ISSN 1063-7710, Acoustical Physics, 2018, Vol. 64, No. 1, pp. 58–63. © Pleiades Publishing, Ltd., 2018.

OCEAN ACOUSTICICS. UNDERWATER ACOUSTICS

An Investigation of the Effects of Internal Waves on Sound Propagation in a Stratified Medium with a Sloping Bed[1]

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Received October 31, 2016

Abstract—Internal waves usually cause temporal and spatial changes of density and consequently affect the acoustic wave propagation in the ocean. The purpose of this study is a laboratory investigation of the effects of internal waves generated by oscillation of a cylinder in a large stratified glass tank with a sloping bed on the sound waves propagation. Results showed that sound waves are affected by internal waves that depend on the slope angle to the direction of internal wave propagation angle ratio. When the ratio is subcritical or supercritical, the acoustic signal is much reduced as compared to the case with no sloped bottom. This can be explained in terms of the internal waves energy reaching the sloped bed and their reflections.

Keywords: internal waves, sound waves, sloping bed, experimental simulations

DOI: 10.1134/S1063771018010049

1. INTRODUCTION

The ocean usually acts like a waveguide or acoustic channel that is confined by the sea surface and the bottom. For the calculation of acoustic pressure in the ocean with common methods, knowing the distribution of density, and hence the sound speed, is very important. The distribution of the density field in the ocean can be affected by many factors [1], and one of them is internal waves. These waves can transfer energy to the deep ocean, changing the density field.

An intriguing effect of internal waves on ships is known as "dead water" that has bewildered sailors for centuries. A fascinating account of the largely erroneous interpretations of this phenomenon and the ways that were adopted to attempt to escape its influence is given by Ekman in 1904 [2].

Internal waves over a depth of more than 50 meters [2] alter the pattern of sound waves in the sea. Several studies on the impact of internal waves on the propagation of sound waves in the sea have been made. In these studies, using a number of transducers that usually work with relatively low frequencies, the influence of internal waves has been investigated [3–5, 7].

The results of these studies show that internal waves at a certain frequency of sound waves can cause the sound intensity to drop substantially. This was explained in terms of the so-called coupling modes. For example, Warren Varnas [8] has studied the coupling of acoustic modes in the presence of internal waves. In this study it was shown that the frequency of 630 Hz and the distance of 28 km had led to a loss of about 25 dB higher than when other frequencies were applied (Fig. 1). This is because at the resonance frequency (630 Hz) the acoustic modes are coupled in terms of energy transfer from one mode to another mode. Equation 1 shows the relationship between the internal wave number and transition between the n-th and m-th acoustic modes.

$$k_{\text{solitarywave}} = \Delta k_{\text{acoustic}} = \left(\frac{2\pi}{\lambda_m} - \frac{2\pi}{\lambda_n}\right), \tag{1}$$

where k is the wave number, λ_m and λ_n are wavelengths of the m-th and n-th acoustic modes respectively. Internal waves in stratified media with two or more layers have been simulated and extensively studied experimentally [9–13].

The impact of internal waves propagation is caused by small sound speed variations $\delta c(x, y, z, t)$ generated by the random vertical variations of isopycnals surfaces in the water column in the ocean. The acoustic refractive index is given as:

$$n^2(x, y, z) \cong n_0^2(z) + \mu(x, y, z, t), \tag{2}$$

where x, y, z are Cartesian coordinates with the z-axis downward, t is time and $n_0(z) = c_0(0)/c_0(z)$; $c_0(z)$ is the average of sound speed profile in space and time

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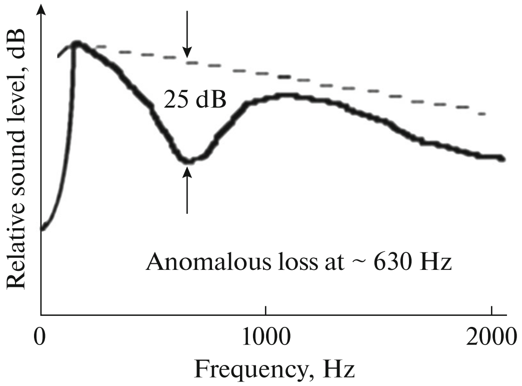

Fig. 1. The impact of the weakening effect of internal waves on sound waves, in which the coupling of the modes reduces the sound intensity [6].

and $\mu(x, y, z, t)$ is the square variance due to the internal wave propagation and given by

$$\mu(x,y,z,t) = -\frac{\delta c(x,y,z,t)\, c_0^2(0)}{c_0^3(0)}. \tag{3}$$

The μ value for the field of internal waves is obtained by

$$\mu = -2QN^2(z)\zeta(x,y,z,t), \tag{4}$$

where Q is dependent on the physical properties of water (for ocean $Q \cong 2.4\ \mathrm{s}^2/\mathrm{m}$), $N(Z)$ is the buoyancy frequency and $\zeta(x, y, z, t)$ is the vertical displacement of fluid. The displacement depends on the internal waves modes in the medium. Figure 2 shows the displacement of layers in the first two modes [14].

Katsnel'son et al. [15–17] and Lynch et al. [7] in their research considered the two limiting cases: the source is in the area of the maximal or minimal values of the soliton amplitude $\zeta_s = 0$ or ζ_o. The first case corresponds to the source position at a point with the minimal sound velocity value. In this case, the horizontal rays launched from the source are deflected toward the x-axis because of refraction. In the second case, the source is at a point with maximal sound velocity value, the rays launched from the source are deflected away from the x-axis. Both cases are presented in Fig. 2. These results show a waveguide in the first case and an anti-waveguide in the second case. The truth of this fact has been resulted numerically in Katsnel'son and Pereselkov's [18] research showing that sound fluctuations in a shallow sea are caused by internal waves.

Also, reflection of internal waves over the sloping topography plays an important role in determining exchanges between the coastal ocean and the adjacent deep waters. Internal waves have different properties of reflections from a rigid boundary than the sound or light waves do. [19] Instead of following the familiar Snell's law, internal waves reflect off a boundary so that the angle with respect to gravity direction is preserved upon reflection.

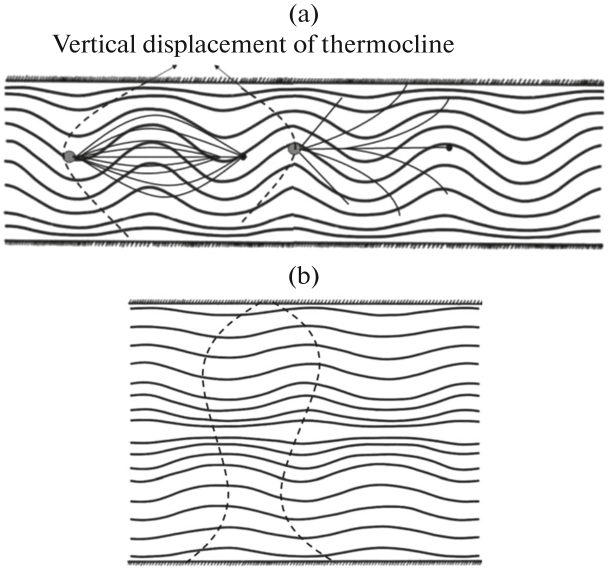

Fig. 2. Displacement of isopycnals caused by internal waves: (a) the first mode in the linear stratification medium (sound focusing and defocusing related to layers displacement are shown [12]); (b) the second mode in the non-linear stratification of the medium.

The behavior of normally incident internal waves approaching a shelf slope from offshore can be predicted from α, the ratio of the topographic slope to the internal wave characteristic slope:

$$\alpha = \frac{s_{\text{topog}}}{s_{\text{wave}}} = \frac{\partial H/\partial x}{\left[\left(\omega^2 - f^2\right)/\left(N^2 - \omega^2\right)\right]^{1/2}}, \tag{5}$$

where s_{topog} is the bed's slope, s_{wave} is the slope of internal wave's beam, H is the total depth, x is the across-slope distance, ω is the angular frequency of the wave, f is the inertial frequency, and N is the buoyancy frequency of the medium. If $\alpha < 1$ (subcritical), waves will be transmitted onto the shelf. If $\alpha > 1$ (supercritical) waves will be partially reflected back offshore. If $\alpha = 1$ (critical), the linear theory breaks down, leading to nonlinear effects, wave breaking, and turbulent mixing [19]. For obliquely incident internal waves, the effective slope has a different criticality.

There are some important studies about internal waves effects on acoustic waves propagation in the continental shelf regions as Worcester et al. [20] in the eastern North Pacific Ocean, Apel et al. [21]; Headrick et al. [22]; Badiey et al. [23]; Rouseff et al. [24] in the SWARM shallow-water internal wave acoustic scattering experiment in the Mid-Atlantic Bight continental shelf; Lynch et al. [25] in the Barents Sea