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Validation of noise propagation models against detailed flow and acoustic measurements

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Abstract. In this paper, four noise propagation models including the parabolic-equation based WindSTAR model, ray-tracing based Nord2000 model, Danish regulation BEK 135 model and ISO 9613-2 standard model are validated against flow and acoustic measurements of a sound source created from a speaker located at a turbine hub of 109 m height. The flow was measured with a fully instrumented met-mast at 350 m and 218 degrees from the turbine tower base. The sound was measured with 11 microphones: 8 were along a line of 45 degrees and a distance up to 1200 m away from the sound source, 3 were located at IEC positions, and 1 microphone close to the speaker, which was used to measure the source strength. White noise and 1/1 band-limited white noise sound at 2 different wind shears with exponents of 0.12 and 0.23 are used for validation. Results show that an overall agreement between experiment and computation is reached for all the numerical models. Among the 4 numerical models, Nord2000 gives the best prediction for the nearfield microphones of mic 4 - mic 6 and WindSTAR gives the best prediction for the far-field microphones of mic 7 and mic 8.

1. Introduction

Wind energy is developing very fast in the world and it will be further developed substantially in the next years. To improve public acceptance, wind turbine noise should be evaluated, not only in the nearfield but also in the far-field. Far-field noise is greatly influenced by the atmospheric conditions and wind turbine wakes. Thus it is very important to carry out detailed measurements for both flow and acoustics at the same time, and to validate the long distance noise propagation models.

There are simple noise propagation models used with noise regulations today. A typical example is the Danish BEK 135 model [1]. Due to its simplicity, it is fast to get a solution. On the international side, the ISO 9613-2 standard propagation model [2] is quite popular and also fast to run. Since the simple models only use a few parameters and have an empirical nature, these models have limitations in predicting the complex sound propagation at large distance as it is influenced greatly by atmospheric flows.

A more sophisticated model Nord2000, documented in [3] and [4] that uses the ray-tracing theory, was developed. On the other hand, the sound propagation model WindSTAR [5, 6] based on solving the parabolic wave equation was also developed where the detailed flow information can be taken into

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account. Moreover, WindSTAR can be coupled with detailed Computational Fluid Dynamics (CFD) solutions and sound source models.

In this paper, all the four different models are validated against measurements performed in an environment field of a parked wind turbine with a source height of 109 m.

The paper is organized as follows. In Section 2, numerical models and measurement details are introduced. Results are presented in Section 3. At the end, conclusions are drawn.

2. Methodology

In this paper, we present the validation of noise propagation models against both flow and acoustic measurements with a sound source created from a speaker at the hub of a wind turbine at standstill. Thus, the objectives of the paper are (1) to carry out both flow and noise measurements at the same time, and (2) to carry out validations of noise propagation models.

2.1. Numerical models

Numerical models are summarized in Table 1. For more details, the reader is referred to the references. Remark that for WindSTAR, 1/15 octave band center frequencies are used.

Table 1. List of numerical models used for estimating sound pressure levels at microphones.

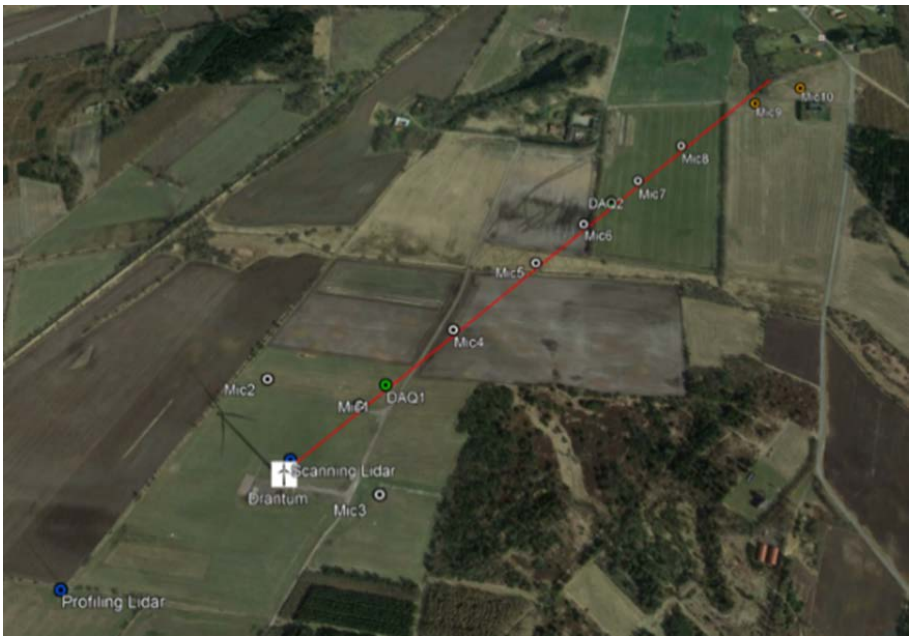
WindSTAR	Calculation using the WindSTAR code based on solving the parabolic wave equation [5]
Nord2000	Calculations using the Nord2000 code based on the ray-tracing theory [3][4]
WindPRO-DK	Calculations using the Danish standard method (BEK 135) in windPRO [1] [8]
WindPRO-ISO	Calculations using the ISO standard model in windPRO with a ground factor of 0.5 [2][8]

2.2. Measurement details

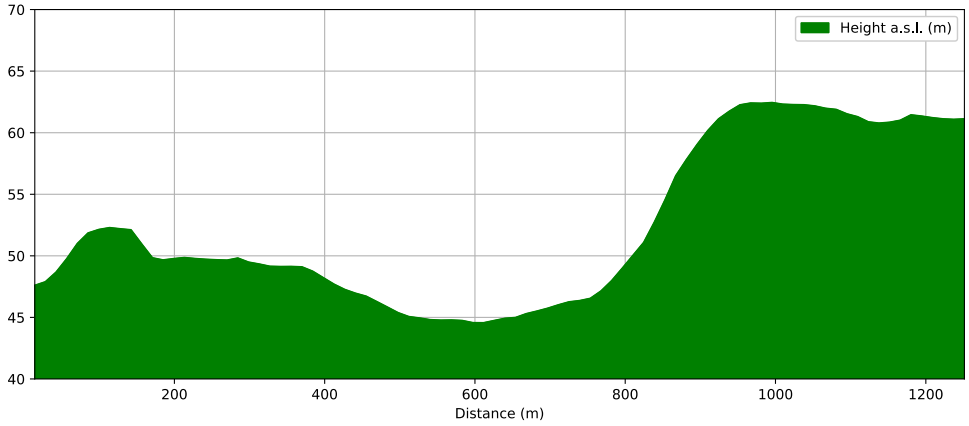
The measurement set-up and terrain height along the microphone line can be seen in Figure 1 for an overview. Remark that the terrain varies in a range of a few meters in height close to the turbine and the variation is slightly big around 17 m in the area between 600 m and 1000 m from the turbine. The detailed instrumentations are:

- The speaker is on the wind turbine hub with a height of 109 m.
- A met-mast is located at 350 m and 218° from the turbine and instrumented with 3 cups at 38 m, 68 m and 109 m, 2 sonics at 7 m and 100 m, 2 temperature sensors at 3 m and 105 m, a wind direction vane at 105 m, and a humidity transmitter at 105 m.
- A profiling Lidar was installed in the neighbourhood of the met-mast to measure the horizontal speed, wind direction and turbulence intensity for heights up to 200 m.
- 11 microphones (mic) were used, 3 of which were installed at the IEC [9] positions at a distance of 167 m from the turbine tower with a separation angle of 60°. Mic 1 and mic 4 to mic 10 were almost along the line of the “principal” wind direction of 225° with a distance to the turbine of 167 m, 378.5 m, 582 m, 707 m, 855.7 m, 982 m, 1174.5 m and 1275.6 m. Mics 4-8 were originally installed at 1.2 m height. Since mic 4 was not working, it was removed there from the first day. In the speaker measurement campaign, mic 4, and mic 9 - mic 10 were added with set-up of Force Technology on a tripod of 1.5 m height. Moreover, a microphone near the speaker noise source with a distance of 1.35 m and along the nacelle direction was used (hereafter referred to as SGRE mic). The SGRE mic is used to estimate the sound power level for noise propagation calculation. It should be stated that all microphones are Class 1 according to IEC 61672.

- A scanning Lidar was installed at the turbine tower bottom to scan the wind speed in the vertical plane through the microphone line.
- Based on the impedance measurements on 2 representative grounds of grassland and soil ground after harvest [10] in the area, the ground impedance in the area between the turbine and the farthest microphone (mic 10) is estimated as follows: 250 kPa.s.m^{-2} from the turbine to the midpoint of mic 1 and mic 4, 500 kPa.s.m^{-2} from the midpoint of mic 1 and mic 4 to the midpoint of mic 8 and mic 9, and 250 kPa.s.m^{-2} from the midpoint of mic 8 and mic 9 to mic 10.
- A 1000W Electro-Voice two-way powered speaker was played with signals in the following order: 60 s white noise; 20 s silence; 60 s 1-octave band noise centred at 125Hz; 20 s silence; 60 s 1-octave band noise centred at 250Hz; 20 s silence; 60 s 1-octave band noise centred at 500Hz; 20 s silence; 60 s 1-octave band noise centred at 1000 Hz; 20 s silence; 60 s 1-octave band noise centred at 2000Hz; 20 s silence; and repeat.



(a)



(b)

Figure 1. (a) Set-up for flow and noise measurements and (b) terrain height along the microphone line.

2.3. Benchmark test cases

Since the speaker measurement campaign was performed in the daytime, two cases in unstable and neutral regimes (no stable regime) have been identified for validation and its features are listed in Table 2. Both cases are measured over 10 minutes when the turbine is stopped. Case 1.1 corresponds to an atmospheric unstable condition with a wind shear of exponent 0.12 and Case 1.2 is a neutral condition with a wind shear of exponent 0.23. Remark that the wind directions are 269 degrees and 279 degrees which are different from the microphone line direction of 225 degrees, hence the sound propagation measurements were carried out with somewhat cross-wind conditions. The parked wind turbine was turned during the measurements, such that the loudspeaker pointed directly towards the microphones.

Table 2. Wind turbine settings and inflow conditions.

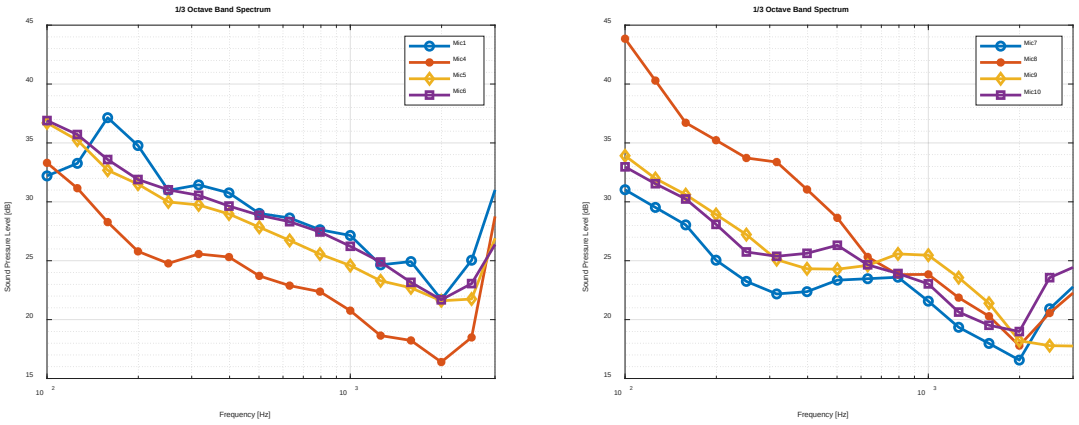
20/3-2019	**Case 1.1**	**Case 1.2**	
Period	12:40-12:50	14:00-14:10	
Inflow			
Wind speed @ hub	5.7	6.7	m/s
Turbulence intensity @ hub	12.0	10.3	%
Wind speed @10m	4.3	3.8	m/s
Shear exponent	0.12	0.23	
Stratification	Unstable	Neutral	
Temperature difference 105m - 3m	-1.22	-1.12	^{o}C
Temperature @ 3m	8.6	8.6	^{o}C
Wind direction @109m	269	279	deg
Humidity @ 105m	100	100	%

3. Results

Results are presented for both Case 1.1 and Case 1.2 with white noise performed during the period of 60 s (see Section 2.2 for the play sequence). Due to the limited length of the paper, results based on the 1/1 octave band-limited white noise are not presented. Results are compared in 1/3 octave bands.

3.1. Analysis of noise data

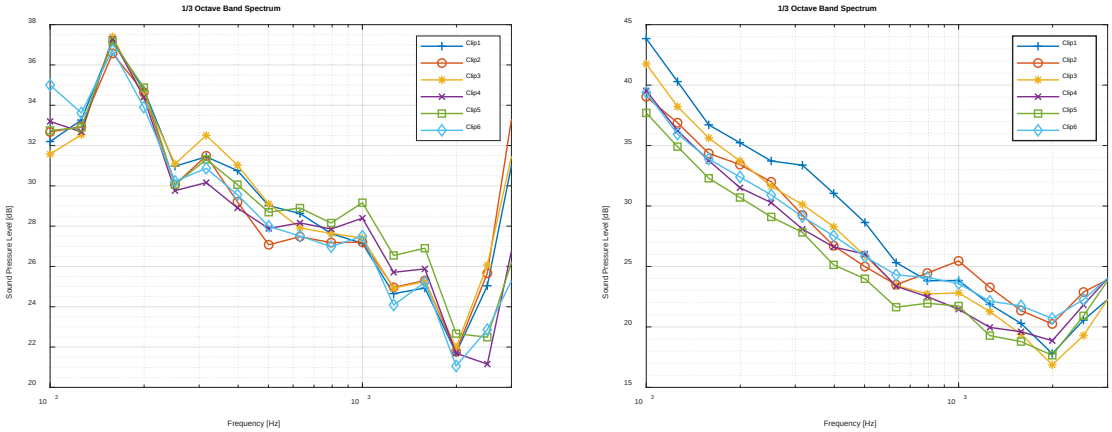
In Figure 2, the background noise (Sound Pressure Level: SPL) measured at mic 1, mic 4 - mic 6, and mic 7- mic 10 before playing the white noise of Case 1.1 is plotted.



(a) (b)

Figure 2. Background noise measured at (a) mic 1 and mic 4 - mic 6, and (b) mic 7 - mic 10, with each spectrum of SPL on a time signal of 15 seconds extracted from the 20 seconds silent time before playing white noise.

From the figure, it is seen that mic 8 had a very high background noise at frequencies < 250 Hz, which could be caused by wind noise at it was installed on the highest position of the hill. In order to see the variability of background noise at mic 1 and mic 8, the SPL for six 5-second time-clips are plotted in Figure 3. From the figure, it can be seen that there are small variations generally.



(a) (b)

Figure 3. Background noise measured at (a) mic 1 and (b) mic 8, at three 5-second time-series before playing white noise and three 5-second time-series after playing white noise.

The variability of SPL at SGRE mic (the microphone close to the speaker that is used for source strength estimation) is plotted in Figure 4. From the figure, it is seen that the variability is very small within 1 dB.

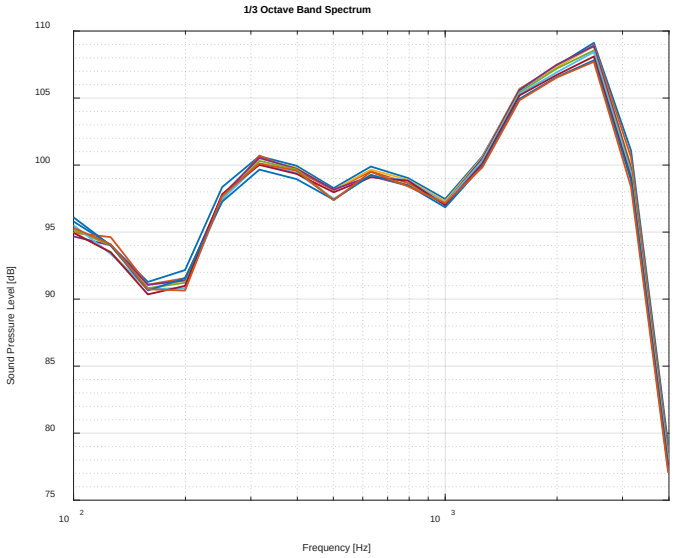


Figure 4. Variability of noise measured at the SGRE mic for nine 5-second time-series during the play of white noise.

The variability of SPL at mic 1, mic 4, mic 5, and mic 6 is plotted in Figure 5. From the figure, it is seen that the variability at mic 1 is also small, but it increases significantly at mics 5 and 6 with a difference of 7 dB. Remark that at a frequency of 200 Hz, the SPLs (with a mean of about 35 dB) are quite close to their background noise levels of 30 dB (mic 5) and 32 dB (mic 6). However, it is seen that for mic 4, SPL at 200 Hz is well above the background noise of 27 dB. The variability of SPL at mic 7, mic 8, mic 9 and mic 10 is plotted in Figure 6. From the figure, a stronger strength of variability is seen

for all the four microphones. Remark that the SPL at low frequencies (35 dB at 200 Hz) is about 5-7 dB above its background noise level, except mic 8.

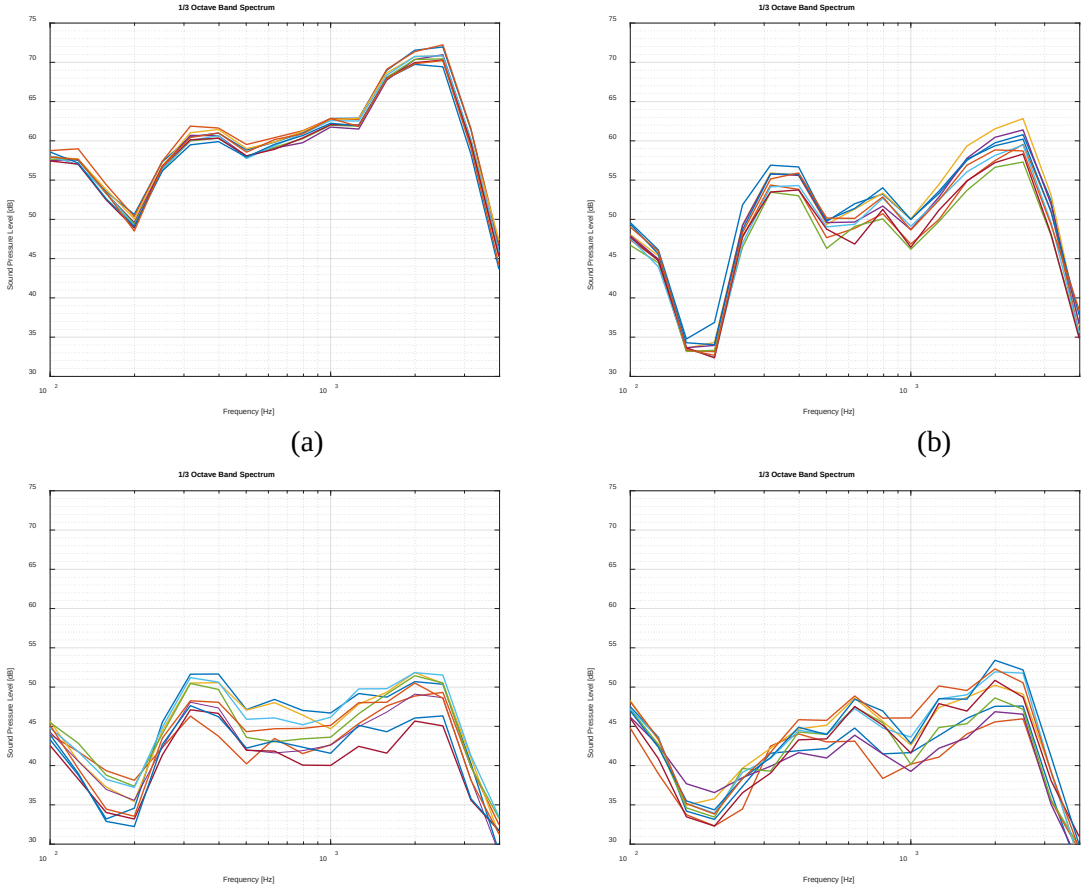
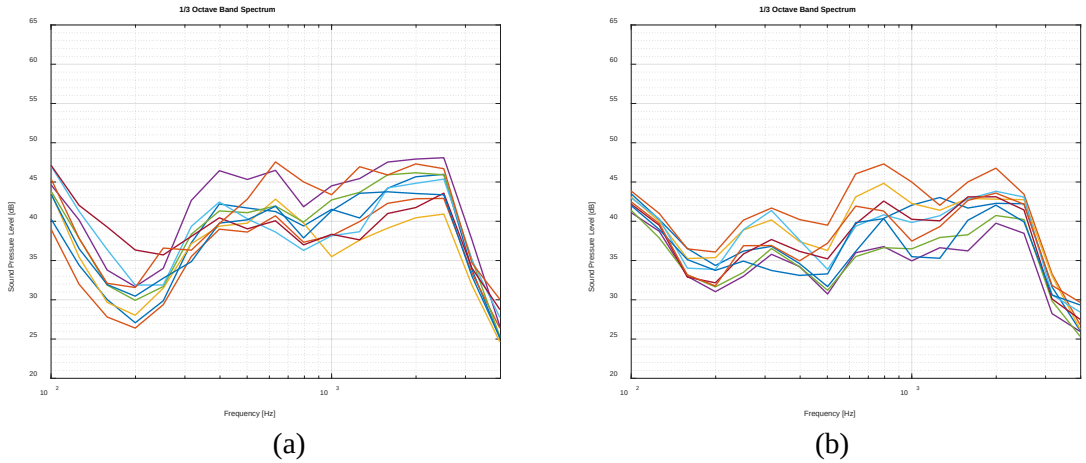
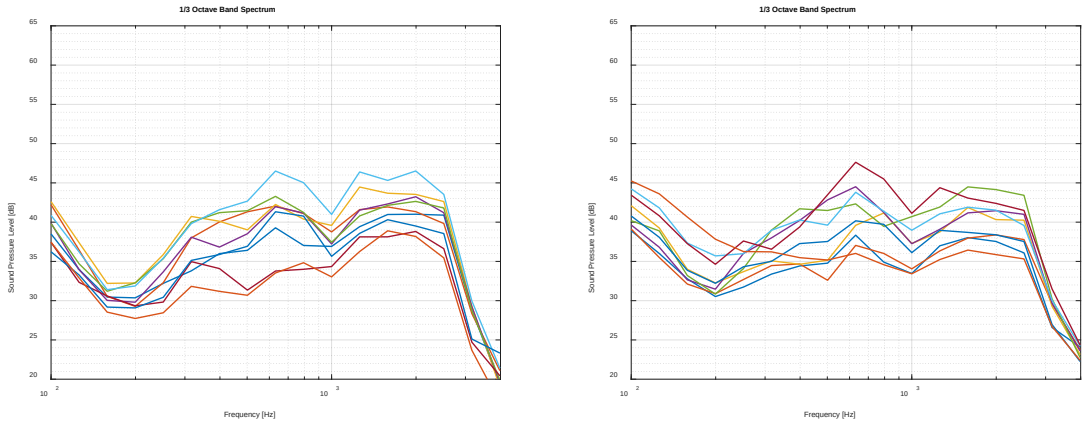


Figure 5. Variability of noise measured at (a) mic 1, (b) mic 4, (c) mic 5 and (d) mic 6 at nine 5-second time-series during the play of white noise.

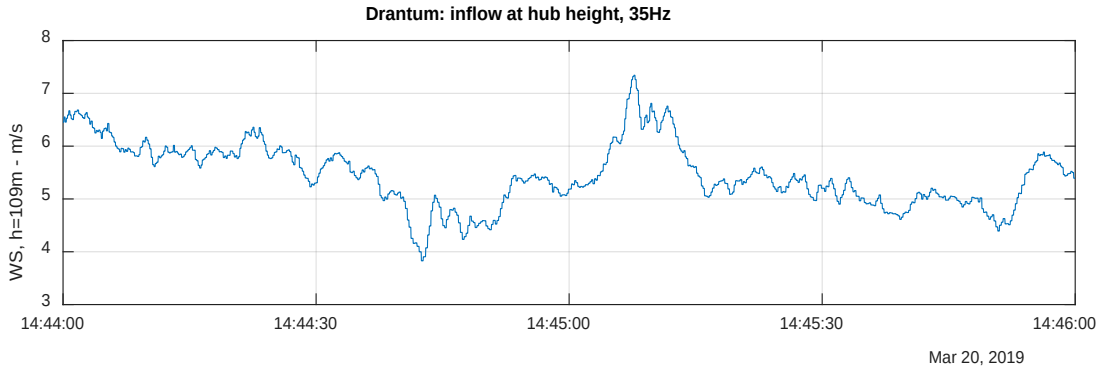




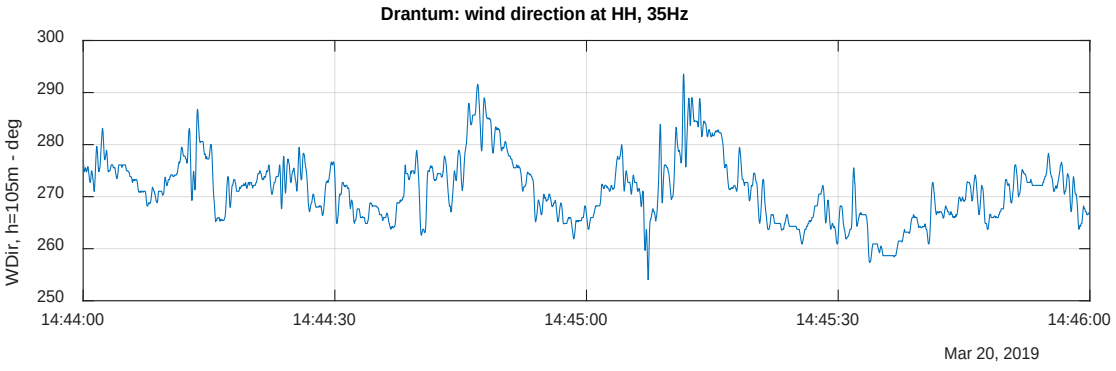
(c) (d)

Figure 6. Variability of noise measured at (a) mic 7, (b) mic 8, (c) mic 9 and (d) mic 10 at nine 5-second time-series during the play of white noise.

The wind speed and wind direction variations during the white noise play from 12:44:00 to 12:46:00 are plotted in Figure 7. From the figure, the wind speed variation is between 4 m/s and 7 m/s. Moreover, the wind direction changes are also quite significant between 260 degrees and 290 degrees. This is often the case in the daytime when the atmosphere flow is unstable.



(a)



(b)

Figure 7. Variation of (a) wind speed and (b) wind direction during the play of white noise.

3.2. Benchmark Case 1.1

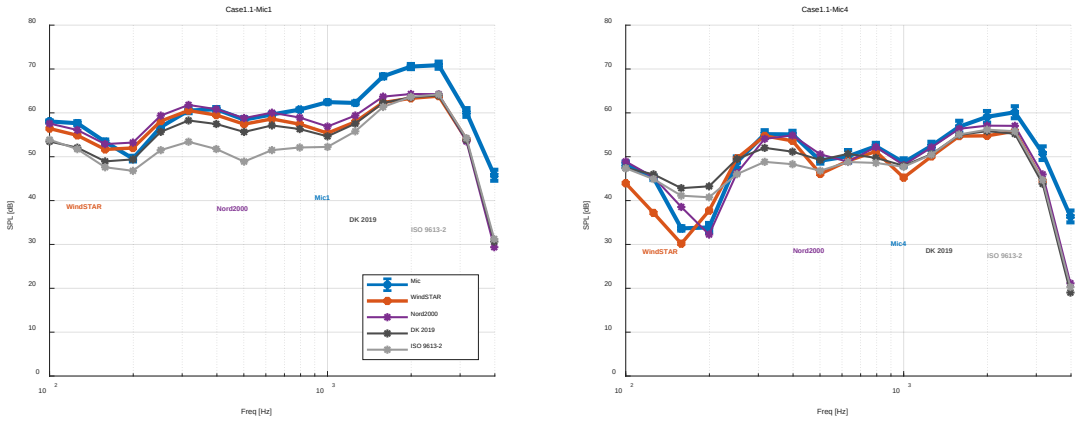
Table 3 summarizes the mean difference in overall SPL in decibels [dB] for the microphones from mic 4 to mic 8 between the measurements and the calculated values from numerical tools based on the

125-1000 Hz frequency range. Out of all the numerical tools, Nord2000 is the best one for predicting the noise at the near-field micophones of mic 4 - mic 6, while WindSTAR provids the best results at far-field microphones of mic 7 and mic 8.

Table 3. Mean absolute arithmetic difference in overall sound pressure level in decibels [dB] between measurement and WindSTAR, Nord2000, DK and ISO for cases 1.1-1.2 with white noise source.

Case	WindSTAR	Nord2000	DK	ISO
1.1_mic4	-1.13	-0.48	-1.65	-3.83
1.1_mic5	-1.09	0.81	0.23	-2.60
1.1_mic6	-1.14	0.48	-1.29	-2.28
1.1_mic7	0.46	1.95	1.80	-1.10
1.1_mic8	-1.71	1.64	1.35	-1.57
1.2_mic4	-1.21	-0.43	-1.68	-3.86
1.2_mic5	-1.59	0.47	-0.17	-3.00
1.2_mic6	-2.39	-0.62	-2.43	-3.43
1.2_mic7	0.69	2.34	2.11	-0.79
1.2_mic8	-0.87	2.45	2.23	-0.69

Figure 8 shows the comparisons between measurement and computation in the 100-2500 Hz frequency range. For the measurement curves, the mean values of SPL are obtained on 45 seconds and the standard deviation is calculated with the nine spectra of 5 seconds signals. Microphones 2 and 3 are not in line with the other microphones and thus are not considered due to its directivity effects. Due to the local wind effects of surrounding trees in the area near mic 9 and mic 10, the results of the two microphones are not presented here. The source is white noise and the measured and calculated SPL are versus frequency values. From Figure 8a, it is seem that the measured SPL at frequency above 800 Hz is very high. Looking closer to the measured noise source spectrum in Figure 4, the SPL is flat at high frequencies. Thus, this discrepancy might be caused by the different reflections at the ground board of mic 1 or by the sound directivity of the speaker. From the figure, it is seen that Nord2000 predicts very well at the nearfield microphones (mic 4 - mic 6) while at far-field, it is slightly over-predicted. Concerning WindSTAR, it has a slight underprediction for the nearfield microphones since these microphones are located on the backside of a small hill where the wind velocity is different from the free-stream wind velocity. At the farfield microphones (mics 7 and 8), excellent agreements are seen. DK and ISO have difficulties to predict the spectra correctly as these two models are simple engineering models.



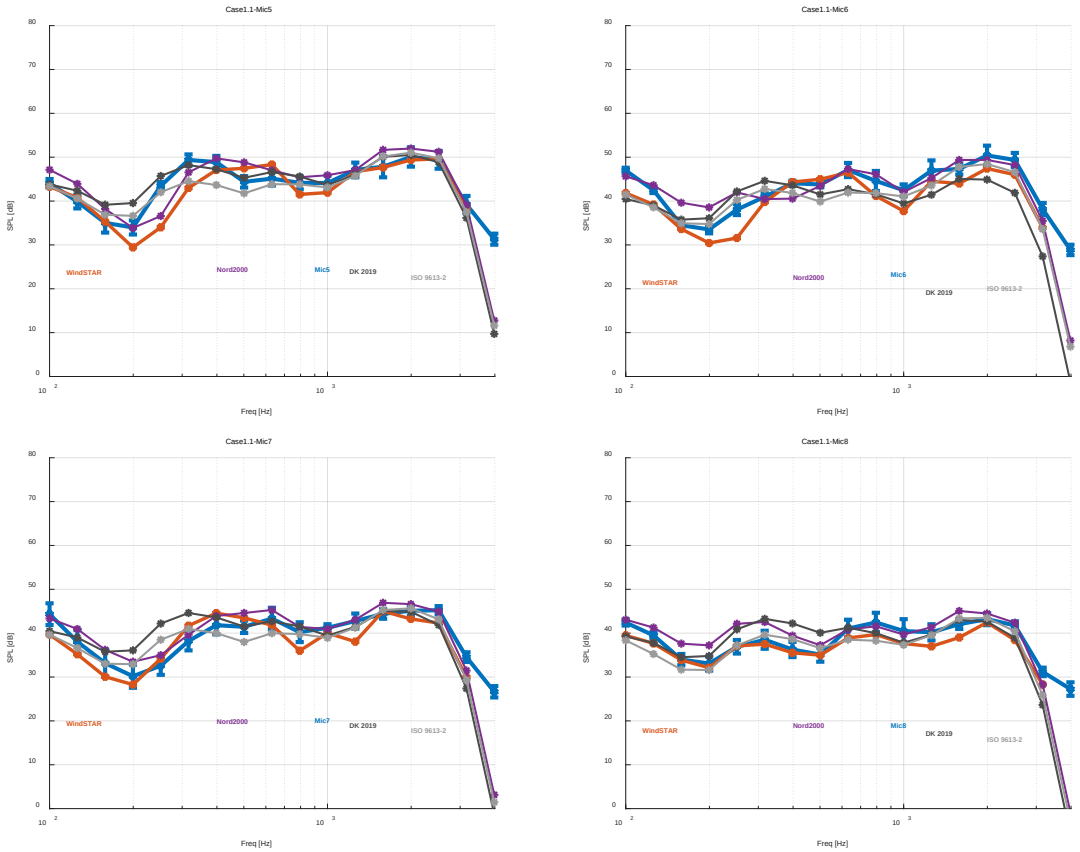
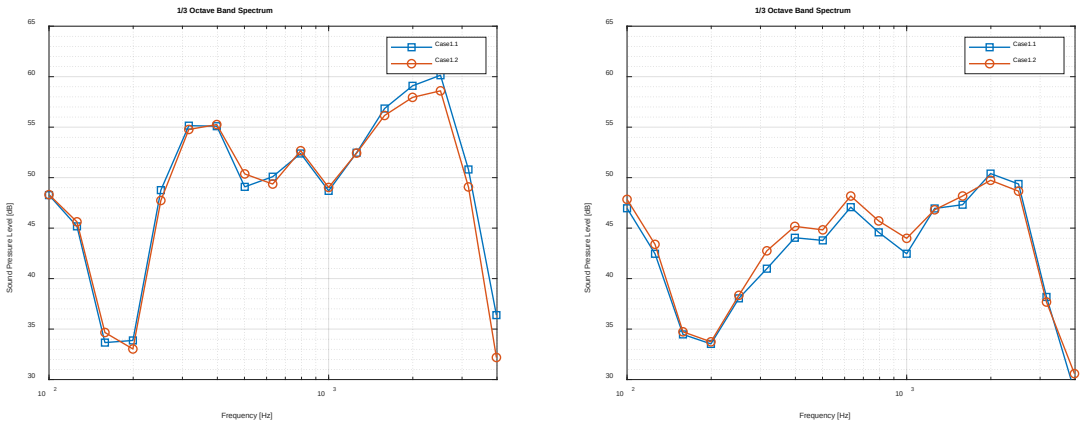


Figure 8. Sound pressure level (SPL) in decibels [dB] vs. frequency comparison between measurement (Mic), WindSTAR, Nord2000, DK and ISO for case 1.1 with white noise.

3.3. Benchmark Case 1.2

The Benchmark Case 1.2 is performed in a case where a higher wind shear exponent of 0.23 is used. The wind shear effect is shown in Figure 9 for mics 6 and 8. In Figure 9(b), the sound pressure level at mic 8 is seen to be slightly increased of about 1 dB. Results of benchmark comparisons are presented in Figure 10. From the figure, similar good agreements with measurement as in Case 1.1 are seen. Detailed differences between computation and measurement are shown in Table 3. From the table, WindSTAR and Nord2000 are the closest to the measured values.



(a) (b)

Figure 9. Sound pressure level (SPL) in decibels [dB] versus frequency of measured data for Case 1.1 and Case 1.2 for (a) mic 6 and (b) mic 8.

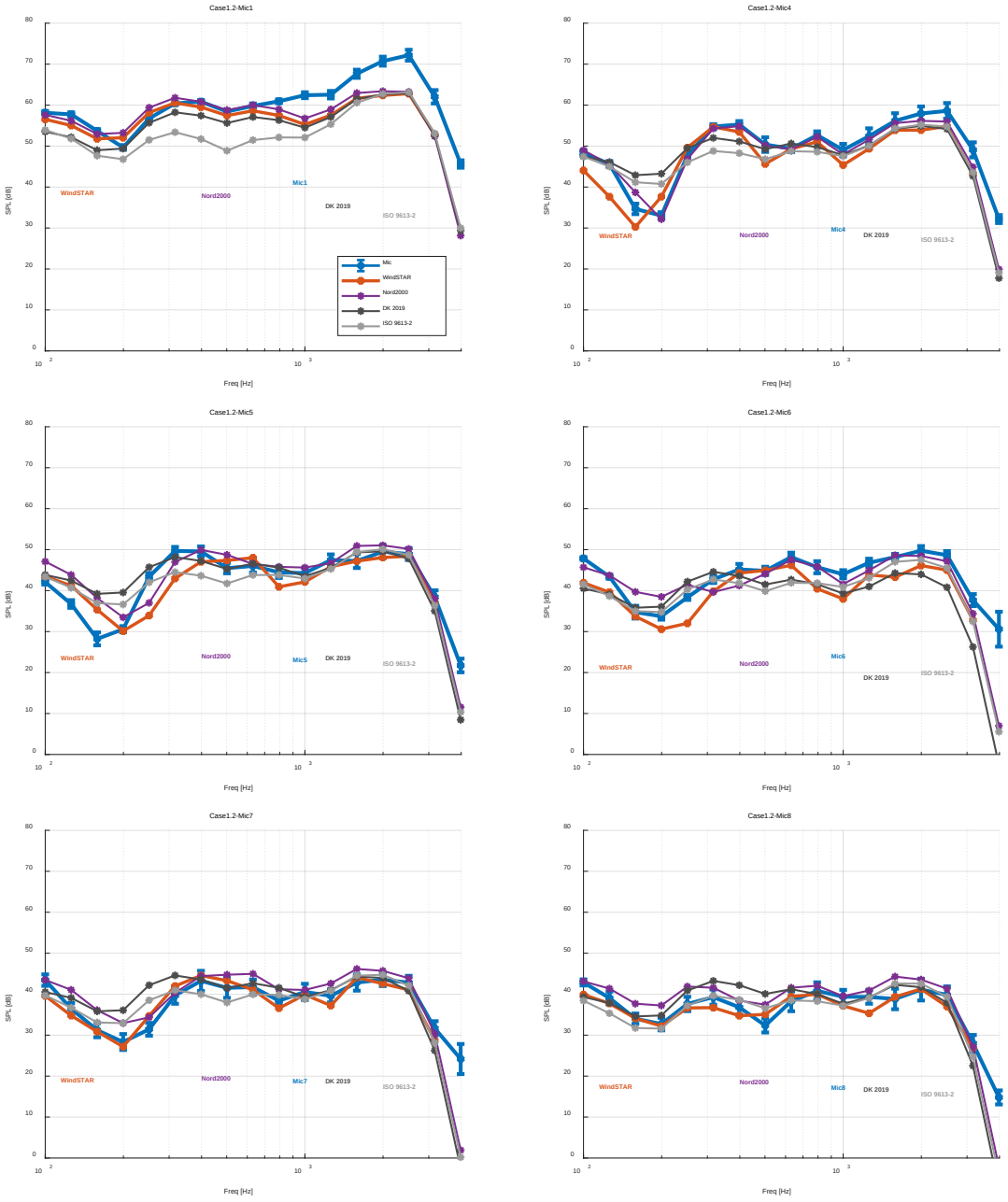


Figure 10. Sound pressure level (SPL) in decibels [dB] vs. frequency comparison between measurement (Mic), WindSTAR, Nord2000, DK and ISO for case 1.2 with white noise.

4. Conclusions

Two numerical tools and two standards: WindSTAR, Nord2000, the Danish standard BEK 135 and ISO 9613-2, have been compared with the speaker measurements performed in the Drantum measurement Campaign 1. In general, an overall agreement was reached between measurement and computation. At the nearfield (mic 4 – mic 6), Nord2000 gives the closest prediction while WindSTAR has a relatively larger discrepancy as mic 4 – mic 6 are located on the backside of a small hill where the velocity field

is different from the free-stream velocity. At the far-field microphones (mics 7 and 8), WindSTAR predicts an excellent agreement with measurement. BEK 135 and ISO 9613-2 predict an overall good agreement but fail to predict the detailed noise spectra. On the measurement side, there are some problems with signal to noise ratio at low frequencies and wind noise from the microphone wind screens.

Acknowledgement
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