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High-frequency wind-driven ambient noise in shallow brackish water: Measurements and spectra

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Abstract: Ambient noise measurements were carried out in shallow brackish water within a frequency range extending up to 70 kHz. The high-frequency spectral slopes become steeper above 10 kHz at intermediate and high wind speeds. This is because the start of the wind speed dependence shifts rapidly to higher wind speeds at frequencies above 13 kHz. A physical explanation for this observation may be the low proportion of bubbles in brackish water that are small enough to radiate sound above 10 kHz. Such bubbles apparently do not begin to develop in brackish water until high wind speeds are attained.

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1. Introduction

Most studies on wind-generated underwater ambient noise are based on measurements carried out in an ocean environment at frequencies below 20 kHz. A characteristic feature of the oceanic spectra is the uniform slope of 5 to 6 dB per octave for frequencies between 1 and 20 kHz.[1] The same spectral slope (about 5 dB/oct) was also obtained for frequencies in the 1 to 20 kHz interval in laboratory experiments where spilling breakers were generated in an anechoic tank filled with tap water.[2] In shallow brackish water sea environments, however, the spectral slopes in the frequency range 1 to 10 kHz were found to be about 1 dB/oct less than those in the ocean.[3] McConnell *et al.*[4] reported broadband ambient noise measurements from the Behm Canal, Alaska, where the frequency band extended up to 80 kHz. The spectral slopes in their data agree well with those of the Knudsen spectra (5–6 dB/oct) up to a value of 20 kHz. Between 20 and 40 kHz their noise spectra show a humplike increase (~4 dB) in level. No physical explanation has been offered for this, but it is assumed that a perturbation of this kind could be generated by a series of spectral peaks from the shape oscillations of bubbles described by Longuet-Higgins.[5]

The wind speed dependence of ambient noise is a function of frequency. Carey and Fitzgerald,[6] compiled a summary for the oceanic wind speed dependence factors up to 1 kHz. Poikonen and Madekivi,[3] presented the wind speed dependence factors for shallow brackish water in the frequency range 100 Hz to 10 kHz. These wind dependence factors were systematically higher than those in the oceanic data. At frequencies above 10 kHz the dependence of ambient noise on wind speed has been reported to decrease with increasing wind speed and frequency, due to scattering and absorption in a thin layer of bubbles produced by breaking waves.[7] Wille and Geyer[8] reported similar behavior in the shallow water measurements performed in the North Sea and the Baltic Sea. The effect of salinity on bubble sound has been studied in several laboratory measurements.[9,10] A clear outcome from these studies is that the bubble size distribution tends to grow in numbers and shift to smaller bubble sizes as salinity increases.

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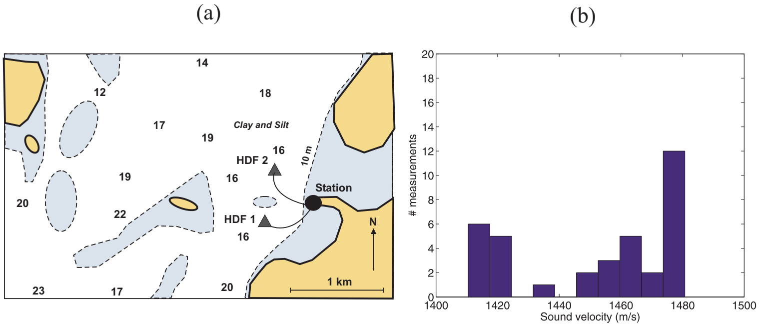

Fig. 1. (Color online) (a) Map of the experimental site. HDF 2 shows the location of the hydrophone in the present study. In the previous study the hydrophone was located at HDF 1. Numbers in sea area refer to bathymetry values in meters. (b) Histogram of sound speed velocities in the ambient noise measurements in HDF 2.

The present ambient noise measurements were carried out in a shallow brackish water environment in a frequency range extending up to 70 kHz. The data set covers a full year, based on measurements made between March, 2008 and March, 2009. The study is a follow-up to the previous campaign which focused on the low-frequency characteristics of ambient noise.[3] The data set is analyzed using methods and tools similar to those introduced in the previous study. Special attention is given to spectral phenomena above 1 kHz. The wind speed dependence parameters are calculated and shown in the extended frequency range from 60 Hz to 70 kHz.

2. Measurements and methods

The high-frequency measurements were carried out at the same site as the first campaign, and consequently the environmental description given in the previous study[3] is also applicable to the present study. The same bottom-mounted hydrophone as used previously was located at a depth of 16 m about 500 m north of the first site, as shown in Fig. 1(a). Water temperatures at the site varied from 0 to 20 °C during the course of the survey. In an archipelago environment sound velocity profiles tend to flatten out quickly due to shallow depths and strong mixing. The sound velocities in the ambient noise measurements are depicted as a histogram in Fig. 1(b).

The data acquisition system used in the previous study was modified by replacing the old sound card with an external high-speed unit. The calibrated analog signal from the preamp was now sampled with a 16-bit resolution at a rate of 176.4 kHz, thus enabling audio recordings up to the Nyqvist frequency of 88.2 kHz. The flat frequency band (2.5 dB) of the hydrophone extends up to 80 kHz.[3] The transmission bandwidth of the analog hydrophone cable must be larger than that to avoid signal attenuation at higher frequencies. The capacitance (C) and the resistance (R) of the cable form a lowpass filter that cuts the signal at higher frequencies. The frequency response of the cable was estimated with a first-order RC circuit that gives the attenuation slope of 6 dB per octave above the 3 dB half-power frequency. With the electrical parameters R and C corresponding to the cable length of 500 m the 3 dB half-power frequency is around 200 kHz and the attenuation in the measuring band is less than 0.5 dB. The present signal processing scheme is the same as in the previous study where the interfering frequency lines were removed from the raw spectra using the 9-point median filter. The final spectra were calculated for $\frac{1}{3}$-octave bands with power normalized to a 1-Hz band.

The wind speed dependence of ambient noise is estimated with the aid of a two-parameter logarithmic curve

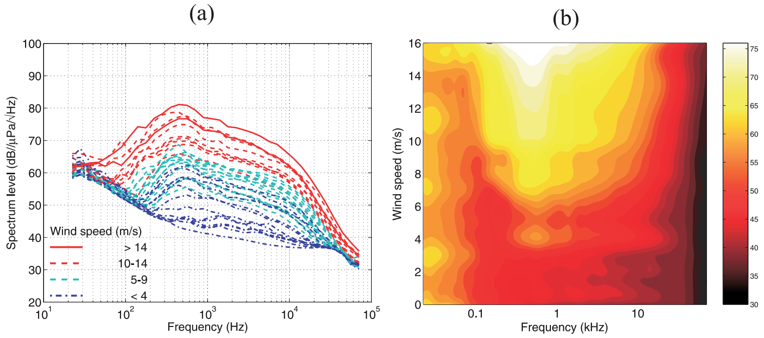

Fig. 2. (Color online) (a) All of the measured spectra as curves. Wind speed is coded in four classes denoted with different line styles and colors. (b) The same data set as a filled contour plot where ambient noise is depicted as function of wind speed and frequency.

$$S(u) = S_0 + 10 \log\left[1 + \left(\frac{u}{u_c}\right)^k\right], \qquad (1)$$

where S and S_0 are noise power spectral densities (dB//μPA/$\sqrt{}$Hz), u is wind speed (m/s), u_c is the threshold wind speed, and k is the wind speed dependency factor. The curve describes the wind speed dependence in two wind speed regions separated by the threshold value of u_c. In the lower noise-limited region no wave breaking occurs and the ambient noise shows no dependency. In the higher region above the threshold wind speed wave breaking starts and the ambient noise rises with increasing wind speed at a rate determined by the factor k. The wind speed dependence is often parametrized by the factor n introduced by Piggott.[11] This has a value half that of factor k, i.e., $n = k/2$. The wind speed dependence parameters u_c and k are estimated for all the $\frac{1}{3}$-octave frequency bands by fitting the model curve to the measured spectrum levels as a least-squares solution. The bandwidth of ambient noise is determined with the effective noise bandwidth β_n already introduced in the previous study.[3]

3. Results

The ambient noise spectra from the 36 broadband measurements are plotted in Fig. 2(a). The same ambient noise data are shown as a filled contour plot in Fig. 2(b), which depicts the noise power as a function of frequency and wind speed. The most distinctive character of the spectra is their band-limited structure with the abrupt low-frequency decline and the more gently sloping high-frequency end. The low-frequency behavior of the broadband spectra up to 10 kHz is almost identical to that of the previous data set with the narrower frequency band.[3] As described by Kennedy,[12] the bandpass pattern relates strongly to the dipole surface source distribution due to oscillating bubbles and bubble clouds generated by breaking waves. The broadband spectra reveal an unexpected feature at frequencies above 10 kHz, where the spectral slopes turn steeper at intermediate and high wind speeds. At the highest wind speed class (>14 m/s) in Fig. 2(a) the medium frequency ($500\ \text{Hz} < f < 10\ \text{kHz}$) spectral slope of ~ 3.3 dB/oct steepens to a value of ~ 11.4 dB/oct as frequency rises above 10 kHz. In terms of the "power law" this corresponds to the shift from f^{-1} (-3 dB/oct) frequency dependence below 10 kHz to almost f^{-4} (-12 dB/oct) dependence at higher frequencies. The gentle slope factor of ~ 3.3 dB/oct at medium frequencies conforms with the dipole spectrum results obtained by Kennedy,[12] who applied the parametric source model to the measured vertical directional spectra of ambient noise. He reported that the dipole term of the source model dominated at frequencies from 80 Hz up to the maximum frequency of ~ 4 kHz used in the experiment. In the dipole source spectra the power law index above 1 kHz was typically "just slightly greater than one," being almost identical with that obtained in the present

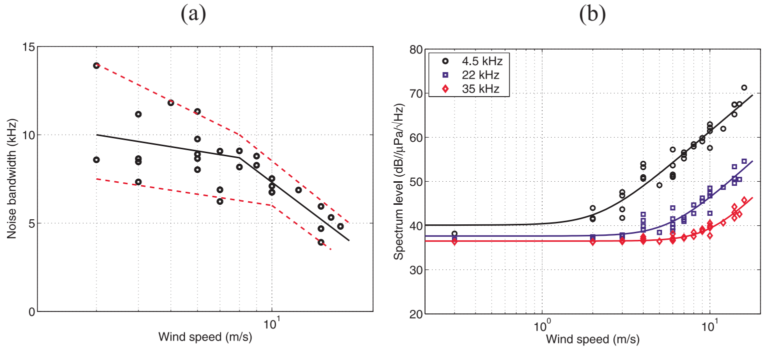

Fig. 3. (Color online) (a) Noise bandwidth of ambient noise as a function of wind speed. (b) Wind speed dependence model curves fitted to the measured ambient noise at frequencies of 4.5, 22, and 35 kHz.

study. It can therefore be concluded that in the present brackish water environment the surface source of ambient noise exhibits a strong dipolar character. Several possible explanations can be proposed for the steeper spectral slope above 10 kHz. Farmer and Lemon[7] concluded that the attenuation effect in the thin layer of bubbles from breaking waves explains the weaker high-frequency wind speed dependence in their measurements. Another potential explanation is the lower bubble density in the smallest radii of the bubble size spectrum in a brackish water environment. These mechanisms will be discussed in detail in subsequent paper focusing on the interpretation of the high-frequency behavior of ambient noise.

The development of the band-limited spectrum with increasing wind speed is shown in the noise bandwidth plot in Fig. 3(a). At lower wind speeds the noise power from other natural sources dominates and the noise bandwidths and their deviation are then relatively large. At higher wind speeds the ambient noise power from the oscillating bubbles gradually overrides that from the other sources and the characteristic bandpass structure develops. The noise bandwidth of a fully grown spectrum lies between 4 and 6 kHz which agrees well with the earlier results.[3] It is evident from Fig. 2(a) that the wind speed dependence of ambient noise weakens at frequencies above 10 kHz. The model curve of Eq. (1) was fitted to the frequencies of 4.5, 22, and 35 kHz and the results are plotted in Fig. 3(b). The curves clearly show that the rapid decline of spectrum levels above 10 kHz can be explained by the gradual increase of the threshold wind speed (parameter u_c) with increasing frequency. The slope of the growing part of the curve (parameter k), however, seems fairly insensitive to the frequency increase. The wind speed dependency parameters k and u_c were estimated for all the $\frac{1}{3}$-octave frequency bands and the parameters are depicted in Fig. 4, together with the earlier results. The wind speed dependencies are presented as the factor n $(=k/2)$ in Fig. 4(a) together with the low-frequency oceanic factors compiled by Carey and Fitzgerald,[6] and the previous brackish water factors up to a frequency of 10 kHz.[3] The corresponding threshold wind speeds are shown in Fig. 4(b). The wind speed dependency factors in brackish water environment are systematically higher than those in the ocean. In the present broadband data the wind speed dependency curve is fairly flat in the frequency range from 300 Hz to 40 kHz where the factor n varies between 1.5 and 2.0, At both ends of the frequency range the wind speed dependency curve exhibits a rapid increase. Interestingly enough, the threshold wind speed behaves in a similar manner at lower frequencies but the high-frequency rise starts at a substantially lower frequency than that of the factor n. The flat region where the threshold wind speed varies between 2 to 3 m/s ranges from 300 Hz to 13 kHz. This implies that the steeper spectral slopes in the ambient noise spectra above 10 kHz can be explained with the threshold wind speed parameter increasing rapidly above 13 kHz.

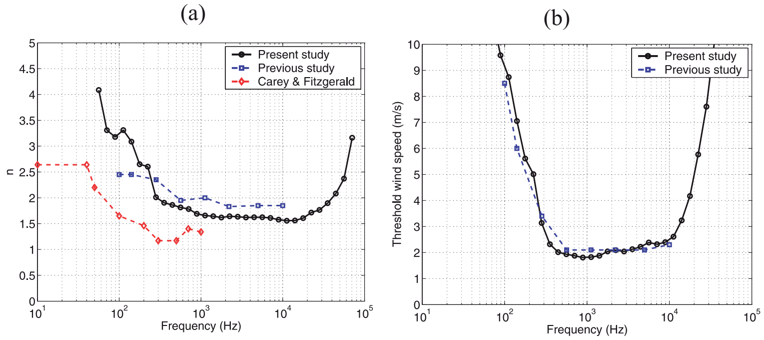

Fig. 4. (Color online) (a) Wind speed dependence factors (n) of the present broadband data set compared to the earlier results. (b) Corresponding threshold wind speed as function of frequency.

4. Conclusions

The present ambient noise measurements were carried out in a shallow brackish water environment over a frequency range extending up to 70 kHz. The measurement site is well isolated against traffic noise and other man-made interferences. The measured ambient noise spectra show a distinctive bandpass structure characteristic of the dipolar source distribution formed by bubbles in breaking waves. The broadband spectra reveal an unexpected feature at frequencies above 10 kHz where the spectral slopes steepen markedly at intermediate and high wind speeds. This is attributed mainly to the threshold wind speed parameter, which increases rapidly at frequencies above 13 kHz. A plausible physical explanation for the observation is that fresh and brackish water are known to contain a lower proportion of small bubbles than salty oceanic water.[3] Bubble sizes required to radiate sound above 10 kHz are less than 0.3 mm in radius. In brackish water it seems that bubbles of this size do not start to develop until the highest wind speeds are attained.

Acknowledgment

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References and links

[1] G. M. Wenz, “Acoustic ambient noise in the ocean: Spectra and sources,” J. Acoust. Soc. Am. **34**, 1936–1956 (1962).

[2] H. Medwin and M. M. Beaky, “Bubble sources of the Knudsen sea noise spectra,” J. Acoust. Soc. Am. **86**, 1124–1130 (1989).

[3] A. Poikonen and S. Madekivi, “Wind-generated ambient noise in a shallow brackish water environment in the archipelago of the Gulf of Finland,” J. Acoust. Soc. Am. **127**, 3385–3393 (2010).

[4] S. O. McConnell, M. P. Shilt, and J. G. Dworski, “Ambient noise measurements from 100 Hz to 80 kHz in an Alaskan fjord,” J. Acoust. Soc. Am. **91**, 1990–2003 (1992).

[5] M. S. Longuet-Higgins, “Bubble noise spectra,” J. Acoust. Soc. Am. **87**, 652–661 (1990).

[6] W. M. Carey and J. W. Fitzgerald, “Low frequency noise from breaking waves,” in *Sea Surface Sound (2): Natural Physical Sources of Underwater Sound*, edited by B. R. Kerman (Kluwer, Dordrecht, The Netherlands, 1993), pp. 277–304.

[7] D. M. Farmer and D. D. Lemon, “The influence of bubbles on ambient noise in the ocean at high wind speeds,” J. Phys. Oceanogr. **14**, 1762–1778 (1984).

[8] P. C. Wille and D. Geyer, “Measurements on the origin of the wind-dependent ambient noise variability in shallow water,” J. Acoust. Soc. Am. **75**, 173–185 (1984).

[9] W. M. Carey, J. W. Fitzgerald, E. C. Monahan, and Q. Wang, “Measurement of the sound produced by a tipping trough with fresh and salt water,” J. Acoust. Soc. Am. **93**, 3178–3192 (1993).

[10] A. R. Kolaini, “Sound radiation by various types of laboratory breaking waves in fresh and salt water,” J. Acoust. Soc. Am. **103**, 300–308 (1998).

[11] C. L. Piggott, “Ambient sea noise at low frequencies in shallow water of the Scotian Shelf,” J. Acoust. Soc. Am. **36**, 2152–2163 (1964).

[12] R. M. Kennedy, “Sea surface dipole sound source dependence on wave-breaking variables,” J. Acoust. Soc. Am. **91**, 1974–1982 (1992).