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CORRESPONDENCE BETWEEN THE SEA NOISE SPECTRUM AND THE SPECTRUM OF NATURAL SURFACE SOURCES

1. INTRODUCTION

The problem of an analogy of the ambient sea noise spectrum and the spectrum of surface noise is not trivial in view of the relationship between the sea-bottom reflectivity and frequency of sound.

The increase in sound absorption by sea water and sea bottom, with increasing frequencies, is undoubtedly one of the reasons for the negative slope of the sea noise spectrum density envelope in the frequencies above hundreds of cycles per second.

The form of the sea noise spectrum envelope in very low frequencies in shallow seas is affected by the geometry of a medium, a decrease occurring at frequencies lower than a certain critical frequency of the waveguide created by the free surface and sea bottom. This phenomenon is discussed in detail in [2] and thus will not be considered herein.

In the literature on ambient sea noise it is common practice to assume that the measured spectrum of ambient sea noise is equivalent to the spectrum generated by surface sources. This point of view is substantiated by the results obtained from mathematical model [3].

Furduyev considered a model in which sources of noise were distributed uniformly over the smooth surface of a medium. The latter was a homogeneous semispace with acoustic properties characterized by the coefficient of sound losses in sea given by Sheehy and Halley [5]

$$\beta(f) = 3.6 \cdot 10^{-2} \cdot f^{3/2} \text{ dB/km} \tag{1}$$

in which:

f — frequency of sound in kilocycles per second.

In physical terms, this is true for a deep ocean with a bottom that absorbs sound very strongly. The assumption of homogeneity of the medium precludes the case of acoustic wave refraction. Basing on experimental results Urick [6] assumed that the sources of ambient noise in the sea are situated on the undulated sea surface or in the thin upper layer. The radiation pattern of sea surface sources has the form [1]:

$$I(\Theta) = I_o \cos^{2m}\Theta \tag{2}$$

where:

I_o — intensity radiated by a small area of sea surface in the downward direction ($\Theta = 0$),

m — coefficient dependent on wind speed and frequency.

So far, no accurate formula for m versus wind speed and sound frequency has been found. It is only known that values of m are contained between 1 and 3 and increase with rising wind speed and noise frequency.

For the above assumption it has been found that the spectrum of noise recorded by nondirectional hydrophone differs slighty from the spectrum of surface sources in audible frequences, even at considerable depths. For instance, if m = 2 and the hydrophone is submerged at a depth of h = 1000 m, for the series of frequences f = 1, 2, 4, 8, and 16 kcps the ratio of the noise intensities measured in a medium characterized by the absorption of sound described by formula (1) to the noise intensities in a medium without losses reads respectively: $\frac{I}{I_o} = 0;\ 0;\ 0.1;\ 0.4;\ 1.2$ dB. As will be shown, the consideration of the selective reflection of the sea bottom, with values of reflectivity for abyssal plains, introduces substantial corrections to the model discussed.

2. THEORY

Let us consider the problem in the geometric acoustics approximation, for the frequencies in which one satisfies the deep-sea condition $10\lambda \leqslant H$,

where

λ — acoustic wave length

H — sea depth

Assume that the speed of sound in the sea does not depend on depth and that the noise recording hydrophone is located sufficiently far from the sea surface. The directional characteristics of the source are taken in accordance with [6].

The noise intensity dI in a narrow frequency band df reaching the hydrophone from the upper hemisphere bounded by a narrow ring on the sea surface (Fig. 1) is given by the formula:

$$dI_1 = \frac{W(f)\,df\,G^2(\Theta)\,\exp\,[-2\beta(f)\,R_1]\,dS_1}{2\pi\,R_1^2} \tag{3}$$

in which:

$dS_1 = 2\pi r_1\, dr_1$,

r_1 — mean radius of the sea surface ring, with centre at the point from which the hydrophone was lowered vertically,

$W(f)$ — surface spectral density of acoustic sources,

R_1 — mean distance from ring to hydrophone.

The solid angle $d\Omega$ based on ring dS_1 also includes the noise generated by another ring dS_n, determined by rules of geometrical acoustics:

$$dI_{n} = \frac{W(f)\,df\,G^2(\Theta)\,\exp\,[-2\beta(f)\,R_n]\,dS_n}{2\pi R_n^2}\,V_1^{2n}\,V_2^{2n} \tag{4}$$

in which:

R_n — mean path of acoustic ray from nth ring on surface to hydrophone,

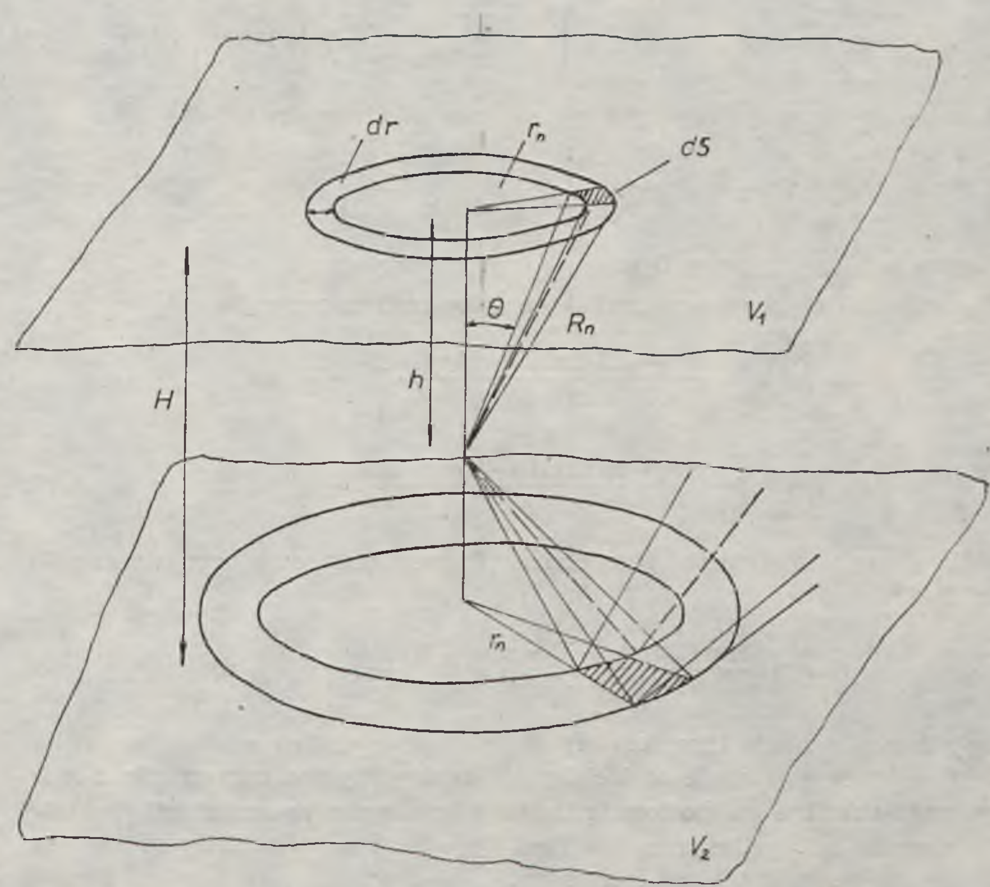

Fig. 1. Geometry for derivation of the expressions (6) and (7)

Ryc. 1. Zależności geometryczne wykorzystane przy wyprowadzeniu wzorów (6) i (7)

$V_1 = V_1(f)$ and $V_2 = V_2(f)$ — effective reflectivities of sea surface and sea bottom.

By summing up over n expressions analogous to Eq. 4 one obtains the overall intensity of noise at frequency f of width df, reaching a receiver from the solid angle $d\Omega$:

$$dI = \sum_{n=0}^{\infty} \frac{W(f)\, df\, G^2(\Theta) \exp[-2\beta(f) R_n]\, dS_n}{2\pi R_n^2} V_1^{2n} V_2^{2n} \tag{5}$$

Since this study is aimed to find the ratios of noise intensities in selected frequencies, one may assume $W(f)df = 1$, without this approximation affecting the ultimate results.

In the case of an infinitely deep sea (or an ideally noise-absorbing sea bottom) the sum given by Eq. 5 will reduce to Eq. 3 derived by Urick.

Substituting, in Eq.5 R_n and r_n, as functions of Θ, H, and m, one obtains

$$dI = \sum_{n=0}^{\infty} \operatorname{tg}\Theta \cos^{2m}\Theta \exp\left[-\frac{2\beta(f)(2nH+h)}{\cos\Theta}\right] \cdot V_1^{2n} V_2^{2n} \cdot d\Theta \tag{6}$$

for the intensity of noise from the upper hemisphere and

$$dI = \sum_{n=1}^{\infty} \operatorname{tg}\Theta \cos^{2m}\Theta \exp\left[-\frac{2\beta(f)(2nH-h)}{\cos\Theta}\right] \cdot V_1^{2n} \cdot V_2^{2(n-1)}\, d\Theta \tag{7}$$

for the intensity of noise from the lower hemisphere.

By substituting $\cos\Theta = x$ and integrating over x one obtains

$$I = \int_1^{\infty} \sum_{n=0}^{\infty} \frac{\exp[-2\beta(2nH+h)x]}{x^{2m+1}} \cdot V_1^{2n} \cdot V_2^{2n}\, dx$$

$$\int_1^{\infty} \sum_{n=1}^{\infty} \frac{\exp[-2\beta(2nH-h)x]}{x^{2m+1}} \cdot V_1^{2n} \cdot V_2^{2(n-1)}\, dx \tag{8}$$

Making use of the sum of geometrical progression one reduces formula (8) to the form:

$$I = \int_1^{\infty} \frac{\exp(2\beta hx) + V_2^2 \exp[-2\beta(2H-h)x]}{x^{2m+1}[1 - V_1^2 V_2^2 \exp(-4H\beta x)]}\, dx \tag{9}$$

This formula holds true for any functional dependence of reflectivities on frequency and angle of incidence. To simplify the computations it is assumed that the sea bottom is flat and homogeneous acoustically, while its acoustic properties are described by effective reflectivity of the sea bottom, dependent only on frequency.

As is shown by the results of experiments carried out in regions with slighty undulated bed [4, 7], the magnitude of the effective reflectivity of an almost flat sea bottom, for a given frequency and for angles of incidence from 0 to about 80° is approximately constant. For angles greater than the critical the bottom reflectivity increases almost linearly to unity.

Considering the fact that surface sources have certain directional characteristics one can readily find that the quantity of acoustic energy reaching the receiver from almost horizontal directions is negligible. This fact allowsus to assume that the effective sound reflectivity of the bottom depends only on frequency.

In our problem the dependence of sound scattering on a rough sea surface on the angle of incidence and frequency of sound does not play an important role, so that we can assume the reflectivity of the surface to be equal to unity. For the above assumptions, formula (8) can be integrated term by term:

$$I(f) = V_2^2 \sum_{n=0}^{\infty} \exp(t_1) \sum_{i=1}^{2m} \frac{t_1^{i-1}}{2m\,(2m-1)\ldots(2m-i)} + \frac{t_1^{2m-1}}{(2m)!} \mathrm{Ei}\,(t_1, x) +$$

$$+ V_2^2 \sum_{n=1}^{\infty} \exp(t_2) \sum_{i=1}^{2m} \frac{t_2^{i-1}}{2m\,(2m-1)\ldots(2m-i)} + \frac{t_2^{2m-1}}{(2m)!} \mathrm{Ei}\,(t_2, x)$$

where:

$$\mathrm{Ei}\,(x) = \int_1^{\infty} \exp(-x)\,/x \cdot dx$$

$$t_1 = -2\beta\,(2nH + h)$$

$$t_2 = -2\beta\,(2nH - h) \qquad (10)$$

The values of effective reflectivities obtained by Volovov, Zhitkovsky, and Kuklin [3] from experiments on abyssal plains of the Atlantic Ocean were used in our computations of noise intensity by formula (10). The character of changes in reflectivities assumed herein agrees with the data of other authors for flat beds (e.g. [4]), whereas the absolute values are likely to differ. The frequencies and the respective reflectivities taken in numerical computations are the following:

Table 1

f, kHz	0.5	1	2	4	8	12	16
V_{eff}	0.8	0.8	0.7	0.5	0.2	0.2	0.2

3. RESULTS OF COMPUTATIONS

The computations for the model presented were accomplished for sea depth H = 70... 5000 m and hydrophone depths of from 60 to 1900 m. The results indicate that changes in the received noise spectrum depend little on variations of H for given hydrophone depths. This finding is attributed to the fact that at higher frequencies the quantity of acoustic energy coming from the lower hemisphere is small in comparison with the component coming directly from the sea surface. This results from strong absorption of sound by the sea floor at these frequencies. In lower frequencies, about 1 cps, if a considerable portion of noise comes from below, the changes in water layer thickness (within the intervals mentioned) have a weaker effect on the level of received noise, because of the small values of the sound absorption coefficient for lower frequencies in water.

Table 2 contains comparison of the results of numerical computations of relative noise intensities at the depth $h = 60$ m, for selected frequencies computed for a sea of finite depth H (in meters) and for an infinitely deep sea.

Table 2

a) $H = 100$ m $h = 60$ m $m = 1$

f kHz	0.5	1	2	4	8	16
I_h/I dB	6.2	6.18	4.54	2.17	0.75	0.3

b) $H = 500$ m $h = 60$ m $m = 1$

f kHz	0.5	1	2	4	8	16
I_h/I dB	6.16	6.09	4.37	1.98	0.58	0.1

It follows from the computations that the low-frequency reflections from the sea floor induce a considerable increase in noise, which amounts to about 6 dB (for the bottom properties assumed), in comparison with a sea of infinite depth.

The slope of the envelope curve for spectral densities of dynamic sea noise in frequencies above 300... 600 cps is 5... 6 dB per octave. One of the reasons should be sought in the physics of noise generation on the sea surface. Also the selectivity of sound reflection from sea bottom is negligible; as also is absorption in sea water. Fig. 2 shows changes in the spectral density, of white noise generated on the sea surface and received at different depths in an ocean with a depth of 2000 m. The axis of abscissae represents the ratio of noise intensity at a given frequency to the intensity at a frequency of 0.5 cps, in dB. The curves are parametrized with respect to the sea depth of noise recording, $h = 100$, 500 and 1900 m.

It can clearly be seen that for relatively small hydrophone depth, the slope of the spectral envelope is caused primarily by an increase in bottom absorption, while sound absorption by sea water must be taken into account for considerable depths.

A numerical analysis of formula (10) shows that consideration of different functions of absorption by sea water versus frequency, given by various authors, slighty alters the results obtained by a few per cent.

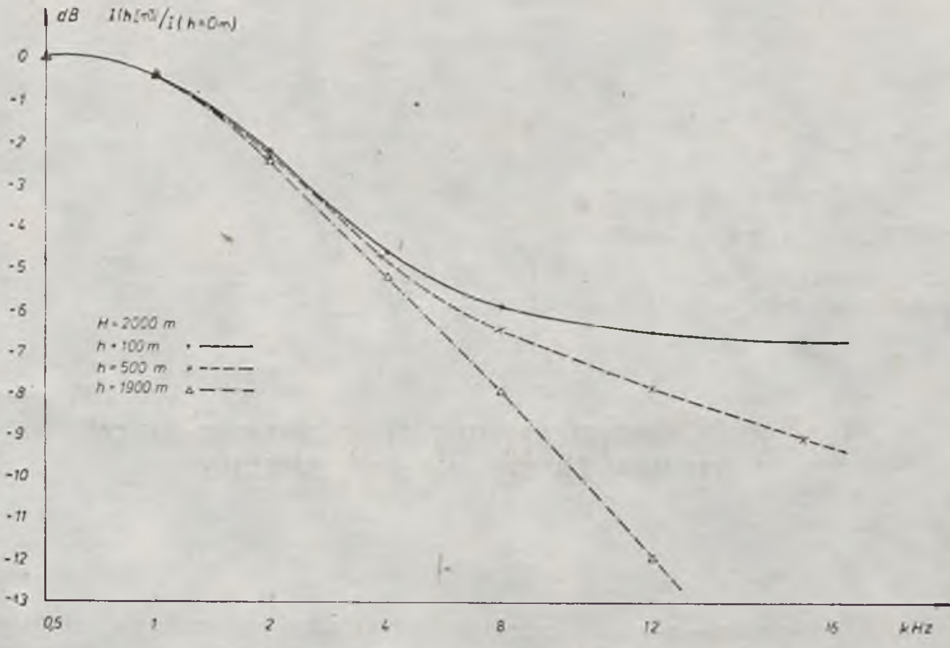

Fig. 2. Changing of spectrum of white noise generated by surface sources at different depths on the basis of the represented model

Ryc. 2. Zmiany widma białego szumu generowanego przez źródła powierzchniowe na różnych głębokościach, obliczone na podstawie przedstawionego modelu

4. CONCLUSIONS

The results of the computations performed within the mathematical model presented in this study have shown that the hypothesis on the equivalence of noise spectra measured in the sea and the spectra of surface sources is not acceptable. The measured noise intensity may, in reality exceed the noise that could be measured at the same point assuming no reflections from the sea bottom by 6 dB in frequencies below 1 kHz.

The additional negative spectral slope due to selective absorption in sea water and by the sea bottom should be taken into account in respective theories, and in estimations of the share of individual types of real sources of ambient sea noise.

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ZALEŻNOŚĆ POMIĘDZY WIDMEM SZUMÓW W MORZU A WIDMEM ŹRÓDEŁ NA POWIERZCHNI

Streszczenie

W literaturze poświęconej szumom morza powszechnie przyjmuje się, że widmo szumów w morzu jest ekwiwalentne widmu naturalnych źródeł szumów znajdujących się na powierzchni morza. Pogląd ten potwierdzają obliczenia wykonane dla morza o nieskończonej głębokości [3]. Przedstawiony model opiera się na założeniach analogicznych jak w pracy [3], lecz przy przyjęciu morza o skończonej głębokości. Założono, że dno morskie stanowi płaszczyzna, której własności akustyczne opisuje w zupełności efektywny współczynnik odbicia dźwięku, zależny wyłącznie od częstości. Obliczenia numeryczne przeprowadzono dla wartości efektywnego współczynnika odbicia dźwięku od dna podanego przez Wołowowa i innych [3].

Znaleziono, że różnice pomiędzy mierzonym w toni wodnej widmem szumów a widmem szumów generowanych przez źródła na powierzchni morza mogą być znaczne i mogą osiągać 6 dB na częstości 1 kHz. Ten brak odpowiedniości pomiędzy tymi widmami występuje zarówno w płytkich, jak i głębokich akwenach.

REFERENCES

LITERATURA

1. Arase T., Arase E., *Correlation of ambient sea noise*, J.A.S.A., 44, 1966, s. 205—210.
2. Briechowskich L.M., *Wołny w słojstych sriedach*, *Nauka*, Moskwa 1973.
3. Briechowskich L.M. (red.), *Akustika okieana*, Nauka, Moskwa 1974.
4. Cole B.F., *Marine sediment attenuation and ocean bottom reflected sound*, J.A.S.A., 38, 1965, s. 291—297.
5. Sheehy M.J., Halley P.R., *Measurement of the attenuation of low frequency underwater sound*, J.A.S.A., 29, 1957, s. 464—469.
6. Urick R.J., *Principles of underwater sound for engineers*, McGraw Hill 1967.
7. Winokur R.S., Bohn J.C., *Sound reflections from a low-velocity bottom.* J.A.S.A., 44, 1968, s. 1130—1138.