Report

Measurement of underwater noise emitted by an offshore wind turbine at Horns Rev

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Content

Summary

Underwater sound radiated from a wind turbine in the Horns Rev offshore wind farm has been measured in November 2005. The overall sound pressure level produced by the turbine is mainly concentrated in two spectral lines. The frequency of these lines depends on the rotation speed; at nominal speed they are approximately 150 Hz and 300 Hz. The maximum levels at 100 m from the turbine were 122 dB re 1 µPa at 150 Hz and 111 dB at 300 Hz. No sound emitted from the turbine was found at frequencies above 800 Hz.

1. General

1.1 Objectives

One of the potential implications of offshore wind turbines on marine life is underwater noise (figure 1.1). The few existing measurements suggest that sound levels induced into the sea by wind turbines are quite low, especially compared to construction noise. However, for a reliable assessment of sound induced into the sea by future offshore wind farms, a larger data base with sound measurements on more turbine types is necessary. Furthermore, data for different grounding constructions are desirable. For these reasons, two measurements were proposed [1], one in the Horns Rev wind farm (monopile), the other one at Nysted (gravity/concrete foundation).

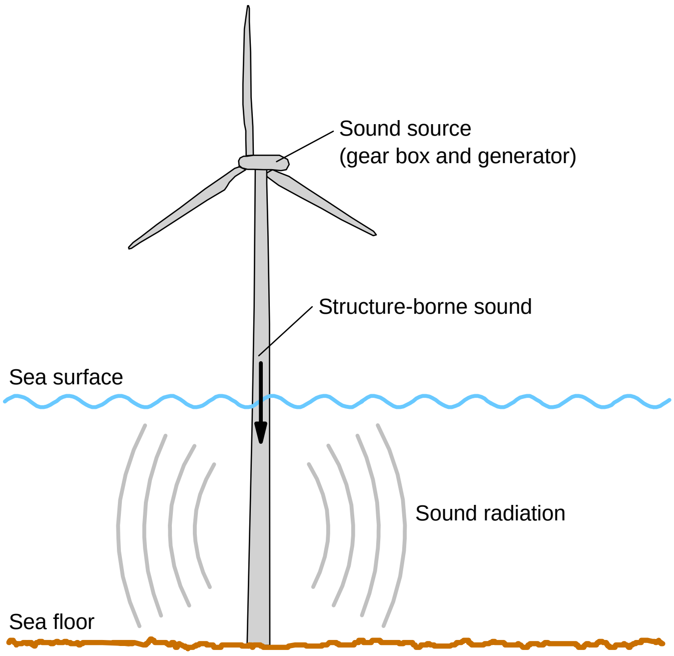


Figure 1.1. Principle of underwater sound radiation from an offshore wind turbine

1.2 Project background

Measurement of underwater noise from offshore wind turbines is one of several tasks in a project funded by the German Ministry of Environment BMU (Project no. 032947: Standardverfahren zur Ermittlung und Bewertung der Belastung der Meeresumwelt durch Schallimmissionen von Offshore-WEA). Participants in the project are:

- ITAP (Institut für technische und angewandte Physik GmbH, Oldenburg)
- DEWI (Deutsches Windenergie-Institut = German Wind Energy Institute, Wilhelmshaven)
- ISD (Institut für Statik und Dynamik, University of Hannover)

In an earlier part of the project [2], ITAP has measured the underwater sound radiated from a 1.5MW offshore wind turbine [3, 4].

The measurements at Horns Rev and Nysted are granted by The Environmental Group (the Danish Energy Agency, The Danish Forest and Nature Agency, Elsam Engineering A/S and

Energie E2 A/S). Furthermore, Elsam and E2 supported the measurements by providing turbine production data and other information that was necessary for evaluating the acoustic data.

The practical work was done in close cooperation with BioConsult SH (25813 Husum, Germany), who is carrying out surveys of harbour porpoises in the Horns Rev and Nysted area. BioConsult SH has considerable experience in offshore measurements and was responsible for selecting the exact measurement position, for the mooring systems and for deployment and recovery of the measurement buoys.

1.3 Deviations from the proposed programme

As stated in 1.1, it was planned to make measurements not only at Horns Rev, but also in the Nysted wind farm. In fact a second measurement buoy has been installed near turbine H7 on 8 November 2005. After recovering the buoy on 7 December, however, it was found that a hardware failure had occured in the memory. Although some recordings could be restored, it was not possible to assign them to date and time, so that the measurement was not succesful.

In the meantime the technical problem has been solved and the measurement at Nysted shall eventually be repeated in spring 2006, which however is beyond the deadline of this report.

2. Measurement procedure

2.1 Instrumentation

Maximum sound radiation from a wind turbine can be expected when it is operating at rated power. Under these weather conditions, a ship-based measurement is not feasible, but automatic unattended recording is necessary. For various reasons, no recording equipment could be installed inside of a turbine at Horns Rev. Hence recordings were made with a measurement buoy (figure 2.1) developed by ITAP within the BMU project mentioned in section 1.2.

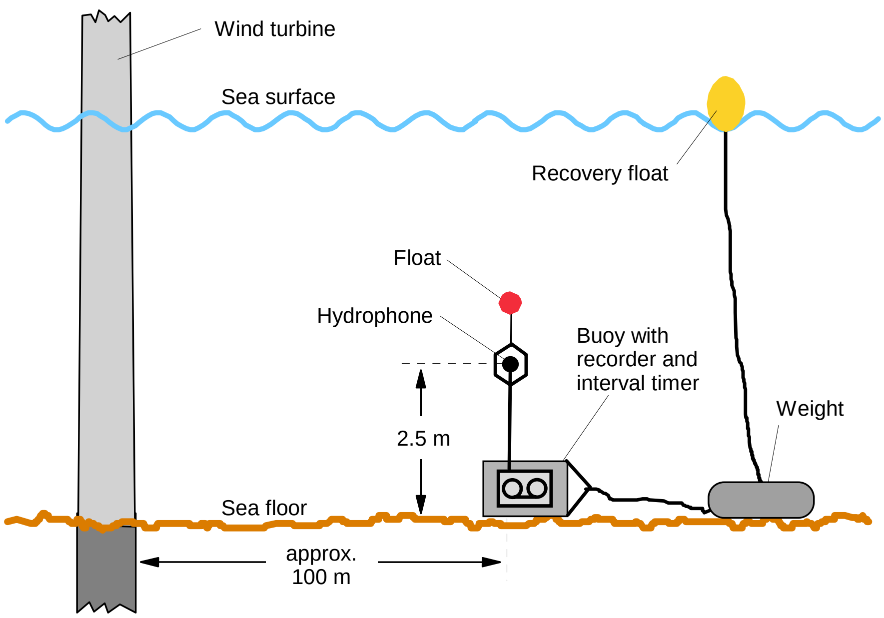


Figure 2.1. Underwater sound measurements at Horns Rev (not to scale)

Such a battery-powered system poses limitations on the recording time. Also the risk of failure or loss is of course higher than for a system installed in a safe place. An advantage of an autonomous system is, that there is no long cable and no connection to the mains grid, which largely reduces the risk of picking up "bogus signals" by electromagnetic interference, e.g. from power converter circuits in the turbine.

The electronic circuitry is housed in a steel tube of about 45 cm length (fig. 2.2). A block diagram is shown in figure 2.3. Signals can be recorded in a frequency range from about 6 Hz to 22 kHz, depending of the selected sampling frequency. In order to save memory and battery life and to avoid an unnecessary amount of data, the recorder is activated only at specific time intervals. For the measurement at Horns Rev, the timer was set to a recording time of 8 minutes every 60 minutes, which was considered to provide more than sufficient acoustic data from the wind turbine.

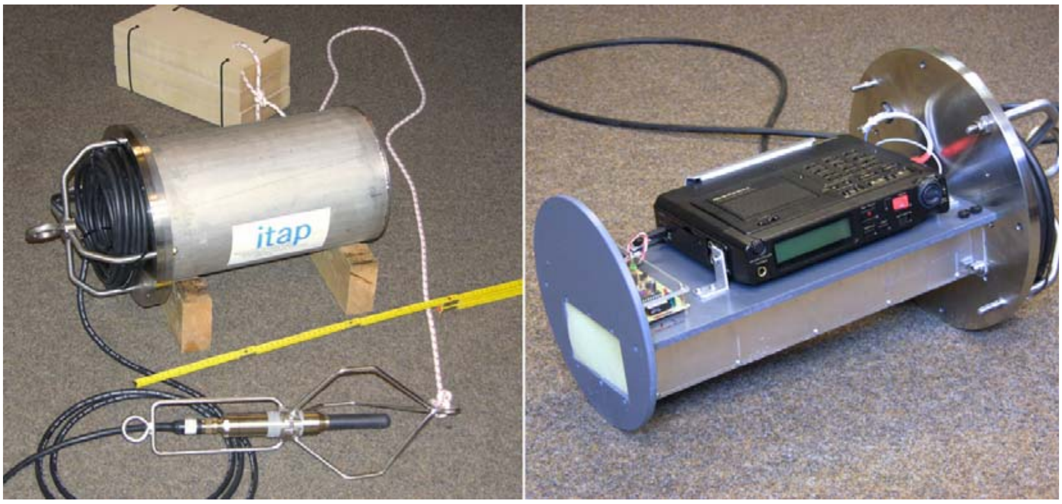


Figure 2.2. Left: Measurement buoy with hydrophone and hydrophone float. Right: buoy opened

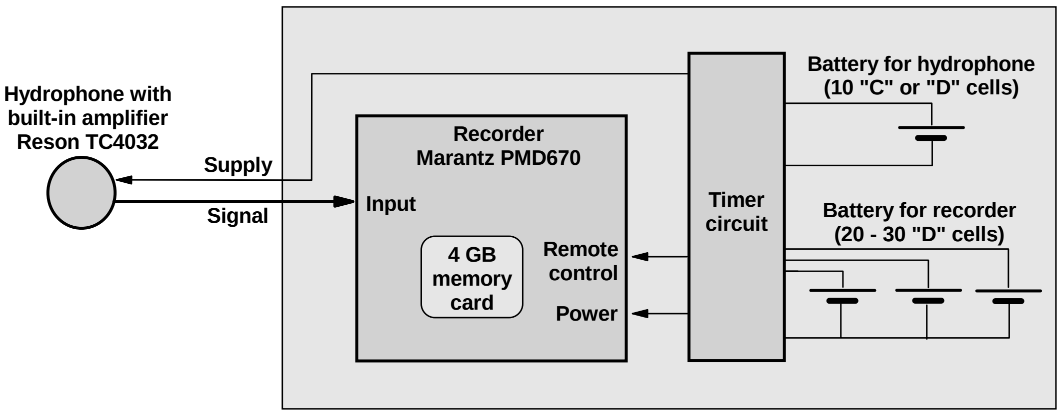


Figure 2.3. Block diagram of the measurement buoy

Calibration: The hydrophone (RESON TC4032, S/N 1901067) has a sensitivity of 3.05 mV/Pa. It has been factory calibrated by RESON A/S 3550 Slangerup, Denmark, in June 2005. Tones with 10 mV and 1 mV were recorded as a reference prior to deployment and after the measurements.

Recordings were stored as MP3 files with 128 kbit/s, which is known as a “lossy” file format. However, since the interest is in spectral values rather than the precise shape of the signal at any time, the loss is negligible. This is illustrated in figure 2.4. For this test, a recording of wind turbine underwater sound from [4] was used.

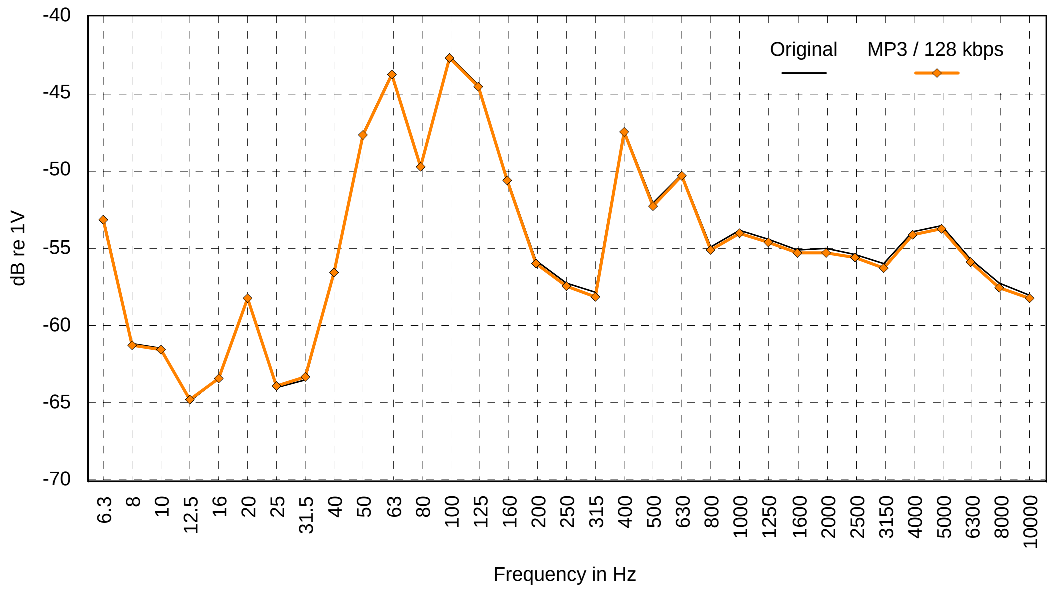


Figure 2.4a. 1/3rd octave spectra of underwater wind turbine noise obtained from recordings with and without MP3 data compression. The difference is small. Note: This diagram does not show sound pressure levels, but raw voltage levels from analyzer.

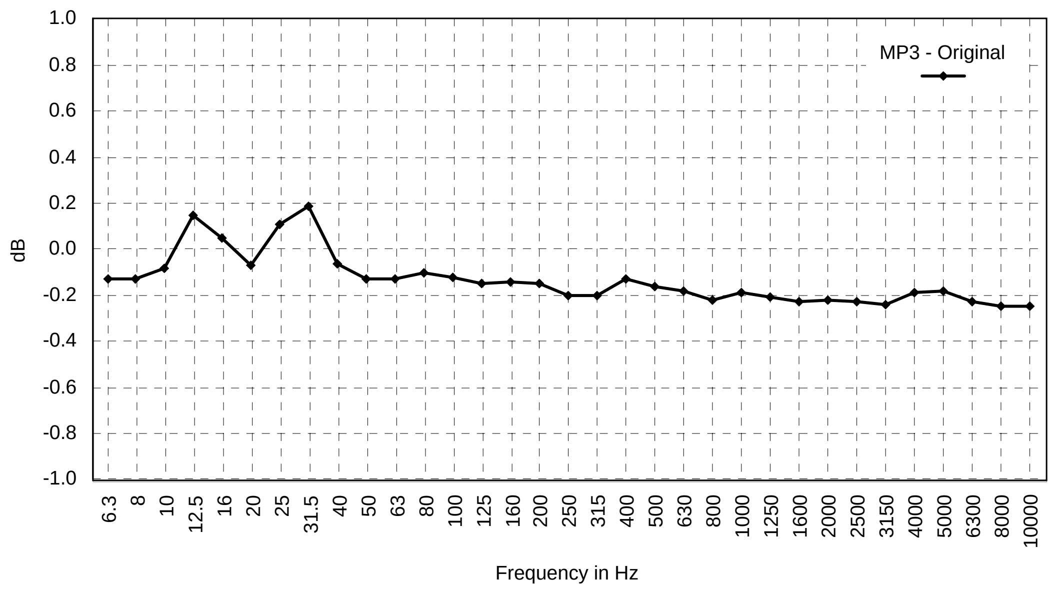


Figure 2.4b. Difference of the two curves in figure 2.4a

2.2 Measurement position and measurement time

The measurement position and duration as well as some other parameters are listed in table 2.1. The location is also sketched in figure 2.5.

In order to obtain a sufficient signal-to-noise ratio, also with respect to sound emitted from the neighbour turbines, the distance between hydrophone and wind turbine must be not too large. On the other hand, if the distance is too short, the level decrease with distance is atypical compared to normal sound propagation at sea. Conversion of such data to other distances is subject to errors and hence they are difficult to compare to other measurements. 50 m to 150 m was thus considered the optimum distance.

Position	55°29.027'e 07°52.782'e, 87 m wsw of turbine no. 95
Date of deployment	02 November 2005
Date of recovery	05 December 2005
Recording interval	8 minutes duration at every full hour
First recording	02 November 2005, 10:00 CET
Last recording	23 November 2005, 13:00 CET
Number of files	513
Frequency range	6 Hz ... 20 kHz

Table 2.1. Measurement location and time, plus some additional parameters

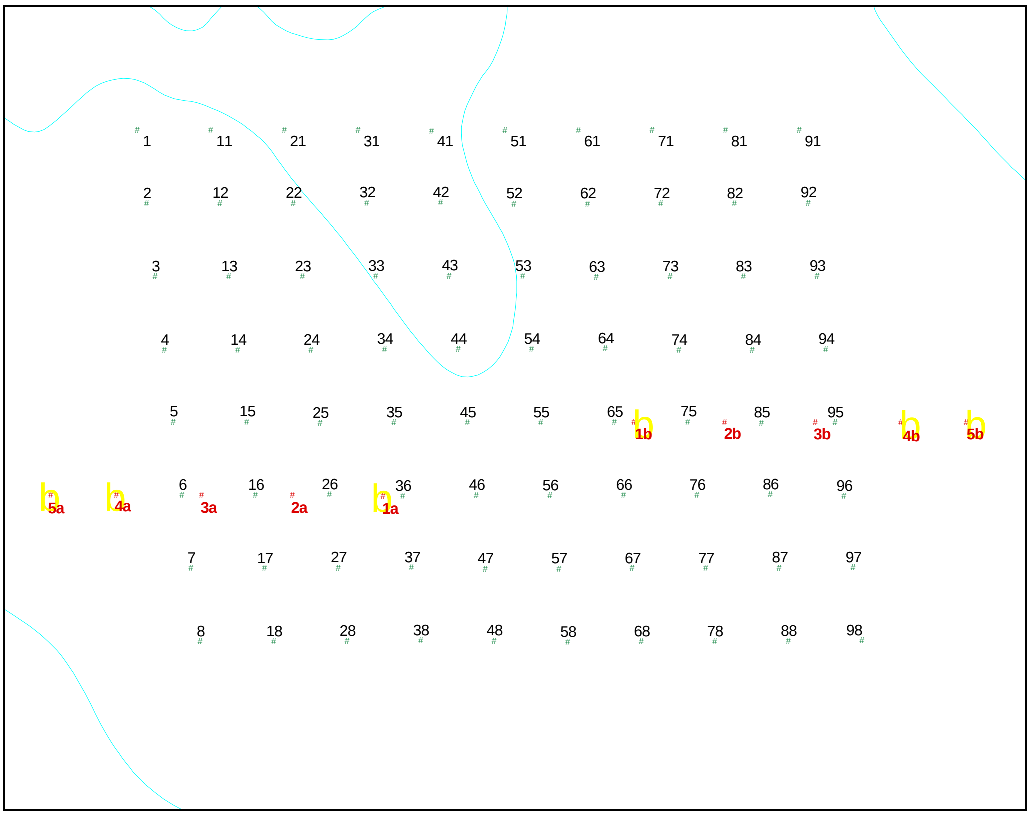


Figure 2.5. Red numbers denote positions of PODs installed by BioConsultSH. The measurement buoy was placed close to position 3B near turbine no. 95.

2.3 Data evaluation

From the production data file for turbine 95, several time periods were arbitrarily selected, three with the turbine operating near its maximum power and two with significantly less than rated power. They are listed in table 2.2. Since the production data contained 10-minute averages, a precise correlation between electric power and/or rotor speed and sound level is not possible for the latter two. For the first three, however, which were chosen out of a series of consecutive 10-minute intervals with average powers near 2000 kW, it is evident that acoustic data taken from these intervals reflect the turbine's sound radiation at or close to its rated power.

File no.	Date and time UTC + 1 (= CET)	Power, kW	Wind speed, m/s	Rotor speed, 1/minute
1080	03.11.2005 19:00	1998	15.6	18.1
1147	06.11.2005 14:00	1983	15.4	18.1
1265	11.11.2005 12:00	1910	11.9	18.1
1223	09.11.2005 18:00	790	8.9	17.7
1259	11.11.2005 06:00	229	5.9	12.1

Table 2.2. Production data (10-minute averages) for the evaluated time periods

The sound files were first checked by ear for atypical sounds like ship noise and then analyzed with a Hewlett-Packard (Agilent) 35670A Dynamic Signal Analyzer. The following diagrams were produced:

- Narrowband (FFT) spectra, 0 - 1600 Hz with 2 Hz resolution
- Spectrograms
- 1/3 octave spectra
- Levels of prominent spectral lines versus time

Narrowband spectra give information about the discrete spectral lines the turbine sound mainly consists of. The frequency of some of these lines are directly related to the turbine speed. The purpose of the spectrograms is to show these frequency variations.

For precise level readings, narrowband spectra are less suitable, because if the speed is varying during the measurement, peaks in the spectrum are "smeared" over several spectral lines and levels may appear lower than they actually are. The effect increases with the frequency resolution of the analysis. It is much less pronounced in 1/3 octave spectra. Furthermore literature data might be available as 1/3 octave spectra only.

Finally, the last type of diagram has been added to display the short-term level variation, which can not be seen from the averaged narrowband or 1/3 octave spectra.

All sound levels except for the spectrograms were normalized to a distance of 100 m by assuming a level decrease of 4.5 dB per distance doubling, that is,

$$L = L_{meas} + 15 \log (r_{meas}/100\ m) \quad dB \tag{1}$$

Since the measurement distance r_{meas} was 87 m, the measured levels L_{meas} had to be reduced by 0.9 dB.

3. Results

3.1 Turbine operating near rated power

As can be seen from figure 3.1, the highest levels occurred at frequencies of about 150 Hz and 300 Hz. There are some smaller peaks at 96 Hz – 100 Hz, near 200 Hz and 300 Hz and at times around 600 Hz. The frequency of all these peaks is not constant, but varies a few Hertz, depending on the turbine's operating state (fig. 3.2). No underwater sound radiation from the turbine was found above 800 Hz.

The level of the dominant peaks vary within a margin of about 6 dB (fig. 3.3). The results are summarized in table 3.1.

Approximate frequency, Hz	Average level, dB re 1 µPa	Maximum level (from 2 -second averages), dB re 1 µPa
150	118	122
300	105	111

Table 3.1. Observed levels of prominent spectral lines at 100 m distance

The third-octave spectra (fig. 3.4) show of course very similar peak hights for the three examples, but differ in the background noise in the low and high frequency range, which is due to the different wind and wave conditions.

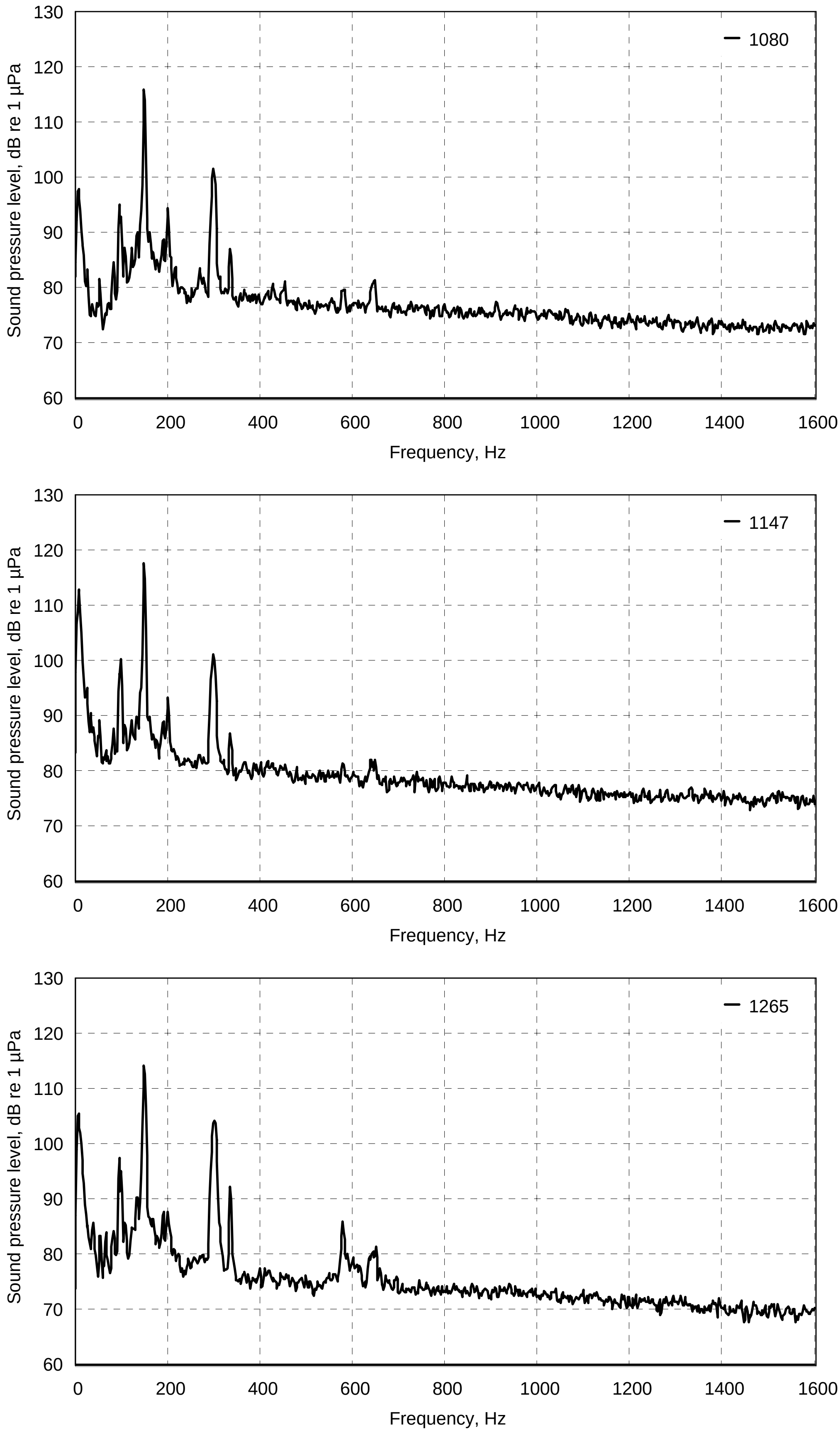


Figure 3.1. Three examples of narrowband spectra; turbine near maximum power. For data sets refer to table 2.2.

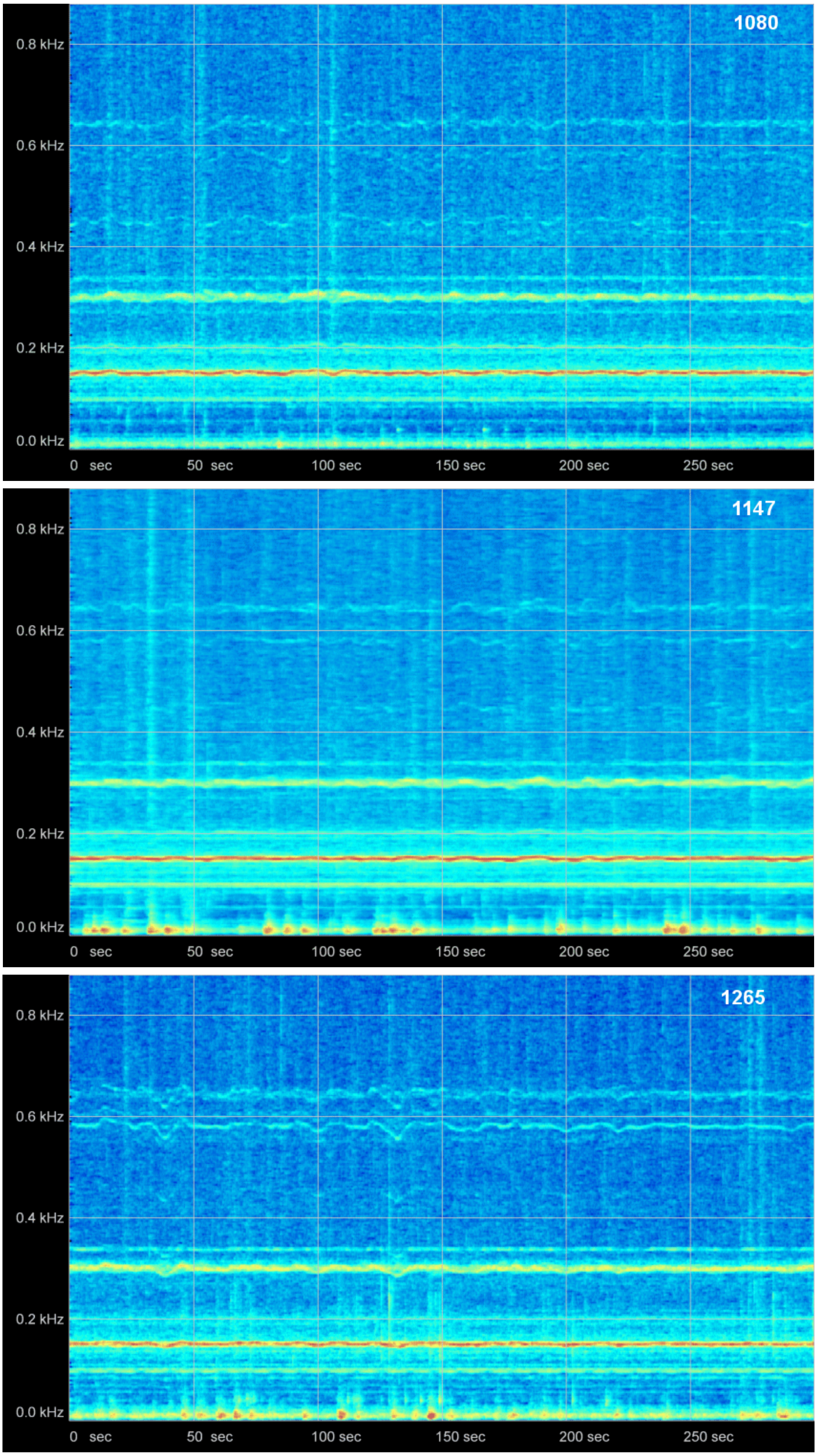


Figure 3.2. Spectrograms recorded over a period of 5 minutes; turbine at or close to maximum power. For data sets refer to table 2.2.

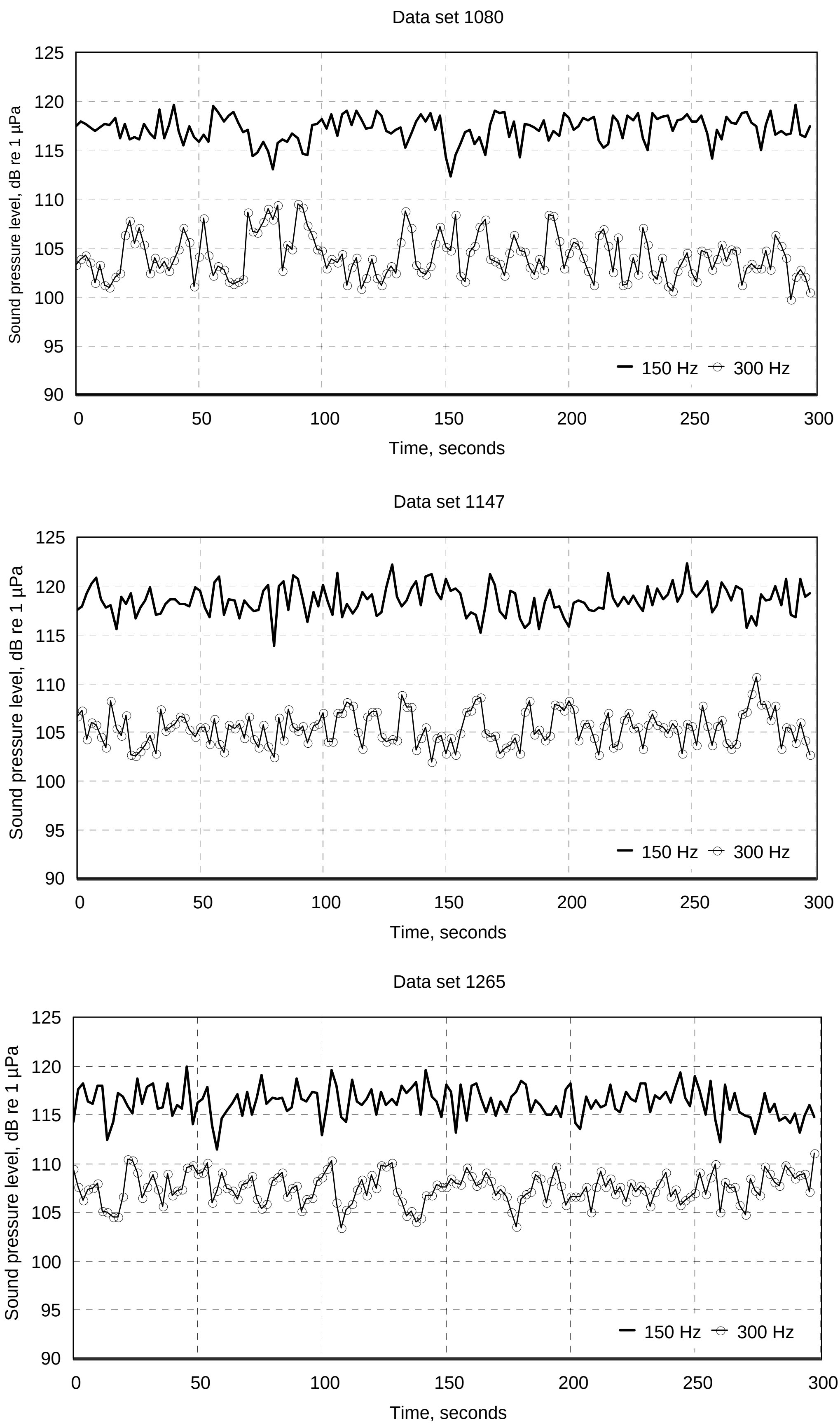


Figure 3.3. Levels of prominent spetral lines (2-second averages) over a period of 5 minutes; turbine at or close to maximum power. For data sets refer to table 2.2.

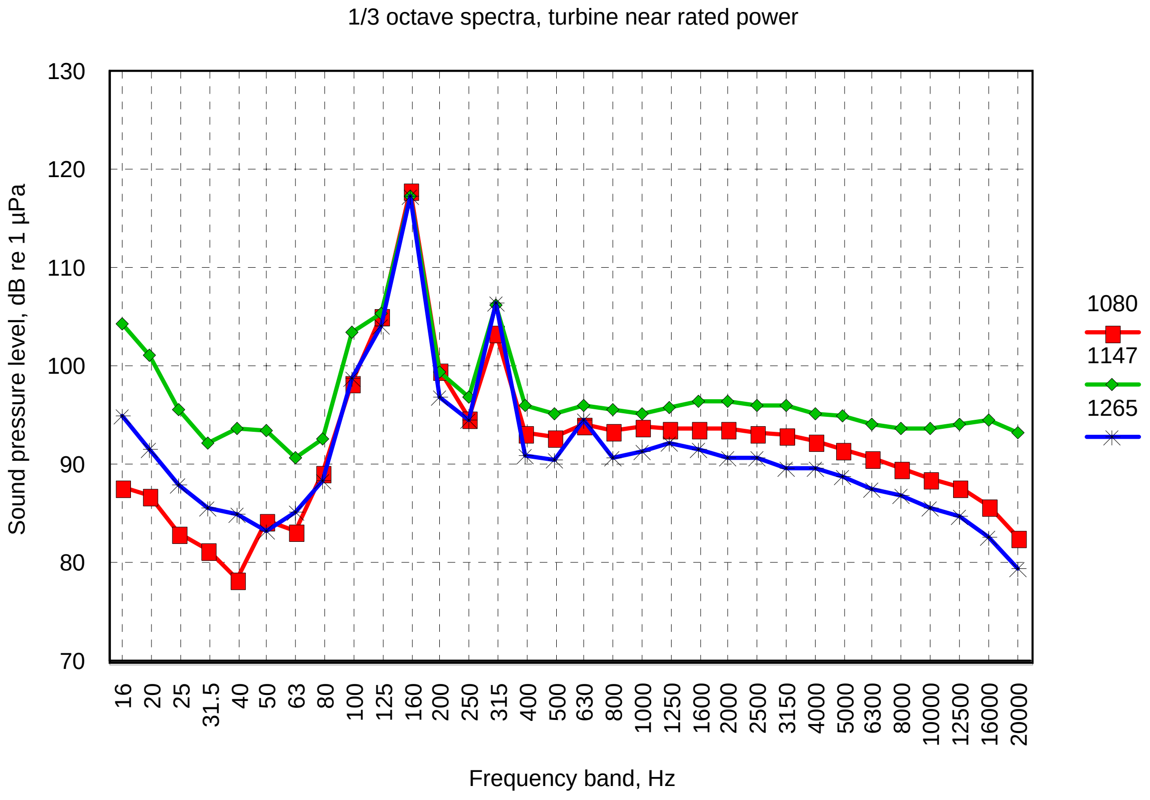


Figure 3.4. 1/3 octave spectra; turbine near maximum power. For data sets refer to table 2.2.

3.2 Turbine operating below rated power

Narrowband spectra are shown in figure 3.5. In the upper example (data set 1223), the turbine is still running close to its maximum rotor speed of approx. 18 rpm, and the spectrum shape is similar to those in the previous section, except that the levels are lower.

For data set 1259, however, the average rotor speed is only about 12 rpm. The 150 Hz line is 20-25 dB lower and its frequency is reduced to 143 to 144 Hz, compared to the full load condition. Since the rotor speed is not clipped, the frequency variation of other spectral lines is relatively large, which produces the wide maximum near 200 Hz in the lower graph of fig. 3.5. The frequency fluctuation can also be seen in the spectrograms in figure 3.6.

The short-term level variation of the prominent spectral peaks is shown in fig. 3.7; 1/3 octave spectra are presented in fig. 3.8.

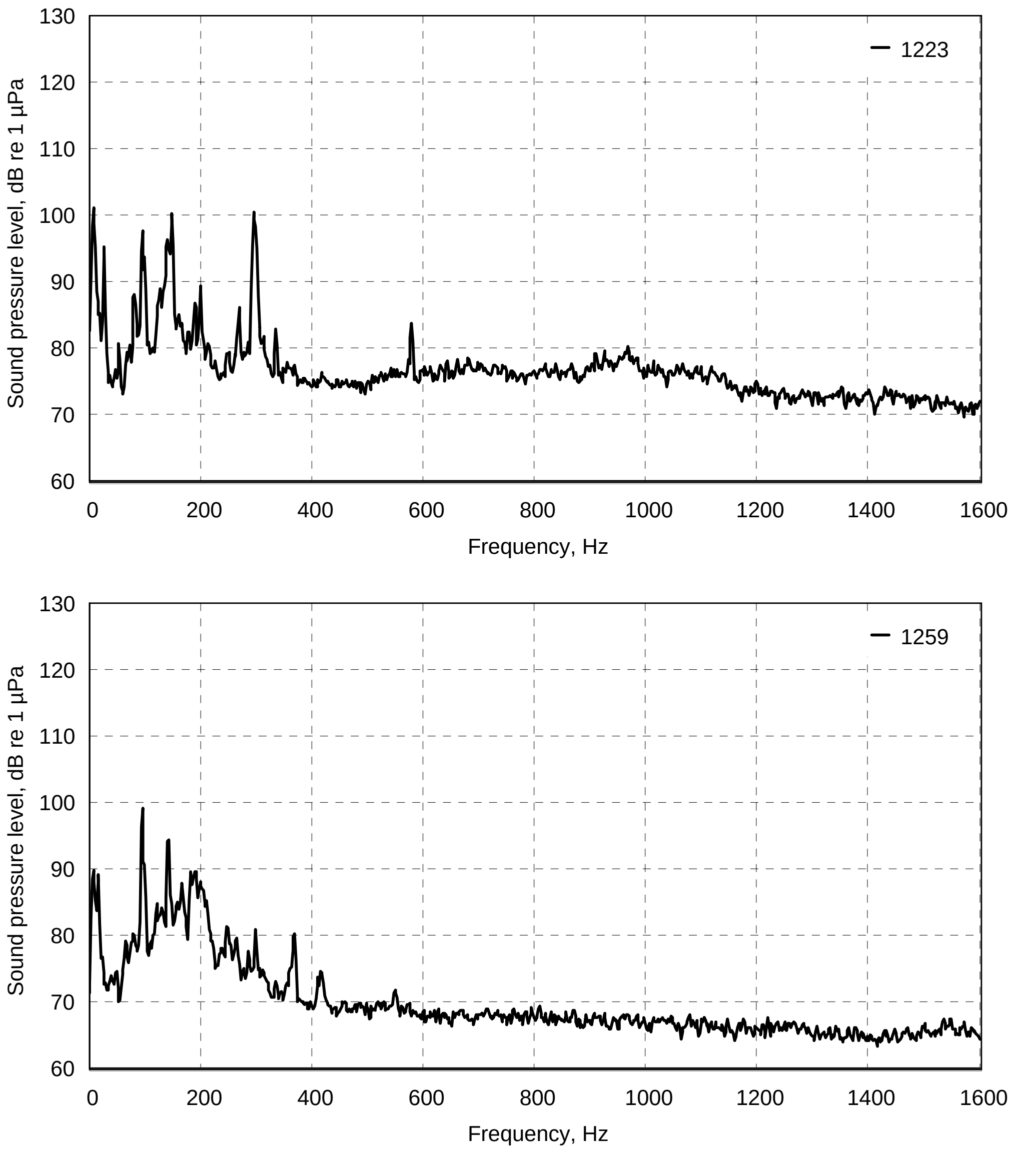


Figure 3.5. Two examples of narrowband spectra for partial load condition (10-minute average = 790 kW for data set 1223 and 230 kW for data set 1259, see also table 2.2).

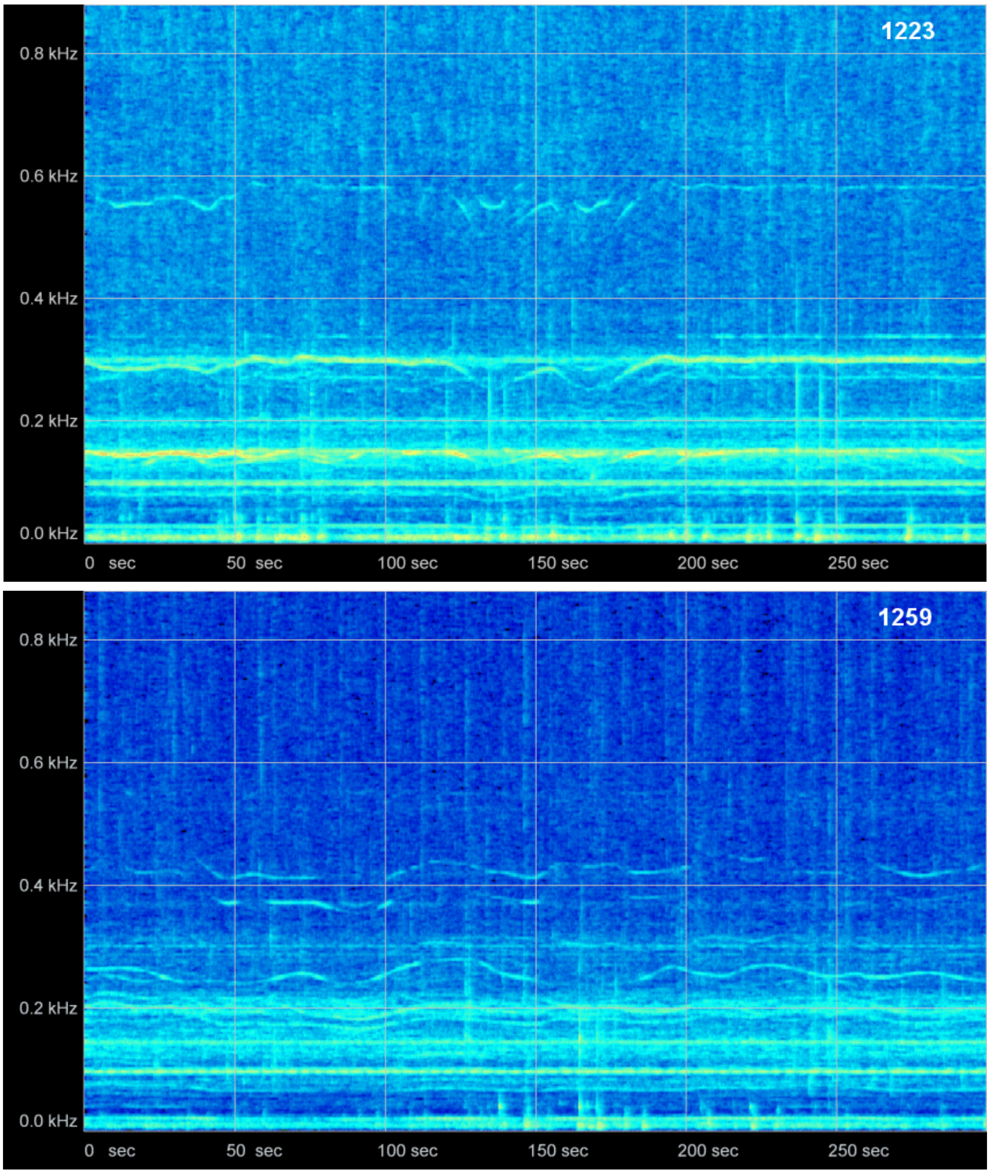
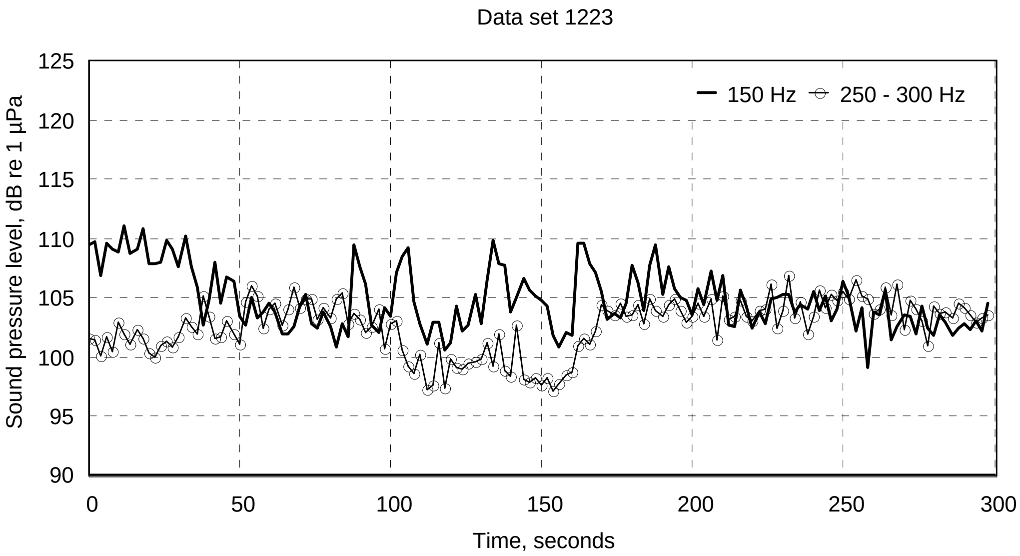


Figure 3.6. Spectrograms recorded over a period of 5 minutes; partial load condition (10-minute average = 790 kW for data set 1223 and 230 kW for 1259, see also table 2.2).



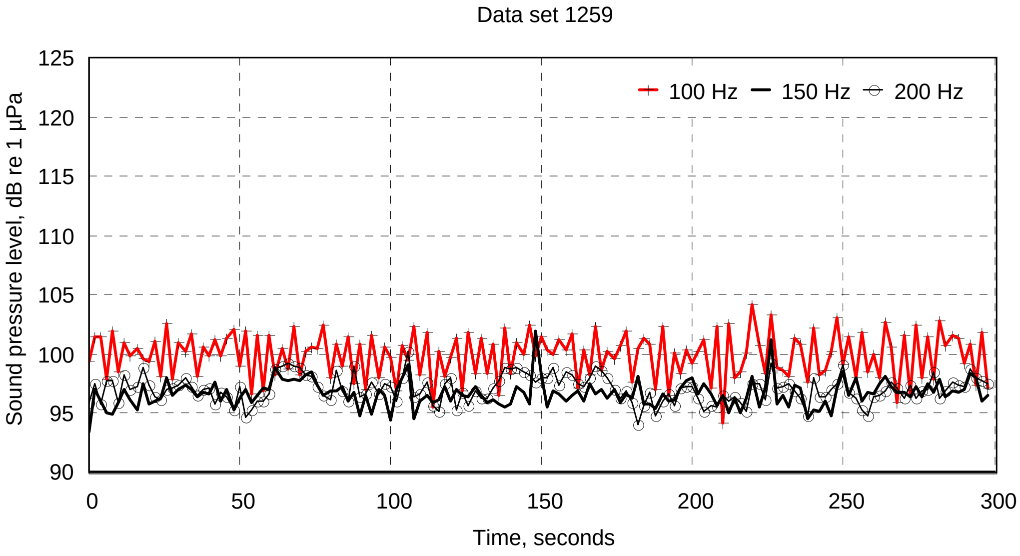


Figure 3.7. Levels of prominent spectral lines (2-second averages) over a period of 5 minutes. Partial load condition (10-minute average = 790 kW for data set 1223 and 230 kW for data set 1259, see also table 2.2).

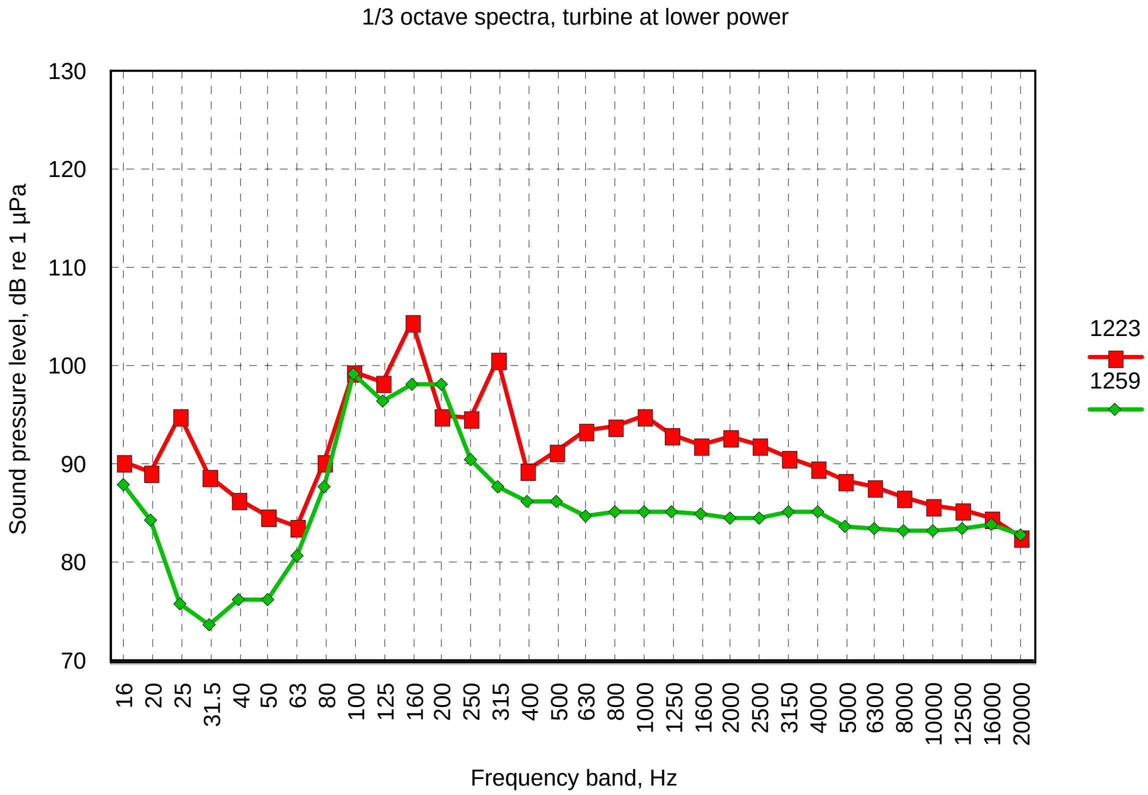


Figure 3.8. 1/3 octave spectra for partial load condition. For data sets see table 2.2.

3.3 Comparison with other measurements

Figure 3.9 and 3.10 shows a typical spectrum measured at Horns Rev together with values measured at the Utgrunden wind farm in Sweden [2, 4, 5], both for rated power and normalized to a distance of 100 m. The actual measurement distance at Utgrunden was 110 m; turbine power is 1.5 MW, versus 2 MW at Horns Rev. The maximum sound pressure levels are similar, but the Horns Rev turbine type emits less and lower tones above 300 Hz.

Also shown is the hearing threshold of a harbour porpoise according to [6] (in principle, spectral peaks can be compared directly to thresholds, however, care should be taken because of the properties of the different spectrum types discussed briefly in section 2.3). At 100 m distance from the Utgrunden turbine, the threshold is just exceeded for the tones at 540 Hz and 720 Hz, while the Horns Revs turbine is just inaudible for the animal. It should be noted, however, that the threshold values known so far are based on a rather small number of individuals, in particular for the frequencies of interest here, which are at the low frequency end of the harbour porpoise's hearing range.

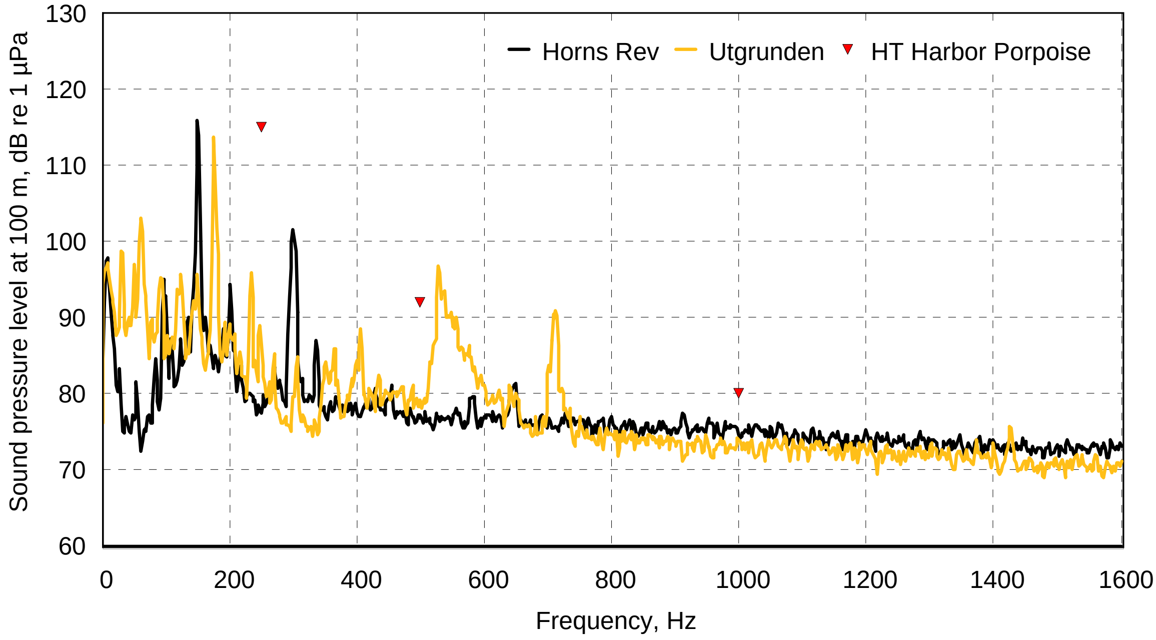


Figure 3.9. Narrowband spectra measured at Horns Rev (data set 1080) and Utgrunden.

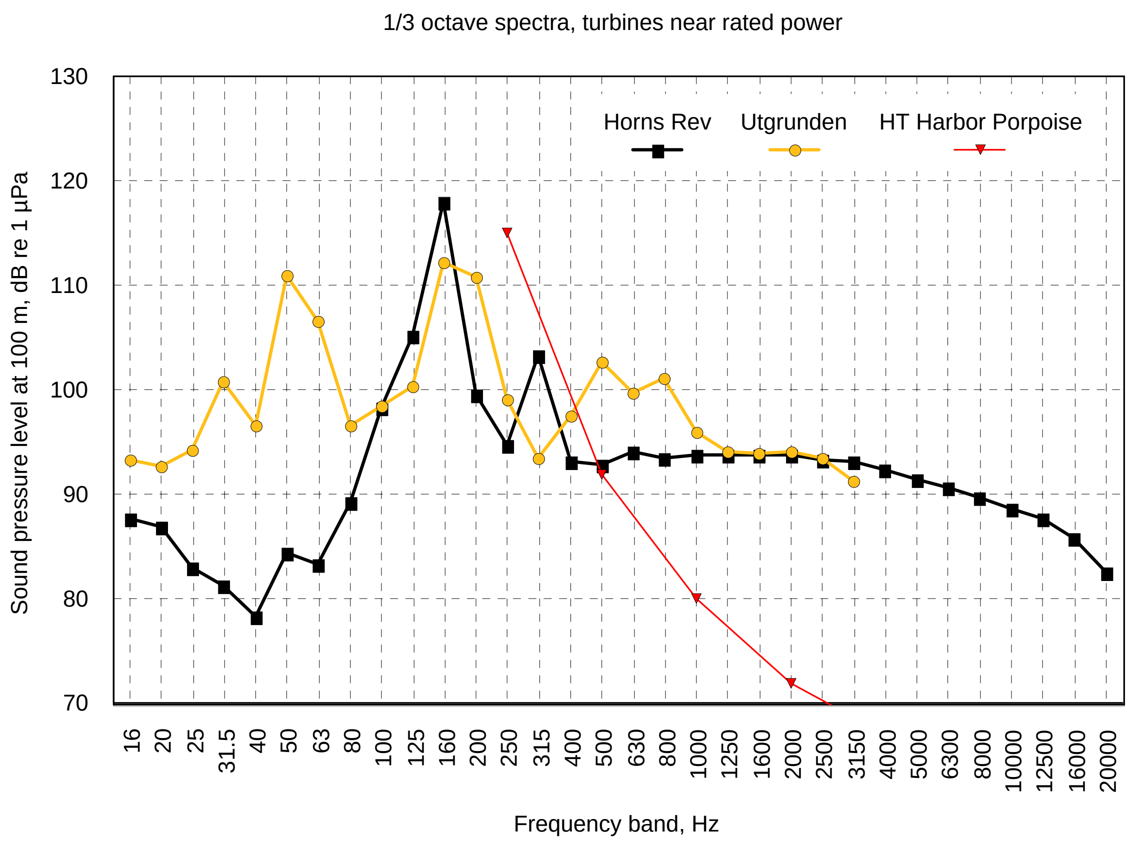


Figure 3.10. 1/3 octave spectra measured at Horns Rev (data set 1080) and Utgrunden.

4. References

[1] K. Betke, M. Schultz-von Glahn (2005): Measurement of underwater noise emitted by offshore wind turbines. Proposal to The Environmental Group, 5 September 2005

[2] CRI, DEWI, ITAP (2004): Standardverfahren zur Ermittlung und Bewertung der Belastung der Meeresumwelt durch die Schallimmission von Offshore-Windenergieanlagen. Final report. German Federal Environment Ministry, Berlin

[3] K. Betke, M. Schultz-von Glahn, A. Petersen J. Gabriel (2003): Messung der Unterwasser-Schallabstrahlung einer Offshore-Windenergieanlage. In: Fortschritte der Akustik - DAGA'03, 322-323 (proceedings of the annual conference of the German acoustical society DEGA)

[4] K. Betke, M. Schultz-von Glahn, R. Matuschek (2004): Underwater noise emissions from offshore wind turbines. In: Proceedings of the joint congress CFA/DAGA'04, 591-592, Strasbourg 2004

[5] J. Gabriel, T. Neumann, W.-J. Gerasch, K.-H. Elmer, M. Schultz - von Glahn, K. Betke (2004): Standards for the Assessment of Acoustical Emissions by Offshore Wind Turbines. DEWEK 2004, 7th German Wind Energy Conference, Wilhelmshaven

[6] R.A. Kastelein, P. Brunskoek, M. Hagedoorn (2002): Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals. J. Acoust. Soc. Am. **112**, 334-344