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Project Report

EFP-06 project
Low Frequency Noise from Large Wind Turbines

Final Report

Performed for Danish Energy Authority

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Page 1 of 70

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Preface

The work presented in this report is carried out in EFP-06 project "Low Frequency Noise from Large Wind Turbines – Quantification of the Noise and Assessment of the Annoyance". The project is funded by the Danish Energy Authority under contract number 033001/33032-008. Supplementary funding to the project is given by Vestas Wind Systems A/S, Siemens Wind Power A/S, Vattenfall AB Vindkraft, DONG Energy, E.ON Vind Sverige AB.

The project has been carried out in cooperation between DELTA, RISØ DTU, DONG Energy, Aalborg University, The University of Manchester and the University of Salford.

This final report sums up the results from the different parts of the project. There is a number of supplementary project reports available describing in more details the different project parts. These reports are referenced in the text.

DELTA, 21 November 2010

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Contents

0 Summary

The project on “Low Frequency Noise from Large Wind Turbines” was initiated due to a growing anxiety in the public that new large wind turbines might have a larger impact on the environment, associated with significantly more low frequency noise than experienced from smaller wind turbines already present.

Since the first summary report [11] was published in 2008 several larger wind turbines has been installed at wind farms in Denmark and measurement results from 14 of these turbines have been compared to 33 older *small* wind turbines. Conclusions based on the new results are considered to give a better description of the trend for low frequency noise from large wind turbines than the original measurements on 4 prototype wind turbines.

It is found that the total A-weighted noise emission from the wind turbines increases with the nominal power of the turbines. The increase in total A-weighted noise emission was slightly less than the increase in electrical power. In short, larger wind turbines are slightly quieter than smaller wind turbines, per kW of generated power.

It is also found that although the A-weighted low frequency emission ($L_{WA,LF}$) from large wind turbines is generally slightly higher than from smaller wind turbines the consequences of this with regard to the low frequency noise impact at the adjacent residences to wind turbines are not solely dependent of wind turbine size. The observed differences between the noise emissions from small and large wind turbines are much smaller than the differences between the individual wind turbine makes, models and configurations both with regard to total noise emission and to low frequency noise emission.

Calculation scenarios at the adjacent residences to wind turbines with determination of low frequency noise levels indoor have been carried out. For scenarios where the results for the total outdoor noise is close to the existing noise limits, the levels calculated for the indoor low frequency noise are close to the guidance limits applicable for industry in Denmark. The difference between indoor low frequency noise levels from small and large wind turbines is small.

Thus it is not shown that large wind turbines do cause a special problem regarding low frequency noise impact at residences close to wind turbines. It is also clear that the evaluation of this always must be made for each specific case based on noise data for the turbines involved and not based on general trends regarding large versus small wind turbines. For projects where outside noise levels are close to the existing noise limits for wind turbines it will be good practice to perform calculations of the indoor low frequency noise impact. This will ensure that appropriate low frequency noise levels are met and hopefully contribute to minimize groundless anxiety in cases where there is no low frequency impact.

In this project adequate methods for performing such calculations are provided and demonstrated. This includes all steps from measurement of noise characteristics of the wind turbines to the calculation of resulting noise levels indoor at neighbours. Measurement methods have been refined so that reliable measurements can be performed in the low frequency range down to at least 20 Hz. The same holds for the sound propagation models

from the turbine to nearby residences, including the sound insulation of houses at low frequencies.

In the project it was found that if tones in the noise from large wind turbines are present in the noise emissions they tend to occur at lower frequencies than for the smaller turbines and do make contributions to the low frequency noise emission. Therefore manufacturers are encouraged to minimize the prominence of tonal components in order to minimize both low frequency noise and the potential for annoyance from tones.

From listening tests carried out by the University of Salford it was found that for the same prominence, low frequency tones are not perceived as more annoying than tones at higher frequencies. It was found that the ISO 1996-2 Annex C method gives excellent agreement between the calculated audibility and the perception of the tones also at low frequencies.

Listening tests simulating an indoor scenario and an outdoor scenario for two actual wind turbine noise samples with and without masking effects from garden noise have demonstrated an *equal annoyance method* as a viable tool for comparing noise from different wind turbine samples.

The results of annoyance ratings when comparing two wind turbine recordings have been explained by spectral and temporal characteristics of the chosen sound samples. The method has given consistent results within the range of stimuli evaluated in this study. The general applicability of the results beyond this scope has not been validated.

In summary, the study has shown that listening tests can be successfully used to find answers to the perception of low frequency tonal wind turbine noise and to compare recordings of wind turbine sounds. Further work can be done to investigate the role of temporal variation such as the level of swishing on annoyance and to relate the annoyance between different scenarios.

Noise levels and sound spectra near adjacent residences to wind turbines have been evaluated. The outdoor noise is here seen to be dominated by noise in the frequency range 200-2000 Hz for both small and large wind turbines. Therefore eventual annoyance will not be dominated by low frequency noise characteristics. The indoor low frequency noise level ($L_{pA,LF}$, that is the most relevant parameter for evaluation of indoor low frequency noise impact) increases by about 1 dB for large wind turbines compared to small wind turbines.

Differences in spectral characteristics of up to 2 dB in the frequency range 100-160 Hz between large and small wind turbines was observed for an indoor scenario. The perception of this spectral difference can be compared to a 2.3 dB change in the “normal” frequency range. This could be characterized as a noticeable but not an essential change.

A theoretical study from RISØ DTU together with the findings from the measurements on large wind turbines and a literature study, confirms that infrasound is imperceptible for this type of wind turbines. Even close to the wind turbines the sound pressure level is much below the normal hearing threshold. Thus infrasound is not considered a problem.

0.1 Resumé (in Danish)

Projektet om "Lavfrekvent Støj fra Store Vindmøller" blev iværksat på grund af en stigende bekymring i befolkningen for, at store nye vindmøller skulle påvirke omgivelserne med betydelig mere lavfrekvent støj end oplevet med de kendte mindre vindmøller.

Siden oversigtsrapporten [11] blev udgivet i 2008, er der opstillet adskillige større vindmøller i vindmølleparker i Danmark. Målinger fra 14 af disse vindmøller er blevet sammenlignet med 33 ældre små vindmøller. Konklusionerne baseret på disse nye resultater giver en bedre beskrivelse af udviklingen i lavfrekvent støj fra store vindmøller end de oprindelige målinger på 4 prototype vindmøller beskrevet i [11].

Det er konstateret, at den totale A-vægtede støjudsendelse fra vindmøller stiger med vindmøllernes nominelle elektriske effekt. Stigningen i den totale A-vægtede støjudsendelse er lidt lavere end stigningen i elektrisk effekt, så kort sagt udsender store vindmøller lidt mindre støj end små vindmøller, regnet pr. kW produceret elektrisk effekt.

Det er også konstateret, at selvom den A-vægtede lavfrekvente del af støjudsendelsen ($L_{WA,LF}$) for store vindmøller er lidt højere i forhold til den totale støj end for små vindmøller, så er støjpåvirkningen af de nærmeste beboelser i forhold til lavfrekvent støj ikke kun afhængig af vindmøllernes størrelse. De konstaterede generelle forskelle i støjeudsendelse mellem små og store vindmøller er således langt mindre end de forskelle, der ses mellem individuelle vindmølletyper, modeller og konfigurationer både mht. til den totale støjudsendelse og den lavfrekvente støjudsendelse.

Der er foretaget beregninger af den lavfrekvente støj indendørs i beboelser i nærheden af vindmølleparker. I situationer, hvor man ligger tæt på den gældende udendørs støjgrænse for totalstøjen for vindmøller, er der indendørs beregnet værdier, der ligger tæt på den vejledende grænseværdi for lavfrekvent støj, der findes for virksomheder i Danmark. Der ses generelt små forskelle i lavfrekvent indendørs støj mellem små og store vindmøller.

Det er således ikke påvist, at store vindmøller udgør et specielt problem i forhold til lavfrekvent støjpåvirkning ved naboer til vindmøller. Det fremgår klart, at vurderinger altid bør foretages for hver specifik situation og baseres på støjdata for de aktuelle vindmøller og ikke på generelle trends for store versus små vindmøller. God praksis vil være, at der for projekter, hvor man ligger tæt på de gældende støjgrænser for vindmøller, foretages beregninger af den indendørs lavfrekvente støjpåvirkning hos naboerne. Dette vil sikre, at relevante niveauer for lavfrekvent støj overholdes og vil forhåbentlig også bidrage til at minimere unødig bekymring i tilfælde, hvor der ikke er betydende lavfrekvent støj.

I dette projekt er der opstillet og demonstreret metoder til gennemførelse af sådanne beregninger. Dette inkluderer alle trin fra måling af vindmøllernes støjkarakteristika til beregning af resulterende indendørs støjniveauer i boliger i nærheden af vindmøller. Der er således foretaget udbygning af målemetoden, så der kan gennemføres pålidelige målinger i det lavfrekvente område ned til mindst 20 Hz. Det samme gælder for lydudbredelses-

modeller fra vindmølle til nabobolig inklusive indvirkningen af lydisolationen af bygninger ved lave frekvenser.

I projektet kunne det i øvrigt konstateres, at når der er toner i støjen for store vindmøller, ligger de ofte ved lavere frekvenser end for små vindmøller. Disse toner bidrager til den lavfrekvente støjudsendelse fra vindmøllerne. Derfor bør fabrikanterne være opmærksomme på at minimere tonebidragene med henblik på at begrænse såvel lavfrekvent støjudsendelse som den potentielle genevirkning fra toner i støjen.

Som en del af projektet er der foretaget lyttetest ved Salford Universitet. Her er det bl.a. konstateret, at toner ved lave frekvenser ikke opfattes som mere generende end toner ved højere frekvenser, når de har samme tydelighed. Det kunne også konstateres, at metoden til toneanalyse, som er beskrevet i ISO 1996-2 Annex C, giver god overensstemmelse mellem den beregnede hørbarhed og den opfattede hørbarhed af tonerne - også ved lave frekvenser.

Med baggrund i lyttetest, der simulerede et indendørs scenarium og et udendørs scenarium for to lydeksempler fra vindmøller hhv. med og uden maskerende effekt fra vegetationsstøj, er anvendeligheden af en *"equal annoyance method"* til sammenligning af genevirkning af forskellige lydeksempler fra vindmøller demonstreret.

Resultater fra genebedømmelserne for to lydoptagelser fra vindmøller kan forklares ud fra spektrale og tidsvarierende karakteristika for de udvalgte lydeksempler. Metoden har givet konsistente resultater for de anvendte stimuli. På grund af de få lydeksempler er en generalisering af resultaterne ikke valideret.

Alt i alt er det vist, at lyttetest kan anvendes til at bedømme genevirkningen af lavfrekvent tonestøj og til sammenligning af forskellige lydoptagelser af vindmøllestøj. Metoderne vil fremover kunne anvendes til nærmere undersøgelser af støjens karakteristika som f.eks. indflydelsen af vingesuset på den oplevede genevirkning for forskellige scenarier.

Der er foretaget en vurdering af støjniveauer og støjspektre ved boliger i nærheden af vindmøller. Det udendørs støjniveau er domineret af støj i frekvensområdet 200-2000 Hz for både små og store vindmøller, og derfor vil evt. gene ikke være domineret af lavfrekvent støj i dette tilfælde. Det indendørs lavfrekvente støjniveau ($L_{pA,LF}$, der er den mest relevante parameter ved vurdering af lavfrekvent støjpåvirkning) stiger ca. 1 dB for store vindmøller i forhold til små.

Forskelle i frekvensindhold på op til 2 dB mellem små og store vindmøller er set i frekvensområdet 100-160 Hz for det indendørs tilfælde. Opfattelsen af disse spektrale forskelle kan sammenlignes med en 2,3 dB ændring i det "normale" frekvensområde. En sådan forskel kan karakteriseres som hørbar, men ikke væsentlig.

Et teoretisk studie fra RISØ DTU bekræfter sammen med resultater fra målingerne på de store vindmøller samt et litteraturstudie, at indfralyd er uden betydning for den normale vindmølletype med vingerne foran tårnet. Selv tæt på vindmøllerne er niveauet for infralyd langt under den normale høretærskel. Infralyd betragtes derfor ikke som et problem.

1. Introduction

A major goal of the project is to make it possible to predict and assess low frequency noise at neighbours to wind turbines or wind farms based on noise measurements close to the wind turbine. The reason for this is that measurements at the neighbours will have a stronger influence from background noise than measurements close to the wind turbine, making it difficult to make valid decisions from the measurements. Other aspects like noise generation and the development of low frequency noise from small to large wind turbines are investigated as well, giving an indication on future development. Also the actual annoyance experienced by neighbours to wind turbines is investigated based on listening tests.

A study of the most referenced literature on low frequency noise from wind turbines has been made leading to a suggestion for evaluating audibility and masking to be able to compare and qualify the data in the literature.

The project deals with noise from large wind turbines. As most wind turbines with a nominal power up to 2 MW are considered as commercially available turbines, large wind turbines in this project is defined as turbines with a nominal power above 2 MW.

It can be difficult to distinguish between infrasound, low frequency noise and what is referred to as normal noise. In Figure 1 the three frequency ranges are illustrated. The ranges overlap with each other meaning there is no distinct physical reason for these definitions of frequency ranges. The hearing threshold is shown in Figure 1 as well. The hearing threshold is the level at which the noise is just audible at that frequency. The hearing threshold changes almost 80 dB in the low frequency range.

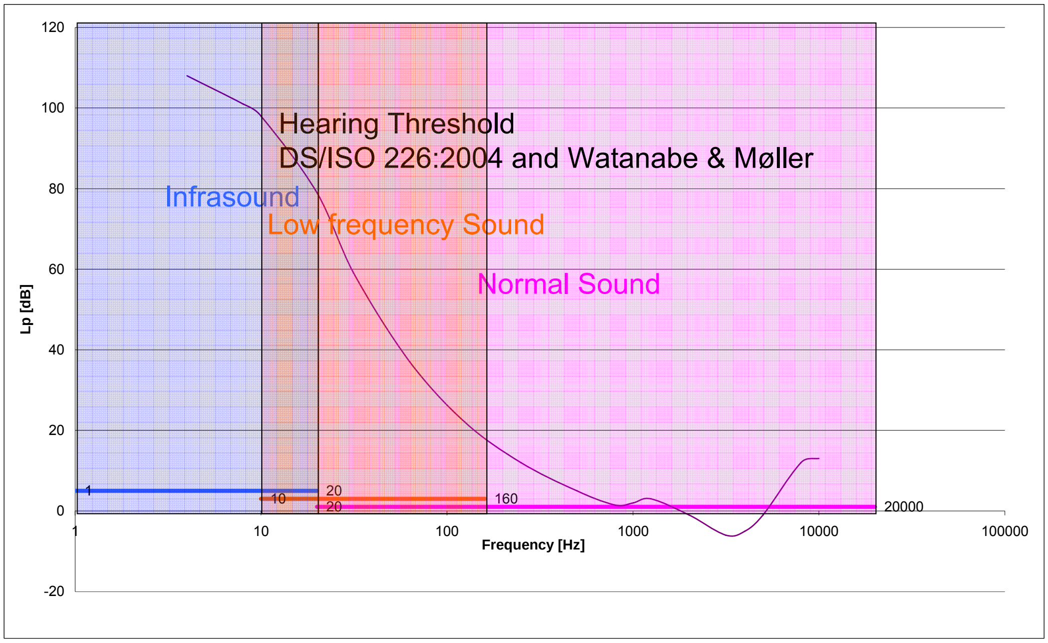

Figure 1
Different frequency ranges and the Hearing Threshold[1].

2. Measurement methods and prediction methods

To be able to make reliable assessment of noise from wind turbines in the environment it is necessary to have reliable and applicable methods for determining the emitted noise, for noise propagation and for determining the noise insulation of houses. This is true in general and also for low frequency noise.

In Figure 2 is illustrated a typical situation of sound propagation from a wind turbine to an indoor neighbour. This includes the strength of the wind turbine sound source, the sound attenuation caused by the propagation over distance with influence of the type of landscape, the weather and the sound attenuation due to sound reduction of the building. All put together giving the indoor noise level experienced by the neighbour to the wind turbine.

[1] When the low frequency range is measured in 1/3-octave bands according to the Danish legislation the 1/3-octave bands with centre frequencies in the range 10-160 Hz are included. This definition is also used throughout this project and the notation $L_{pA.LF}$ for low frequency sound pressure levels and $L_{WA.LF}$ for low frequency sound power levels are used.

The 3 steps illustrated in Figure 2 are sound power measurements, noise propagation and sound insulation. Each of these will be discussed in the following paragraphs.

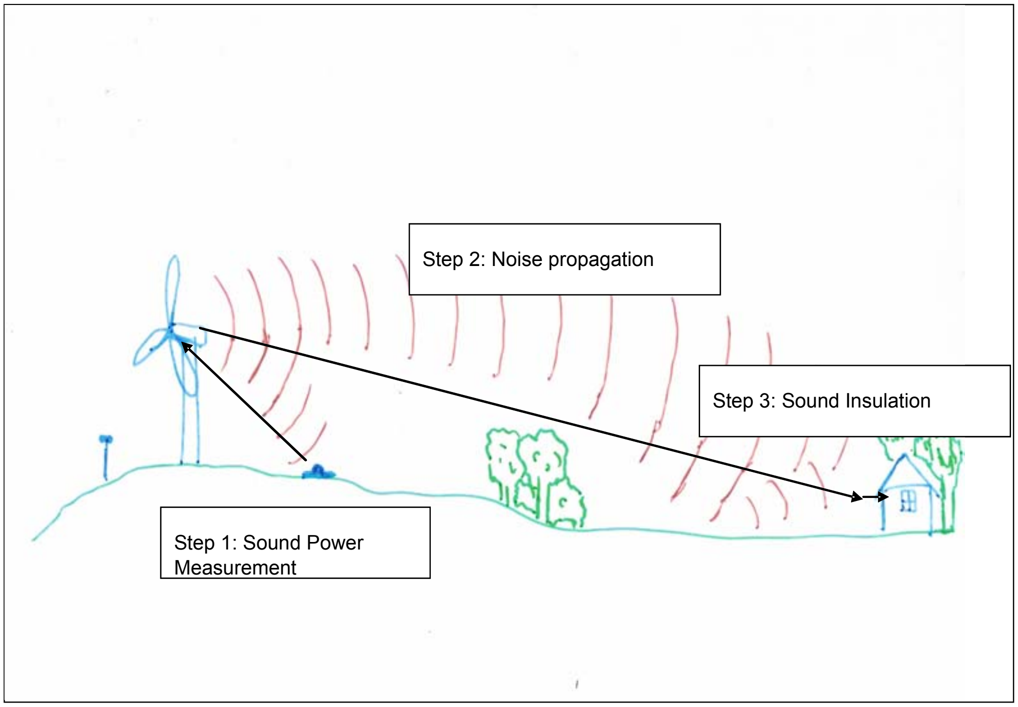

Figure 2
The 3 steps in noise prediction.

2.1 Sound power measurements

Reference [1] Søndergaard, Bo and Ryom, Carsten
Low Frequency Noise from Large Wind Turbines - Sound Power measurement method. AV 135/08. DELTA April 2008

At the moment there is a widely accepted measurement method described in the measurement standard IEC 61400-11:2002 edition 2.1. Since 1998, where the first version of the standard was published, this measurement method has been preferred around the world when it comes to comparison of noise emission from different wind turbines and giving input to noise predictions. The result of this method is a wind speed dependent apparent sound power level of an equivalent point source located at the rotor centre. Information on the horizontal directivity of the equivalent point source can be determined as well. The tonality of the noise is analyzed and reported too.

A new edition 3 of the above mentioned measurement standard is expected to be approved in the beginning of 2011. The measurement method itself is unchanged but some of the analysis and presentation of results are changed. Also important for this study, the frequency range is extended in the low frequency range from 50 Hz in edition 2.1 down to 20 Hz in edition 3.

The setup for the measurement is shown in Figure 3. The measurement distance d = hub height + half a rotor diameter.

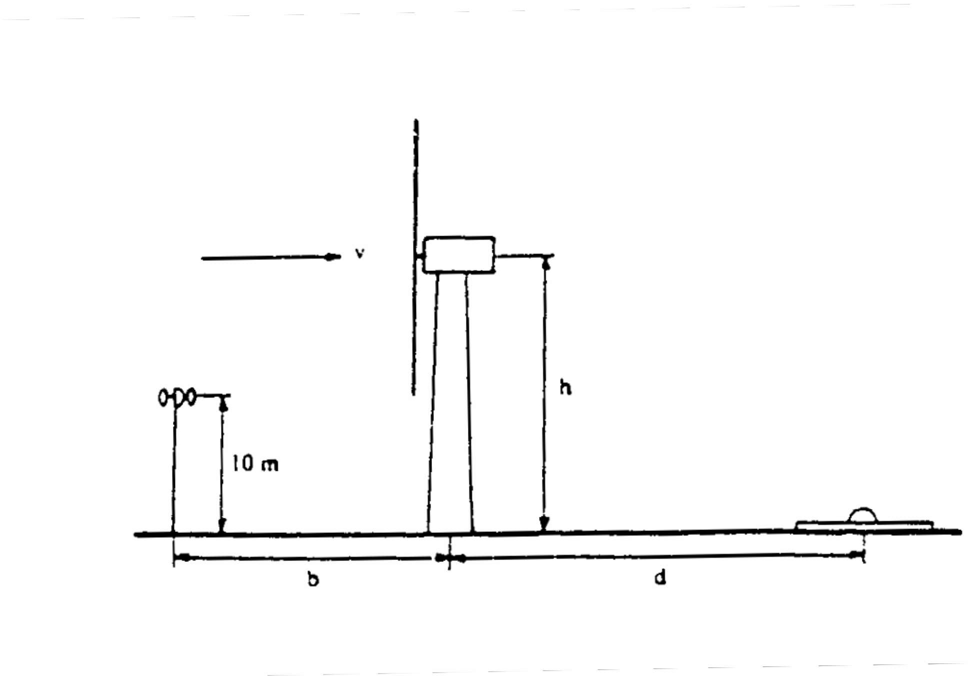

Figure 3
Measurement setup.

The microphone is put on a board on the ground mounted with a half standard wind screen. The used ground board is shown in Figure 4 and Figure 5 and has a diameter of at least 1 m. The wind speed is measured through the produced power and a calibrated power curve. An anemometer is placed in front of the wind turbine making it possible to measure the wind speed when the wind turbine is stopped for background noise measurements. The distance b to the anemometer is between 2 and 4 rotor diameters.

The measurement position on a ground board serves 2 purposes:

- It keeps the microphone out of the wind and reduces the wind noise in the equipment.
- It reduces the ground reflections to a simple +6 dB correction at all frequencies due to pressure doubling.

The wind induced noise in the measurement equipment is considered the most significant problem when extending the measurement standard to frequencies below 50 Hz. Experiences from a JOULE project led to designing a secondary wind screen as shown in Figure 5. Measurements in the project indicate an improved signal to noise ration at frequencies below 50 Hz, indicating a reduction in the wind induced noise in the measurement equipment. The insertion loss of the wind screen is measured and corrected for.

Figure 4 (Left)
Standard measurement setup with ground board.

Figure 5 (Right)
Measurement setup with DELTA H wind screen.

2.2 Noise propagation model

Reference [2] Plovsing, Birger
Low Frequency Noise from Large Wind Turbines – Selection of a Propagation Model. AV 1096/08. DELTA April 2008

Existing propagation models considered in the project can be divided into three groups:

- Empirical models
    - ISO 9613-2: Attenuation of sound during propagation outdoors – Part 2: General method of calculation
    - Nordic general prediction model for noise from industrial plants
- Wave equation models
    - Parabolic Equation method (PE)
    - Boundary Element Method (BEM)
    - Fast Field Program (FFP)
    - Linearized Euler (EU)
- Ray models
    - Numerical ray tracing models
    - Semi-analytical ray models

Empirical models

Most calculations of noise from wind turbines are made according to empirical models.

The two models under consideration have common characteristics and share, among other things, equations for ground attenuation. The advantage of both methods is that they are available in commercial software. However, the weather condition in the model has been fixed to moderate downwind, and the model has been developed for moderate propagation distances and with the source and receiver close to the ground. A general weakness of empirical models is that they cannot be expected to produce reliable results outside the range of model variables where measurements have been available. It is well known that the two methods do not produce good results for high sources such as wind turbines.

Wave equation models

Wave equation models are numerical models based on the wave equation. Calculations may be performed in the frequency or time domain although frequency domain models are most often used. The only model relevant to consider is the Parabolic Equation method (PE). However, PE will, due to the calculation time and lack of commercial software, only be of relevance in special cases where strong weather effects at long distances have to be predicted accurately.

Ray models

In numerical ray tracing models a ray path is constructed numerically by making small steps along the ray path in such a way that the elevation angle of the ray satisfies Snell's law. A ray tracing algorithm is an iterative computational algorithm which calculates many ray paths and selects those that arrive at the receiver.

In a semi-analytical ray model an algorithm is applied which directly calculates the ray without the iteration necessary for numerical ray tracing. However, a solution for direct calculation of the ray is only available for an atmosphere with a linear vertical sound speed profile leading to circular rays. Therefore, more realistic sound speed profiles have to be approximated by linear profiles. It could be expected that numerical ray tracing models would be more accurate than semi-analytical ray models as the correct ray path is calculated avoiding the approximation of the real sound speed profile by a linear profile. However, in practice the use of simple numerical ray tracing does not seem to increase the calculation accuracy significantly compared to a well adjusted semi-analytical ray model. Therefore, taking into account the considerable reduction in calculation time by the semi-analytical ray models, these models are often preferred for engineering purposes.

The Nord2000 model and the European Harmonoise model

The Nord2000 model and the European Harmonoise/Imagine model are both semi-analytical ray models, although the former is using circular rays while the latter is based on the analogy of curving the ground instead. However, the curving of the ground is based on circles assuming linear sound speed profiles as well. It is expected that the accuracy of the two methods are almost the same, also in the low frequency range. At present, the Harmonoise method is not fully documented and has not been thoroughly tested in practical cases.

The Nord2000 method has matured, since the method was completed, and has been adjusted based on practical experience with the model. A software implementation is available at DELTA. The Nord2000 method has been validated by a large number of measurements or other kind of reference results. In an Energinet.dk project PSO F&U project nr. 2007-1-2389 Nord2000 was tested for wind turbine noise propagation. The results show very good agreement between measurements and calculations and the full documentation is found in [15].

The general recommendation is to use Nord2000 method for prediction of outdoor sound propagation from wind turbines. The method is fast, compared to the wave equation models and software implementations are available.

2.3 Sound insulation measurements

Reference [3] Hoffmeyer, Dan and Søndergaard, Bo
Low Frequency Noise from Large Wind Turbines – Measurements of Sound Insulation of Facades. AV 1097/08. DELTA April 2008

2.3.1 Project results

As low frequency noise is often most prominent indoors it is necessary to know the sound insulation of the neighbouring houses. It is not possible to give data for all types of houses so the project has focused on how to measure the sound insulation. A measurement method based on EN ISO 140-5:1998, supplemented by findings from Acoustics at Aalborg University (AAU) on how to select microphone positions was used. Microphone positions, according to EN ISO 140-5:1998 and the Danish Environmental Protection Agency (DEPA) recommendations, were used as well. The measurement positions suggested by AAU give most reproducible results. It is, however, not clear at this moment whether the results underestimate the insertion loss for practical uses.

The specified method for measuring the outdoor/indoor level difference for a building façade at low frequencies is based on the use of a large loudspeaker outside the house and several microphones inside the house. A microphone mounted on the façade under consideration represents the outside noise level. The level differences are averaged on energy-basis.

There is no correction for the indoor room-acoustic environment.

Using this procedure to determine the insertion loss of a house at frequencies below 200 Hz requires considerable signal power and a low background noise level. Especially at 8 Hz and 10 Hz it is difficult to obtain a sufficient signal to noise ratio, and correlation techniques like MLS could be considered. However, the energy content of wind turbine noise at these frequencies is limited and the insertion loss could be assumed to be zero without serious consequences for the results or conclusions.

An example of one of the four 3D positions suggested by AAU is shown in Figure 6.

Figure 6
Example of a 3D position with the microphone placed in the three-dimensional corner where two walls and the ceiling meet.

A comparison of the insertion loss determined with the 3 types of measurement positions for one of the 5 houses included in the project are shown in Figure 7. At frequencies below 50 Hz the 3 methods are in good agreement. At frequencies above 63 Hz the 3D corner positions give higher noise levels inside resulting in lower noise insulation. The ISO and DEPA (LFM in the chart) methods both include positions in the room away from room boundaries.

The noise measurements in the corners give results 4-5 dB above the room average. It might be reasonable to correct measurements to the room average for frequencies above 63 Hz. If this is done, the results of the three measurement methods will be close. However, a correction of the method is still subject to discussion.

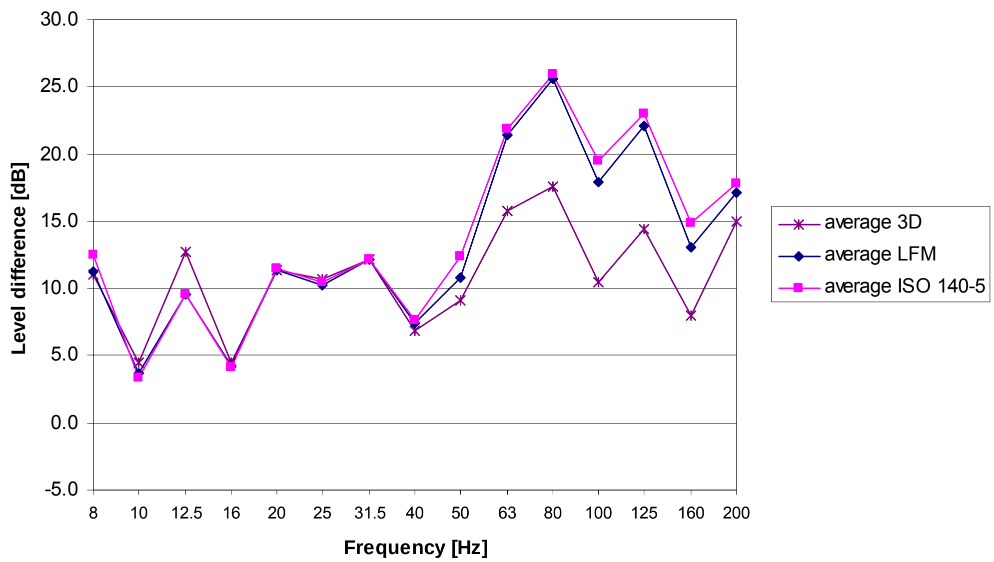

Figure 7
Location: Værløse. Measurement results for the small-sized room. Outdoor/indoor level differences in dB per one-third octave measured with the specified method (3D), with the low frequency method and with the ISO method.

The variation among the results from the different houses and rooms houses is wide. The standard deviation calculated for the level differences of the 10 rooms is between 2.1 to 7.8 for the frequencies measured.

In the present work, it has not been possible to conclude on the connection between building and window types, sizes and the measured level differences at low frequencies. If the results from the project are used for specific situations, the average value of the results should be used or a large uncertainty stated.

2.3.2 Supplementary results for sound insulation at low frequencies

Since the first report was published in 2008 [3] and [11] the results have been further processed and combined with results from other sources. This has resulted in a paper submitted in the Journal of Low Frequency Noise, Vibration and Active Control,Volume 29 Number 1 2010 [14]. In this connection, the results are based on indoors measurement positions that represent normal occupation of the rooms, as is recommended by the Danish Energy Protection Agency.

In this paper data have been treated statistically, and the level difference expected to be exceeded by 80-90% of typical Danish dwellings (ΔL_σ) has been determined in the frequency range 10-200 Hz. In Figure 8 the resulting ΔL_σ level difference is shown.

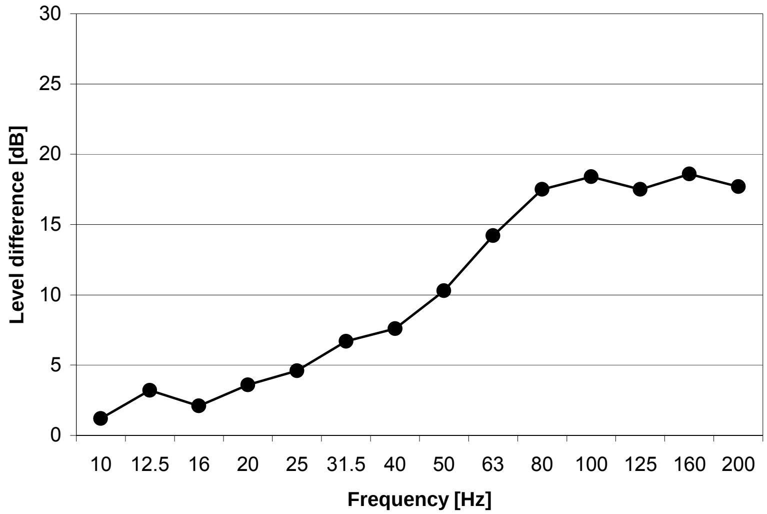

Figure 8
Outdoor to indoor level difference expected to be exceeded by 80-90% of typical Danish dwellings (ΔL_σ) [14]. This means that the "sound insulation" is expected to better in 80-90 % of the dwellings. (New figure November 2010).

The results presented in [14] have been used for preparation of samples for the listening tests described in chapter 6 and for calculation of low frequency sound pressure levels indoor described in section 5.2.

2.4 Conclusions

When predicting the noise according to the principles described in the previous sections, the results are dependent on the input data like sound power, noise insulation and the details of the transmission path.

In the sound power measurement method IEC 61400-11:2002 a guideline is given on how to assess the uncertainty of the results. The uncertainty of L_{WA} is of the order of 2 dB. The uncertainty in the individual 1/3-octave bands is higher, specifically at the lower frequencies.

For the noise insulation data given in [14], the standard deviation on the average of all houses was between 4 and 7 dB. In the most important, upper frequency range the standard deviation was about 4 dB.

In the noise propagation the most important parameters are the wind direction and the wind speed. For frequencies below 200 Hz and for high sources, the noise propagation is simpler than in most situations. Uncertainties in the individual 1/3-octave bands are expected to be of the order 5 dB.

The predicted indoor levels of the $L_{pA,LF}$ must be expected to have an uncertainty of approximately 5 dB. If specific data for a house type is available the uncertainty is reduced for this particular house. For a general analysis it is recommended that the values for typical Danish dwellings presented in [14] are used and are regarded as cautious estimates of the sound insulation in the actual houses.

3. Audibility of low frequency noise from wind turbines

Reference [4] Pedersen, Torben Holm
Low Frequency Noise from Large Wind Turbines – A procedure for evaluation of the audibility for low frequency sound and a literature study. AV 1098/08. DELTA April 2008

Reference [16]
Hünerbein, Sabine von; King, Andrew; Hargreaves, Jonathan; Moorhouse, Andrew and Plack, Chris
Perception of Noise from Large Wind Turbines (EFP-06 Project)
The University of Manchester, Greater Manchester UK, November 2010

Large amounts of literature on low frequency noise from wind turbines are available when a search on the internet is made. Not all of this literature has the necessary documentation to make results comparable or even understandable.

Conclusions on the audibility of the low frequency noise in the literature are often made from psycho-acoustic inadequate procedures and methods. In order to qualify the conclusions of the audibility of low frequency sounds, a procedure for calculating the audibility of low frequency sound (and infrasound) has been defined, as a first part of this literature study.

Furthermore reasonable demands to the documentation of data in literature are specified.

3.1 Assessment of audibility

The audibility of low frequency noise is important because the differences between just audible sounds and annoying sounds are smaller than in the mid-frequency range. The hearing threshold is only defined for tones and narrow band sounds. Therefore a method for defining the threshold for broad band (wind turbine) sounds is defined as part of the project. The methods based on the so called critical bands of the hearing. The basis for the detection and loudness perception of a sound, as well as the basis for the masking of one sound with another, is the critical bands. Below 500 Hz, the critical bands are approximately 100 Hz wide.

In the above mentioned method the inverse hearing threshold (HT) is applied as a frequency weighting of the measured spectrum and the total HT-weighted energy within each critical bands is calculated from the spectrum. For spectra with a resolution better than 1/3-octaves the method is not very sensitive to the resolution of the frequency analysis

The low frequencies of the wind turbine noise will be regarded to be below the hearing threshold, if the critical band levels found from the HT-weighted wind turbine spectra are less than 0 dB.

The method is illustrated in Figure 9 and Figure 10.

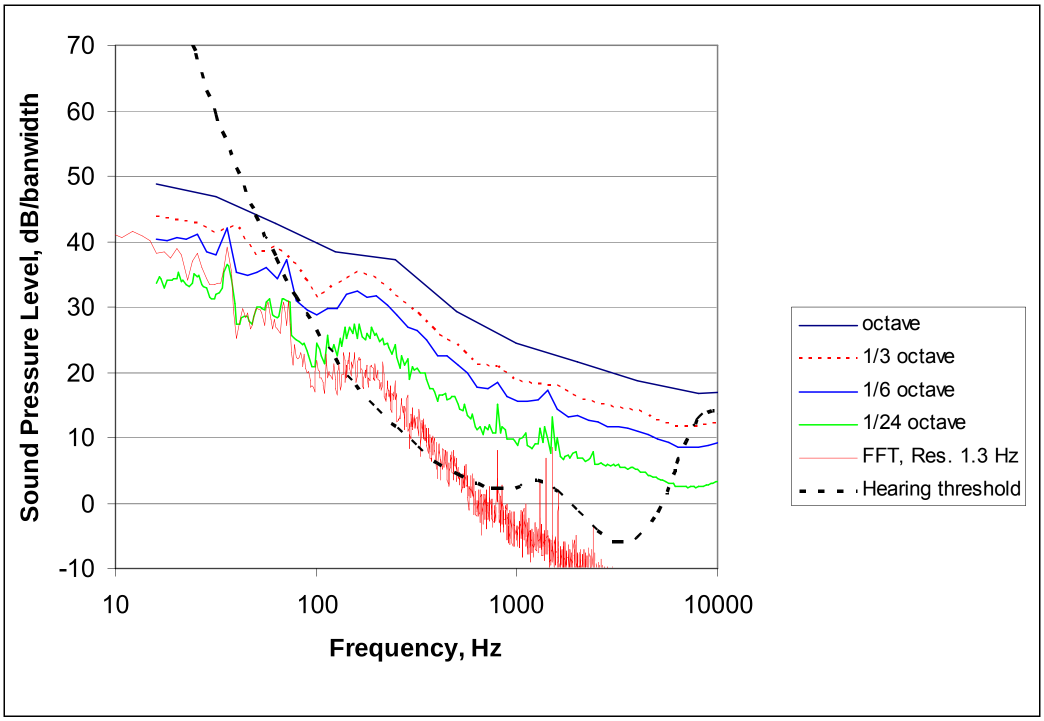

Figure 9
Spectra with different resolution of the same noise from a 1.3 MW wind turbine, referred to a distance of 280 m (measured at 70 m). The abscissa is the level per effective analysis bandwidth. The hearing threshold for tones is also shown at the graph. The A-weighted sound pressure level of the noise is 33 dB.

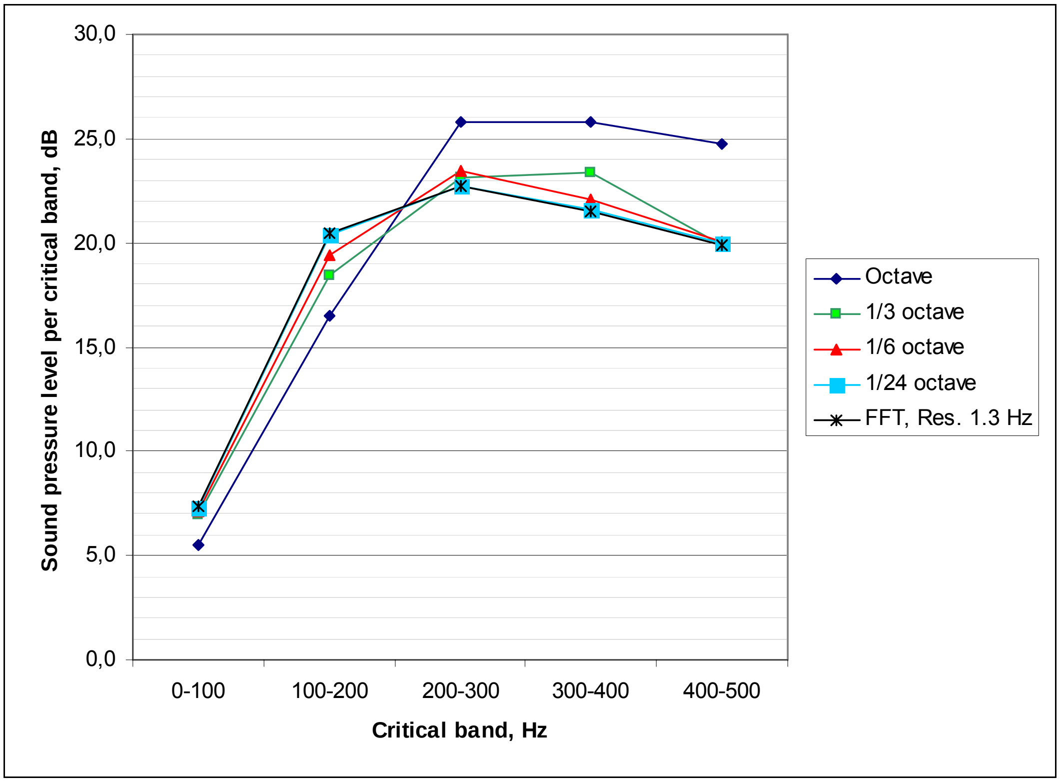

Figure 10
The critical band levels computed from HT-weighted frequency analyses of the noise from the 1.3 MW reference wind turbine shown in Figure 9. The different curves are the result of calculations based on analyses with different analysis bandwidths.

It can be seen that the method is relatively insensitive to the analysis bandwidth except for the 1/1-octave band analysis.

In connection with the listening tests an informal assessment of the method has been made by Salford University. On the basis of a few examples they conclude that the " method for determining the audibility of broadband noise near the hearing threshold works well in the frequency bands between 0 and 500 Hz."

3.2 Assessment of masking

In the preceding section, a method was defined for comparing the wind turbine noise in quiet surroundings with the hearing threshold. In practice there is always some background noise, at least from wind in vegetation and buildings, so the wind turbine noise may not be audible due to masking, even if the HT-weighted critical band levels are above the hearing threshold.

Assuming that no tones are present in the noise, the wind turbine noise is broadband and varying as is the wind-induced noise from vegetation or buildings.

In this case the following principles can be used:

1. In simple cases the spectre of the wind turbine noise and the background noise can be compared directly and independent of any frequency weighting (the spectra shall be measured or referred to the same frequency weighting and analysis bandwidth (1/3-octave bands or less):

    a. The wind turbine noise will be masked if the levels in all analysis bands of the wind turbine noise are more than 2 dB below the levels of the background noise

    b. If the levels of all analysis bands of the *total noise* are less than 2 dB above the background noise the wind turbine will be masked.

If this is not the case, the wind turbine noise may be masked even if the levels of some analysis bands of the wind turbine exceed the levels of the background noise. In this case the following rule applies:

The wind turbine noise is masked if the levels of the critical bands of the A-weighted wind turbine noise are more than 2 dB below the levels of the critical bands of the A-weighted background noise.

The energy sum of the levels of the two lowest critical bands of the A-weighted wind turbine noise equals in practice $L_{pA, LF}$.

3.3 Audible tones

Prominent tones in the wind turbine noise may be a major source of annoyance. It is therefore important that the methods used for detection of tones are in agreement with the perception of these in the whole frequency range.

At Salford University the ISO 1996-2 Annex C method for audible tones was tested by the listening test. In Figure 11 the calculated masking thresholds according to the ISO method (x-axis) are compared to the results of the listening tests (y-axis).

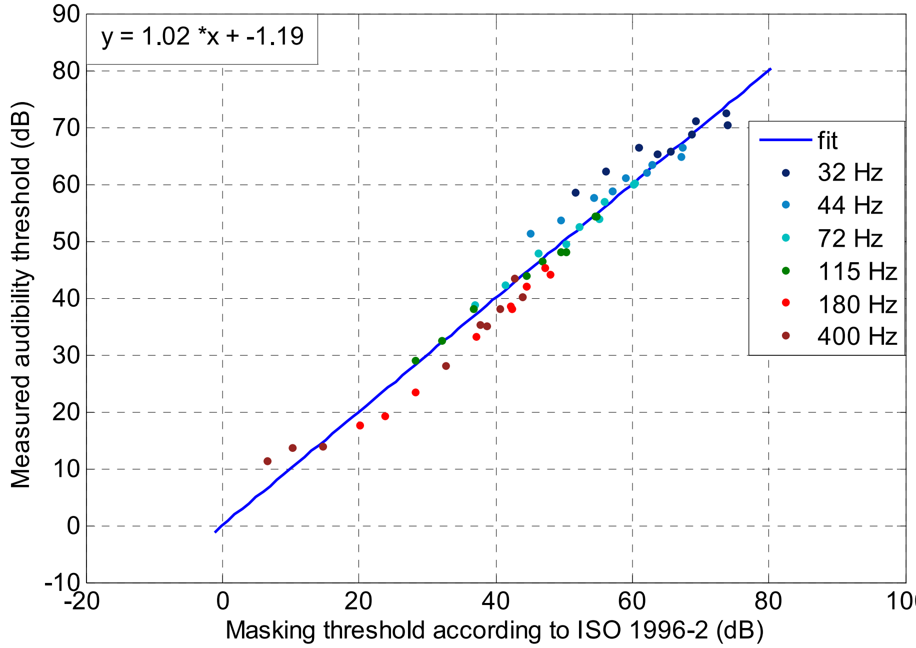

Figure 11
Correlation of measured audibility thresholds in masking noise with masking threshold calculated in accordance with ISO1996-2. Linear regression shows a slope of 1. $R^2 = 0.96$. *(New figure November 2010).*

The figure contains data from both an indoor and an outdoor scenario. The comments from Salford University are:" Although single values deviate by more than 6 dB from the regression line the slope has a value of 1.02 which indicates excellent agreement between measured and calculated thresholds. If the values of the indoors scenario were left out of the regression because of concerns over the applicability of the masking threshold then the correlation equation would change to y=1.09*x-6.38 with an R^2 value of 0.98. In conclusion, the calculations defined by ISO 1996-2 are in good agreement with the low frequency measurements."

3.4 Literature study

Based on the principles in 3.1 and 3.2, it is possible to compare and evaluate data from different sources.

Ideally, the comparisons and conclusions of a literature study should be based on reliable and well documented information suitable for comparison with other studies eventually by conversions to other situations.

With regard to spectra or other results from measurements of wind turbine noise the following information should ideally be available (The key information is marked with an asterisk):

1. Measured sound pressure level/spectrum or sound power level/spectrum*
2. Frequency weighting*
3. Background noise level/spectrum*
4. Indoor or outdoor measurements*
5. Analysis bandwidth of spectrum*
6. Measurement distance*
7. Wind speed
8. Measurement direction (upwind, downwind...)
9. Microphone position (on a plate or free field at a specified height)
10. Type of windscreen
11. Height of turbine
12. Number of turbines
13. Wind type (turbulent...)
14. Make and effect of wind turbine(s)

The six key parameters are sufficient if we are satisfied with information of the type: There were some wind turbines; did they generate low frequency sound of any significance in the surroundings?

If we want more specific information for comparison across references more that the key information may be needed.

Many references do not provide the key information. This makes comparisons or references to a common basis difficult and time consuming, and may only be made by combining information from other sources or by use of general knowledge applied to the specific situations.

3.5 Conclusions on literature study

There seems to be solid evidence and general agreement among researchers and technicians that wind turbines do not emit audible infrasound. The levels are far below the hearing threshold.

Audible low frequency sound occurs both indoors and outdoors, but the levels in general are close to the hearing and/or masking threshold. Many other noise sources, e.g. road traffic, emit low frequency noise. For road traffic noise (in the vicinity of the roads) the low frequency noise levels are higher both indoors and outdoors. In general the noise in the critical band up to 100 Hz is below both thresholds, but the level in the 100-200 Hz critical band is audible for normal hearing persons, if no other sound than the natural background noise is masking the wind turbine noise. At a distance of 6 hub heights it seems that in average the noise levels from the turbines are close to the Danish outdoor noise limits, but in all cases the indoor limit for $L_{pA, LF}$ seems to be observed.

The swishing sound from the blades is noted by a number of authors. It is found that for large modern turbines the most modulated range is the frequency band 350-700 Hz. In an earlier study from 1996 it was found, that the smaller turbines, which were common at that time, had maximum modulation in the range around 1 kHz. The swishing sound is actually more low frequent, but it is not in the low frequency range. Anyway, this effect may be called low frequency by some people in connection with the sound from the large turbines. Together with the slower rotation this is a noticeable change of the sound characteristic from wind turbines.

Tones may occur from the turbines, but for well designed turbines they are usually not prominent. The large turbines may have tones of lower frequencies due to the lover rotational speed.

4. Masking of low frequency noise from wind turbines

The methods in chapter 2 describe how to predict the noise contribution from wind turbines in the environment based on sound power measurements. Results achieved from these methods are without background noise. Knowledge of the predicted level has to be supplied with information on whether the noise is actually perceived or whether it is masked by background noise, as described in chapter 3

In Denmark background noise from traffic, industry etc. is not accepted as masking background noise. This leaves only the natural background noise to be considered. As wind turbine noise is dependent on wind speed a series of measurements have been made of the wind induced background noise indoors and outdoors at undisturbed residences far from wind turbines, traffic etc.

4.1 Background noise measurements

Reference [5] Søndergaard, Lars S. and Søndergaard, Bo
Low Frequency Noise from Large Wind Turbines – Background noise measurement and evaluation. AV 138/08. DELTA April 2008

The measurements have been made at 2 residences with different types of vegetation: One with primarily coniferous vegetation and one with primarily foliferous vegetation. For the residence with foliferous vegetation, measurements have been made for a summer and a winter situation.

Indoors the measurement positions were selected as four 3D-positions, while the outdoor measurements were made in a single free field position. The wind speed and direction was measured at 10 m height in a position representing the free wind at the residence. All measurements were synchronized and averaged over 1 minute periods.

A linear regression of the noise versus wind speed is assumed for the wind speed range considered from 4-10 m/s.

To be able to present a background noise spectrum at any wind speed a linear regression is made in each 1/3-octave band. In Figure 12 predicted A-weighted spectra are shown. Indoors there is a difference between coniferous and foliferous, but not between summer and winter. This could indicate that the building is more important than the vegetation at low frequencies. Outdoors there is a difference between foliferous summer and winter, while summer is close to coniferous.

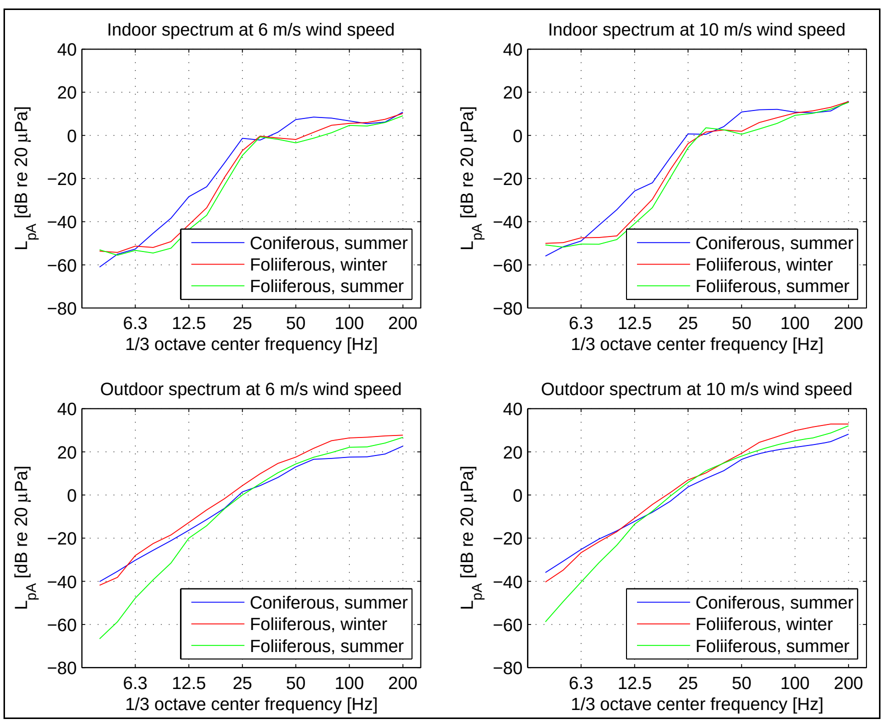

Figure 12
A-weighted spectra of indoor and outdoor background noise from vegetation at 6 and 10 m/s. The indoor values are the mean of measurements in four 3D corners.

A summary of the results are shown in Table 1. The outdoor levels for the infrasound is of the same order as measured close to the wind turbines according to IEC 61400-11:2002, indicating that there is no significant amount of infrasound in the noise from wind turbines.

Measurement Campaign	$L_{pA,LF}$ [dB re 20 µPa]	L_{pG} [dB re 20 µPa]	Wind speed [m/s]
Site 1 Summer	Outdoor: 16.5 – 39.6 Indoor: 7.4 – 27.8	Outdoor: 51.4 – 69.3 Indoor: 42.6 – 58.8	3-11
Site 2 Winter	Outdoor: 30.9 – 40.5 Indoor: 9.5 – 20.1	Outdoor: 60.6 – 69.7 Indoor: 39.1 – 48.2	5-10
Site 2 Summer	Outdoor: 25.4 – 44.1 Indoor: 7.1 – 27.0	Outdoor: 51.5 – 73.3 Indoor: 35.9 – 54.8	4-11

Table 1
Typical background noise levels of infrasound and low frequency noise from wind induced noise indoor and outdoor. The indoor values are the mean of measurements in four 3D corners.

5. Noise from large wind turbines

5.1 Sound power measurements

Reference [6] Søndergaard, Bo and Madsen, Kaj Dam
Low Frequency Noise from Large Wind Turbines – Results from sound power measurements. AV 136/08 Rev. 1. DELTA December 2008

Reference [7] Søndergaard, Bo
Low Frequency Noise from Large Wind Turbines – Results from previous sound power measurements. AV 137/08. DELTA April 2008

In this section results from measurements on large wind turbines are presented and compared to measurement results for small wind turbines. In section 5.1.1 the original results reported in the summary report from 2008 [11] are shown. In section 5.1.2 results from new measurements carried out on large turbines in 2009 and 2010 are shown and compared to the earlier measurements. All the measurements presented are made at the reference wind speed at 8 m/s (wind speed at 10 meters height above the ground).

5.1.1 Original measurement comparison

As part of this project measurements were made on 4 prototype wind turbines, mainly situated at the RISØ DTU test site for large wind turbines at Høvsøre. The wind turbines at the site were the largest and newest types of wind turbines available in Denmark at that time. These wind turbines were selected for the measurements, even though they are to be considered as prototypes.

The wind turbines included in the project are:

Vestas V100 3MW, Siemens S3.6 VS, and Siemens S2.3 VS (2 different turbines).

All measurements are made and reported after the principles of IEC 61400-1:2002 by DELTA, with the deviations necessary for the work in this project. The reports are not published but are internal project reports only made available for the project partners.

As the noise from the wind turbines was low at the lowest frequencies the measurement results in the infrasound region up to 20 Hz was influenced by background noise.

The measurement results are compared to results from previous measurements made by DELTA on smaller wind turbines. For these turbines data for sound pressure levels are not available below 25 Hz. Also the levels below 50 Hz the measurements can to some degree be influenced by background noise as discussed in [7]. Measurements at that time were made without extra precaution regarding protection of the microphone against wind induced noise as it has no significance or the A-weighted levels from the turbine. The following conclusions involving data from the small turbines for the frequency range below 50 Hz will comment on this.

In order to decide whether a development of the low frequency noise has occurred all spectra were normalized to the same A-weighted level, L_{WA} =100 dB re 1pW, making it possible to compare the spectral shape of the noise and evaluate the relative content of low frequency noise for different wind turbines.

In Figure 13 the spectra are grouped after produced power and then compared.

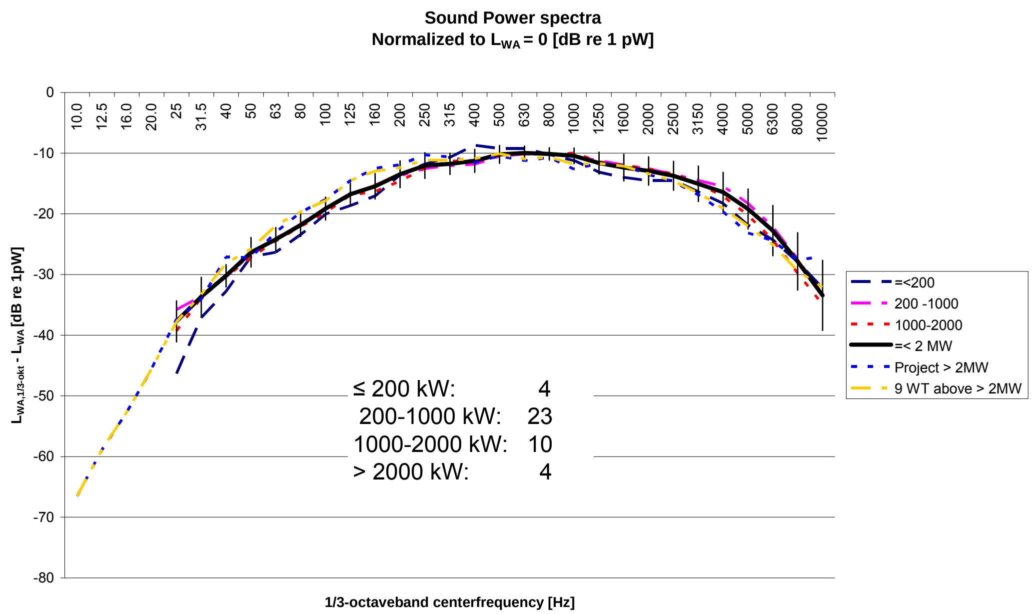

Figure 13

A-weighted sound power spectra grouped according to rated power and averaged. The 37 wind turbines from previous measurements are grouped as described. Included in the figure are 2 curves for wind turbines above 2 MW. The blue curve is the average of the four wind turbines from the project. The orange curve includes another 5 measurements made before the beginning of the project. These measurements only include data down to 25 Hz. The vertical bars represent plus/minus one standard deviation on the average of wind turbines up to 2 MW.

The spectra in Figure 13 show that the general spectral shape of the noise from wind turbines has not changed over time even though the general level has. The curves representing the large wind turbines are approximately 2-3 dB above the average of all the smaller wind turbines in the frequency range below 200 Hz. This is mainly due to the content of gear tones in the noise.

In Figure 14 narrowband (fft) spectra are shown for the wind turbines original included in the project. It is obvious that the tones increase the A-weighted noise level at frequencies below 200 Hz. Two modes of operation are included for wind turbine 2. In mode 3 the tones are shifted slightly and the level of the tones are reduced.

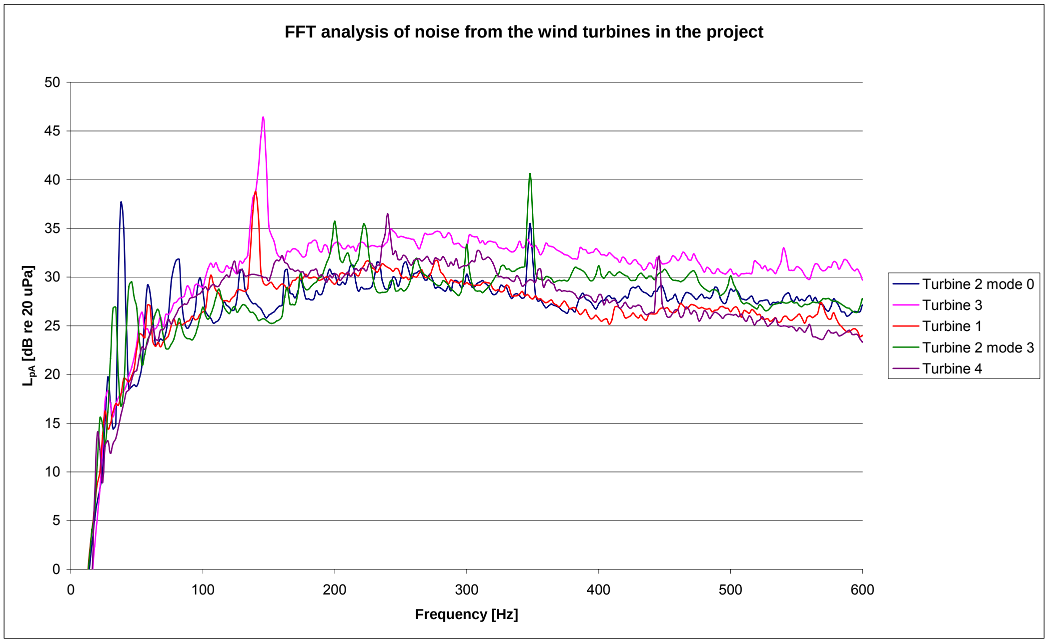

Figure 14
A-weighted narrowband (fft) spectra for the wind turbines original included in the project. The tones in the noise are present in 3 out of 4 wind turbines at this stage.

The general noise is mainly omnidirectional but the tones can be more prominent at other directions than directly downwind.

An important result from the measurements is that infrasound is negligible for this type of wind turbines.

The trend is that the new wind turbines are able to vary the rotational speed of the rotor considerably. Thus there is an extra challenge when designing the wind turbines to avoid resonances in the structure at main frequencies of the drive train.

5.1.2 Results from new measurements on large turbines

After a period from 2004 to 2007 where only a few new turbines were installed in Denmark the number of new installed turbines increased in 2008, 2009 and 2010.

Table 2 shows the statistics for turbines installed in Denmark during 2008, 2009 and 2010 until end of September 2010 (only turbines with a max capacity larger than 1 MW are shown). The statistics are taken from the wind turbine register at The Danish Energy Agency homepage [12] (updated ultimo September 2010).

Since the first report was published in 2008 [11] measurements have been carried out by DELTA on a number of these new turbines installed at different wind turbine parks in Denmark. In Table 2 the number of measurements available is shown for the different turbine types.

The measurements were made in accordance with Danish regulations [13] to verify compliance to these regulations on the noise from the wind turbines. The measurement method is compliant with IEC 61400-11 (2002) that has been used for the other measurements referenced in this report. For the measurements the frequency range was extended to include the low frequency content of the noise according to [1].

Turbine type	**Max capacity [kW]**	**Hub height [m]**	**Rotor diameter [m]**	**Total height [m]**	**Installations**			**Measure-ments available**
					2008	2009	2010	
Vestas V90	1800	80	90	125	0	4	0	3
Vestas V100	1800	107	100	157	0	1	0	0
Vestas V80	2000	60-78	90	105-123	11	1	1	0
Vestas V90	2000	80	90	125	1	0	0	0
Vestas V112	3000	94	112	150	0	0	1	0
Vestas V90	3000	80	90	125	0	6	5	2
Siemens 2.3	2300	80	93	126.5	17	25	12	5
Siemens 101 DD	3000	98.5	101	149	0	1	0	0
Siemens 3.6	3600	80	107	133.5	0	3	0	3
Siemens 3.6	3600	90	107	143.5	1	0	2	1
Siemens 3.6	3600	90	120	150	0	0	6	1
Siemens 107 DD	3600	90	107	143.5	0	2	0	2
Total					30	43	27	17

Table 2
Turbines with capacity above 1 MW installed in Denmark in the period 2008 until end of September 2010 [12] shown together with the number of new measurements carried out by DELTA on large wind turbines in 2009 and 2010. (New table November 2010).

All the new turbines introduced here are turbines placed as part of wind farms in Denmark (none of them taken from the Høvsøre test site) and all turbines were found to comply with Danish regulations regarding the A-weighted sound immission at dwellings close to the wind farm. In Figure 15 the A-weighted sound power spectra in 1/3-octave bands are shown for all 17 new measurements.

In section 5.1.1 it was discussed that the noise spectra from the large project turbines contained tonal components in the low frequency range. From Figure 16 it is clearly seen from the fft spectra for 7 different newly installed turbines, that there still are contributions from tones to the low frequency noise emission.

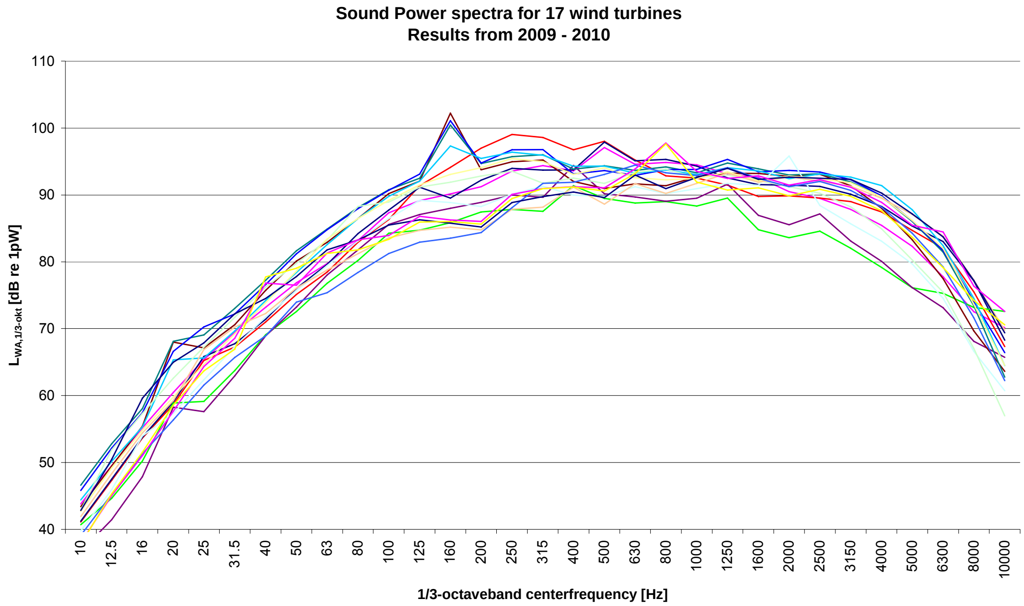

Figure 15
A-weighted sound power spectra for new measurements on newly installed turbines with a nominal power between 1800 and 3600 kW. (New figure November 2010).

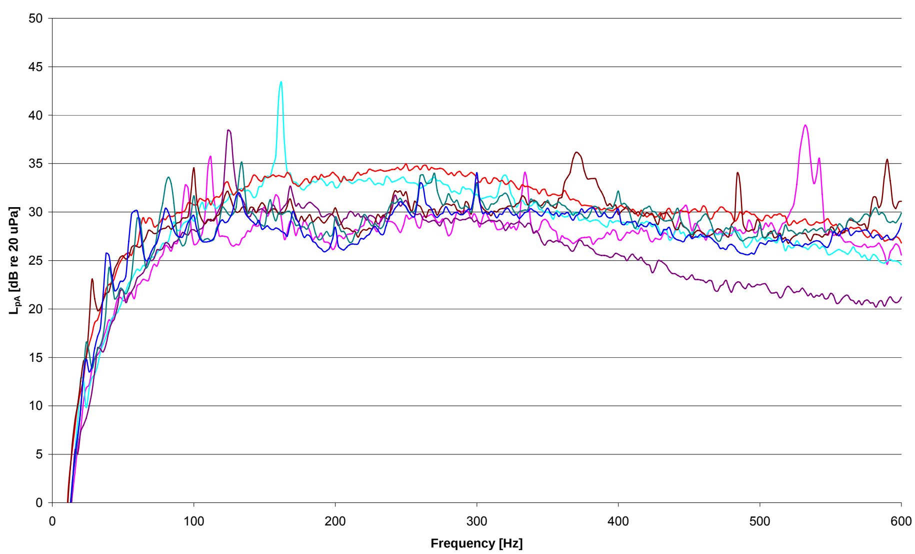

Figure 16
A-weighted narrowband (fft) spectra for 7 different new turbines.
Frequency spacing 2 Hz. (New figure November 2010)

Some of the tones from the new measurements were characterized as clearly audible tones when analyzing recordings made at the measurement plate close to the turbine according to [13]. None of them were found to be clearly audible when measured in the positions at the neighbouring dwellings and therefore they did not result in any tone penalty additional to the A-weighted levels according to Danish regulations. It has not been pursued further in this project how much these tones contribute to the increase seen in the low frequency end of the 1/3 octave band spectra and the increase in $L_{pA,LF}$. Anyway this finding supports that the character of broadband aerodynamic noise does not differ much between small and large turbines.

In the following analysis of the new measurement results, only measurements from the 14 turbines with a nominal power capacity above 2 MW are taken into account following the definition chosen for the rest of the work in this project, where large turbines are defined as turbines with a nominal power capacity above 2 MW.

From Table 2 it is seen that the 14 new measurements give a good representation of the large turbines installed in the period 2008-2010 and based on the above referenced compliance to Danish regulations they represent turbines that can be placed in wind farms in Denmark respecting Danish regulations. Only two types of wind turbines above 2 MW with each one installation are not represented in the analysis.

Due to the fact that large turbines are now installed in Denmark at wind farms and that a larger amount of measurement results are available a more relevant evaluation of the development of low frequency noise is now possible.

The analysis on the new turbines is based on normalized spectra as described in section 5.1.1. In Figure 17 the average sound power spectra normalized to the same A-weighted level for each of the years 2008, 2009 and 2010 are shown. When averaging the spectra the data are multiplied with weighting factor for each wind turbine type corresponding to the actual number of installed turbines of different types and size for each year according to the presented statistics.

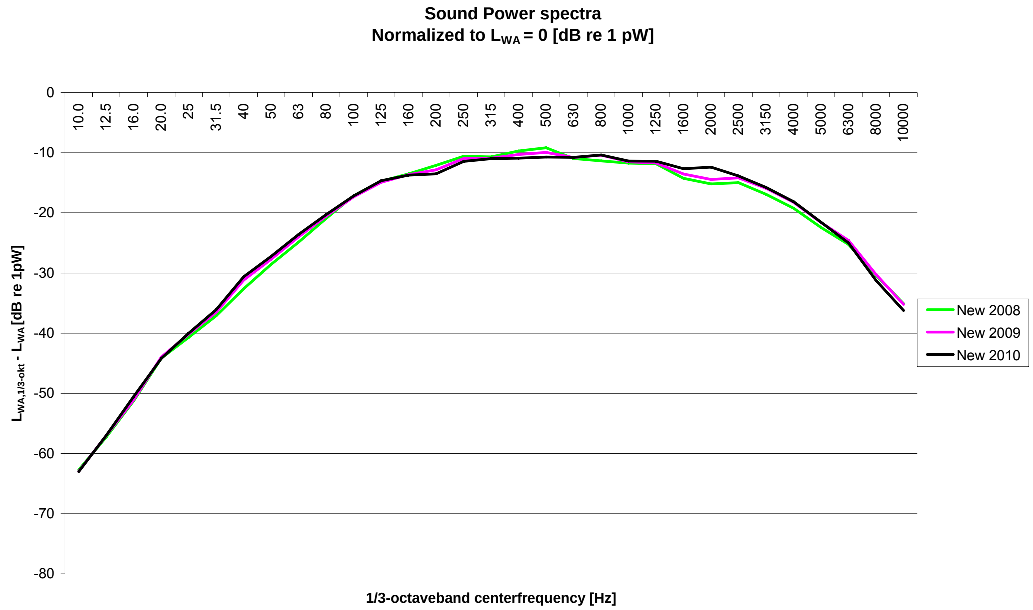

Figure 17
Normalized sound power spectra for large wind turbines above 2 MW installed in 2008, 2009 and 2010. The spectra represent weighted averages corresponding to the actual number of installed turbines of different type and size each year. (New figure November 2010).

From Figure 17 it is seen that the deviations in the normalized spectra from year to year are very small especially in the low frequency range. Therefore a weighted average spectrum for all three years together is used in the following comparison with small wind turbines.

The new normalized average spectrum for large wind turbines is compared to results for small turbines as they are presented in Figure 13 except that the 4 small turbines below 150 kW that were included in earlier analysis are left out because they cannot be considered as representative for small turbines installed today.

The total number of installed wind turbines in Denmark taken per ultimo September 2010 with a nominal power between 400 and 2000 kW is 3263 and the average nominal power of these turbines is 800 kW [12]. The 33 small wind turbines included in the following analysis have an average nominal power of 950 kW. For comparison the 82 large turbines above 2 MW installed in the period 2008-2010 and represented by the new measurement results have an average nominal power of 2500 kW.

In Figure 18 the normalized spectrum representing the installed wind turbines from 2008-2010 is compared to results from older small turbines and the 4 large project turbines described in earlier reports.

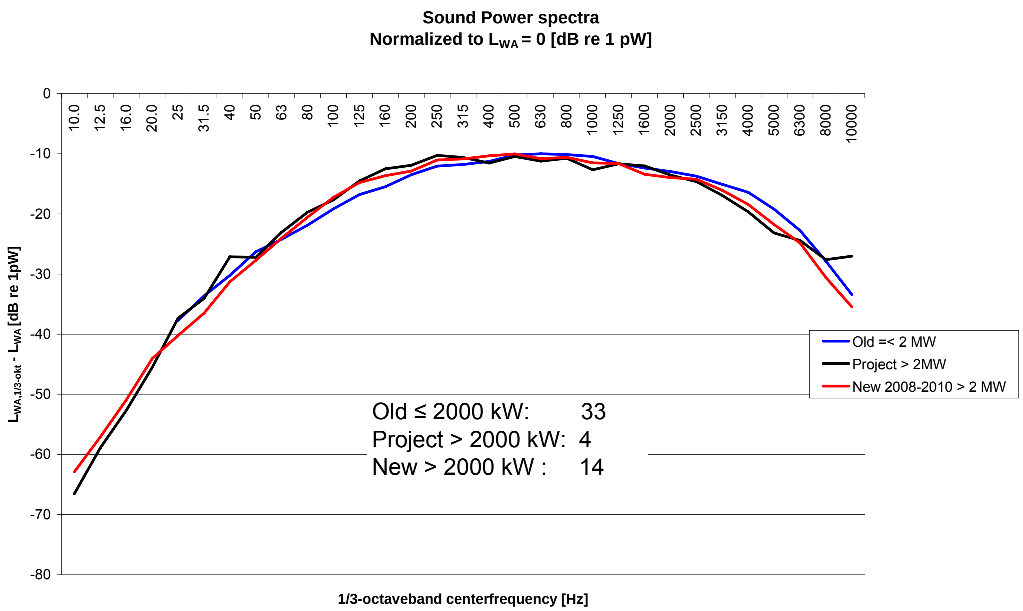

Figure 18
Comparison of A-weighted normalized sound power spectra.
Older small turbines (blue), the 4 large "project" turbines (black) and the new large turbines representing the turbines installed in Denmark the period 2008-2010 (red).
(New figure November 2010).

The tendency is the same for both the project turbines and the new turbines. There is a small increase in the relative content of low frequency noise for the large turbines compared to the small. When compared to the project turbines the results from the new installed turbines from the period 2008-2010 show a smaller increase in the frequency range from 63 Hz and upwards.

In Figure 19 the normalized spectra for old small and new large turbines are shown again with indication of plus/minus one standard deviation of the average value.

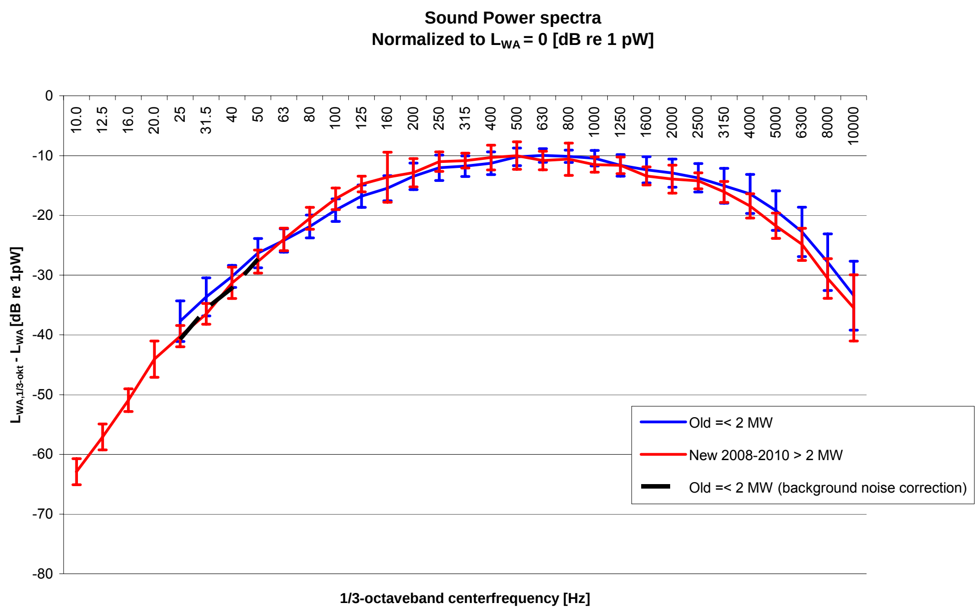

Figure 19
Comparison of A-weighted normalized sound power spectra.
Older small turbines (blue) and the new large turbines representing the turbines installed in Denmark the period 2008-2010 (red). Values for small turbines with estimated background noise correction below 50 Hz (black dotted line). The vertical bars represent plus/minus one standard deviation on the average value for each spectrum.
(New figure November 2010).

As mentioned in section 5.1.1 the old measurements on small wind turbines were made with a higher uncertainty due to the influence from background noise below 50 Hz. From analysis of the old data a best estimate of the potential influence from background noise has been determined. In Figure 19 a corrected mean spectrum for the frequency range below 50 Hz is indicated with the black dashed line. The correction corresponds to -3 dB at 25 Hz, -2 dB at 31.5 Hz, -2 dB at 40 Hz and -1 dB at 50 Hz. In the following data presentation the direct data are presented but conclusions are commenting on the possible inclusion of background noise below 50 Hz in the small wind turbine data.

When considering the differences between the small and the large turbines two different viewpoints are relevant.

As it can be seen from Figure 19, which shows the sound emitted from the small and the large turbines, there is an essential overlap of the standard deviations for the two groups of turbines. As 68 % of the levels of the individual turbines will be found within the interval of +/- one standard deviation this means that you will easily find small turbines with normalized levels that exceed the levels of a large turbines and vice versa. I.e. a certain small turbine may have larger low frequency components than a larger and vice versa.

Therefore, in a specific case it is more relevant to be concerned about the spectra of the individual turbines than whether it is a small or a large turbine. As it also can be seen from Figure 21 the differences between the individual makes, models and configurations are generally much larger than the general difference between small and large turbines.

In a more generalized view, it is relevant to know whether there are some general trends. In this case we will compare the spectra by the confidence intervals. If we choose the 95 % confidence interval around the mean value, then we will with a probability of 95 % expect to find the true value for the average within this interval. If the confidence intervals for the levels of the small and the large turbines do not overlap, then as a first approximation[2] the difference between the two values is significant.

The difference between small and large turbines is illustrated in Figure 20, where the difference in normalized sound power spectra for old small turbines and new large turbines is shown. It is seen that the large turbines emit up to 2 dB more in the 100-160 Hz range. It is seen from the confidence intervals that these differences are statistically significant (whether it is a perceptual significant difference will be discussed later). The small turbines emit in average 2 dB more in the 25-60 Hz range. The latter is without consideration of the potential background noise influence of up to 3 dB at 25 Hz for the small turbine data as discussed on page 37.

[2] In the details this test is too conservative. If two confidence intervals overlap, the difference between the two means still may be significantly different. A specific test for the significance is needed for the details.

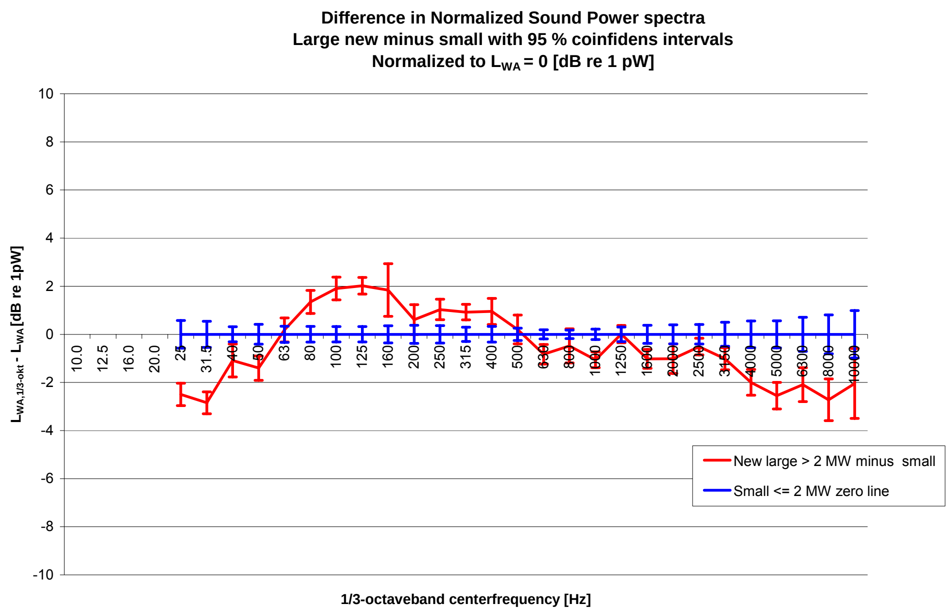

Figure 20
Difference between normalized spectra for new large and old small turbines. The vertical bars represent the 95 % confidence interval on the average. (New figure November 2010).

In Figure 21 and Figure 22 all available data for sound power levels, L_{WA}, and the low frequency content of the sound power level, $L_{WA,LF}$ are plotted against nominal power for the wind turbines. The plots and analysis includes data for the 33 small wind turbines, the 17 new measurements and the 5 measurements on large turbines from before the project (also shown in Figure 13). Whether the 5 measurements from before the project are included or not does not affect the general trend.

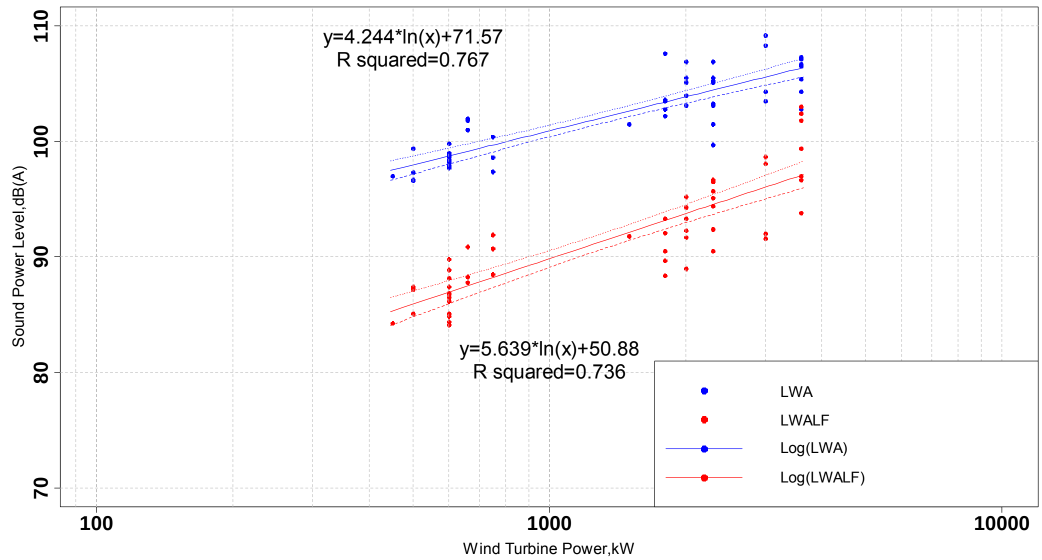

Figure 21
Sound power level L_{WA} and the low frequency sound power level $L_{WA,LF}$ as a function of nominal wind turbine power. The full lines are the regression lines. The dotted lines are the 95% confidence intervals for the regression. Results are included from 33 small turbines, the 17 new turbines and 5 large turbines from before the project.
(New figure November 2010).

In Figure 21 the regression lines for L_{WA} and $L_{WA,LF}$ are shown. Furthermore the confidence intervals for the lines are shown. The confidence lines show the interval around the regression lines, where we with a probability of 95 % expect to find the true value for the regression lines.

The statistical analysis[3] shows that the difference in the slope of the two lines is significant. This means that the relative amount of low frequency noise is increasing with increasing wind turbine size. According to the regression shown in Figure 21 a doubling of nominal electrical power will in general increase the sound power level, L_{WA}, by approx.

[3]The regression has been done with a linear model after linearization of the wind turbine power with a natural logarithm. A t-test has been performed on the slope of the regression lines. The analysis showed that the difference between the slopes is significant (p = 0.009, α=0.05). An analysis of covariance has been performed in order to confirm the previous t-test on the slopes. The results of the analysis of covariance support the results of the t-test (p=0.01, α=0.05).

2.9 dB(A) and the low frequency sound power level, $L_{WA,LF}$, by 3.9 dB(A). This means a relative increase of $L_{WA,LF}$ of 1 dB. The relative increase in $L_{WA,LF}$ from a 1 MW turbine to a 5 MW turbine will be 2.4 dB. How this is perceived is discussed in section 5.3.

In Figure 22 the data from Figure 21 is presented as the logarithm to the ratios between sound power and electrical power plotted against nominal power for the wind turbines. This shows the relative decrease of total sound power with increasing wind turbines size and the increase of low frequency sound power with increasing wind turbine size. It is clearly seen that the differences between small and large wind turbines are much smaller than the differences between the individual wind turbine makes and models both with regard to total noise emission and to low frequency noise emission. For example the relative general difference in low frequency noise emission from the smallest to the largest turbines is less than 3 dB where a spread in noise emission for the same wind turbine size is up to 9 dB.

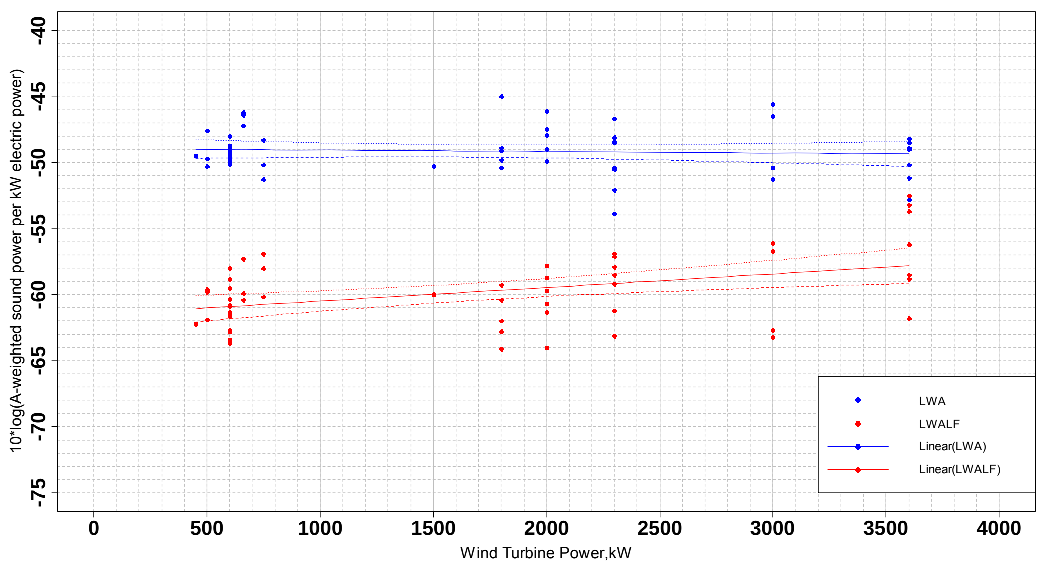

Figure 22
Emitted A-weighted acoustic power per kW electric nominal wind turbine power shown as the logarithm to the ratio between the acoustic sound power and the nominal electric wind turbine power in kW. The full lines are the regression lines. The dotted lines are the 95 % confidence intervals for the regression. Results are included from 33 small turbines, the 17 new turbines and 5 large turbines from before the project. (New figure November 2010).

5.2 Sound immission at neighbours to single wind turbines and wind farms

To evaluate the noise impact from wind turbines on the surroundings it is relevant to look at the sound pressure levels at distances relevant for the nearest residences close to single wind turbines or groups of wind turbines. Based on the results from section 5.1.2 a study of this has been made.

According to Danish regulations a wind turbine cannot be installed closer to the nearest residence than at a distance corresponding to at least 4 times the total height of the wind turbine. This distance is referenced as "the minimum distance". Another part of the regulations state that the maximum A-weighted sound pressure level at the nearest residences are not allowed to exceed 44 dB(A) in none noise sensitive areas.

Based on these regulations two situations have been chosen for further investigation: If the noise limits are not exceeded at 4 total wind turbine heights then it is relevant to compare the spectra for the two groups of turbines for this distance (for single turbines at this distance), this is shown in Figure 23 and Figure 24 . If the noise limits are just met at four total heights (e.g. for more than one turbine in a wind farm at that distance) then it is relevant to normalize the spectra for the two groups of wind turbines to the same A-weighted level (44 dB(A)) and compare, this is shown in Figure 25 and Figure 26.

Calculations of sound pressure levels at the minimum distance have been made for all turbines using the Nord2000 method, not to underestimate the noise at the lowest frequencies. For the calculations downwind propagation at wind speed 8 m/s at 10 m height over a flat agricultural area are supposed.

In Figure 23 it is seen that at high frequencies the noise is reduced for the large turbines compared to the small ones. This is due to increased air absorption of the sound at the larger minimum distances for the large turbines.

In Figure 24 it is seen that the large turbines give a small (1 dB) barely significant higher level at 100-160 Hz. The smaller turbines give significant higher sound pressure levels below 50 Hz when not considering the background noise influence of up to 3 dB at 25 Hz for the small turbine data as discussed on page 37.

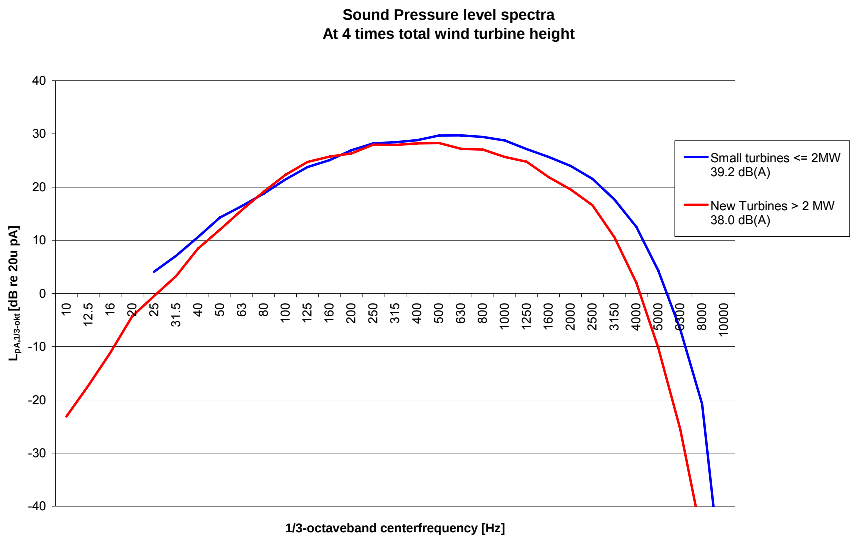

Figure 23
Sound pressure level spectra for new large and old small single turbines at a distance of 4 total heights. (New figure November 2010).

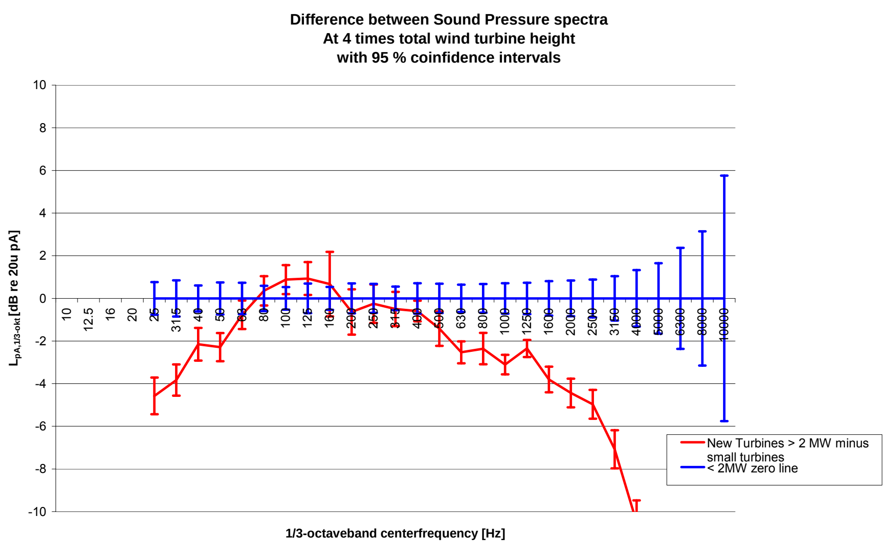

Figure 24
Difference between sound pressure level spectra for new large and old small single turbines at a distance of 4 total heights. The vertical bars represent the 95 % confidence intervals on the average. (New figure November 2010).

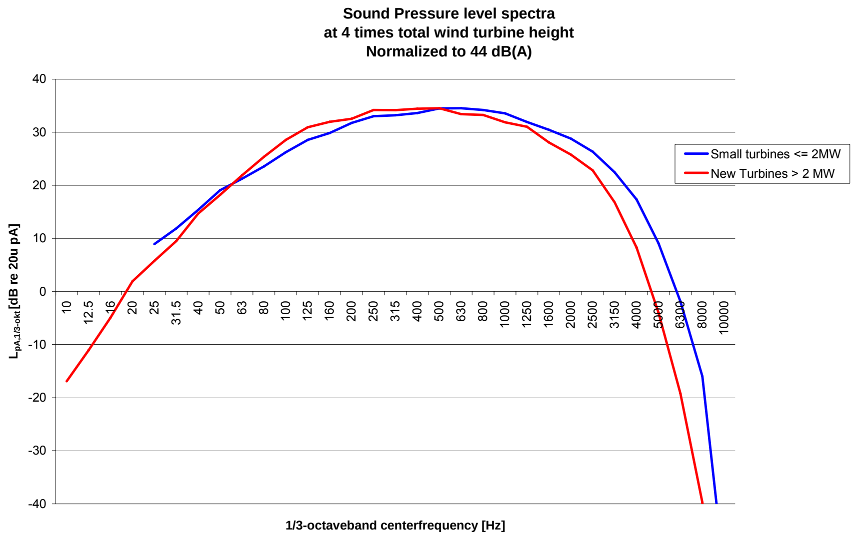

Figure 25
Sound pressure level spectra for new large and old small turbines at a distance of 4 total heights. The spectra are normalized to 44 dB(A). (New figure November 2010).

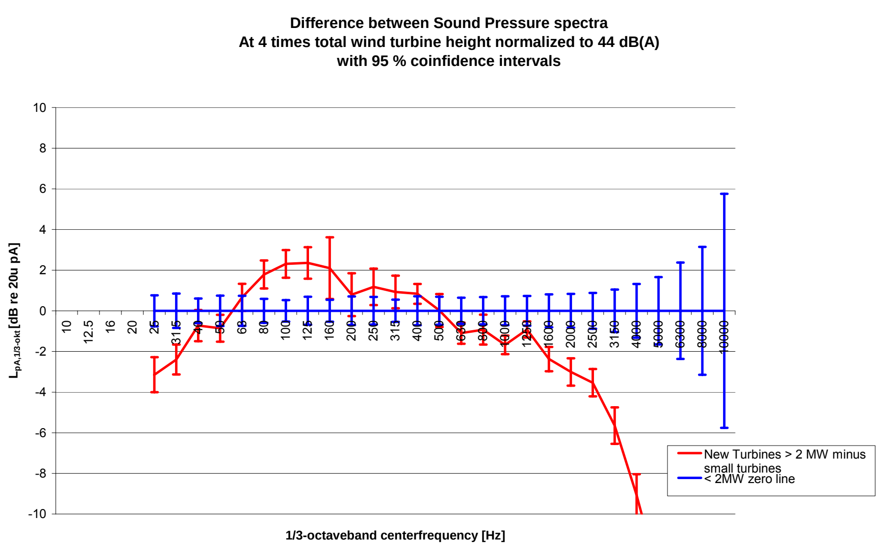

Figure 26
Difference between sound pressure level spectra for new large and old small turbines at a distance of 4 total heights. The spectra are normalized to 44 dB(A). The vertical bars represent the 95 % confidence intervals on the average. (New figure November 2010).

From Figure 26 it is seen that for the same A-weighted sound pressure level (the noise limit 44 dB(A)) at the minimum distance the large turbines give a 2 dB higher level in the 100-160 Hz range. This is statistically significant. The small turbines give higher levels below 50 Hz not considering the background noise influence of up to 3 dB at 25 Hz for the small turbine data as discussed on page 37. How the differences are perceived is discussed in section 5.3.

In Figure 23 the A-weighted sound pressure calculated at a distance corresponding to 4 times total height is 39.2 dB(A) for the small turbines representing an average nominal power of 950 kW and 38.0 dB(A) for the large turbines representing an average nominal power of 2500 kW. To raise the sound pressure level at a distance corresponding to 4 times total height to 44 dB(A) it would require 3 small turbines at this distance representing an average nominal power of 3 MW or 4 large turbines representing an average nominal power of 10 MW.

In Figure 27 and Figure 28 indoor frequency spectra are shown for the two calculation scenarios. The indoor values are calculated using the sound insulation values proposed by [14] representing values that are expected to be exceeded by 80-90 % of typical Danish dwellings.

For the scenario with a 44 dB(A) outdoor level it is seen from Figure 28 that the large turbines give a 2 dB higher level in the 80-160 Hz range. Below 63 Hz the small turbines give higher values. Again the conclusions regarding the frequency range below 50 Hz must be taken with caution regarding the potential background noise influence of up to 3 dB at 25 Hz for the small turbine data as discussed on page 37.

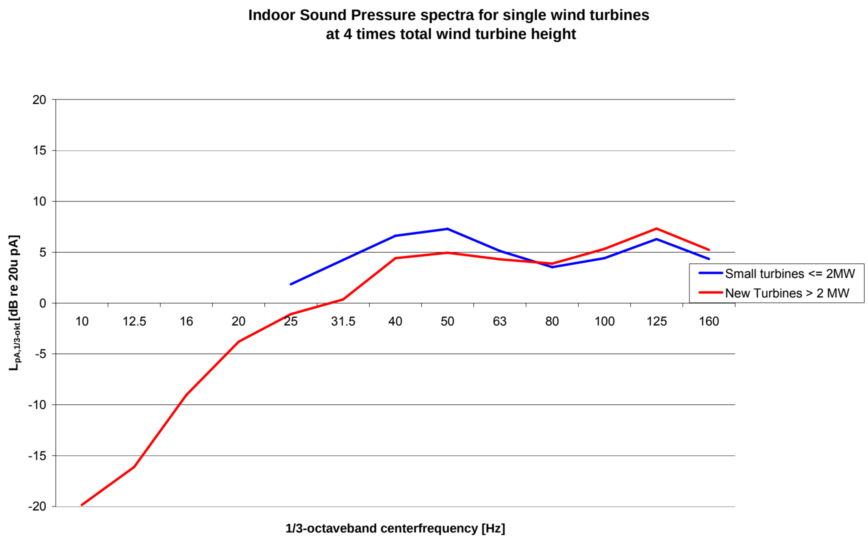

Figure 27
Indoor sound pressure level spectra calculated at minimum distance (4 times total turbine height) for small and large turbines. (New figure November 2010).

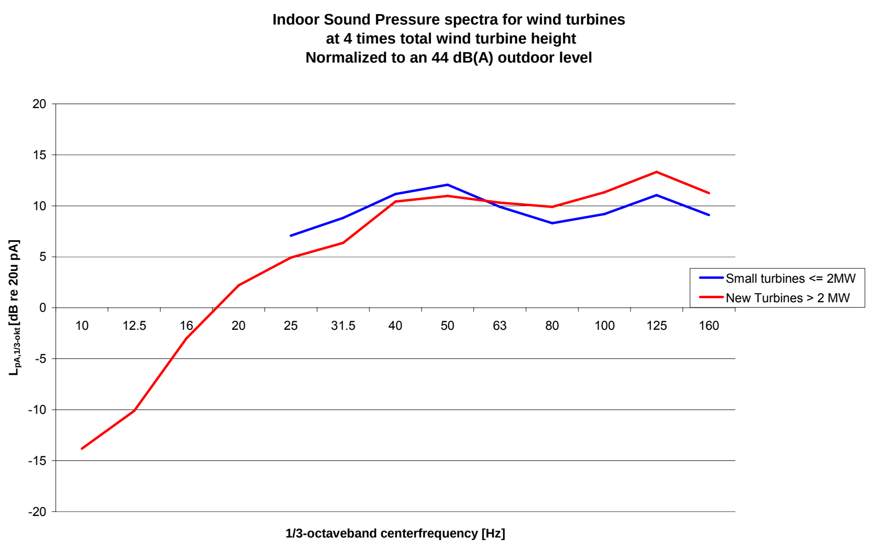

Figure 28
Indoor sound pressure level spectra calculated at minimum distance (4 times total turbine height) for small and large turbines. Normalized to an outdoor sound pressure level of 44 dB(A). (New figure November 2010).

In Table 3 and Table 4 the calculated sound pressure levels L_{pA} and $L_{pA,LF}$ for the two scenarios are presented for both outdoor and indoor situations.

Nominal power	**L_{pA} Outdoor**	**$L_{pA,LF}$ Outdoor**	**$L_{pA,LF}$ Indoor**
400 - 1000	39.1	29.7	14.6
1000 - 2000	39.5	30.4	15.3
400 - 2000	39.2	29.9	14.8
>2000 New turbines	38.0	30.4	14.4

Table 3
Noise levels at minimum distance for single wind turbines. L_{pA}, $L_{pA,LF}$ and $L_{pA,LF}$ outside and inside a house in dB re 20 µPa. (Table updated November 2010).

Nominal power	**L_{pA} Outdoor**	**$L_{pA,LF}$ Outdoor**	**$L_{pA,LF}$ Indoor**
400 - 1000	44.0	34.6	19.5
1000 - 2000	44.0	34.9	19.9
400 - 2000	44.0	34.7	19.6
>2000 New turbines	44.0	36.5	20.4

Table 4
Values from Table 3 recalculated for a wind farm situation with 44 dB(A) outside the residence. (Table updated November 2010).

For both scenarios it is seen that the indoor low frequency noise level ($L_{pA,LF}$), that is the most relevant parameter for evaluation of low frequency noise impact at neighbours to wind turbines, only show small differences for the different wind turbine groups.

For the single wind turbine scenario $L_{pA,LF}$ is 0.4 dB lower for the large turbines compared to the small turbines. For the scenario with a 44 dB(A) outdoor level $L_{pA,LF}$ is 0.8 dB higher for the large turbines compared to the small turbines. Corrections for potential background noise influence in the frequency range below 50 Hz for the small wind turbines as discussed on page 37 would reduce the indoor values for these turbines with approximately 0.5 dB. Still the differences between large and small wind turbines for both outdoor and indoor scenarios are small.

The scenario with a 44 dB(A) outdoor level could also be realized with a larger number of wind turbines placed at larger distances to the receiver position at residence. Longer distances between the wind turbines and the receiver position will due to the effect of air absorption result in a damping of the high frequency part of the noise from the wind turbines as it is seen from Figure 25 and thereby increase the relative amount of low frequency noise. This effect will however be the same regardless of the size of the wind turbine.

It is therefore worth mentioning that the results from the study presented above are based on general noise data for large and small wind turbines. For evaluation of absolute values at different distances to wind farms the specific data from the involved wind turbines and distances based on the actual wind farm layout must be taken into account.

5.3 How are the differences in sound pressure levels at low frequencies perceived?

In this section the perception of the differences in noise emission from the turbines and the noise immission at the neighbours to wind turbines presented in section 5.1.2 and 5.2 are discussed. Due to the measuring uncertainty for the small turbines below 50 Hz it can not be concluded whether the small turbines have larger or similar levels in this frequency range. In the discussions below it is anticipated that the small turbines will be perceived like the large in the range below 50 Hz.

From Figure 23 and Figure 25 it is seen that for the large turbines the high frequencies due to absorption in the air at larger distances will be perceived as attenuated relative to the small turbines.

If we look in details at the low frequency part of the spectrum it should be taken into account that the hearing is more sensitive to changes in sound pressure levels at low frequencies: A small increase in level at a low frequency will be perceived as a larger increase in loudness than the same level increase at higher frequencies, but how pronounced is this effect at the relevant frequencies?

From the equal loudness contours, Figure 4 in [4], it can be found that a 2 dB increase of sound pressure levels at 125 Hz corresponds to an increase of the loudness level of 2.3 phon. This means that a 2.3 dB change at 1000 Hz will be perceived as a similar change. (At lower frequencies the effect is larger but that is not relevant here).

The above finding can be concluded into that the level differences around 125 Hz are not perceived significantly different than at higher frequencies.

From Figure 24, the situation where the distance of four total heights determines the levels, it is seen that the small turbines will be generally be perceived as louder. Only in the range 125-160 Hz the large turbines have up to 1 dB hardly significant and barely audible increase of the levels.

From Figure 26, the situation where the A-weighted level equals the noise limit, the large turbines will be perceived with a more low frequency characteristic. The increase in the 100-160 Hz range is approx. 2.3 dB.

Although this difference between the spectra is statistically significant it cannot be characterized as an essential change of the sound characteristic. The loudness changes in this frequency range are small and the A-weighted outdoor spectra are dominated by higher frequencies. It is therefore doubtful whether the small changes described above will be noted in the total characteristics of the noise.

In the indoor situation the low frequencies are dominating, so here the changes in the low frequency part of the spectra will be perceived to a higher degree than outdoors.

For the indoor situations the same considerations about the changes in loudness corresponding to sound pressure levels as above will lead to the conclusion that the differences are so small and insignificant that it is unlikely that any difference between small and large turbines can be perceived.

For the indoor situation shown in Figure 28, where the outdoor spectra are normalized to an outdoor sound pressure level of 44 dB(A), it is seen that there is a 2 dB increase in the range 100-160 Hz corresponding to an increase in loudness level of 2.3 phon. This is characterized as a noticeable but not an essential change.

5.4 Noise monitoring

Reference [8] Søndergaard, Lars Sommer; Madsen, Kaj Dam and Ryom, Carsten Low Frequency Noise from Large Wind Turbines – Noise monitoring af Høvsøre. AV 139/08. DELTA April 2008

This part of the project investigates if a relationship can be found between noise-related annoyance experienced by people living at residences close to large wind turbines (henceforth termed neighbours), and meteorological parameters and specific noise characteristics.

Noise monitoring was carried out at a residence close to the Risø DTU Test Site Høvsøre as a free field measurement outside the house for two periods. The monitoring position can be seen in Figure 29. At the same time registrations were made of meteorological data and operation of the turbines at the Risø DTU Test Site Høvsøre. During the measurement campaign, the occupants at the neighbour residence registered when they felt annoyed by the noise from the test site.

Figure 29
Noise monitoring position at Neighbour to Høvsøre Test Site.

For periods with registered annoyance data analysis was made and a typical example of analyzed data is shown in Figure 30. The figure shows time traces of the recordings made just before, during and after such a period of registered annoyance. Each data point represents an average of 10 minutes of recording. The vertical lines indicate the beginning and ending respectively of registered annoyance. It can be seen that just before the ending of annoyance the amplitude of the 40 Hz 1/3-octave noise level drops about 6 dB. Apart from the 40 Hz 1/3-octave values the other noise parameters do not give any clear indication that can be coupled with the annoyance registration.

In Figure 31 are shown frequency spectra taken from the same period of registered annoyance, and just after the period of registered annoyance. A clear difference can be seen in the low frequency range and especially at the 1/3-octave band 40 Hz a tonal content can be seen for the annoying period.

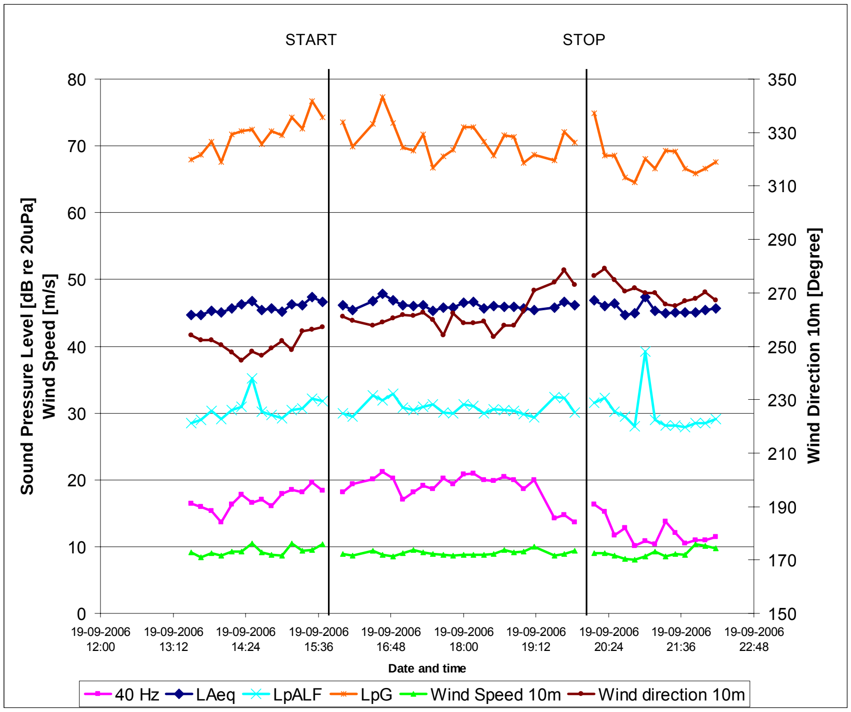

Figure 30
Time trace before, during and after a period with registered annoyance. Start and stop of registered annoyance are marked in the plot. Wind direction and wind speed are plotted along with noise parameters

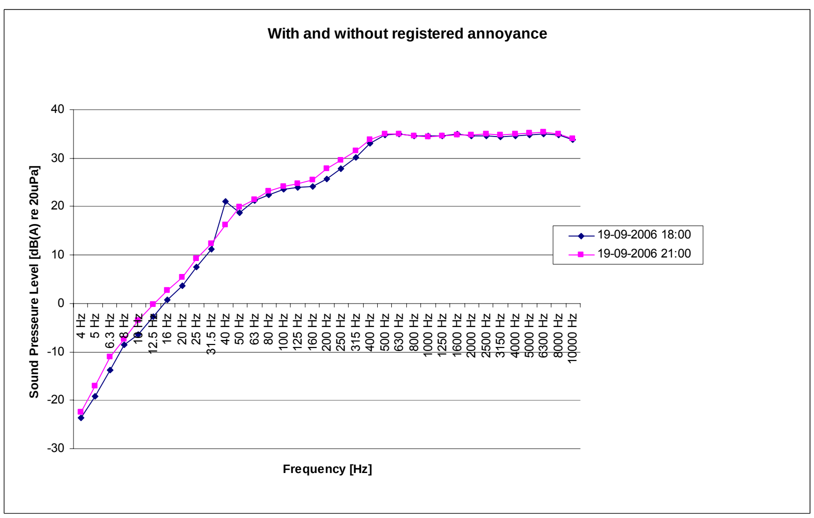

Figure 31
Frequency spectra for periods with and without annoyance. 19-09-2006 18:00 is from the annoying period.

From the registration of operating conditions for the wind turbines at the test site it can be seen that turbine number 2 was shut down exactly at the time where the 40 Hz noise is reduced by approximate 6 dB at the monitoring position.

For the whole period a rather constant wind speed at 10 m height at the Høvsøre Test site of 10 m/s is seen. The wind direction changes from 250 degrees to 270 degrees at the end of the annoyance period. Stable meteorological conditions were seen for the analyzed period. A more thorough analysis is given of the meteorological parameters during the monitoring periods in [9].

From the monitoring measurements the following was seen:

- During periods where the occupants registered annoyance a tonal noise in the 40 Hz 1/3-octave band was present in the measurements.
- Removal of the 40 Hz tone made the annoyance disappear even with other wind turbines still operating.
- No coupling between other noise parameters and registered annoyance could be seen.
- The 40 Hz noise could be coupled with the operation of one of the turbines at the test site. The specific prototype wind turbine in this test configuration was not pursued further by the manufacturer.
- Investigation of annoyance from low frequency tones are relevant to include in the listening tests discussed in chapter 6.

5.5 Mechanism for generation of low frequency noise

Reference [10] Helge Aagaard Madsen
"Low frequency noise from MW wind turbines – mechanisms of generation and its modeling" Risø-R-1637(EN). April 2008

In the present project the causes of low frequency noise for upwind rotors have been investigated. From previous work in the US and Sweden on 2 bladed downwind wind turbines of MW-size it has been found that the main source of low frequency noise is the unsteady forces on the rotor from wind shear and the interaction with the tower.

A 3.6 MW turbine has been modelled with the above mentioned noise prediction model. Running the model on this turbine a number of important turbine design parameters with influence on the low frequency noise have been identified as well as other parameters, not linked to the turbine design. Of important parameters can be mentioned:

• rotor rotational speed

• blade/tower clearance

• rotor configuration - upwind/downwind

• unsteadiness/turbulence inflow

Furthermore, the directivity characteristics of low frequency noise have been computed as well as noise reduction as function of distance from the turbine.

In general, low levels of low frequency noise have been computed for the upwind rotor in standard configuration. When in-flow turbulence was included good agreement with noise measurements was found. The study confirms the findings from the measurements that infrasound is negligible for this type of wind turbine.

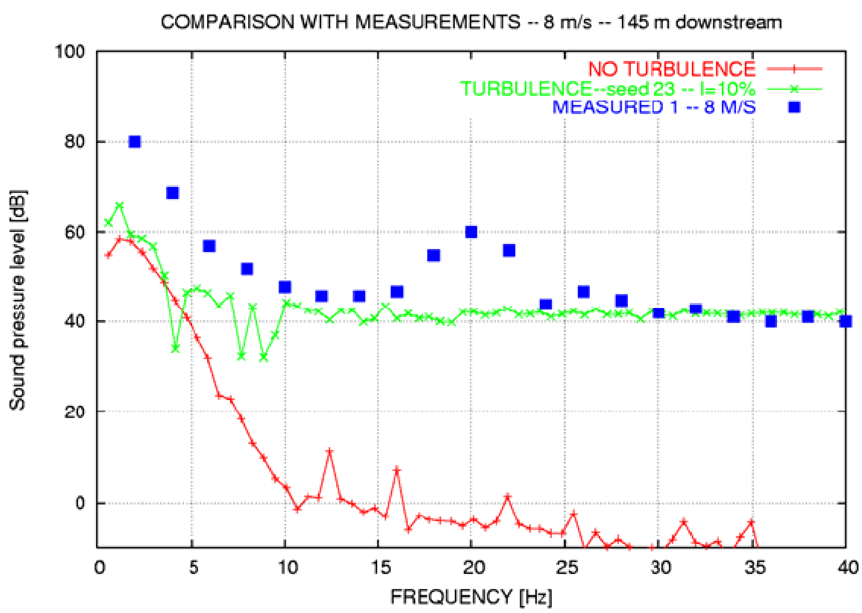

Figure 32
Comparison of measured and predicted sound pressure levels. When in-flow turbulence is included (in the present case 10 % turbulence intensity) there is a good agreement between measured and predicted values. The bump around 20 Hz is related a discrete frequency from the drive-train. Below 10 Hz the background noise dominates the measurements as was also seen in the measurement reports of the individual measurement campaigns.

Thus, it seems that in the present case the blade/tower interaction only contributes to the low frequency noise level for frequencies below 10-15 Hz, and for higher frequencies it is the interaction of the blade with the non-uniformities in the in-flow such as turbulence that generates the low frequency noise.

6. Listening tests

Reference [16] Hünerbein, Sabine von; King, Andrew; Hargreaves, Jonathan; Moorhouse, Andrew and Plack, Chris
Perception of Noise from Large Wind Turbines (EFP-06 Project)
The University of Manchester, Greater Manchester UK, November 2010

Listening tests have been performed at the University of Salford with the following main objectives:

- To establish audibility and relative annoyance thresholds for LF tones in the presence of broadband masking noise
- To establish relative wind turbine levels that produce equal annoyance for two sizes of turbines taking into account the effect of masking noise on these estimates.
- Enlighten the question whether noise from large wind turbines is more annoying than noise from small wind turbines

The tests have been made in a listening room simulating indoor and outdoor scenarios with and without wind noise from vegetation. 20 listeners participated in the tests

6.1 Study design

To relate sound characteristics of small and large turbines with the perception of wind turbine noise, listening tests have been conducted to establish audibility thresholds and equal annoyance contours for idealised wind turbine sounds containing low frequency tones. The focus has been on the question whether annoyance changes with the frequency of a tone. The test sounds have consisted of a broadband spectrum with a specific tone at one of the frequencies 32, 44, 72, 115, 180 and 400 Hz. Idealised sounds with features broadly representative of wind turbine sounds have been used. In the listening room shown in Figure 33 the participants have been asked to imagine being in different scenarios. The outdoor scenario has presented sounds broadly representative of a wind turbine at three A-weighted sound pressure levels, each with and without garden noise, whereas the indoor scenario has omitted the garden noise since the facade attenuation rendered it inaudible.

Figure 33
Listening room setup. Detail on sound reproduction is available in [16].

A comparative adaptive method was used to establish relative equal annoyance levels in the form of equal annoyance contours. The tests have been designed to enable comparisons between different scenarios, broadband levels, tone frequencies, masked and unmasked 'wind turbine' sound, and two different prominence levels for the reference tone at 180 Hz. Temporal variation like "swishing" has been avoided to keep the research questions well focused.

In a second part of the study wind turbine recordings from a large and a small wind turbine have been compared in annoyance with steady traffic noise. The recordings were manipulated to include the effect of sound propagation and façade attenuation. They were also normalised to equal A-weighted levels.

6.2 Results on audibility and masking thresholds

Results on tone audibility in quiet are shown in Figure 34. The measured audibility threshold (blue line) is compared to the published hearing threshold (black line) according to ISO 389-7 (2005). Tones in quiet were heard at levels that agree well with that hearing threshold. As the broadband noise level increases the tones were heard at levels that were determined by the masking level as shown in Figure 35 (blue lines).

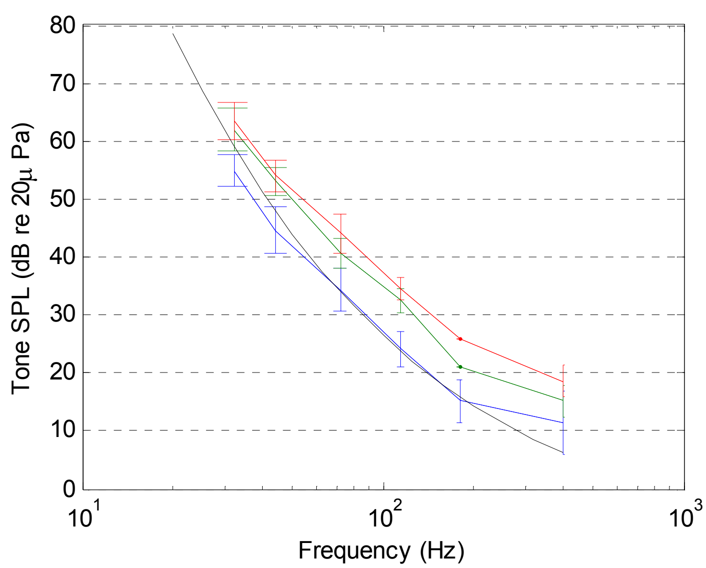

Figure 34
Room background without masking noise - Audibility threshold (blue), equal annoyance to 180 Hz tone at 5 dB audibility (green) and 10 dB audibility (red) of low frequency tones. Black solid line: Hearing threshold according to ISO 389-7 (2005). Error bars denote 95 % confidence intervals.

Masking thresholds predicted by the ISO 1996-2 standard (black dashed lines in Figure 35) have been shown to agree well with the measured tonal audibility thresholds as long as the masking noise clearly exceeds the hearing threshold of the tones. As low levels can frequently occur indoors in the neighbourhood of wind turbines when the Danish noise regulations are observed it would be useful to extend the standard to include a method to evaluate the hearing threshold.

The method to establish the audibility of broadband spectra described in Section 3.1 has been successfully tested for two examples: a broadband spectrum of room background noise and the broadband spectra of wind turbine noise at levels close to the hearing threshold. The calculated critical band levels agree to within 2 dB with perceived audibility. Theoretical considerations support the conclusion that the method should be adequate for use in standard applications.

6.3 Results on the annoyance of tones in background

Low frequency tones have been adjusted to higher tone levels above the masking threshold to be equally annoying as higher frequency tones. Examples of the measured equal annoyance contours in quiet are shown by the red and green lines in Figure 34 and for equal annoyance contours in the outdoor scenario in Figure 35. In both figures the equal annoyance contours are almost parallel to the masking threshold thereby demonstrating that annoyance is dominated by the frequency dependence of hearing. This is also demonstrated by the fact that the equal annoyance levels increase as the masking noise levels increase.

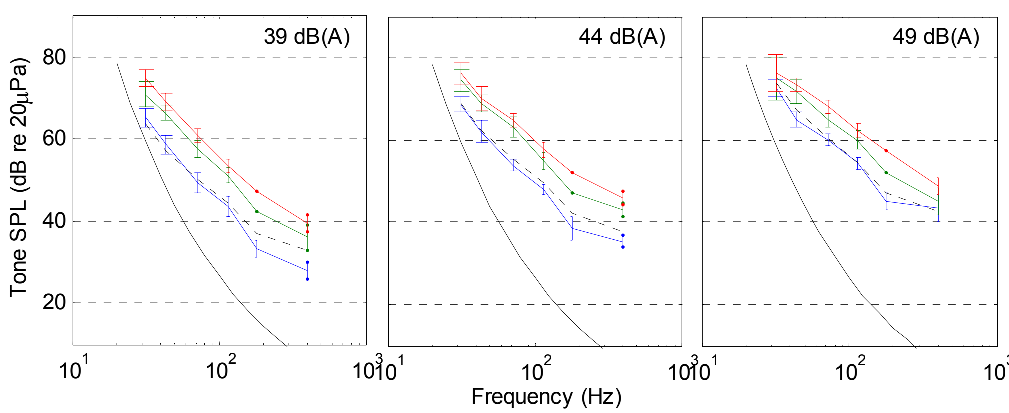

Figure 35
Outdoor scenario – Masking thresholds (blue), equal annoyance to 180 Hz tone at 5 dB audibility (green) and 10 dB audibility (red) of low frequency tones within broadband masking noises at A-weighted levels as labelled. Black solid line: Hearing threshold according to ISO 389-7). Dashed black line: Masking threshold according to ISO 1996-2. Error bars denote 95 % confidence intervals.

It was shown that increasing the tone level by 5 dB (at 180 Hz: red line level – green line level) increases the equal annoyance level by a smaller value both for tone frequencies lower than 180 Hz and at 400 Hz. This casts doubt on the appropriateness of the adjustment used in the ISO 1996-2 standard which adds penalty adjustments which are increasing linearly with sound pressure level above masking.

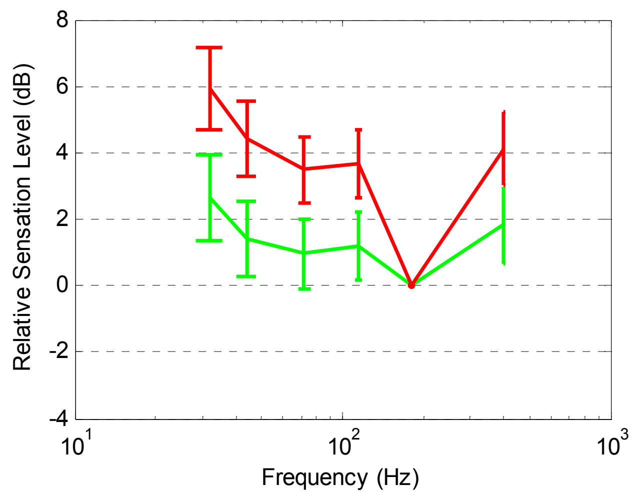

Figure 36
Relative sensation level for equal annoyance averaged over all masking noise types and scenarios at reference tone prominence levels of 5 dB (green) and 10 dB (red). Error bars show 95 % confidence intervals.

Relative sensation levels were calculated from equal annoyance contours to determine whether low frequency tones are relatively more annoying than high frequency tones. The results for all scenarios were very similar and an average relative sensation level is shown in Figure 36. When accounting for a familiarisation effect at 180 Hz the frequency dependence was not shown to be significant. This is also commented in section 3.3. The main influence on these levels is the tone level above masking level: Tones at higher levels are more annoying than tones at lower levels above masking. Both findings are common for the indoor and outdoor scenarios.

6.4 Results on annoyance when comparing recordings of a small and a large wind turbine

To compare real recordings of a large and a small wind turbine a test protocol was developed. An example of outdoor results is seen in Figure 37.

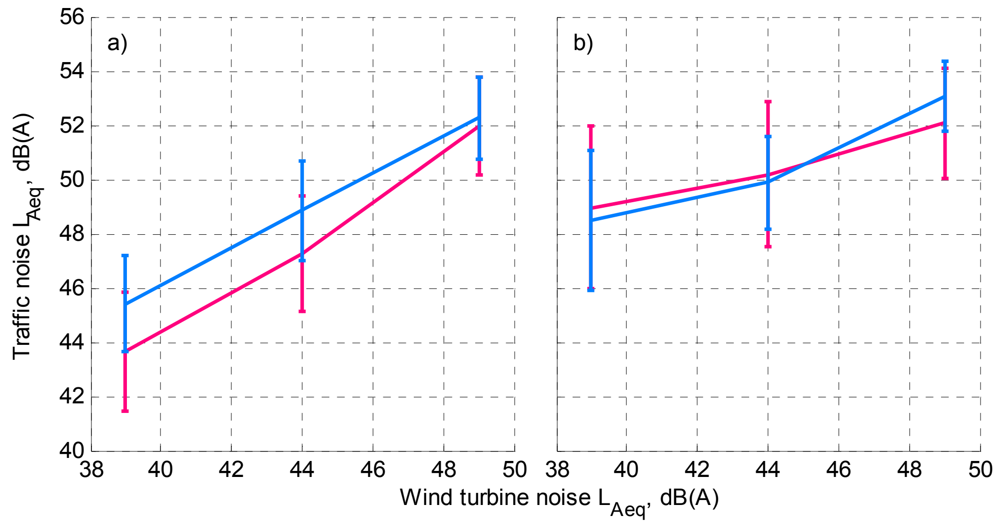

Figure 37
Equal annoyance contours for recorded turbines small wind turbine (blue lines) and a large wind turbine (red lines) matched to a neutral noise source (traffic noise) a) Outdoor scenario without garden noise, b) Outdoor scenario with garden noise. Error bars are confidence intervals (alpha = 0.05).

The comparison between normalized recordings showed the spectral characteristics of the small turbine to be more annoying outdoors than those of the large turbine recording. This has been attributed to the different spectral and temporal characteristics of the two turbines. These differences are effectively masked by garden noise and the equal annoyance ratings change accordingly. The indoor scenario does also not find the turbines to be differently annoying. If these results can be reproduced in other listening experiments then it follows that the specific differences in spectral content will determine the annoyance levels from a wind turbine more than whether it is a small or a large turbine. It would also mean that the differences in annoyance between wind turbines get smaller when sufficient masking noise is present. Presently, the finding that the small turbine is more annoying cannot be generalised to large and small wind turbines or to a wider range of wind and terrain conditions than were used in the test. The listener responses were however consistent and therefore demonstrate the potential of the comparison method.

In answer to the initial question whether large turbines are more annoying than small wind turbines, the results of this study find no evidence for a significant difference in annoyance between small and large wind turbines as long as total noise levels and tonal characteristics are taken into account in the assessment. Temporal variations of wind turbine noise such as the level of swishing might also have to be evaluated in the future.

7. Conclusions

The project on “Low Frequency Noise from Large Wind Turbines” comprises a series of investigations carried out to give increased knowledge on low frequency noise from wind turbines.

This report gives an overview of the results from the different parts of the project. One part of the project covers objective measures such as noise generation, noise measurement methods, results from noise measurements on small and large wind turbines (>2 MW), noise propagation, audibility and masking. Another part of the project covers the annoyance of low frequency wind turbine noise.

7.1 Changes of noise characteristics with increasing size of wind turbines

7.1.1 Noise emission from wind turbines

During the last stage of the project it has been possible to include measurement results from 14 new large wind turbines representative for large wind turbines installed at wind farms in Denmark in the years 2008-2010 instead of only 4 prototype turbines that were originally included in the project. Based on these new measurement results a more valid evaluation of the development of low frequency noise for large turbines compared to small turbines is now possible. For this evaluation small wind turbines represent an average nominal electrical power of 950 kW and the large turbines represent an average nominal power of 2500 kW.

It is found that the emitted A-weighted sound power level from the wind turbines increases with the nominal power of the turbines i.e. the turbine size. Doubling the wind turbine size (e.g. from 2 MW to 4 MW) gives a 2.9 dB increase (less than doubling) on the sound power level from the average wind turbine. This means that a certain amount of electrical power can be produced by large wind turbines with slightly less noise emissions than with small turbines.

The emitted low frequency sound power level also increases with wind turbine size. It is seen that this increase is higher with increasing size meaning that doubling the wind turbine size (e.g. from 2 MW to 4 MW) gives an 3.9 dB increase (more than doubling) on the sound power level from the individual wind turbine. This means that in general the total low frequency noise emission increases slightly more with wind turbine size than the A-weighted total sound power levels.

In general the frequency spectra of the aerodynamic noise from the rotor blades of the large wind turbines do not deviate significantly from the spectra for smaller wind turbines. From the total sound power spectra it is seen that the large turbines emit up to 2 dB more in the 100-160 Hz range. The consequences of the observed differences to the perceived sound pressure levels at the wind turbine neighbours are described below.

From the new study of noise from large wind turbines tonal components in the noise spectra are still observed in the low frequency range and are seen to contribute to the noise emission in the low frequency range. It has not been pursued further in this project how much these tones contribute to the increase seen in the low frequency end of the 1/3-octave band spectra and the increase in $L_{pA,LF}$. Anyway this finding supports that the broadband aerodynamic noise does not differ much between small and large turbines.

None of the tones were clearly audible at the nearest neighbour positions and therefore did not result in any penalty when evaluated against noise limits. Nevertheless manufacturers are encouraged to minimize the prominence of tonal components in order to minimize both low frequency noise and the potential for annoyance from tones.

As an important result it is also seen that the general differences in sound emission between the small and large wind turbines are generally much smaller than the difference between individual wind turbine makes, models and configurations.

7.1.2 Consequences for wind farms and indoor noise levels at neighbours

The low frequency noise levels indoor at residences close to wind farms do not necessarily increase when comparing large wind turbines to small turbines.

If a single wind turbine is placed at the “minimum distance” corresponding to 4 times the total height of the turbine, the indoor low frequency sound pressure level indoor will not be increased based on the general data for large wind turbines compared to the small turbines.

When respecting the noise limit of 44 dB(A) outside dwellings at a distance corresponding to 4 times the turbine total height 3 small turbines representing a nominal power of 3 MW could be installed at this distance or 4 large turbines representing a nominal power of 10 MW could be installed. The calculated indoor low frequency sound pressure level for both the small and large wind turbine case is close to the Danish guidance limit ($L_{pA,LF}$ 20 dB(A)) for general industrial noise sources. The large wind turbine case gives about 1 dB higher values compared to the small turbines.

Thus it is not shown that large wind turbines do cause a special problem regarding low frequency noise impact at residences close to wind turbines. It is clear that the evaluation of this always must be made for each specific case based on noise data for the turbines involved and not based on general trends regarding large versus small wind turbines. For projects where outside noise levels are close to the existing noise limits for wind turbines it will be good practice to perform calculations of the indoor low frequency noise impact. This will ensure that appropriate low frequency noise levels are met and hopefully contribute to minimize groundless anxiety in cases where there is no low frequency impact.

7.1.3 Perception of changes in noise levels and noise spectra

Although some of the observed differences in the spectra from small and large wind turbines are statistically significant they are not necessarily heard as essential changes of the sound characteristics.

For the outdoor situation at residences adjacent to wind turbines the A-weighted spectra for both small and large turbines are dominated by frequencies in the range 200-2000 Hz. It is therefore doubtful whether the small changes found in the low frequency part of the spectra will be noted in the total characteristics of the noise.

In the indoor situation the lower frequencies are dominating, so here the changes in the low frequency part of the spectra will be perceived to a higher degree than outdoors.

One of the two indoor situations considered is where the turbines are placed at the minimum distance (4 times total turbine height). From the calculated indoor spectra it is found that the differences are so small and insignificant that it is unlikely that any difference between small and large turbines can be perceived.

The other indoor situation is where the outdoor spectra at 4 total heights are normalized to a sound pressure level of 44 dB(A). Here it is seen that there is a 2 dB increase in the range 100-160 Hz corresponding to an increase in loudness level of 2.3 phon. This could be characterized as a noticeable but not an essential change.

7.1.4 Infrasound

A theoretical study from RISØ DTU together with the findings from the measurements on large wind turbines and a literature study confirm that infrasound is negligible for this type of wind turbines with the blades in front of the tower. Even close to the wind turbines the sound pressure level is much below the normal hearing threshold. Thus infrasound is not considered a problem.

7.2 Methods for measurement of low frequency noise from wind turbines and evaluation of noise impact at neighbours

In this project adequate methods for performing an evaluation of noise impact at residences close to wind turbines are provided and demonstrated. This includes all steps from measurement of noise characteristics of the wind turbines to the calculation of resulting noise levels indoor at neighbours to prove that the general guidelines for low frequency noise limits are met. The different steps are described below:

- Measurement of the sound emission from wind turbines must be performed with the proposed extension of the frequency range down to at least 20 Hz. In a coming revision of the IEC measurement method measurements down to 20 Hz has been implemented. Appropriate measures such as special wind screens must be taken into account to reduce measurement uncertainties at lower frequencies.

- Calculation of sound propagation from turbine to receiver points outdoor at nearby residences should be made using the Nord2000 sound propagation model.

- Calculation of indoor noise levels should be made using the sound insulation for houses given in [14].

7.3 Noise monitoring at Høvsøre

From the results of a measurement campaign carried out at a residence close to the Høvsøre test site a good correlation was found between annoyance registered by the neighbour and the occurrence of a low frequency tone in the noise from one of the wind turbines at the test site. This was one of the reasons to give special focus to the investigation of annoyance from low frequency tones in wind turbine noise in the listening tests.

7.4 Annoyance from wind turbine noise

The study on the perception of wind turbine noise based on listening tests has been divided in two:

- Establishment of audibility thresholds and equal annoyance contours for idealised wind turbine sounds containing low frequency tones at frequencies between 32 Hz and 400 Hz. The listening test simulated an indoor scenario and an outdoor scenario with and without masking garden noise.

- Investigation of perception of real wind turbine samples. Samples from a large and a small wind turbine have been compared with traffic noise in the same scenarios used in the first part of the listening tests.

Within the scope of the test stimuli, the listening tests found no evidence for a significant difference in annoyance between small and large wind turbines.

More specifically the results showed that for the same tone prominence there was no evidence that tones at lower frequencies were more annoying than tones at higher frequencies.

It was also shown that frequency dependence of annoyance level is strongly related to hearing and masking thresholds and that increasing the level of a tone in noise made the tone more annoying. Both of these effects are covered in current standards but some improvements are suggested: Where the masking thresholds are close to the hearing thresholds in quiet a standard method of calculating the audibility of broadband noise should be defined. For tone penalty regulations more work needs to be done to establish whether annoyance scales linearly with tone levels above masking thresholds.

A method to assess the audibility of broadband stimuli [4] was tested for two different examples which were a) the background noise in the listening room with vents and loudspeakers switched on and off b) the indoor scenario masking noise at three different levels. The method has been found to give reliable audibility estimates in a number of critical bands in the frequency range between 0 and 500 Hz.

The results of annoyance ratings when comparing two wind turbine recordings have been explained by spectral and temporal characteristics of the chosen sound samples. The method has given consistent results within the range of stimuli evaluated in this study. The general applicability of the results beyond this scope has not been validated.

In summary the study has shown that listening tests can be successfully used to find answers to the perception of low frequency tonal wind turbine noise and to compare recordings of wind turbine sounds although. However, a large number of sound samples would be required to get representative and general results on a sufficient number of wind turbine models, sites and meteorological conditions all of which will change the sound characteristics and therefore the annoyance. Further work can be done to investigate the role of temporal variation on annoyance and to relate the annoyance between different scenarios.

8. Konklusion (in Danish)

I projektet “Lavfrekvent Støj fra Store Vindmøller” er der gennemført en række undersøgelser med henblik på at afklare, om lavfrekvent støj fra store vindmøller udgør et særligt problem.

Denne rapport giver et overblik over resultaterne fra de forskellige delprojekter. Den ene del af projektet har omhandlet objektive begreber som støjgenerering, metoder til støjmålinger, resultater fra målinger på små og store vindmøller (> 2 MW), lydudbredelse samt hørbarhed og maskering. En anden del af projektet har behandlet genevirkning af forskellige karakteristika for lavfrekvent støj fra vindmøller.

8.1 Ændringer i støjens karakteristika med øget vindmøllestørrelse

8.1.1 Lydudstråling fra vindmøller

I den sidste del af projektet blev det muligt at inkludere måleresultaterne fra 14 nye store vindmøller, der er repræsentative for de store vindmøller, der er opstillet i vindmølleparker i Danmark i årene 2008-2010 i stedet for de kun 4 prototypevindmøller, som oprindeligt var med i projektet. Baseret på disse nye måleresultater har det været muligt at foretage en mere dækkende vurdering af udviklingen i lavfrekvent støj fra store vindmøller sammenlignet med små. I denne vurdering repræsenterer små vindmøller en middel, nominel, elektrisk effekt på 950 kW og store vindmøller en middel, nominel, elektrisk effekt på 2500 kW.

Det er konstateret, at den udsendte A-vægtede lydeffekt fra vindmøller stiger med vindmøllernes nominelle, elektriske effekt; dvs. møllernes størrelse. En fordobling af vindmøllestørrelsen (f.eks. fra 2 MW til 4 MW) giver en gennemsnitlig stigning på 2,9 dB, dvs. mindre end en fordobling af den udsendte lydeffekt. Dette betyder kort sagt, at store vindmøller støjer lidt mindre end små vindmøller regnet pr. kW produceret elektrisk effekt.

Den lavfrekvente andel af den udsendte lydeffekt stiger også med vindmøllens størrelse. Det ses, at denne stigning er større, hvilket betyder, at en fordobling af vindmøllestørrelsen (f.eks. fra 2 MW til 4 MW) giver en gennemsnitlig stigning på 3,9 dB, dvs. mere end en fordobling af den udsendte lydeffekt. Det betyder, at den lavfrekvente andel af lydudstrålingen gennemsnitligt stiger lidt mere med vindmøllens størrelse end den totale A-vægtede lydudstråling gør.

Frekvensspektrene af den aerodynamiske støj fra vindmøllevingerne afviger ikke væsentligt for store vindmøller i forhold til de mindre vindmøller. Fra lydeffektspektrene ses, at de store vindmøller udsender op til 2 dB mere i frekvensområdet 100-160 Hz. Hvordan denne forskel opfattes hos naboer til vindmøller er diskuteret nedenfor.

Fra måleresultaterne ses, at der er toner i støjudstrålingen fra de store vindmøller i det lavfrekvente område, og at disse toner har betydning for den lavfrekvente støjudsendelse. Det er ikke i dette projekt undersøgt nærmere, hvor meget disse toner bidrager i den lavfrekvente del af 1/3-oktav spektrene samt i stigningen i $L_{pA,LF}$. Det understøtter dog, at karakteren af den bredbåndede aerodynamiske støj ikke varierer meget mellem små og store vindmøller.

Ingen af de nævnte toner er konstateret tydeligt hørbare ved de nærmeste naboer til de pågældende vindmøller og resulterer derfor ikke i tonetillæg i forbindelse med dokumentationen i forhold til danske støjgrænser. Ikke desto mindre bør fabrikanterne være opmærksomme på at minimere tonerne med henblik på at begrænse såvel lavfrekvent støjudsendelse som potentiel genevirkning fra toner i støjen.

Som et vigtigt resultat ses det, at forskellene i støjudstrålingen mellem små og store vindmøller er meget mindre end de forskelle, der ses mellem individuelle vindmølletyper , modeller og konfigurationer.

8.1.2 Konsekvenser for det indendørs støjniveau ved naboer

Det lavfrekvente støjniveau indendørs hos naboer til vindmøller stiger ikke nødvendigvis som følge af vindmøllens størrelse ud fra en sammenligning af påvirkningen fra hhv. små og store vindmøller.

Hvis det er ”minimumsafstanden” svarende til 4 gange vindmøllens totalhøjde og ikke støjgrænsen, der er begrænsningen i afstanden til naboerne, vil det lavfrekvente støjniveau indendørs hos naboer til vindmøller ikke stige ud fra de generelle data for store møller i forhold til små møller.

Hvis det er støjgrænsen, der er begrænsningen, kan der ud fra de generelle støjdata for hhv. små og store vindmøller med overholdelse af den danske støjgrænse på 44 dB(A) udenfor nabobeboelser, f.eks. opstilles 3 små vindmøller (repræsenterende en nominel effekt på 3 MW) eller 4 store vindmøller (repræsenterende en nominel effekt på 10 MW) i minimumsafstanden. I dette tilfælde vil det indendørs lavfrekvente støjniveau, $L_{pA,LF}$, for både små og store vindmøller ligge tæt på den vejledende danske grænseværdi på 20 dB(A) gældende for virksomhedsstøj. De store vindmøller vil her give ca. 1 dB højere værdier sammenlignet med de små vindmøller.

Det er således ikke påvist, at store vindmøller udgør et specielt problem i forhold til lavfrekvent støjpåvirkning ved naboer til vindmøller. Det fremgår klart, at vurderinger altid bør foretages for hver specifik situation og baseres på støjdata for de aktuelle vindmøller og ikke på generelle trends for store versus små vindmøller. God praksis vil være, at der for projekter, hvor man ligger tæt på de gældende støjgrænser for vindmøller, foretages beregninger af den lavfrekvente støjpåvirkning hos naboerne. Dette vil sikre, at relevante niveauer for lavfrekvent støj overholdes og vil forhåbentlig også bidrage til at minimere unødig bekymring i tilfælde, hvor der ikke er betydende lavfrekvent støj.

8.1.3 Opfattelsen af ændringer i støjniveauer og støjspektre

Selvom nogle af de konstaterede forskelle i støjspektre fra små og store vindmøller er statistisk signifikante, høres de ikke nødvendigvis som væsentlige ændringer i støjens karakter.

For den udendørs situation ved naboer til vindmøller er det A-vægtede støjspektrum domineret af frekvenser i området 200-2000 Hz for både små og store vindmøller. Det er derfor tvivlsomt, om de små ændringer, der for denne situation er fundet i den lavfrekvente del af støjspektrene, vil blive opfattet i den totale oplevelse af støjen.

I den indendørs situation er det de lave frekvenser, der dominerer, så her vil ændringer i den lavfrekvente del blive opfattet mere end udendørs.

En af de betragtede indendørs situationer, hvor en enkelt vindmølle er opstillet i minimumsafstand (4 gange vindmøllens totalhøjde), ses fra de beregnede indendørs støjspektre, at forskellene er små og ikke signifikante, og det er sandsynligt, at der ikke vil blive opfattet nogen forskel mellem store og små vindmøller.

Den anden indendørs situation, hvor flere vindmøller er placeret i minimumsafstanden, ses en stigning på 2 dB ved 100-160 Hz i de beregnede indendørs støjspektre. Dette opfattes svarende til 2,3 dB stigning i det ”normale” frekvensområde, hvilket kan karakteriseres som en hørbar, men ikke væsentlig ændring.

8.1.4 Infralyd

Et teoretisk studie fra RISØ DTU bekræfter sammen med litteraturstudier og resultater fra målinger på store vindmøller, at infralydniveauerne er ubetydelige for de mest almindelige vindmøller med vingerne foran tårnet. Selv tæt på vindmøllerne er niveauet for infralyd langt under den normale høretærskel. Infralyd betragtes derfor ikke som et problem.

8.2 Metoder til måling af lavfrekvent støj og beregning af støjpåvirkningen ved naboer til vindmøller

I dette projekt er der angivet og demonstreret metoder til dokumentation af lavfrekvent støj hos naboer til vindmøller. Dette inkluderer alle trin fra måling af støjdata fra vindmøllerne til beregning af den resulterende lavfrekvente støjpåvirkning indendørs i nabobeboelser. De forskellige trin er beskrevet nedenfor:

- Måling af støjudstrålingen fra vindmøllerne skal gennemføres i frekvensområdet ned til mindst 20 Hz. I en kommende version af IEC-målestandarden for vindmøller er dette implementeret. Der skal træffes særlige foranstaltninger for at reducere måleusikkerheden ved de lave frekvenser bl.a. ved anvendelse af en speciel vindskærm under målingerne.

- Beregning af lydudbredelsen fra vindmølle til beregningspunkter udendørs ved nabobeboelser foretages med anvendelse af Nord2000-lydudbredelsesmodellen.

- Beregning af det indendørs lavfrekvente støjniveau i nabobeboelser foretages ud fra data for lydisolation for huse som beskrevet i [14].

8.3 Overvågning af støj ved nabobeboelse på Høvsøre testcenter

I projektet er der gennemført en målekampagne ved en nabobeboelse til testcenteret for vindmøller på Høvsøre i Vestjylland. Målingerne viste, at der kunne ses en tydelig sammenhæng mellem registreret gene i beboelsen og tilstedeværelsen af en tydeligt hørbar, lavfrekvent tone i støjen fra en af vindmøllerne på testcenteret. Bl.a. dette har dannet baggrund for, at der i lyttetestene er arbejdet specielt med genevirkningen af lavfrekvente toner i vindmøllestøj.

8.4 Genevirkning af støj fra vindmøller

Der er udført lyttetest ved Salford Universitet til belysning af opfattelsen af de lavfrekvente karakteristika i støjen fra vindmøller. Studiet er opdelt i to:

- Opstilling af kurver for høretærskler og genevirkning for et eksempel med generaliseret vindmøllestøj med indhold af lavfrekvente toner ved frekvenser mellem 32 Hz og 400 Hz. Lyttetesten simulerede et indendørs og et udendørs scenarium hhv. med og uden maskerende vindstøj fra vegetation.

- Undersøgelse af genevirkning af lydoptagelser af vindmøllestøj. Lydeksempler fra en stor og en lille vindmølle er sammenlignet med trafikstøj som reference i de samme scenarier som i første del af lyttetesten.

Med baggrund i gennemførte test er der ikke fundet en signifikant forskel i genevirkningen mellem små og store vindmøller.

Mere specifikt viser resultaterne, at det for den samme tydelighed af tonerne ikke kan påvises at lavfrekvente toner er mere generende end højfrekvente toner.

Ligeledes viser resultaterne for forsøgene med tonestøj, at genevirkningens frekvensafhængighed er kraftigt relateret til høre- og maskeringstærsklen, og at et stigende toneniveau gør støjen mere generende. Tonernes tydelighed beregnet efter gældende standarder er i god overensstemmelse med den opfattede tydelighed af tonerne, men nogle forbedringsforslag er foreslået. Når maskeringstærsklen er tæt på høretærsklen i stille omgivelser, bør denne tages i betragtning. For genetillægget for toner vil det være relevant at undersøge, om genevirkningen stiger lineært med toneniveauet, som det antages i de nuværende metoder.

En metode til bestemmelse af hørbarheden af bredbåndede lavfrekvente signaler [4] blev testet i to forskellige tilfælde. Test blev foretaget for a) baggrundsstøjen i lytterummet, hvor ventilationsanlæg og højttalere hhv. blev slukket og tændt og b) det indendørs scenarium med maskerende baggrundsstøj ved tre forskellige niveauer. Metoden gav pålidelige estimater for hørbarheden i et antal kritiske bånd i frekvensområdet mellem 0 og 500 Hz. Teoretiske overvejelser støtter, at metoden kan være fyldestgørende til mere generelle anvendelser.

Resultaterne af genebedømmelser af to lydoptagelser fra vindmøller er forklaret ud fra spektrale og tidsmæssige karakteristika for de udvalgte lydeksempler. Metoden har givet konsistente resultater for de anvendte stimuli. På grund af de få lydeksempler er en generalisering af resultaterne ikke valideret.

Alt i alt er det vist, at lyttetest kan anvendes til at bedømme genevirkningen af lavfrekvent tonestøj og til sammenligning af forskellige lydoptagelser af vindmøllestøj. Metoderne vil fremover kunne anvendes til nærmere undersøgelser af støjens karakteristika. Dette kræver dog et stort antal testeksempler for at få repræsentative og generelle resultater dækkende for et passende antal vindmølletyper, lokaliteter og meteorologiske situationer - alle forhold, der har indflydelse på lydens karakter og dermed genevirkning. F.eks. vil indflydelsen af vingesuset på den oplevede genevirkning for forskellige scenarier kunne udføres med de beskrevne metoder.

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