.

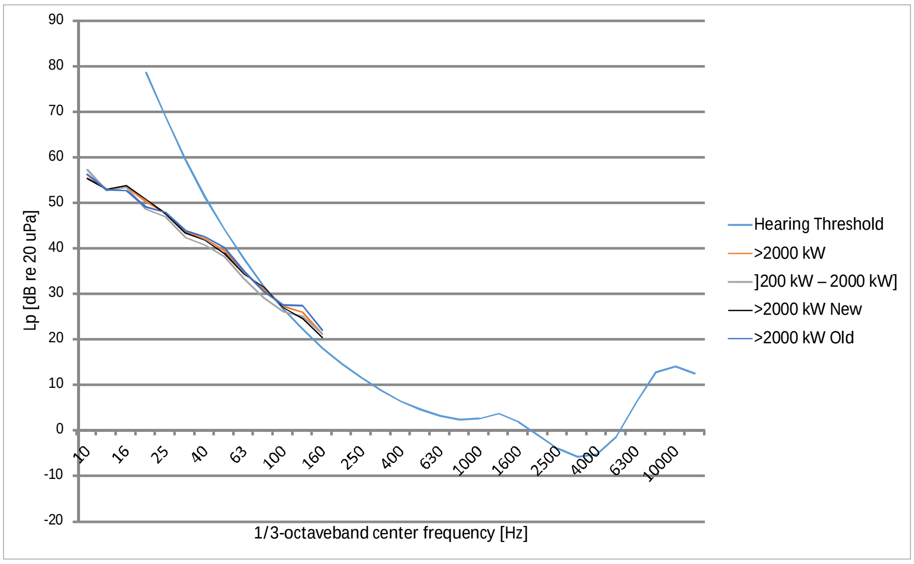

Figure 14. Comparison of in-door wind turbine noise levels with the hearing threshold.

3. Conclusions

The purpose of this review is to investigate if the new Danish regulation on low frequency noise has had any impact on the emitted low frequency noise and the low frequency noise at the neighbours or not. The wind farm examples do not give a clear answer. It gives the impression, that the situation has not changed and the amount of low frequency noise at the residents is the same as for wind farms with smaller and/or older wind turbines.

Looking at the sound power levels and sound power spectra gives more information. Analysis of the sound power spectra shows that after 2010 the relative amount of noise in the frequency range from 100 to 400 Hz is reduced significantly. This includes the important part of the low frequency range from 100 Hz to 160 Hz. Whether this is because of the Danish regulation is impossible to say, but it is likely that the regulations have increased the focus on this in the design phase. It is the experience of Grontmij, that the low frequency tones, which were a significant part of low frequency noise in (1), (2), (3), (4) and (5) are reduced for series produced wind turbines.

In general the analysis shows that the development of low frequency noise with size do not follow the conclusions from the analyses in (3), (4) and (5). The analysis show that on average the amount of low frequency noise is the same for large and small wind turbines, relative to the total noise level and that the amount of low frequency noise for new large wind turbines is less than for old large wind turbines, relative to the total noise level.

The analysis is based on a larger number of measurement reports than previous analyses and experiences from post construction documentation. The results can change if the dataset is increased further, but the conclusions are in line with the conclusions in (1) and (2), where the results were influenced by prototype wind turbines. There is a large variation in sound power levels and sound power spectra within each group of wind turbines used in the analysis and it is important to check the details for each wind farm project. It is also important to follow the development into the next generation of wind turbines where new technologies are likely to be introduced.

The comparison between wind turbines with different types of regulation shows that the development with wind speed of the low frequency part of the sound power level LWA,LF follows the general development of the sound power level LWA. This means that for a modern pitch-RPM regulated wind turbine the low frequency noise does not increase above 8 m/s. For stall and active stall regulated wind turbines the low frequency part of the noise increases above 8 m/s but at a lower rate the noise in general. These conclusions are expected to be valid when no significant tones are present in the low frequency part of the spectrum.

REFERENCES

1. Søndergaard B. Low Frequency Noise from Large Wind Turbines – Summary and Conclusions form Measurements and Methods. AV 140/08. DELTA April 2008
2. Madsen K. D. Low Frequency Noise from Large Wind Turbines – Final report. AV 1272/10. DELTA November 2010
3. Møller H. Low Frequency Noise from Large Wind Turbines, Acoustics University of Aalborg June 2010 (in Danish)
4. Møller H. Low Frequency Noise from Large Wind Turbines – update 2011, Acoustics University of Aalborg May 2011 (in Danish)
5. Møller H. Low-frequency noise from large wind turbines, J. Acoust. Soc. Am. 129 (6), June 2011
6. Statutory order 1284 of 15. December 2011, Noise from wind turbines, from the Danish ministry of the environment (in Danish)
7. Jakobsen J. Danish regulation of low frequency noise from wind turbines. 15th International Meeting on Low Frequency Noise and Vibration and its Control Stratford upon Avon UK 22nd – 24th May 2012
8. Sørensen T. Experiences with the New Danish Rules for the Calculation of Low Frequency Noise from Wind Turbines, 15th International Meeting on Low Frequency Noise and Vibration and its Control Stratford upon Avon UK 22nd – 24th May 2012
9. S. Wagner, R. Bareiss and G. Guidati. Wind Turbine Noise. Springer 1996.
10. D. Bowdler and G. Leventhall. Editors. Wind Turbine Noise. Multi-Science Publishing CO. Ltd. 2011.
11. Søndergaard B. Low Frequency Noise from Wind Turbines: Do the Danish Regulations Have Any Impact?, 5th International Conference on Wind Turbine Noise Denver 28 – 30 August 2013
12. B. Søndergaard. Low Frequency Noise from wind turbines, Do the danish regulations have any impact? An analysis of measurements. Grontmij Report. January 2014. Published on internet. http://www.acoustica.dk/backoffice/modules/FileManager/manager/39/view/