ARE THE KNUDSEN CURVES ACCEPTABLE IN THE BALTIC SEA?

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Results of ambient noise measurements performed in the southern part of the Baltic Sea are presented. An autonomous measurement buoy was deployed in two Baltic Deeps under dissimilar sound propagation conditions - at the Bornholm Deep in winter and at the Gdansk Deep in summer.

The sound was registered and analyzed in the frequency range from 350 Hz up to 35 kHz. The parameters of dependence of the ambient noise sound pressure level versus wind speed were determined.

It was found that the measured ambient noise spectrum level depends not only on wind speed and location but also on a depth of observation.

The results show that the wind dependent ambient noise component in the Baltic Sea frequently does not match the Knudsen curves, and we have found that at some specific location sound level at low frequencies does not depend on wind.

The collected data on the noise levels are discussed with other historical and contemporary data on the noise level in the Baltic Sea.

INTRODUCTION

From the first studies on ambient sea noise by Knudsen's research team [1], the parameterization of the noise level in terms of wind speed or wind classes was proposed. The published results have been known as the Knudsen or sometimes as Wenz curves (after investigations performed and aftermath published by Wenz in 1962 [2]).

At present, rich literature exists on ambient sea noise based on data collected in the different regions of the deep ocean and shelf seas and its dependence on the local wind condition is well established.

It was recognized very early that aside from random variations of the noise level related to the weather conditions (wind, rain) diurnal and seasonal variations occur at individual locations due to changing ratio of different noise sources. Despite the known fact that in the Baltic Sea the noise level strongly depends on the season and the observation depth ([3], [4], [5]), in some sources relating to the ambient noise in this area, the Knudsen or Wenz curves as representative of the noise levels are referred to. According to different sources ([5], [6]), the shape of the ambient noise level in the Baltic Sea at frequencies in the range 100 Hz – 1000 Hz follows the standard Wenz (Knudsen) curves, however the level is higher on 3-5 dB, and at very low frequencies below 100 Hz is much lower as in a deep Ocean.

Swedish Defense Research Agency (FOI) recommends the functional dependence of the noise spectra level NSL on the wind speed in the Baltic Sea (after [7]), as independent of other factors except the wind speed:

$$NSL = \max[24\log(1+U)\ 17\log(f)+35,\quad 20\log(f/6)] \tag{1}$$

where - U – wind speed in knots, f – frequency in kHz, max - means that we choose between two options depending on the value, NSL in dB re 1μPa^2/Hz.

1. SET-UP

Noise recordings were made using the autonomous hydroacoustical buoy constructed to record the ambient noise and to sound the subsurface water layers. The noise section of the buoy consists of the pair of omnidirectional hydrophones. During registrations the vertical distance between hydrophones is equal 22m. The system is oriented towards registration of wind/rain ambient sea noise components so the bandwidth of the tract was reduced to the frequency range from 350 Hz to 35 kHz. The ambient noise data recorded simultaneously at two depths by two hydrophones during the experiment presented a unique opportunity to investigate the Baltic wave guide properties.

The data are acquired in two modes – in the first one, the system made a one-minute measurement simultaneously every ten minute from two hydrophones, and afterwards from the one hydrophone with higher sampling frequency. The two channel ADC samples signals at 16-bit resolution in each channel with frequencies 32051 or 84745 Hz. To reduce the saturation from hydrodynamic pressures coming from the surface wave motion and cable vibrations, the high-pass analogue filter was set at the input of the preamplifier of each hydrophone. The level of the sampled signals is analysed online and in case of a too low values, the signal amplification is changed. The raw data samples are stored in the hard disk memory.

The buoy can be deployed at depths up to 100m.

2. ACOUSTIC RECORDS

The locations of the hydrophones were as follows:

a) in the summer period (October 2004, September 2005) one of the hydrophones was placed nearby the acoustical axis of deep water waveguide (with minimum of the sound speed) and the other in the mixed water layer above the seasonal thermocline. The records were made in the Gdansk Gulf Deep.
b) in winter season (April 2005, February 2006) the area of investigations included the Bornholm Deep only. The upper hydrophone was placed in the winter Baltic water masses, in the winter acoustical waveguide, the deeper one in the North Atlantic water

masses with higher salinity and temperature (the waveguide with a positive sound speed gradient - upwards surface propagation).

In both cases sediments in the area consisted mostly of the water saturated muds.

Simultaneously with the ambient noise, the sound speed profiles, atmospheric pressure, wind, humidity, air and sea temperatures were collected from the board of RV “Oceania” anchored at the distance 1-1.5 NM from the buoy. The number of ships in the 12 NM radius was registered each hour using the ship’s radar.

During measurements in February 2006, an additional measurement of the surface bubble population was performed. In September 2005, the noise of rainfall was estimated and its signal matched up to the pictures registered by the weather radar.

3. DATA PROCESSING

The noise records were performed in a digital form and post processed using MATLAB procedures. At the first stage, the noise spectrum and statistical analysis have been applied to characterize the noise. Spectral characteristics presented below were obtained for sub-samples of signals each consisted of 16 KB points and afterwards averaged in 512 frequency bands. Our task was to define the characteristics of these signals i.e. the frequency band, signal intensity, and other parameters of the spectra, such as a spectrum slope, central frequency, and wind dependency among others.

During the records an intense ship and traffic, the fishery activity and rainfall sounds were observed in the area. An algorithm was proposed to recognize and then exclude the realizations with shipping and rainfall noises dominated in the whole or part of the registered frequency band i.e. in the range 350–35000 Hz.

The interpretation of the ambient sound spectral properties allows classification of noise sources into categories: wind, rain, ships. The methods of the noise classification were based on the spectrum slope and rates of the spectral levels in selected bands of frequencies and afterwards using clustering to categorize the noise.

We introduce three classes of the noise type: with prevailed wind sources, “distant” and close shipping and traffic, and also the one with the presence of the rain noise. After careful testing only two noise signatures were chosen as descriptors of the noise classes:

a) the mean spectral slopes in the frequency band 1-5 kHz and 5-10 kHz. To avoid difficulties identifying shipping noise using the spectrum slope only, we suggest using also the deviation from the long term running mean. The expected slope for wind sources is the relatively constant. To identify a record as the prevailing wind component the observed slope should be within +/-3 dB per decade of the mean value. However, we should mention here that the spectral slope varies, depending on location, a depth of observation and the shape of the local sound speed profile. Usually, the noise spectrum level is more reddish in the presence of a ship noise (Fig.1 below).

b) to detect the rain noise presence we compare the spectral levels in two selected third-octave frequency bands followed by the use of clustering. In the classification, we use the observable information that rain produces a broad peak at frequencies around 14 kHz. Due to this a rainfall could be simply detected when data points around 14 kHz arise above the wind curve, and when we compare the noise level around this frequency with the data at 6-8 kHz.

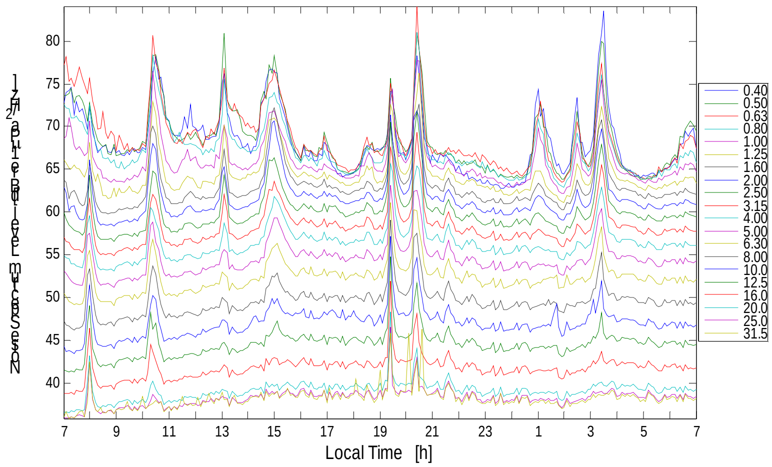

Fig. 1. Example of the time history of the behavior of the ambient noise spectra in one-third octave bands in presence of traffic and fishery noise. Data were collected in the Bornholm Deep in 28 February-1 March 2006, at the depth of 43m, under the winter propagation conditions. On the right, central frequencies of the one-third octave bands in kHz are presented.

Figure 2 shows inter-frequency dependence of the noise spectral levels in bands of 8 and 14 kHz, for the summer data, when intensive rainfall was observed. Most points lie along a well-recognized line with only some points outlying from the predominant tendency. The heavy rain records were confirmed by straight observations and the weather-radar data. However, the detection of an observed drizzle event was not possible.

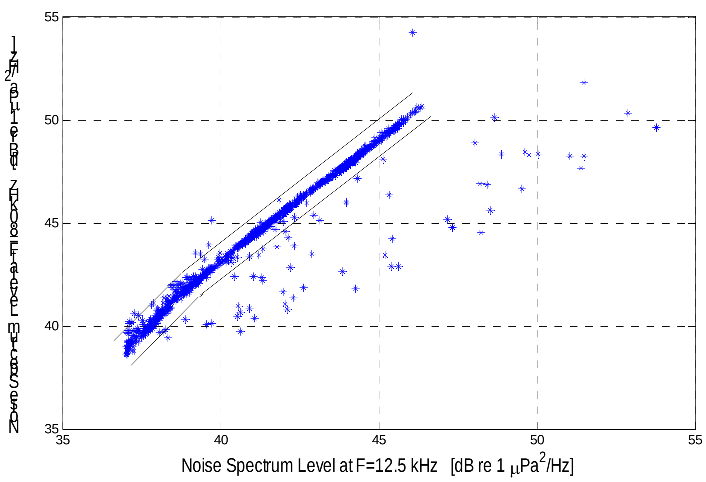

Fig. 2. The inter-frequency relationship of the noise spectral levels in the one-third octave bands with central frequencies of 8 and 12.5 kHz. Data were registered in the summer of 2005 at the Gdansk Deep.

Additionally, for several records, the multiple listening was very useful to settle on a noise class. The samples recognized as dominated by sources such as ships or rain were not included in the analysis leading to relationships between noise and wind speed.

4. RESULTS

As was stated in the historical papers printed in 70-80s the ambient acoustic environment in the Baltic Sea was found to be highly variable in the same way due to influence of the strong anthropogenic noise and due to fluctuations of the wind-dependent component ([3], [4], [8]). Because of intensive traffic and fishery in the Baltic Sea the events attributed to non-wind sources, occur quite frequently.

As far as depth dependence is concern, unexpectedly our data at low frequencies exhibit strong differences between the closely vertically separated hydrophones. However, Klusek suggested some remarks on this phenomenon yet in 1986 [8]. It was hypothesized, probably erroneously, that high level of noise field in the mid-water waveguide is due to scattering of the noise on the slope bottom of the Hel Peninsula, what could 'pump' acoustical energy into the deep summer waveguide.

4.1. WINTER TIME

Due to low acoustic attenuation in the brackish Baltic water, in the subsurface winter waveguide at frequencies of interest, excellent propagation from distant sources is expected and the wind- depended noise is frequently contaminated by a ship and traffic noise what is observed in the whole frequency band under analysis. Because of the positive refraction propagating waves in the deeper water layers, the observed noise level is to be less at the deeper hydrophones than in the shallower ones. The traffic and fishery noise is uncorrelated to the high-frequency noise component.

Looking into Fig. 1 at presented data we observe local maxima in the time series emitted by the ship or fishery. Turning to the wind dependence of the noise beneath the sea surface, we observe that at lower frequencies the noise level could decrease with growing wind. (Fig. 3). The noise level in the winter waveguide depends not only on intensity of noise sources but also on the local propagation condition. We observe that with the increasing wind speed, the noise level is decreasing. We try to explain this phenomenon due to bubble's clouds, generated by breaking waves, propagation conditions are declining and the noise is attenuated more rapidly with range than wind-dependent noise sources rising**.**

4.2. SUMMER TIME

In the summer time the upper hydrophone was located at the lower mixed water masses boundary, the second one in the deep-water summer sound channel.

We found that noise at the relatively small vertical distance (only 22m) is very different at frequencies up to about 4 kHz. While above 3-4 kHz the spectra are of the same general shape and level, for the same wind speeds, at lower frequencies the noise spectrum level in the waveguide run about 12 dB higher those registered in the upper layers.

At the hydrophone placed above the thermocline, in the absence of the non-wind-dependent noise component, the sound intensity level is quite good correlated to wind speed. The opposite have been observed in the data recorded in the deep summer waveguide. The noise level up to 3-

4 kHz does not depend on the wind speed. We can assume that above this frequency threshold the local wind sources prevail in the registered signals at the both hydrophones. In the fundamental work by Wenz [2] it was also stated that in different shallow-water areas (according to the Wenz definition water less than 180m in depth).

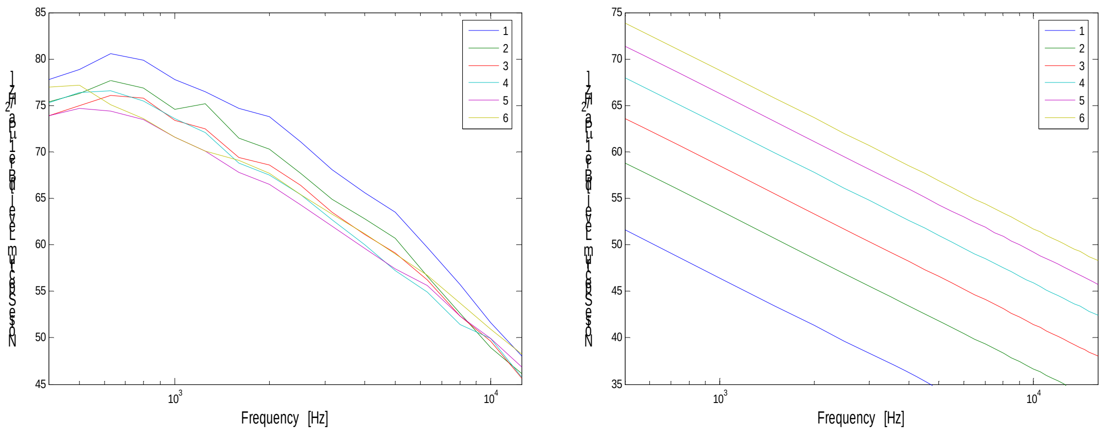

Fig.3. Time series of sound intensity in third octave frequency bands. Data were collected in February/March 2006 in the winter subsurface acoustical waveguide are on the left. For comparison the noise spectrum levels computed from the formula proposed by FOI. In the legend numbers correspond to the wind speed in the Beaufort scale.

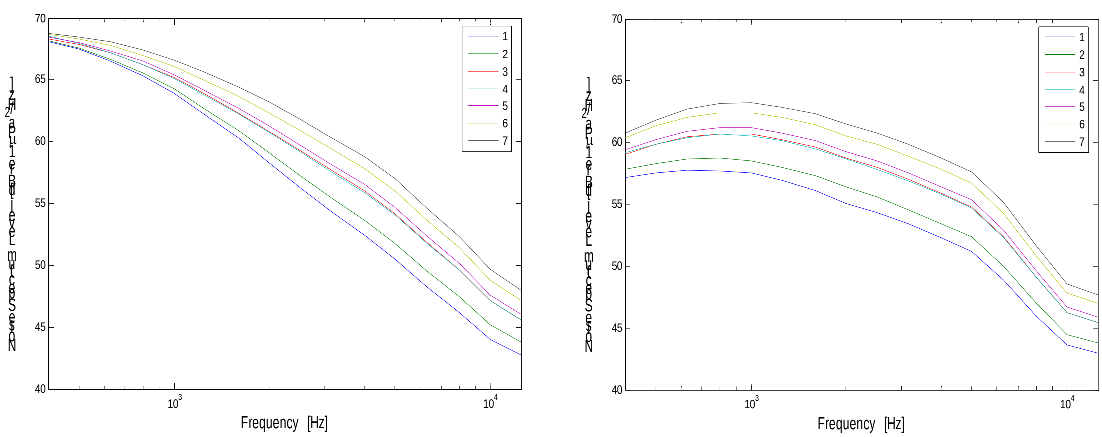

Fig. 4. Ambient Noise Spectrum Level in the Baltic Sea under summertime propagations conditions for the wind speed presented in Beaufort scale. Data above the thermocline in the surface mixed layer on the right, in the waveguide on the left.

Fig. 4 shows the ambient noise levels filtered in the third-octave frequency bands in the range between 350 and 12.5 kHz as a function of wind speed averaged in each of Beaufort-scale wind-speed ranges. Because of a small number of records in bins below Beaufort 1 scale, the noise level curves for these bins are not presented in the Figures 3 and 4.

The spectrum for the high frequency component is characterized by the spectrum-level slope of -8 dB to -10 dB per octave. Furthermore, it was found that the spectrum-level slope depends on wind speed.

We observe that at a specific location noise level at winter in the surface sound channel is higher comparing to the FOI formula and Wenz/Knudsen curves. In the subsurface winter sound channel and in the deep-water summer channel the noise wind positive correlation is poor especially at low frequencies.

5. STATISTICS OF AMBIENT NOISE

Beyond categorisation of spectra and computing parameters of the noise spectra, the statistical analysis and probability distribution of the ambient noise intensity were determined. Trends and seasonality of the local ambient sound level over year period were analysed. We also tried to answer question, what are the fluctuation characteristics of the noise in the area in the different frequencies bands – fundamentally problem for the passive detection.

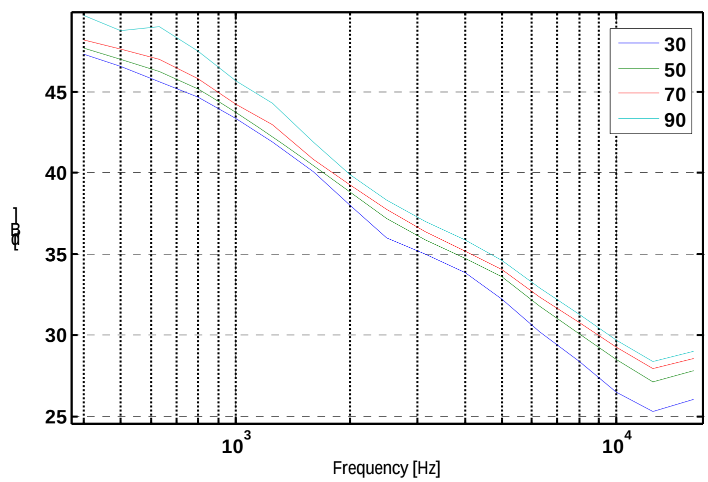

Fig.5. Ambient sound level cumulative distribution function at low winds. Example of quantiles in noise spectra (in dB) collected in the summer period in the Baltic Sea (Gdansk Gulf) area. The percentiles, are labelled at curves. Data were collected at very low winds. Hydrophone located above the limit of the summer deep water waveguide.

As the example the results of one investigation under almost zero of the wind speed is presented in Fig.5. The data analysis spectrum was done from noise segments selected from each recording. The total number of one-minute records is equal 443 of third-octave spectra in the 350 Hz- 20 /32 kHz band. The noise spectrum level and the band-pressure level were computed using the power spectrum and rms functions.

The set of received statistical and spectral data consist of:

- the differential distribution functions for 1/3 octave band spectra in form of histograms;
- the ambient sound level cumulative distribution functions (20,30,40,50,60,70,80,90-% quantiles); In Fig.5 are shown several quantiles in absolute sound level (dB re 1 $\mu Pa^2/Hz$). The 50% curve is the median;
- average values of the ambient noise level – <NSL>, and acoustical intensity I(ω) in an 1/3 octave band;

- average values of square deviation of the ambient noise level.

SUMMARY AND CONCLUSIONS

In this paper, the averaged in the Beaufort wind-speed classes noise spectra are presented for the different seasons and depths of observation. Though the amount of ambient-noise data is not large, we can make some conclusions and generalisation.

The difference in the noise spectrum level between seasons is to be noted. A comparison of the noise inside and outside of seasonal waveguides at lower frequencies indicates that the ambient noise level inside the seasonal Baltic waveguides is higher than outside of the waveguides. The correlation with the wind speed of low- and mid-frequency components inside of the seasonal waveguides is relatively low.

When examined on a seasonal basis, the low frequency component noise registered outside the summer waveguide noise were much closer to winter noise levels outside the surface waveguide than to the noise inside the summer waveguide.

Also the introduction to the statistical analysis of the ambient sea noise in the two seasons and areas is presented. We believe that further analysis and modelling should improve our understanding the influence of the sound propagation conditions in the Baltic Sea.

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