

## In situ measured facade sound insulation of wind turbine sound

Pontus THORSSON

Akustikverkstan AB, Lidköping, Sweden

### ABSTRACT

In most countries there are regulations of wind turbine sound level outdoors at dwellings. Often there are also regulations of the sound levels inside the dwelling, however not often directly aiming at wind turbine sound. The sound level indoors from wind turbines has attracted more interest in the latest years, and then especially in the low frequency region (up to 200 Hz). Studies on the in situ sound level difference between outside and inside of dwellings are however scarce. This paper presents the in situ measured sound level difference for two Swedish houses in rural locations, both using a loudspeaker and using the wind turbine sound as exciting signal. This is possible due to a 2 month long measurement series with simultaneous sound recordings outside and inside. The sound pressure level differences from the two methods are shown to differ substantially.

Keywords: Wind turbine sound, sound insulation, low frequencies

### 1. INTRODUCTION

Wind turbines produce sound that, as all other community noise sources, can be perceived as annoying and self-reported sleep issues [1,2]. Most countries have national regulations that limit the noise exposure from wind turbine sound on the outside of dwellings. Some countries also have explicit regulations on the sound levels indoor of dwellings, e.g. Denmark where there is a limit of maximum 20 dB(A) sound pressure level from wind turbines in the low frequency region, 10 – 160 Hz. The Danish regulations states that the low-frequency contribution shall be calculated using previously measured sound pressure level differences that are given in the regulation text [3]. In the regulations from 2019 there are two different sound pressure level differences; one for regular dwellings, and one significantly lower sound pressure level difference for summer houses. These sound pressure level differences were measured in a number of Danish houses using a loudspeaker.

In Sweden there is no explicit regulation for wind turbine sound indoors of dwellings, and a general regulation for maximum sound pressure levels is instead used irrespective of sound source [4]. Those regulations state limits of A-weighted equivalent levels and linear equivalent levels in the 1/3 octave bands 31.5 – 200 Hz.

In the following, the sound pressure level difference measured using both loudspeaker and in situ wind turbine sound is presented and compared to the Danish guidelines.

### 2. MEASUREMENT SERIES

A very long measurement series (roughly 2 months) was performed on two houses in Sweden. The sound was recorded in audio quality during the whole series in order to ascertain that all evaluated sound levels were coming from wind turbines only. The microphones were mounted on the facade of each house on a flat measurement board, and equipped with double windscreens. No high-pass filter was applied to the signal, and the sampling frequency used was 25.6 kHz thus making it possible to evaluate sound pressure levels in the 1/3 octave bands up to at least 5 kHz. Meteorological data was simultaneously recorded using a weather station mounted on a 10 m wind mast. Thirty-five 10 minute long periods were chosen for the evaluation of the sound pressure level differences. The periods were chosen subjectively for strong presence of wind turbine sound, mainly identified with perceived amplitude modulation.

## 2.1 EVALUATION OF OUTDOOR SOUND LEVELS

Figure 1 shows the measured sound pressure level spectra in the 1/3 octave bands between 20 Hz and 5 kHz for all periods on house 1. All evaluations have been made in the same way for both houses, but detailed measurement data is only presented for house 1. The presented spectra are the measured levels, i.e. not corrected for the facade reflection. For the measurement periods with lowest sound levels at high frequencies the noise floor of the measurement system was reached.

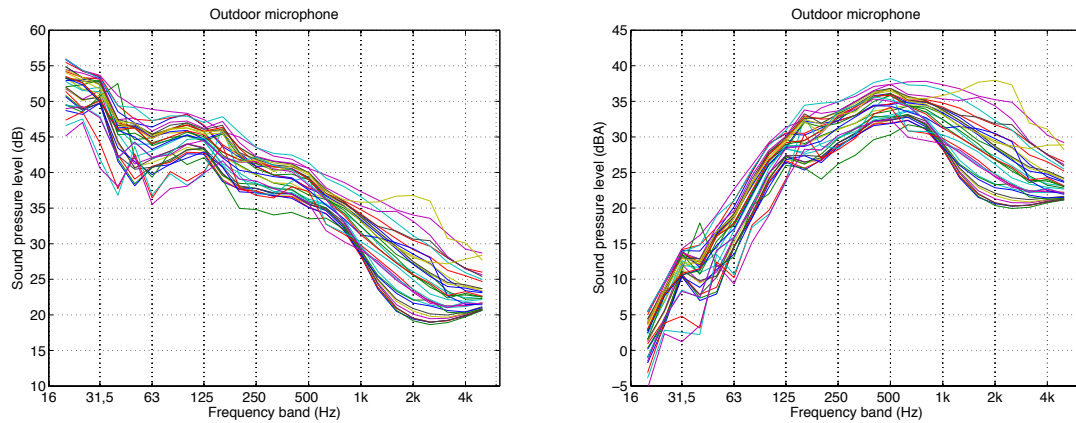


Figure 1 – Evaluated 1/3 octave band spectra outdoors for all measurement periods at house 1.

Left: unweighted with respect to frequency; Right: A-weighted levels.

From the data in Figure 1 it can be seen that the A-weighted total levels are in most cases dominated by 1/3 octave bands below 1 kHz. This is due to the lowered sound power level from the wind turbines towards higher frequencies, and to air absorption. The high levels in some measurement periods at 1-2 kHz is caused by background disturbances, such as bird song or wind hiss in nearby vegetation. This has been corroborated through listening to the recorded sound.

## 2.2 EVALUATION OF INDOOR SOUND LEVELS

The sound levels indoors have been evaluated through inspection of the variations of the measured sound pressure level with time, and by subjective listening. In house 1, the measurement room was not used and the background level was thus sufficiently low at most times to give relevant indoor sound levels. The measured sound pressure level spectra for all measurement periods are presented in Figure 2.

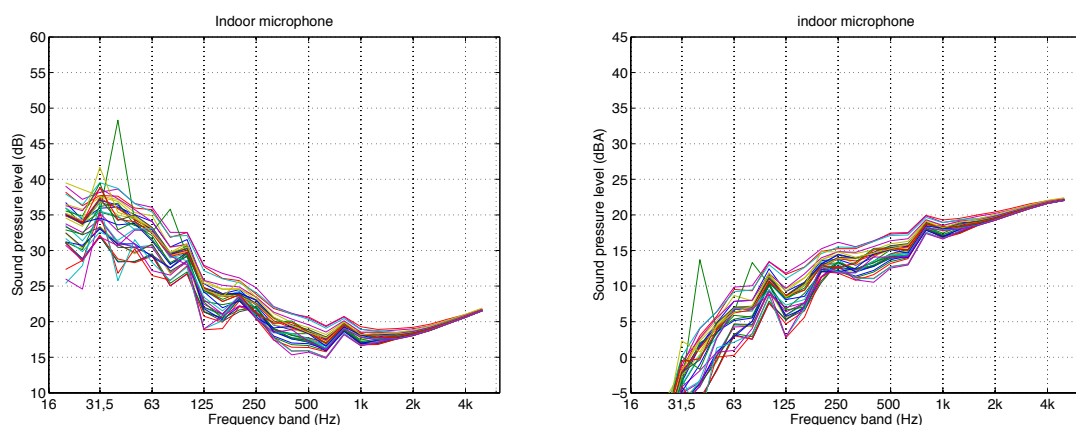


Figure 2 – Evaluated 1/3 octave band spectra indoors for all measurement periods at house 1.

Left: unweighted with respect to frequency; Right: A-weighted levels.

Again, the limiting noise floor of the measurement equipment can be seen at the higher frequencies. The measured indoor sound levels can be trusted up to the 630 Hz 1/3 octave band because of the noise floor.

### 3. EVALUATION OF SOUND PRESSURE LEVEL DIFFERENCE

It is tempting just to subtract the levels in Figure 2 from the levels in Figure 1, but before that can be done it is necessary to test if such an evaluation would give credible results. Here this is done by analysing the correlation between outdoor and indoor levels in each 1/3 octave band. The result for this is shown in Figure 3 for selected 1/3 octave bands.

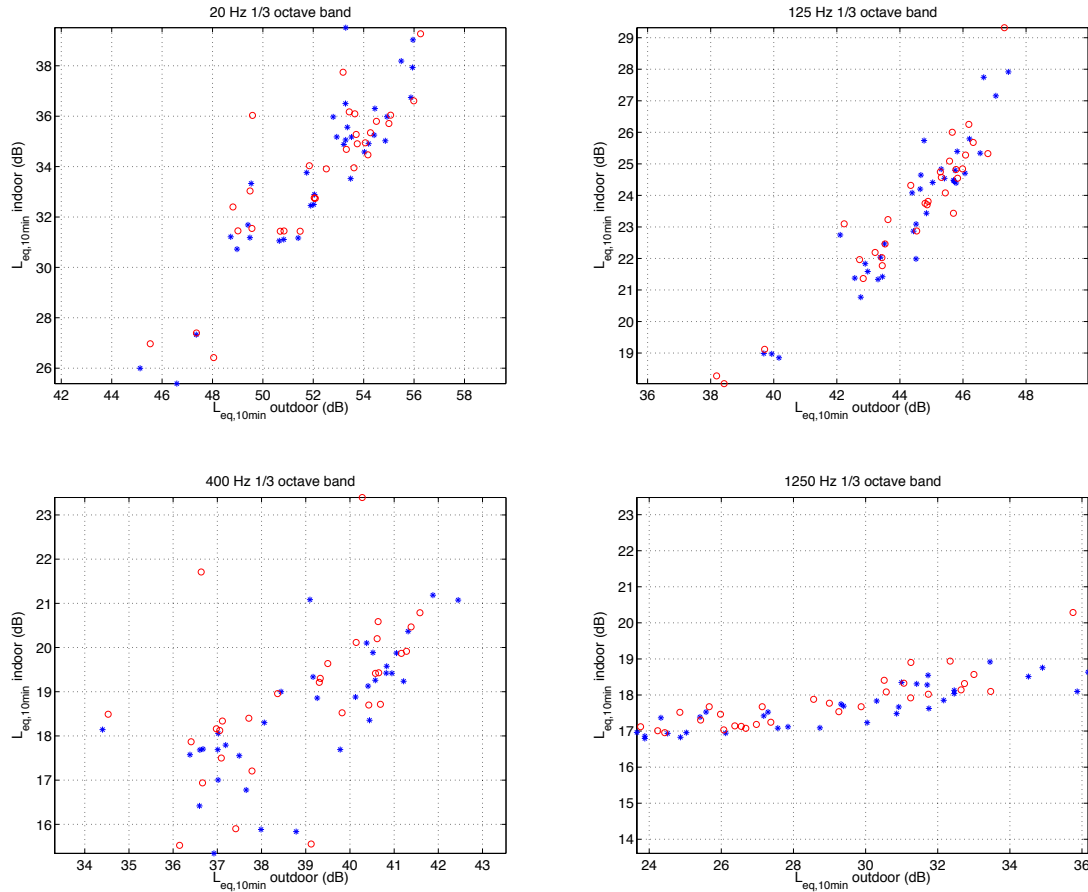


Figure 3 – Correlation between outdoor and indoor sound pressure levels in selected 1/3 octave band for all measurement periods at house 1. The x- and y-scales are equal in scale.

In the figures, blue stars represent levels evaluated through standard equivalent levels, i.e. removing the portions that contain subjectively identified background disturbances and then evaluating for the equivalent level. Red circles represent equivalent levels identified through the existence of amplitude modulation in the A-weighted signal. The amplitude modulation is calculated through

$$\Delta L_{AM} = \left( \frac{p_0 + p_f}{p_0 - p_f} \right) \quad (1)$$

where  $p_0$  is the steady-state RMS value of the sound pressure (corresponding to the equivalent level), and  $p_f$  is the RMS value of the sound pressure at the blade pass-by frequency. This formulation comes from Lee et al [5].

The identification is made for all 10 second clips in each measurement period, and the corresponding equivalent level (red circles) is evaluated from the identified 10 second clips.

It is clear in Figure 3 that there are differences from the methods for individual measurement periods, but the overall trend and corresponding global results in each 1/3 octave band are very similar. Note that the x- and y-scale have the same scaling in the graphs, so that a slope of 1 dB/dB corresponds to a good correlation between indoor and outdoor levels. In the lower frequency bands there is a clear correlation between outdoor and indoor levels, which shows that the indoor sound levels are indeed coming from the outside. In general, the correlation in each 1/3 octave band should

be composed of two straight lines; one horizontal line that corresponds to the background level, and one sloped line that is caused by sound coming from outdoors. It has been validated that the measurement periods are dominated by wind turbine noise, so it can be concluded that the indoor sound levels are wind turbine sound up to 630 Hz. The sound pressure level differences for the measurement periods are shown in Figure 4.

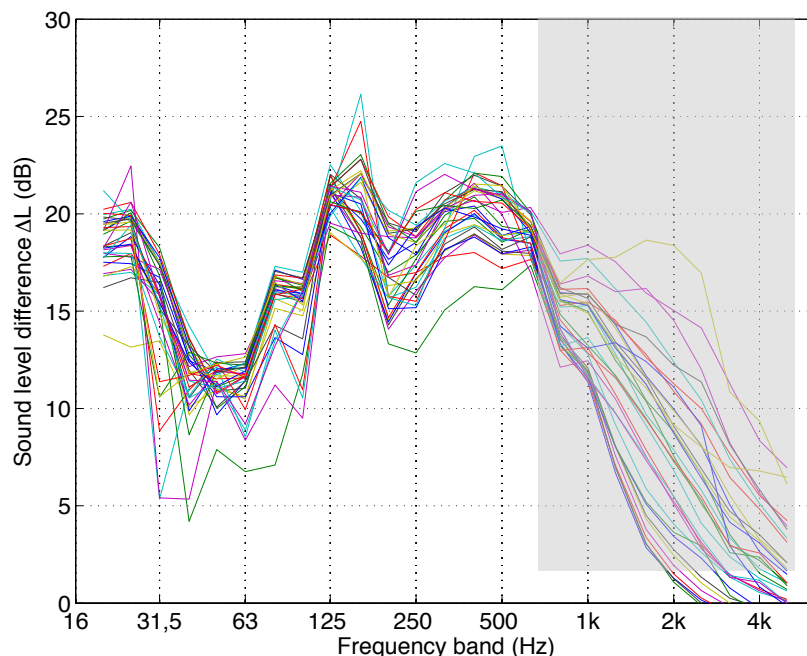


Figure 4 – Sound pressure level difference for all measurement periods at house 1.

The grey area represents frequency bands where background noise dominates.

It can be argued that the higher values of the sound pressure level difference are more relevant, since background noise disturbances are more likely in the indoor measurement. Here the 70 % level has been chosen as relevant for the houses to not exaggerate the sound level difference. A final sound pressure level difference using this choice is shown in Figure 5 for both house 1 and house 2 in the 1/3 octave bands between 31.5 and 200 Hz. These frequency bands are used in Swedish regulations of sound pressure levels indoors.

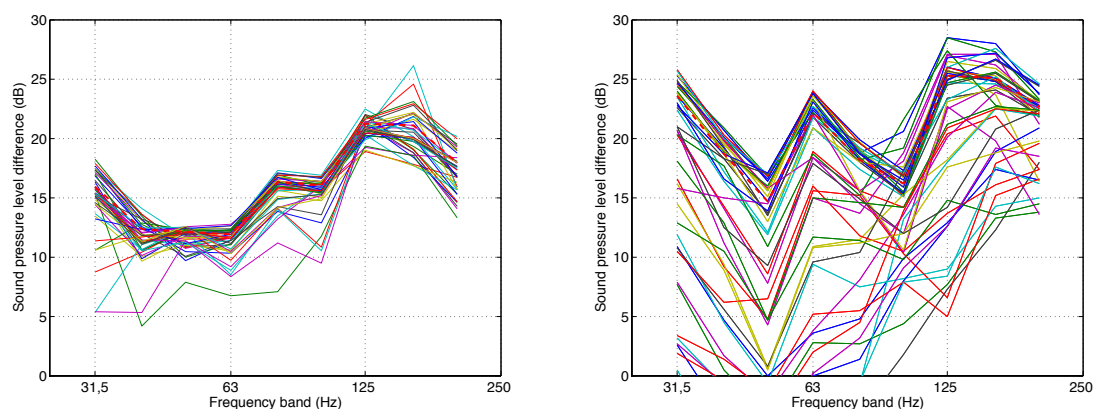


Figure 5 – Sound pressure level differences for house 1 (left) and house 2 (right).

Red dashed line show the 70 % level.

The facade sound insulation of both houses has also been measured using the loudspeaker method in ISO 16283-3:2016. In those measurements a 15 inch loudspeaker was used for the 1/3 octave bands from 125 Hz and upwards, and a high-power subwoofer was used for the 1/3 octave bands from 20 to 125 Hz. The results from those measurements are shown in Figure 6 together with the results in Figure 5, and with the Danish calculation values from [3]. In the figure it can be seen that the in situ measured sound pressure level differences using wind turbine noise as source is considerably lower in the low frequency range than both the loudspeaker measurements and the values given in the Danish regulations. For house 2 the in situ wind noise measurements are in relatively close to both the loudspeaker measurements and the Danish values for summerhouses. The difference between the measurements in house 1 and house 2 is that the measurement room in house 1 was on the upper floor, thus having sound transmission through the roof as well. It is clear that using measurement data from a loudspeaker measurement does not necessarily give representative values. Further studies on this is clearly needed.

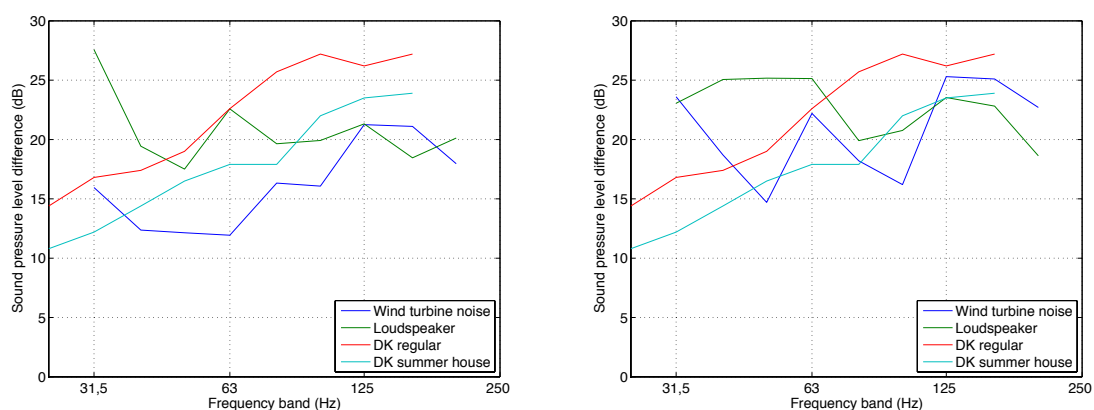


Figure 6 – Sound pressure level differences for house 1 (left) and house 2 (right).

## 4. CONCLUSIONS

It is shown here that it is possible to measure the sound pressure level difference for wind turbine sounds in situ using the wind turbine as sound source. This is however only possible if it can be ascertained that the sound on the outside is dominated by wind turbine noise in all relevant frequency bands. From long measurement series it was shown here that the sound pressure level difference is acoustically relevant, e.g. it can be the dominating noise source, and the values can differ significantly from measurements using loudspeakers. In one case presented here, the in situ measured sound pressure levels were significantly lower than values that are available in the planning stage of new wind turbines. More studies on relevant values for the sound insulation from wind turbine sound are thus needed.

## REFERENCES

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