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THE EFFECT OF INTERNAL WAVES ON THE FLUCTUATIONS OF THE NOISE FIELD IN THE SEA

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1. INTRODUCTION

In recent years hydroacoustics specialists have shown particular interest in the effect of internal waves on the propagation of acoustic waves in the sea. Internal waves in the seas have been found to cause random fluctuations of the acoustic field of point sources. According to the hypothesis put forward in [1], internal waves may also cause fluctuations of the natural noise field when observations are made by means of hydroacoustic arrays of narrow directional characteristics.

In this paper the effect of internal waves on the observed values of noise intensity at the input of hydroacoustic arrays is estimated in the approximation of geometrical acoustics. This problem was considered on a deterministic model for sound velocity distribution characteristic of the Baltic Sea during the summer and winter seasons. Despite being much simplified, the model enables the extent of the phenomena to be estimated.

2. BASIC ASSUMPTIONS OF THE MODEL

Let us assume that sea consists of three layers differring in sound velocity. The lower and upper layers are homogeneous and have a constant sound velocity (c_1 and c_2, respectively), whilst in the intermediate layer the velocity varies linearly with the depth from c_1 to c_3. Let us also assume that the depth of the sea is infinite and the noise sources are distributed uniformly over its surface. The directional characteristics of an elementary source is assumed in the commonly accepted form of

$$G^2(\varphi_p) \sim \cos^{2m}(\varphi_p)$$

where φ_e is the angle measured from the normal vector to the surface and directed into the sea, and $m = 1, 2, 3$. The values of m depend on the wind velocity and observed interval of noise frequency of the noise. It is observed that these values increase with the noise frequency and wind velocity. The intermediate layer (the so-called pycnocline) provides a sinusoidal internal wave (the first mode) with a length λ and amplitude **A** (Fig. 1). According to the foregoing assumption the sound velocity in the medium can be described as follows:

$$c(x,z) = \begin{cases} c_1 & z < \xi_1(x) \\ c_2 = c_1[1 + \Gamma(z - \xi_1(x))] & \xi_2(x) > z \geq \xi_1(x) \\ c_3 & z > \xi_2(x) \end{cases} \quad (1)$$

$$\text{where} \quad \begin{aligned} \xi_1(x) &= h_1 + A\cos(2\pi/\lambda\, x + \phi(t)) \\ \xi_2(x) &= h_2 + A\cos(2\pi/\lambda\, x + \phi(t)) \end{aligned} \quad (2)$$

and the gradient of sound velocity, Γ, can assume both negative and positive values.

It is assumed that the receiver is zero level and the z axis is directed to the surface.

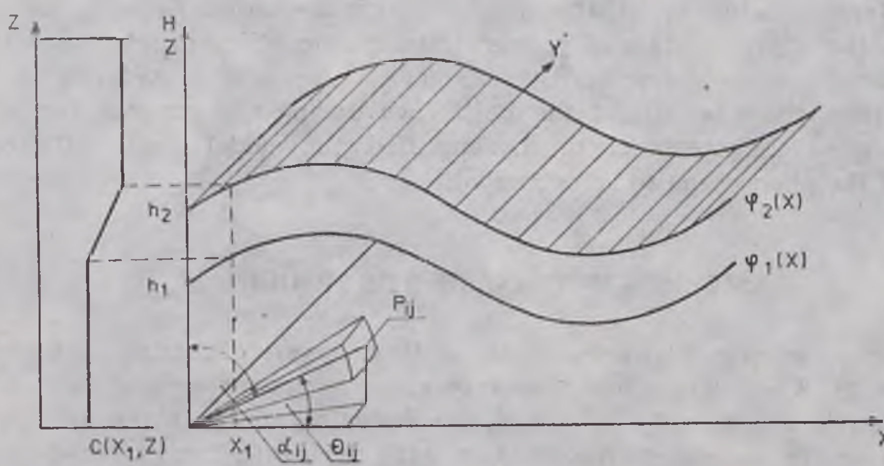

Fig. 1. Schematic diagram of the sound velocity distribution in the sea in the presence of an internal wave.
Rys. 1. Schemat przyjętego rozkładu prędkości dźwięku w morzu w obecności fali wewnętrznej.

3. THEORY

Let a selected acoustic ray (Fig. 1) leave the receiver situated at point P^{o}_{k} (x^{o}_{k}, 0, 0) at an azimuthal angle of Θ^{o}_{ij} (the angle between the 0x axis and projection of the acoustic ray on the y0x surface) and the polar angle φ^{o}_{ij} (the angle between the 0z axis and the acoustic ray). The ray intersects with the lower boundary of the internal wave at a point of co-ordinates determined by the following set of equations:

$$\xi_1(x^{(1)}) = A\cos(2\pi/\lambda\, x^{(1)} + \Phi(t)) + h_1$$
$$\frac{x^{(1)} - x^{(0)}}{\cos\alpha} = \frac{y^{(1)}}{\cos\beta} = \frac{z^{(1)}}{\cos\gamma} \qquad (3)$$

where cos α, cos β, and cos γ are direction cosines of the straight line, expressed by angles φ and Θ

$$\begin{aligned} \cos\alpha &= \sin\varphi\,\cos\theta \\ \cos\beta &= \sin\varphi\,\sin\theta \qquad (4) \\ \cos\gamma &= \cos\varphi \end{aligned}$$

For the sake of simplicity, the indices i and j are omitted here and in the following formulae.

The trajectories of the acoustic ray in the intermediate layer can be found from the eikonal equation (3).

$$\left(\frac{\partial W}{\partial x}\right)^2 + \left(\frac{\partial W}{\partial y}\right)^2 + \left(\frac{\partial W}{\partial z}\right)^2 = n^2(x,y,z) \qquad (5)$$

To do this, the formula for the square of the refractive index, $n^2(x, y, z)$, is simplified to bring it to the additive function of co-ordinates:

$$n^2(x,y,z) = n_1^2(x) + n_2^2(y) + n_3^2(z)$$

One can assume with considerable accuracy that

$$n^2(x,y,z) = \frac{1}{1 + \Gamma(z - \xi_1(x))} \approx \frac{1}{1 + 2\Gamma(z - \xi_1(x))} \approx$$
$$\approx 1 - \Gamma(z - \xi_1(x)) \qquad (6)$$

The solution of the eikonal equation will then assume the form:

$$W = \int_{x^{(1)}}^{x} \sqrt{n_1^2(x) - k_1^2}\, dx + \int_{y^{(1)}}^{y} \sqrt{k_2^2 + k_1^2}\, dy + \int_{z^{(1)}}^{z} \sqrt{n_2^2(z) - k_2^2}\, dz =$$

$$= W_1(x) + W_2(y) + W_3(z) \tag{8}$$

where for $\Gamma > 0$ $\quad n_1^2(x) = 1 - \Gamma\, \xi_1(x)$

$n_2^2(z) = \Gamma z$

The $k^2{}_1$ and $k^2{}_2$ values are determined for individual acoustic rays from conditions for direction cosines of the ray:

$$\cos \alpha^0 = \frac{1}{n(x,z)} \frac{\partial W_1(x)}{\partial x} \Big|_{x=x^{(1)}}$$

$$\cos \gamma^0 = \frac{1}{n(x,z)} \frac{\partial W_2(x)}{\partial z} \Big|_{z=z^{(1)}} \tag{9}$$

After transformation:

$$k_1^2 = \cos^2\alpha^0 - \Gamma\, \xi_1(x^{(1)})$$

$$k_2^2 = 1 - \Gamma z_1^{(1)} - \cos^2\gamma^0 \tag{10}$$

By using formulae for direction cosines, we find the equation of the acoustic ray in the differential form:

$$\frac{dx}{\sqrt{\cos^2\alpha^0 - \Gamma\, \xi_1(x^{(1)})}} = \frac{-dy}{\sqrt{k_2^2 - k_1^2}} = \frac{dz}{\sqrt{\cos^2\gamma^0 + \Gamma z^{(1)} - \Gamma z}} \tag{11}$$

As assumed, the direction characteristics of natural noise sources on the sea surface are azimuthally homogeneous, hence to calculate intensity coming from the direction determined by angles Θ and γ, only the value of the γ angle at the surface is required. This can easily be found from the equation:

$$\gamma = \cos(z, \vec{r}) = \arccos \frac{\sqrt{n_2^2(z) - k_2^2}}{n^2(x,z)} \Big|_{x^{(2)}, z^{(2)}} \tag{12}$$

where $x^{(2)}$ and $z^{(2)}$ are co-ordinates of departure of the acoustic ray from the jump layer.

By combining equations (11), depending on x and z, and integration we obtain the expression for the trajectory of the acoustic ray:

$$\frac{2}{\Gamma}\left(\sqrt{A-\Gamma z}-\sqrt{A-\Gamma \xi_1(x)}\right)=\int_{x^{(1)}}^{x}\frac{dx}{\sqrt{B+\Gamma \xi_1(x)}} \qquad (13)$$

where $A=\cos^2\chi^0+\Gamma z^{(1)}$

$B=\cos^2\alpha^0-\Gamma z^{(1)}$

The $x^{(2)}$ and $z^{(2)}$ values were determined numerically from eq. (13).

The noise intensity in the frequency band df, reaching the receiver from a small solid angle $d\Omega$ — from a surface with uniformly distributed directional sound sources, when ignoring reflections from the bottom and losses in the medium, can be expressed by (9):

$$dI(\alpha,\chi,z,f)=\frac{W(f)\,G^2(\chi_p)\,c_p^2\cos\chi_p\,d\chi_p\,d\Theta_p\,df}{2\pi\left(\int_0^{\pi/2}G^2(\chi_p)\,d\chi_p\right)c^2(0)\sqrt{1-\left(\frac{c_p}{c_0}\cos\chi_p\right)^2}} \qquad (14)$$

where W is the surface density of the spectrum of strength of noise sources, c (0) is the sound velocity at the level of the receiver; γ_p was determined from the equation. The index p denotes parameters referring to the sea surface.

The noise intensity arriving from the solid angle Ω and recorded by an acoustic antenna placed at the point $P(x^{(0)}, 0, 0)$ can be obtained by summing up the dI_{ij} values

$$I=\sum_i\sum_j a_{ij}\,dI_{ij} \qquad (15)$$

where a_{ij} are coefficients describing the solid figure of the directional characteristics of a given hydroacoustic antenna in the frequency band df.

For the sake of simplicity, in calculations, the directional characteristics of the receiver were assumed to provide a regular pyramid composed of 64 acoustic rays. In this case $a_{ij}=1$. The apex angle of the pyramid was 8°. As it can be seen from eq. (15), transition to another definite directional characteristic of the hydroacoustic antenna is easy.

4. RESULTS AND CALCULATIONS

The results of calculations of relative variations in the noise intensity of the ambient-sea-noise at the input to hydroacoustic antennas under an internal wave were accomplished in approximation of geometrical acoustics and refer to the ~ 1 to 20 — 30-kHz frequency band. The lower limit of the frequency is determined by the values of sound velocity gradients assumed in the model and actually occurring in the southern Baltic [4], as well as characteristic dimensions of inhomogeneities, in this particular case the thickness of the intermediate layer. The upper limit is determined by frequencies at which the intensity of thermal noises of the medium is still small as compared with those generated by dynamic processes on the surface of the sea.

Numerical calculations were carried out for two types of sound velocity profiles encountered in the southern Baltic during the summer and winter seasons. During these seasons internal waves occur (particularly intensively in the winter) on the boundary separating Baltic Sea waters from those of the North Sea.

The parameters assumed to describe the internal wave were as follows: amplitude A = 10 m, length $\lambda = 1000$ m and $h_2 - h_1 = 20$ m.

For the sound velocity distribution characteristic for the winter season, the values of $c_2 = 1410$ m/s and $c_1 = 1450$ m/s were assumed, whilst for the summer season $c_2 = 1480$ m/s and $c_1 = 1440$ m/s. These values were taken from a paper by Tymański [4] on sound velocity in the southern Baltic. The variations in the noise intensity were calculated for the following inclination angles of the solid figure of the directional characteristics to the level: = 5°, 10°, 15°, 20°, 25°, 45° and 90°. The acoustic axis of the antenna was directed toward the direction of propagation of the internal wave. Three values of the coefficient m characterizing the directivity of elementary sources on the surface ware assumed, namely $m=1,2$ and 3, which corresponded to various frequencies and states of the sea surface (wind velocities).

The depth of immersion of the hydroacoustic antenna was assumed to be fixed.

The low velocity of internal waves enabled the problem to be treated statically. The whole picture of the phenomenon is obtained by taking a series of „photographs" of an immobile internal wave shifted to a various extent in respect of the fixed receiver.

The calculations showed that the noise intensity increased with the decrease in the angle of observation at a given sound velocity profile and directional characteristic of sources. This is due to greater changes in the direction of individual acoustic rays emitted by sources at small slip angles.

Another regularity observed is the increase in noise fluctuations with increasing anisotropy of the noise field (i. e. at higher m values). Exemplary results of calculations of the variations in noise intensity during the propagation of an internal wave above the receiver, normalized in relation to the minimum value, are shown in Fig. 2. The abscissa is scaled in time units and T denotes the period of the internal wave (at $t \geq T$ the situation is repeated). The example shown in Fig. 2 refers to the winter stratification of the water masses in the Baltic when the sound velocity is minimal in the upper layer. The inclination angle of the acoustic axis of the antenna is 5°.

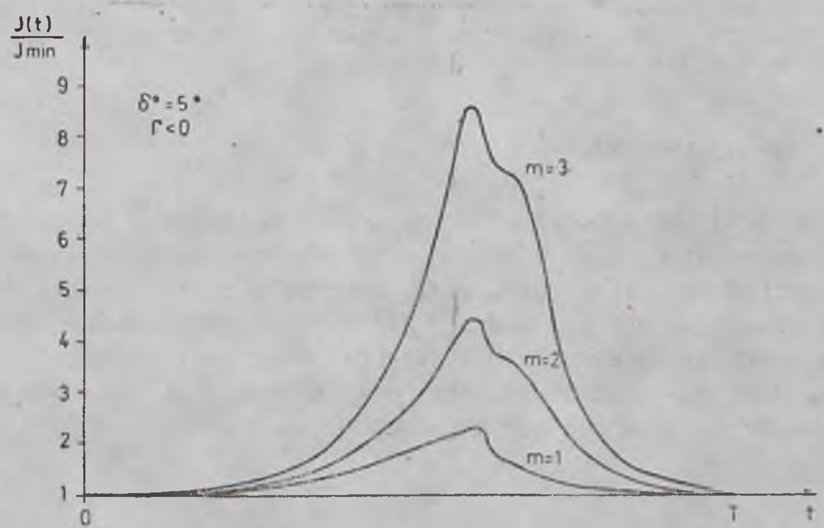

Fig. 2. Relative variations of the noise intensity below the internal wave at various directional characteristics of sources.
Rys. 2. Względne zmiany natężenia szumów pod falą wewnętrzną przy różnych charakterystykach kierunkowych źródeł.

Relative variations in the noise intensity below the internal wave, at a fixed observation angle of $\delta = 15°$ and $m = 2$, as a function of the shape of the sound velocity profile considered, is shown in Fig. 3. It is clear from this that at the same angle of inclination of the axis of the antenna, noise fluctuations are greater during the summer (curve *a*). This is due to the fact that at the same observation angle, in winter acoustic rays are emitted at a larger slip angle than in summer, owing to refraction. It is, however worth noting that absolute noise intensities recorded from a given direction are greater for small δ angles in winter.

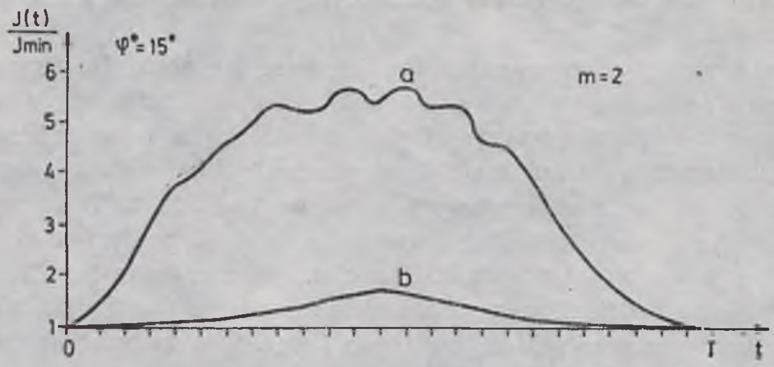

Fig. 3. Relative variations of the noise intensity below the internal wave for summer (a) and winter (b) sound velocity profiles.
Rys. 3. Względne zmiany natężenia szumów pod falą wewnętrzną przy (a) letnim i (b) zimowym profilach prędkości dźwięku.

5. CONCLUSIONS

The results of the calculations point to the possibility of indicating internal waves in a water body by means of observation of an acoustic noise field of natural origin. The fluctuations of noise intensity depend on the directional characteristics of the antenna, thermohaline situation in the basin, parameters of the internal wave and sound frequency. The fluctuations of intensity occur regularly with a variation period equal to the period of the internal wave.

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WPŁYW FAL WEWNĘTRZNYCH NA FLUKTUACJE POLA SZUMÓW W MORZU

Streszczenie

Na podstawie modelu matematycznego rozpatrzono zjawisko fluktuacji naturalnych szumów morza spowodowanych przez fale wewnętrzne.

Morze przedstawiono jako ośrodek trójwarstwowy, w którym warstwy wierz-

chnia i dolna są jednorodne, z prędkościami dźwięku c_1, $c_2 = \text{const}$, warstwa pośrednia z liniową zależnością $c = c(z)$ jest zaburzona sinusoidalną falą wewnętrzną (rys. 1).

Przy założeniu o izotropowym rozkładzie źródeł szumów na powierzchni, wychodząc z równania eikonału, znaleziono wzory na obliczenie natężenia szumów poniżej fali wewnętrznej (12 — 14).

Przedstawiono przykłady obliczeń zmian natężenia szumów na wejściu ukierunkowanej anteny akustycznej umieszczonej pod falą wewnętrzną — dla zimowego i letniego profilu prędkości dźwięku charakterystycznego dla Bałtyku, przy różnym stopniu kierunkowości powierzchniowych źródeł szumów.

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