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Shipping noise propagation at the shallow sea

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ABSTRACT

The paper proposes a method to determine the noise map on the shallow sea basin based on the classical solution of the wave equation for specific boundary conditions. As a result, we get a solution consisting of a superposition of analytical solutions for the issue of own waves related to the depth in relation to changes in the function responsible for changes from distance to source. For a stationary problem, the expression describing the noise of the selected vessel in spectral form will be used as a function of excitation. This formulated issue allows us to estimate the underwater noise level at any distance and depth from the source. The analysis of the superposition of underwater acoustic disturbances makes it possible to determine the value of the sound pressure level from the sources of these disturbances.

Keywords: Shipping noise, Shallow sea, Modal propagation

1. INTRODUCTION

The issue of rapid noise growth in the oceans and seas is currently a challenge for research teams dealing with underwater pollution. At present, for the EU water areas, a directive has been developed, which is intended to cause a reduction of acoustic background, the main component of which is underwater noise caused by human activities, mainly related to maritime transport (shipping noise).

It's common knowledge that the underwater environment contamination by noise has been growing year by year especially close to fairways along which transport ships, touristic motor boats and other water surface communication means operate [1], but also close to active objects of marine infrastructure [2]. The situation becomes relatively serious as excessive noise and other energy sources significantly affect not only living conditions inside ship [3] but also underwater biological life [4,5] which becomes more and more endangered not only by noise, light, uncontrolled impact of chemical products, but also unbalanced management of fish resources.

For that reason the EU has issued an appropriate directive obligating EU countries to obey definite acoustic standards concerning water environment. The directive of EU Parliament and Council 2008/56/WE of 17 June 2008 enacts framework for EU activities in the domain of sea environmental policy, within which EU countries have to undertake necessary actions aimed at reaching or maintaining a good environmental status of sea waters (Good Environmental Status – GES) not later than before 2020 [6,7]. According to the directive, in order to protect sea water environment, EU countries have to prepare and implement a maritime strategy and sea water monitoring program.

In the directive 2008/56/WE there are defined 11 descriptive indices for which an assessment as to the defined criteria of good environmental status should be performed. One of them is the index W11 – Underwater noise and other energy sources.

Relating the considerations to the Baltic Sea, especially to its southern region, one can state that propagation of acoustic waves is of a specific character associated with small depth of the water areas in question [8,9]. In view of occurrence of the geometrical limitations of the medium in which acoustic wave propagates, namely, close presence of free water surface and seabed, a form of propagation of disturbances definitely differs from that typical for deep waters [10,11,12] where water depth is much greater than length of wave of the lowest frequency produced by a ship sailing nearby.

Therefore in a distance from the ship there is produced an acoustic field which has a character of moving waves, called wave modes. This results from a complex structure of interferring waves which multifold reflect from both seabed surface and free sea water surface [13,14]. Apart from the phenomenon of reflection from free sea water surface we have to do with the change in wave phase by the angle π, which means that the wave reflected from the surface is in counter-phase in regard to the projecting wave. Therefore the interferential acoustic field has a property of moving the wave modes, for which a group velocity is characteristic. It means that we have to do with the phenomenon of geometrical dispersion of velocity, known from physics.

Apart from the modal propagation of acoustic waves, additional phenomena associated with presence of seabed take place. The seabed has physical features called the material constants such as density and elastic wave propagation velocity [15,16], of values close to respective properties of sea water. It means that seabed impedance is usually greater or a little greater than that of sea water.

For this reason some part of acoustic wave energy penetrates the seabed. In case of a rocky seabed, i.e. that having shape elasticity additional transverse acoustic waves in the range associated with a spectrum of acoustic waves produced by underwater acoustic disturbance sources (i.e. ships), may occur. In this paper there are presented results of numerical investigations based on the real data from measurements of noise produced by a selected floating unit (ship) [17], concerning selected characteristic spectral components. The simulations were performed by applying a shallow sea model of definite physical parameters such as acoustic wave propagation velocity, geometrical dimensions (water depth) as well as acoustic parameters of seabed, that was discussed more thoroughly in the publications [18,13]. The data in question were presented in the form of distribution of particular wave modes in function of water depth for selected horizontal distances from source of disturbances. Results of the investigations will be used for the determining of acoustic climate of a water area, that is the key procedure for taking into account a single object emitting underwater noise.

2. UNDERWATER NOISE EMITTED BY SHIPS

Ship traffic is a main source of underwater noise, especially in regions of fairways. Ship is a broad-band source of spectral characteristics which is tightly associated with applied design solutions as well as current working parameters of shipboard devices.

On ships, their propellers are the most efficient source of underwater noise. One of its parts is the propeller rotation frequency and its harmonics. Noise components coming from the propeller constitute usually a dominating part of underwater disturbances in the low-frequency band at large speeds of ship, especially when the propeller is in developed cavitation state [11]. Ship propulsion engine is the main source of underwater noise at a moderate speed of ship. Generally, a level of underwater noise spectrum components of a ship is not stable due to changes in propeller load in different sea states. The acoustic power radiated at the fundamental ignition frequency is associated with engine output and may be estimated equal to about 0,1% of the total engine power.

Information on spectrum characteristics, called also ship's signatures, we obtain on the basis of underwater noise measurements carried out in mobile or stationary testing grounds [17,11]. The mobile testing ground may be consisted of a few hydrophones fastened on a frame in some distance from each other. The measurements can be conducted with hydrophones arranged either in horizontal or vertical plane. A merit of such measuring system is its possible location in an arbitrary point of water area. More precise measurements of underwater noise are conducted in stationary testing grounds. In this case sensors are located in strictly determined points and strictly determined depth whereas a tested ship moves over them at a given course. A drawback of the solution is that there is not possible to obtain results for one depth and one kind of seabed. On the basis of measurement results a series of ship underwater noise characteristics can be obtained, that allows to assess pressure level changes in function of distance and depth for different ship speed values and different settings of shipboard devices. One of the characteristics is spectrum characteristics, called often ship's signature. An example of ship's signature is shown in Fig. 1.

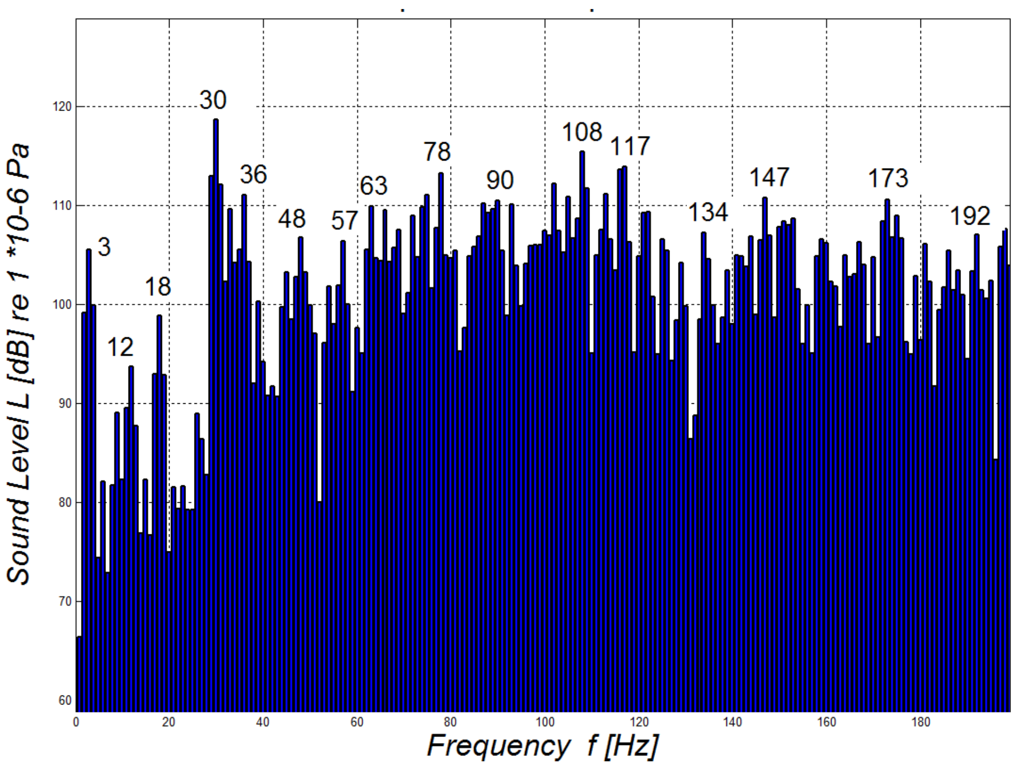

Figure 1 – An example of ship's signature

Worth stressing, that, independent of ship's type, the main part of acoustic energy radiated to water is located within low frequency band, up to a few hundred Hz.

3. PROPAGATION OF ACOUSTIC WAVES IN THE WATER LAYER OVER A BOTTOM WITH FINITE ACOUSTIC IMPEDANCE

The case of propagation of acoustic waves generated by a source of zero order in flat-parallel waveguide corresponded to idealized conditions. The simplifications concerned, in particular, the lower half space. In reality, the sea bottom with properties close to these of the perfectly rigid medium is rather an exception [19,20,21]. The assumption allowing us to simplify the effects occurring on the water-air boundary is in principle always valid, as the acoustic impedance of water is about 3500 times higher than the acoustic impedance of air [6,22].

On the lower boundary of the system, the situation is entirely different. Acoustic impedance of the sea bottom is typically close to this of water. In the case of sandy seabed, acoustic impedance of water is only four times lower than impedance of the sea bottom. For silty and clayey bottom the ratio is even lower. Therefore, some portion of acoustic energy will be transferred from the water layer to the bottom, resulting in a decrease of the acoustic pressure level with increasing distance. After many transformations which were presented at work [23] we obtained, finally,

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

where

$$\delta_{2n} = \frac{-\pi\left(n+\frac{1}{2}\right)}{h} \frac{\ln\left|\hat{b}_1\left(\alpha_n^0\right)\right|}{2\sqrt{(hk)^2 - \left[\pi\left(n+\frac{1}{2}\right)\right]^2}}\ , \tag{2}$$

$$\hat{b}_1(\theta)=\frac{m\cos\theta-\sqrt{n_1^2-\sin^2\theta}}{m\cos\theta+\sqrt{n_1^2-\sin^2\theta}}, \tag{3}$$

$$\alpha_n^0=arc\ \sin\frac{\pi\left(n+\frac{1}{2}\right)}{kh}. \tag{4}$$

Symbol r denotes the distance from the source in a horizontal plane, z is the depth of the receiver, Q stands for source volumetric velocity, ρ – density of medium in which wave propagates, h – depth of water layer, z_0 – depth of the source, k_{rn} – horizontal wave number.

$$k_{rn}=\sqrt{1-\left[\frac{c}{\omega}\frac{\pi}{h}\left(n+\frac{1}{2}\right)\right]^2} \tag{5}$$

$b(\alpha_n^0)$ is the reflection coefficient at incident angle α for a zero-order point source, m – relative density of bottom material, $m=\rho_1/\rho$, n – relative sound speed in bottom material, $n=c_1/c$, ρ_1, c_1 – density and speed of sound in bottom, ρ, c - density and speed of sound in water.

The impact of sea bottom properties on acoustic wave propagation is included in the expression exp ($-\delta_{2n}r$). When deriving expression (1), modulus of the reflection coefficient constituting a multiplier at hyperbolic functions was assumed to be unity. This allowed us to obtain a simple representation of wave modes propagating along depth of the layer. However, the actual value of the reflection coefficient responsible for attenuation of individual wave modes was retained in the exponent.

Relationship (1) describes the acoustic field generated by a zero-order point source. Comparing it with perfectly reflecting the bottom it can be seen that they include additional terms. The terms represent a decrease of the acoustic potential with the distance.

The relationships (1) will be further used in numerical investigations of the impact of properties of sea bottom on acoustic fields and confronted with results measured in the experiment. Reflection coefficients, for different sea bottom materials, have been determined by the authors by means of the impulse method.

4. WAVEGUIDE SOUND PROPAGATION IN SHALLOW

Characteristic features of waveguide propagation in shallow sea will be presented on the example of results of experimental and numerical investigations of a tug. In the spectrum there is possible to distinguish a series of characteristic components within a rather broad frequency band, namely almost up to 1000 Hz. In Table 1 are shown the components determined on the basis of measurements conducted under the ship in a 20 m deep water area with the use of a hydrophone placed 1 m over the seabed, whose pressure level exceeded 155 dB.

Table 1 – Components of underwater noise spectrum of a tug whose pressure level exceeded 155 dB, i.e. about 56 PA

Frequency [Hz]	48	60	107	169	213	322	426	449	459	484	851	966
Pressure p_0[Pa]	91.9	123.2	121.8	60.1	113.6	95.5	137.9	96.5	75.6	79.1	59.3	90.1

The calculations were made for all distinguished frequencies under the following assumptions:

- Water depth h=20 m
- Salinity S=7.1 PSU
- Water temperature T=14°C
- Sound speed in water, c=1470.8 m/s
- Water density, ρ = 1004.7 kg/m3
- Source immersion depth z = 1m under water surface.

There were considered situations of sound propagation over a sand, gravel and silt seabed, respectively, of the following geo-acoustic parameters [15,16,24,21]:

- Medium silt: m = ρ1/ρ = 1.147; n = c1/c = 0.9801

• Fine sand: m = ρ1/ρ = 1.2236; n = c1/c = 1.0364
• Fine gravel: m = ρ1/ρ = 2.4923; n = c1/c = 1.338

Distributions of the total underwater noise of the tug within the frequency band up to 1000 Hz in the distance from the ship equals 1000 m, in the case of disturbance propagation over different types of seabed: fine sand, fine gravel and medium silt, is presented in Fig. 2. It should be observed that the spatial pressure distribution depends on a type of seabed. The non-uniform pressure distribution in function of water depth results from the forming and propagating of wave modes.

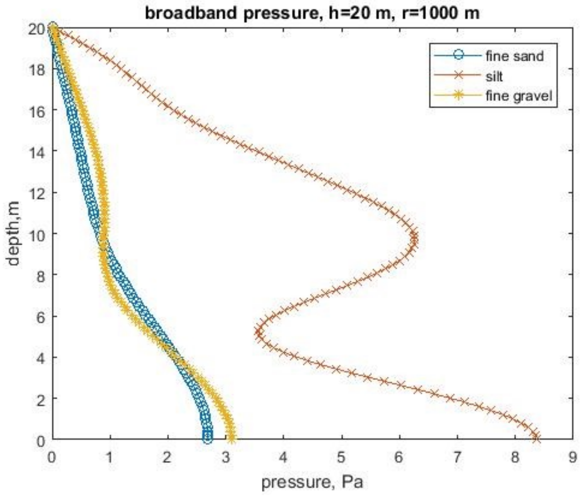

Figure 2 – Broadband pressure at distance of 1000 m from the source for different types of bottom

Based on the results of calculation, there is possible to examine an impact of formation of wave modes on distribution of resultant acoustic pressure for particular components of frequency spectrum of the tug in question. On the diagram, Fig.3, are shown the vertical wave modes pressure distributions for the tug's spectrum component of 213 Hz frequency and the resultant pressure at the distance of 100 m from the ship.

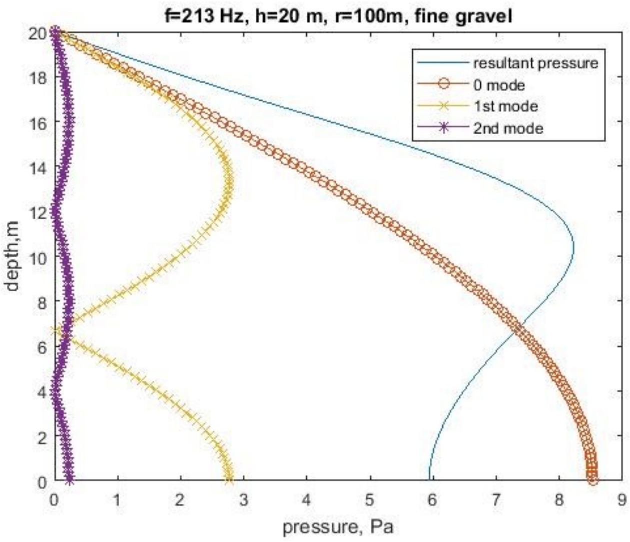

Figure 3 – Modes of the spectrum component of 213 Hz frequency at the distance of 100 m from the ship

The wave modes start to form in a rather small distance from source, namely that at which spherical propagation resulting from reflections from the surfaces limiting the layer becomes conversed into cylindrical one. In the case in question the wave modes are formed for all components of the tug's spectrum, and their number depends on frequency. The higher the frequency the bigger the number of wave modes.

In the case of modes propagation we have to do with dispersion of sound propagation velocity. Every wave mode propagates with a different velocity. The modes gradually fade out along with growing distance and finally we have propagation of a single mode.

The assessment of impact of a kind of seabed on acoustic energy absorption we conduct on the basis of changes in the resultant pressure which is a sum of modes for a selected component of the tug's frequency spectrum. In Fig. 4 and 5 there is demonstrated in which way the vertical resultant pressure distribution for the 213 Hz frequency component changes at different distances from the ship and under the assumption that we have to do with the seabed formed of fine gravel and fine sand, respectively.

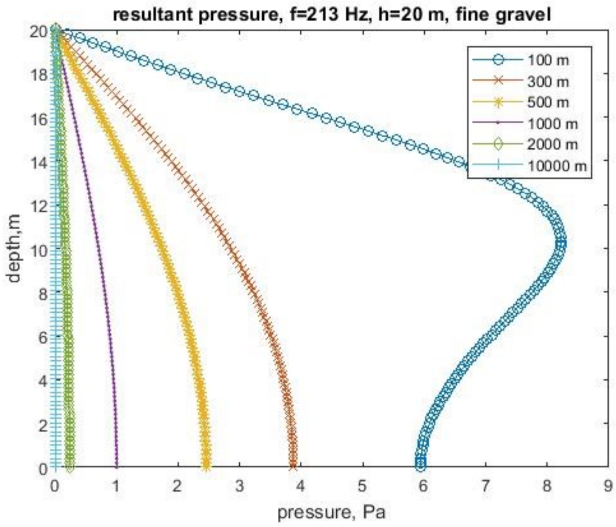

Figure 4 –Vertical resultant-pressure distribution for the 213 Hz frequency spectrum component in different distances from the ship, in case of fine gravel seabed

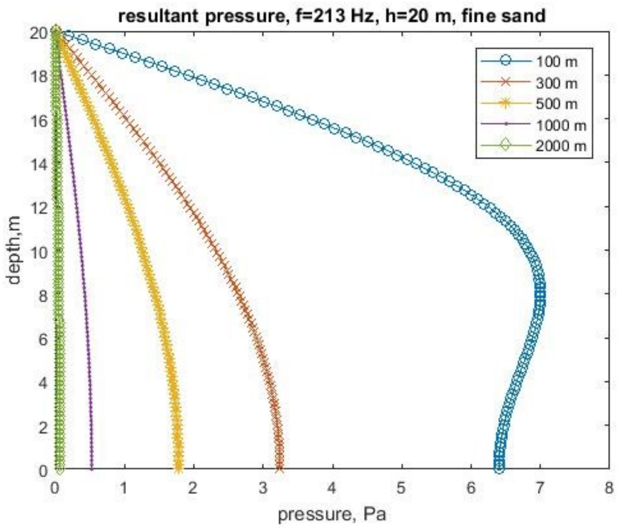

Figure 5 –Vertical resultant-pressure distribution for the 213 Hz frequency spectrum component in different distances from the ship, in case of fine sand seabed

The 213 Hz frequency component reaches 1000 m distance over the fine sand seabed and up to 2000 m – over the fine gravel seabed. 12 significant frequency components were distinguished within the tug's spectrum. The acoustic energy emitted to water is composed mainly of them.

Examining the diagrams we are able to assess the changes in vertical distributions of total tug–generated pressure, which occur along with growing distance. We may also assess impact of a kind of seabed on disturbance propagation range, as it is shown in Fig. 6.

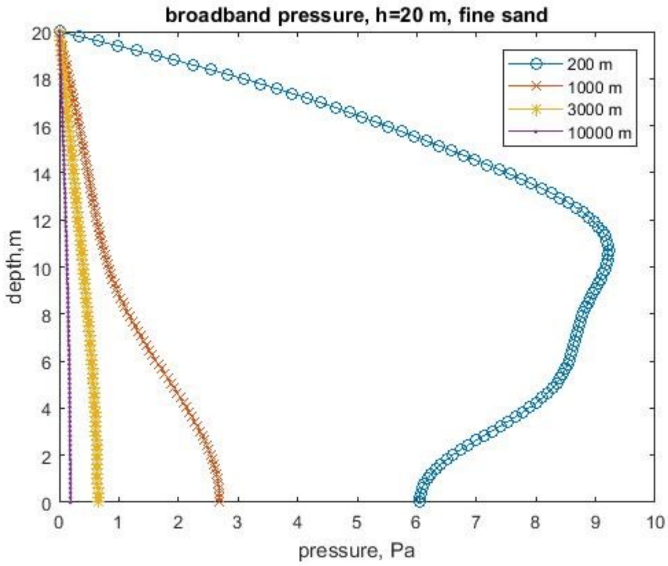

Figure 6 – Vertical distribution of total tug-generated pressure in the distance up to 10000 m from the ship in the case of propagation over the seabed composed of fine sand

The total ship-generated pressure distributions confirm that effects of disturbance propagation in the form of wave modes are visible only up to some distance. The wave propagates further in the form of one mode. The distance depends on a kind of seabed. In the considered case higher modes fade out fastest over fine sand seabed and latest over medium silt seabed.

5. FINAL REMARKS

While assessing the range of acoustic disturbances in the Baltic Sea one should take into account that the acoustic wave propagation in this water area completely differs from the propagation in a deep sea. Application of the spherical propagation model is a too -far -going simplification which may lead to an erroneous estimation of energy transmission losses. The Baltic Sea exemplifies a shallow sea which can be represented as an acoustic system of a flat-parallel waveguide structure filled with liquid layer and separate boundary conditions for each of the boundaries of the layer. In this paper the use was made of the method, presented already in the preceding publications, for estimation of energy transmission losses in shallow sea for case modal propagation of broad-band signal in water areas of different kinds of seabed. The investigations were performed on the basis of these author's own measurements of underwater noise emitted by ships, for definite bottom sediments. Attention was paid to the forming of modes for all frequencies contained in underwater noise spectrum of the considered ship. For the higher spectral frequency components, a greater number of modes is formed and multi-mode propagation phenomenon reaches a greater range than in the case of the low frequency components. A kind of seabed, i.e. its geo-acoustic parameters, affects the range of the total noise generated by the ship, similarly – the range of the propagation in the form of wave modes, that results from that a part of acoustic energy penetrates into seabed. Attention was drawn to the fact that the water layer has discriminative features which make propagation of the waves having length fourfold greater than water depth, impossible in the conditions assumed in the considered case.

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