TRACKING OF THE BROADBAND SOURCE OF THE UNDERWATER NOISE IN THE VERY SHALLOW WATER CONDITIONS

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The paper contains the results, both theoretical and experimental, connected with the tracking of an underwater noise source as small ship, pontoon, diver, etc. The problem of security in the shallow water region is a challenge for underwater acousticians. In this paper, the detection of the sources that move on the surface of the sea or underwater in shallow and very shallow water is considered. The main goal concerns characterization of sound propagation in a shallow water channel. The next problem is formulation of the sound propagation inside such an acoustic duct, including normal mode creations and dispersion of acoustic energy. When we consider the noise of a small ship, two main sources are analyzed. The first is the vibration energy produced by mechanisms located inside of the ship hull. The acoustical energy is transferred through structural elements of the hull to surrounding water. This energy propagates as broadband underwater noise. The second source is the ship propeller. The sources of the underwater noise augment the total acoustical energy, specifically the ambient noise. The problem that should be solved is to discover, identify, classify and track these acoustical disturbances.

INTRODUCTION

Problems of generation and noise control in air are generally well recognized, and in certain cases, noise limitation gives satisfying results. Due to the undesirable effects of noise on humans, noise control is a matter of public policy and subject to State and NGO organizations, their main goal being the diminution to minimize undesirable vibro-acoustical effects.

We are confronted with considerably worse situation in water environment [5]. Binding law of particular states as well as EU Directives concerning care for the natural environment, lack clear rules, forcing owners of technical devices to limit the level of underwater noise [1].

The only exception, however loosely connected with care for natural environment, is the limitation of underwater noise produced by warships [9]. Military techniques of detection utilize the phenomena of generation and propagation in water of the acoustic waves produced by ships [6, 14] for monitoring their movement in a fixed sea area [11], enabling their classification and identification [3]. This fact induces users of military equipment to reduce noise produced by their individual ships, in the limiting case, to the spectral level of the environmental noise [17]. In any case, it is currently possible, by changing the temporal and spectral structure of ship-generated noise, to make their immediate classification and detection difficult or even impossible [9].

Taking into account that this paper does not deal with military production of ship noise and other underwater sources, we shall devote our attention mostly to the quantitative characterization of this noise including its disadvantageous influence on the natural underwater environment. It is commonly known that the impact of noise on aquatic organisms is harmful, as is noise in the aerial environment on any living organism, including man [2].

Passing and underwater moving objects produce noise of variable intensity, significantly increasing the overall level of noise in the sea [1, 5, 9, 10, 15]. This applies in both the sonic and ultrasonic range. Excessive levels of underwater noise adversely affect the so-called underwater ‘acoustic climate’, which is the reason that this phenomenon has been intensively investigated for a number of years [5].

The results of experimental work conducted in sea conditions pertaining to ship noise measurement are presented in this paper. Their primary aim is a detailed analysis of the generation and propagation of acoustic waves produced by vessels. The detailed analysis of acoustic signals illustrated in the form of spectrograms is presented. The receiving antenna, which provides for designating the direction and, in certain circumstances, the distance from sources of acoustic waves, was used in the majority of studies.

Elaborated research methods can be applied to diagnostics, identification and classification of sources of underwater acoustic waves [4, 12].

1. MAIN SOURCES OF UNDERWATER NOISE PRODUCED BY SHIPS

Using the conventional classification of noise produced by ships, it is possible to segregate them into [1, 8, 14] the following:

– noise generated by dynamically active devices placed inside and on the surface of the hull, mainly by engines -both propulsion and auxiliary - as well as systems of involving the transport mechanical energy – such as shafting,
– noise produced by ship propellers,
– acoustic effects connected with [?associated with] cavitation of propellers and flow around the underwater part of the hull.

At the low speed, the ship's service generator is the main source of the underwater noise generated by ship. Its tonal components which are independent of ship speed, contribute almost all of the radiated noise power of the ship. Few of these components are strong enough to be contributors to the high-speed signature. The tonal levels of the ship's service diesel generator are nearly stable in amplitude and frequency [8]. The wide-band energy of the noise generated by ship's service generator is proportional to the square of its generated power [17].

For a ship traveling at a higher speed, discrete components, which could be associated with the mechanical activity of the propulsion engines and the propellers, appear in the spectrum of the underwater noise. They are mainly noticed in the frequency range up to 100 Hz [1].

1.1. NOISE GENERATED BY A PROPULSION MACHINERY

The propulsion engine is the main source of underwater noise for a ship traveling at moderate speed. In general, the tonal level is not stable due to variations of load on the propeller for different sea states. The radiated power at the fundamental firing rate frequency is related to engine horsepower and can be estimated up to 0.1 % of total engine power. The tonal components are connected with the firing rate. For a two-stroke x-cylinder diesel engine, the firing rate is defined as [17]

$$FR = \frac{x}{60} \quad [\text{rpm}], \tag{1}$$

where *FR* = firing rate, *x* = number of cylinders, rpm = revolutions per minute.

The tonal level is not stable in general because of variations of load on the propeller caused by different sea states [6]. The radiated acoustic power at the fundamental firing rate frequency *F* is related to engine horsepower *H* as [17]

$$W \sim (\text{HF})^2 . \tag{2}$$

In analyzing the vibration caused by a diesel engine that is converted into acoustic energy, one should consider the possibility of structural resonances occurring. These may play a great role in determining the radiation efficiency of the ship's engine tones. Comparison of the spectrum of underwater noise and the spectrum of engine vibration enables us to determine the components in underwater noise caused by engine activity alone (Figure 1).

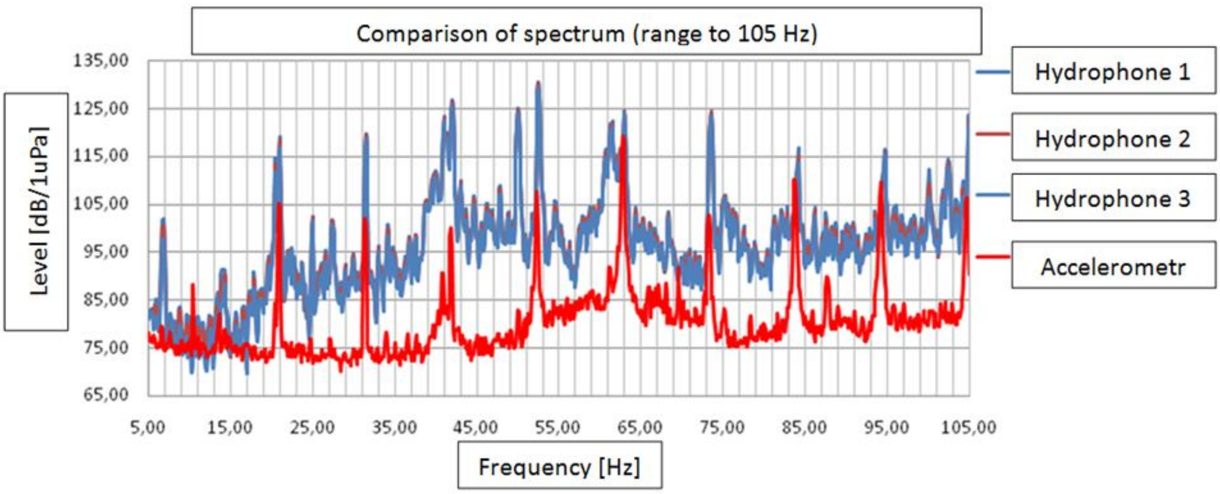

Fig. 1. Spectrum of underwater noise produced by a moving small ship measured by 3 hydrophones (H1, H2 and H3) 2.4 m distant form each other (blue) and spectrum of the vibration of the main engine (red)

1.2. NOISE GENERATED BY A PROPELLER

The most salient underwater noise source on the ship is the propeller noise. One part of it is the blade rate, which is a signal embodying the blade passing frequency and its associated harmonics. This usually gives the dominant contribution to the low frequency tonal level for a ship traveling at high speed, when the propeller is heavily cavitating [6, 7].

Given that the propeller is near the hull, the water inflow velocity is reduced significantly near the top of the propeller. The propeller of a surface ship operates behind the hull which creates a nonuniform distribution of water flow velocity in the screw disk. Additionally, the variation of the sea surface due to wind causes the area of lowest pressure to be in the region at the upper part of the propeller. At high rotation speed, a cavity can be formed which in turn collapses when the pressure increases during blade movement downward. Because such a collapse of a cavity occurs every time, the blade necessarily passes through the region of low pressure. Noise that appears in this case has a fundamental harmonic that equals the blade rate, and includes its harmonics.

Estimation of the sound pressure generated by the cavitating area can be done accomplished by assuming that the pulsation of the cavity may be approximated by a monopole source. Because the process takes place in the vicinity of the free-pressure surface, nearly perfect reflections of the sound waves occur as a second source. The result of this is that the radiation pattern of the propeller noise has a dipole character with a dipole directivity pattern. The simple expression describing the dipole pressure P_d is [14]

$$P_d(t) = \frac{d\rho}{2\pi rc}\frac{d^3V(t)}{dt^3} \quad , \tag{3}$$

where r = distance from the source, ρ = density, d = source depth, c = speed of sound, $V(t)$ = instantaneous cavity volume and t = time.

In the spectrum of underwater noise can be distinguished components whose origins can be directly linked to the activity of various mechanisms of the ship. In Figure 2 are shown consecutive spectra of underwater noise of a small ship calculated for particular sections of a track length of 1 kilometer, as well as the averaged spectrum for the track.

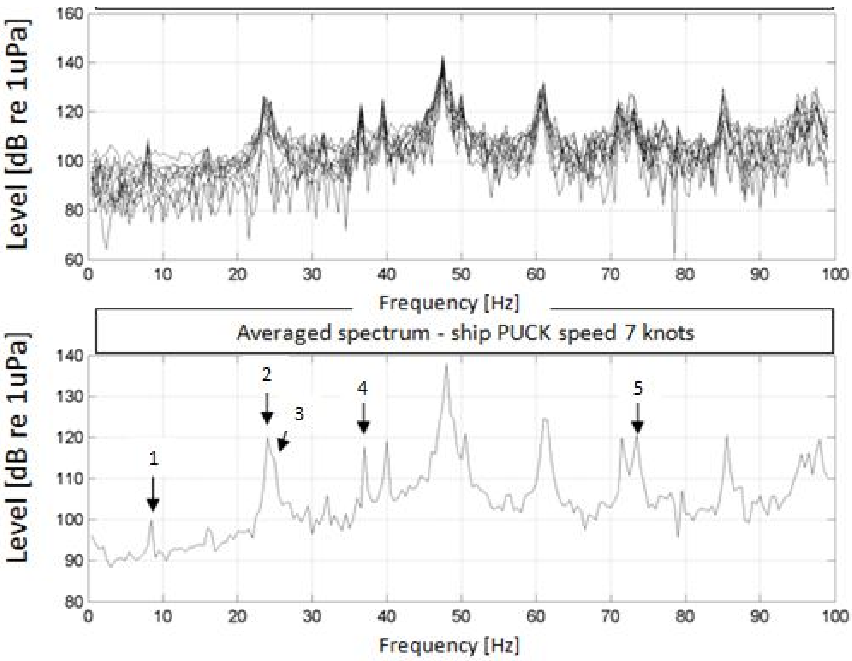

Fig. 2. Consecutive spectra and spectrum averaged for the 1 km track of the small ship: 1 - shaft, 2 – fundamental frequency of the propeller, 3 – unbalance of the propeller, 4 - combustion detonation of fuel in the cylinders, 5 - 3rd harmonic of propeller noise

2. THEORETICAL ANALYSIS OF THE ACOUSTIC FIELD DISTRIBUTION IN SHALLOW WATER

We can determine the distribution of the acoustic field generated by a source by solving the wave equation, assuming horizontal symmetry of the problem and introducing cylindrical coordinates.

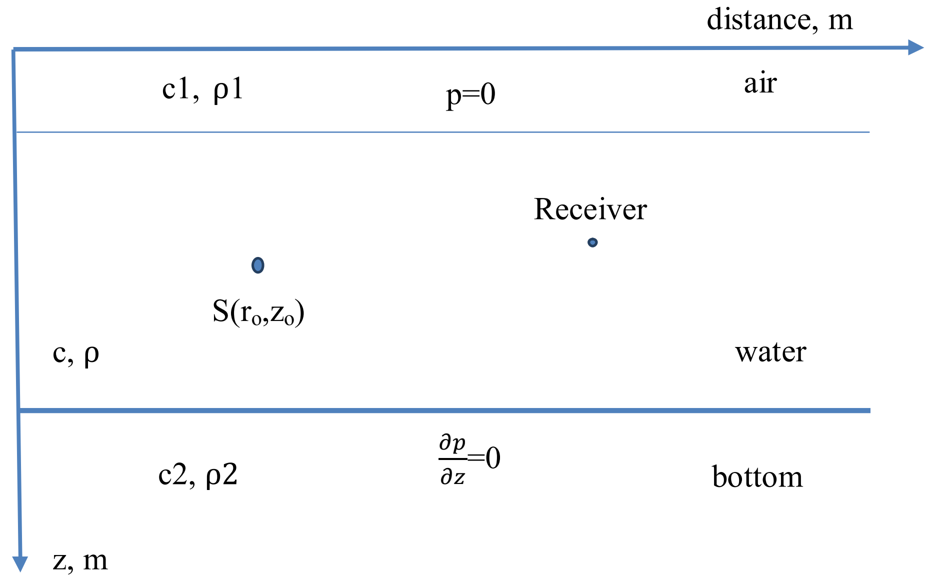

Fig. 3. Flat acoustic system limited by two liquid media

In that case [14]

$$\Delta\varphi(r,z)+k\varphi(r,z)=f(r_0,z_0) \tag{4}$$

with the boundary conditions

$$\left.\frac{\partial p(x,y,z)}{\partial z}\right|_{z=0}=0$$

$$p(x,y,z)\big|_{z=h}=0$$

$$\text{for}\quad \begin{cases}-\infty<x<\infty\\ -\infty<y<\infty\end{cases}.$$

The acoustic velocity potential $\varphi(r,z)$, from a zero-order source located inside the liquid layer, can be therefore written in the form [13]

$$\varphi(r,z)=\frac{2\pi i}{h}\cdot e^{i\pi/4}\sum_{n=0}^{\infty}\cos\frac{\pi}{h}\left(n+\frac{1}{2}\right)z_o\cos\frac{\pi}{h}\left(n+\frac{1}{2}\right)z\sqrt{\frac{2}{\pi k_{rn}r}}e^{ik_{rn}r}\quad, \tag{5}$$

where
k_{rn} is the horizontal wave number,
z_0 is the source position,
r,z are the coordinates of receiver,
h is the depth of water.

Multiplying (5) the time-dependent factor and differentiating with respect to the time according to the fundamental relationship

$$p = \rho \frac{\partial \varphi}{\partial t} \quad , \tag{6}$$

we obtain an explicate expression for the pressure in the layer [13]

$$p(r,z,t) = \frac{2\pi\rho Q}{h} \cdot e^{i\pi/4} \sum_{n=0}^{\infty} \cos\frac{\pi}{h}\left(n+\frac{1}{2}\right) z_0 \cos\frac{\pi}{h}\left(n+\frac{1}{2}\right) z \sqrt{\frac{2}{\pi k_{rn}}} e^{i(k_{rn} r - \omega t)} \tag{7}$$

where

Q is the volume velocity of the source,
ρ is the density,
ω is the angular frequency.

The formula (7) represents a series of wave modes that propagate along the layer.

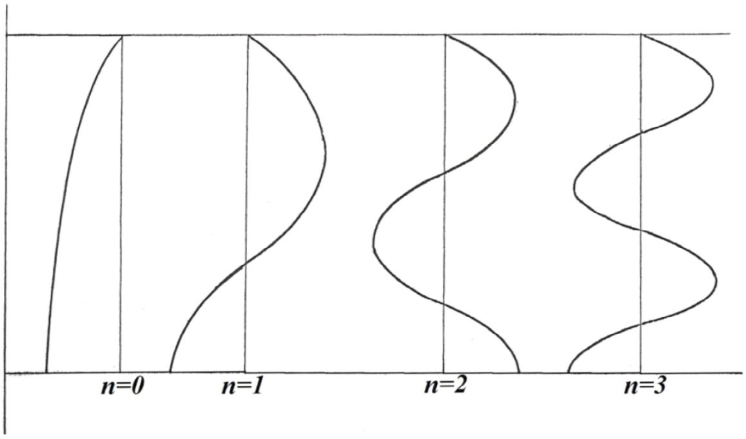

Fig. 4. Pressure distribution in cross-section of a liquid layer for wave modes of order n = 0,1, 2, 3 (as a function of depth, acoustic pressure showing behavior typical for a standing wave)

2.1. SHALLOW WATER AS A FILTER

The horizontal wave number is defined as

$$k_{rn} = k\sqrt{1-\left[\frac{c}{\omega}\frac{\pi}{h}\left(n+\frac{1}{2}\right)\right]^2} \tag{8}$$

Wave modes propagate along the layer with different group velocity defined as

$$u_n = \frac{d\omega}{dk_{rn}} = c\sqrt{1-\left[\frac{c}{\omega}\frac{\pi}{h}\left(n+\frac{1}{2}\right)\right]^2} \tag{9}$$

Wave modes of *n-th* order will be able to propagate in a layer with depth h without strong attenuation, provided that the following criterion is met:

$$k_{rn} \geq 0 \quad (10)$$

Condition (10) induces a limit for length of waves that can propagate in the layer:

$$\lambda \leq 4h \quad (11)$$

Tab.1. Upper limit of wave length that can propagate in water of depth *h*

f [Hz]	λ[m]	h=λ/4 [m]
10	150	37,5
20	75	18,75
50	30	7,5
100	15	3,75
200	7,5	1,875
500	3	0,75
1000	1,5	0,375

In spectra of natural small moving objects, components in the low frequency band are present, as, for example, in Fig. 5. Therefore, in tracking them, we must take into account the fact that their spectra are filtered due to shallow water.

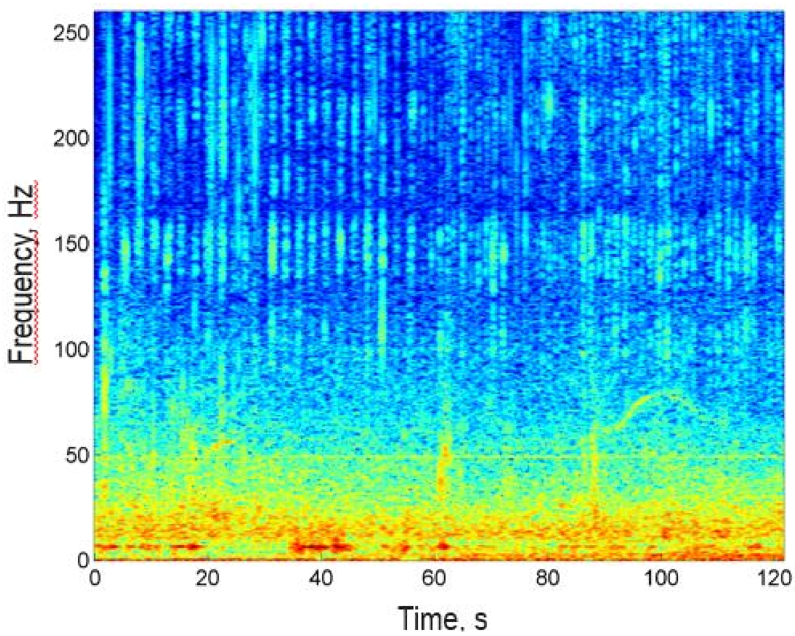

Fig. 5. Noise produced by pontoon at the paddles

3. PROPAGATION OF ACOUSTIC DISTURBANCES IN A WATER LAYER LIMITED BY FLUID MEDIA WITH FINITE ACOUSTIC IMPEDANCE

The equation for an acoustic field generated by a zero-order point source in shallow water with bottom of finite acoustic impedance [13] is

$$\varphi(r,z)=\frac{2\pi i}{h}\cdot e^{i\pi/4}\sum_{n=0}^{\infty}\cos\frac{\pi}{h}\left(n+\frac{1}{2}\right)z_o\cos\frac{\pi}{h}\left(n+\frac{1}{2}\right)z\sqrt{\frac{2}{\pi k_{rn}r}}e^{ik_{rn}r}e^{-\delta_{2n}r}\quad, \tag{12}$$

where

$$\delta_{2n}=\frac{\pi\left(n+\frac{1}{2}\right)}{h}\frac{\ln\left|b\left(\alpha_n^0\right)\right|}{2\sqrt{(hk)^2-\left[\pi\left(n+\frac{1}{2}\right)\right]^2}}\quad. \tag{13}$$

The relation (12) is a simple representation of wave modes. In comparison to the relations (7), it includes additional terms that represent a decrease of the acoustic potential with the increasing distance. The actual value of the reflection coefficient responsible for attenuation of individual wave modes is retained in the exponent. $b\left(\alpha_n^0\right)$ is the reflection coefficient at incident angle α for a zero-order point source.

Converting relationship (12) into logarithmic form for individual wave modes, we obtain the following expression [13]

$$L(r,z,z_0,n)=L_0(r_0,z_0,n)-10\log r-\delta_{in}(20\log e)r \tag{14}$$

where δ_{in} is the quantity determined for individual cases.

Thus, the acoustic pressure level of individual modes decreases as $-10\log r$ and is additionally lowered by the term $\alpha_n r=\delta_{in}(20\log e)r$.

The relationships derived above have been further corroborated with results obtained by experiment. Reflection coefficients, for different sea bottom materials, have been determined by the authors by means of the impulse method.

CONCLUSIONS

Sound propagation in the shallow water is quite different from that in deep oceanic waters. This is mainly due to the imposed boundary conditions. There appears to be a type of waveguide creation that causes the introductory mode propagation. Shallow water presents, in fact, a scenario, as it were, of two parallel sources contained inside the normal mode, whereby it follows that we should use the group speed of sound waves instead of the phase speed. In this manner one can observe the geometrical dispersion of a single frequency wave. The main purpose of this paper was to extract the ship noise embedded in surrounding noise. This was the first step, because the correlation method was used to find the parameters of movement of the chosen source, taking into consideration that the cross-correlation features of any non-correlated signal were removed. This allows us to track the given source or multiple sources.

The waveguide propagation phenomenon is strictly connected with the relation between the depth of the sea and wavelength of the sound wave. The waveguide acts as a kind of spatial filter that eliminates the low frequency waves. This can be seen as a limitation of applying the method for low frequency sources. Examples show that this method can be used successfully for tracking small boats and sea-tenders.

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