Acoustic and Biomedical Engineering

Shipping Low Frequency Noise and Its Propagation in Shallow Water

E. Kozaczka[a,b,*] and G. Grelowska[a]

[a]Gdańsk University of Technology, G. Narutowicza 11/12, 80-223 Gdańsk, Poland

[b]Polish Naval Academy, Śmidowicza 69, 81-103 Gdynia, Poland

One of the most significant factor influencing acoustical climate of the sea is underwater noise generated by moving ships. If the considered sea area has features of the shallow water, namely the wave frequency fulfils relation $f < \frac{10c}{h}$, where c denotes phase speed of sound, and h is depths of the sea, then in certain distance from the wave source specific image of sound pressure distribution in the mean of wave modes appears. The modes constitute wave packet propagating with group speed in the direction parallel to the sea surface. The paper presents results of the experimental investigation concerning the distribution of the sound field created by moving ship in the shallow water, in a small distance from the ship. The main acoustical characteristics, describing features of the field are spectrograms in pseudo-3D system: distance and frequency in geometrical form, and sound intensity in the optical one (color). Results presented in such a way pointed individual features of the sound source known often as acoustical signature of the source (ship).

PACS: 43.30.Nb, 43.50.Yw, 43.50.Rq

1. Introduction

For decades the high interest in acoustic noise produced by ships, has caused that it was subject of intense investigation, both theoretical and experimental [1–3]. The primary practical aspect of this investigation is military usage of noise produced by ships in reference to their detection and localization. Precise localization is essential for implementation of means of destruction, mainly underwater ones. In turn, detection and tracking, including determination of trajectory of ship, and possible classification and identification, are used as an element of imaging the spatiotemporal situation in the given sea area.

Thorough analysis of underwater signal generated by moving ships, can be valuable complementation of the vibroacoustic procedure, directed to diagnosis of the technical state of the investigated ship.

One of the main characteristics of ship noise is instantaneous power spectrum, which allows to distinguish so-called "harmonic components" from spectral band, characterizing underwater noise produced by ship. They can be easily bounded with dynamic of propulsion and auxiliary systems. Set of such characteristics determined directly one by one creates so-called spectrogram of underwater noise. If ship noise propagates in the shallow water, then acoustical images of their intensity have diversified shape in the form of sharp curves, like exponential functions in the coordinate system: distance–frequency (lengths of wave).

2. Measurement setup

The experimental investigation was carried out in the sea area of depths to 50 m. The received array in a line-form, whose axis was parallel to sea bottom and mostly perpendicular to the direction of the ship movement, was used for the measurement of acoustical characteristics. During experiment the measurements of the pressure and of the intensity of the wave by means of gradient method were carried out simultaneously. Measuring setup ensured linearity and equal receiving sensitivity in frequency range 5 Hz–30 kHz. Before the investigation the setup was calibrated according to the procedure, whose block-situational diagram is presented in Fig. 1.

In the investigation multichannel measuring setup was used, composed of underwater part (linear antenna, hydrophones) and surface registering and analyzing setup.

3. Results of *in situ* investigation

The acoustic noise measurements of ships are carried out periodically. During the measurements ships pass at least twice through the trial area with the set work parameters of the propulsion system. The determined ship parameters are reached at the distance of 300 m at least before the trial area and maintained over the distance of 600 m at least. Sound pressure registration at a distance afore and astern the ship make it possible to characterize

* corresponding author; e-mail: kozaczka@pg.gda.pl

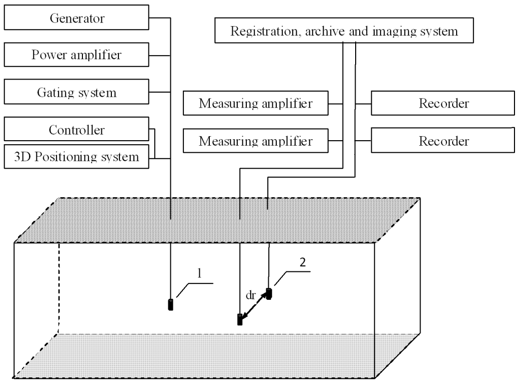

Fig. 1. The diagram of setup for calibration elements of measuring system: 1 — transmitter (source of sound), 2 — receiving hydrophones.

underwater disturbances of the ship. The results of measurements of ship noise are very often presented in the form that allow to assess changes of sound pressure as function of time and frequency. An example of the spectrogram obtained basing on recorded data is presented in Fig. 2.

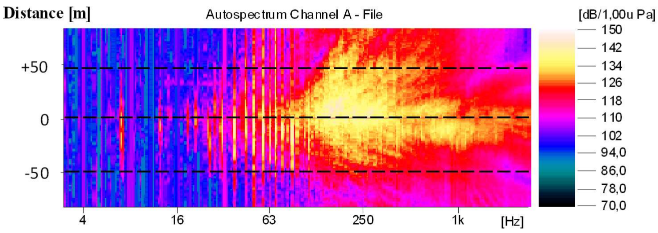

Fig. 2. The acoustic field spectrogram of the ship moving with forward speed of 4 kn.

The spectrogram consists of 299 spectra recorded every 312 ms with the resolution of 0.04167 of octave in the frequency range from 3 Hz to 2818 Hz. Dashed lines mark the distance of the ship from the acoustic sensor.

In the spectrogram two areas could be distinguished clearly. The first area is the one of low frequencies range to about 100 Hz. In this area the spectrum is composed of distinctive components resulting from working ship mechanisms. The second area created in the frequency range from 100 Hz to 2.8 kHz contains a continuous spectrum. Noise in that range is connected mainly with activity of cavitating propeller and flow around the hull. Such a way of underwater noise analysis makes it possible to select a spectrum in any part of the ship path over the trial area as well as in chosen range of frequency.

On the basis of the simultaneous measurements of underwater noise and vibration of main mechanisms and auxiliary equipment of the ship, it is possible to define unambiguously the components visible in the first of area distinguished in the spectrogram [4, 5]. To identify the components, the spectral analysis with using constant band width filters is often performed. A representative spectrum of the ship in motion is shown in Fig. 3.

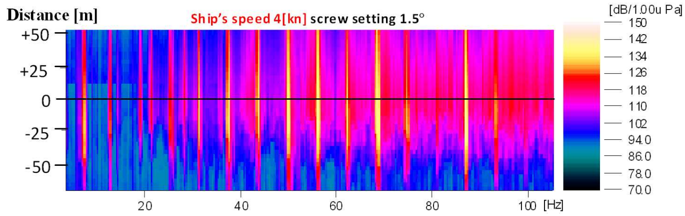

Fig. 3. The acoustic field spectrogram of the ship with forward speed of 4 kn, performed in the frequency band up to 100 Hz.

The spectrogram consists of 74 spectra recorded every 1.333 s with the resolution of 0.25 Hz in the frequency band up to 100 Hz. From the set of spectra the one was selected when the ship's power plant was situated just above the acoustic sensor (the place distinguished with black line at the spectrogram).

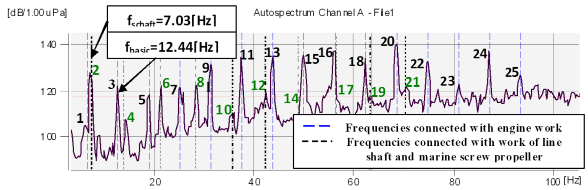

Fig. 4. The ship noise spectrum at the distance marked "0" in Fig. 3.

In Fig. 4 discrete components are noticeable which are the effect of activity of main engines, shaft lines and propeller, and also an electric generating set. Each particular component was distinguished by a successive number, namely one group of numbers (2, 4, 6, 8, 10, 12, 14, 17, 19, 21) indicate components coming from propeller and shaft lines, and other group of numbers (1, 3, 5, 7, 9, 11, 13, 15, 16, 17, 18, 20, 22, 23, 24, 25) show components coming from working main engines. The identification results obtained by using the method in question have been confirmed in the following papers [4–7]. Above figures present only an example of results of spectrum analysis performed for a given working regime of ship propulsion system. The spectral characteristics of ships change according to working regimes of their propulsion systems and also differ significantly for particular classes of ships.

One of the fundamental features, which differed the sound intensity measurement from the sound pressure one, is the possibility of determining the phase differences between active and passive part of the sound field [7–9], which allows to determine direction of propagation of acoustic waves in water.

In view of the limitations imposed on the application of the measurement method in question [8, 9], the frequency band for processing the measurement results was limited from 6.9 Hz to 1 334 Hz. The accuracy of determination of the level for the frequency of 6.9 Hz should not exceed ± 3 dB, and for the upper frequency: ± 1 dB.

In Fig. 5 the example of spectrogram of the sound intensity is presented that was determined basing on data recorded by two hydrophones in accordance with the equation

$$I = \frac{1}{2\pi k \rho \Delta r} \mathrm{Im}\left(G_{xy}(k)\right), \tag{1}$$

where I — intensity of sound, k — wave number, ρ — density of medium, Δr — distance between sensors, $\mathrm{Im}(G_{xy}(k))$ — imaginary part of the cross-spectrum.

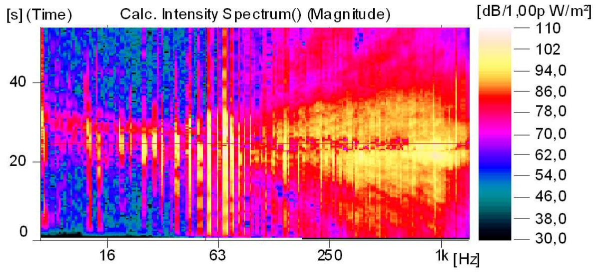

Fig. 5. The spectrogram of underwater noise intensity obtained in the frequency band from 6.9 Hz to 1334 Hz.

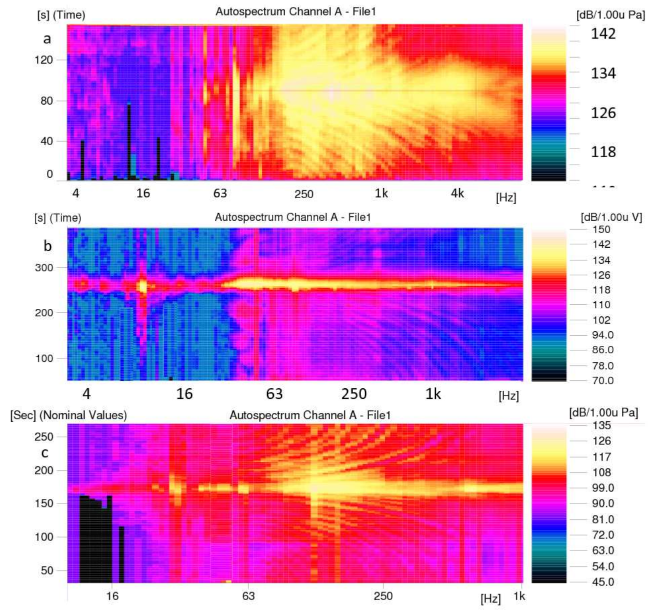

Fig. 6. Acoustic noise image obtained during the test ship on the range set: (a) depth $h = 10$ m; ship speed 13 kn; (b) a turbine-powered ship; $h = 10$ m; ship speed 9 kn; (c) depth $h = 27$ m; ship speed 15 kn (bottom).

4. Characteristic forms of ship noise spectrograms connected to noise propagation in shallow water

In the study of underwater acoustic disturbances involving the appointment of three-dimensional characteristics of the noise in the system — the frequency, distance and intensity, some characteristic lines were observed, associated with the energy density, which take the form of hyperbolas, where the frequency axis is one of the asymptotes.

In the shapes of the acoustic field characteristics of different classes of vessels with different types of main propulsion (diesel engines and turbines) and measuring at different depths and at different speeds numerous lines are visible when the ship approaches and departs from the sensor. Characteristic lines representing more local energy density are the specific characteristic of acoustic waves in shallow seas. These lines are more evident during the longer distances traveled by ship. Sample spectrograms of the ship noise in shallow sea is shown in Fig. 6.

Local reinforcement (rays) visible on the spectrograms are associated with the propagation of acoustic waves of different lengths in a shallow sea. In order to explain this phenomenon, simulation of a description of these rays was carried out [4]. In the simulation theoretical model of Weston [3] was used describing the propagation of waves in the sea. For simplicity, the model assumed a depth measurement $h = 20$ m, speed of sound in water, $c = 1450$ m/s, and also assumed that the medium is lossless.

In the proposed simulation, set of rays have been determined, corresponding to waves of different lengths, which reflect from the borders (water–air and water–sea bottom). For this purpose, a numerical code was elaborated, in which the waves were determined for varying distance from sound source to the sensor. For the calculation it was assumed that the maximum wavelength that can be propagated at this depth is 40 m. The calculations were performed for wave length range from 0.1 m to 40 m with a resolution of 0.1 m. Since in real conditions, underwater noise is recorded before and after the measuring range, so the program makes adjustments to make possible the appointment of rays that may arise during ship reaches the range. The resulting matrix make it possible to draw the shape of those rays as a function of frequency, as shown in Fig. 7. Just as the ship was directly above the sensor, a wavelength of standing wave was 40 m. The length of this wave sets the creation of the fundamental mode, which is associated with the depth [3, 6].

5. Summary

In the shallow sea, it is possible to identify underwater acoustic waves associated with propulsion systems and auxiliary mechanisms working in ship. Extensive tests conducted on ranges have shown that, based on measurements of underwater noise, in the structure of underwater acoustic field of the ship, one can, in vast majority, identify the specific components, associated with the work of the main engines, shafting, propellers and also from working electrical sets. The method used to identify the acoustic waves, work-related machinery and

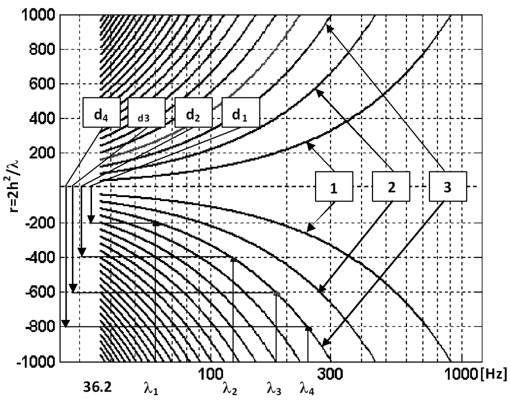

Fig. 7. The shapes of the line with higher intensity in function of normalized depth of the sea and frequency: 1 — distance d_1 of 200 m from the source of wave of length $\lambda = 24$ m; 2 — distance d_2 of 400 m from the source of wave of length $\lambda = 12$ m; 3 — distance d_3 of 600 m from the source of wave of length $\lambda = 8$ m; 4 — distance d_4 of 800 m from the source of wave of length $\lambda = 6$ m.

equipment mounted on board, which consists of simultaneous measurement of vibration and sound pressure, allowed accurate determination of the frequency of these waves.

The received results of investigation conducted in natural conditions were acoustical images of ship noise, known as spectrograms, and underwater noise spectra, which created valuable characteristics allowing to describe vessels and to rate dynamic parameters of mechanical devices placed both inside and outside the hull.

The interesting and original contribution was the interpretation of the way of ship noise propagation in shallow water, proving the mode theory of propagation of a wave packet (group wave) into geometrical form known as plano-parallel acoustic waveguide.

Acknowledgments

Authors express acknowledgments to Dr. Jacek Domagalski for access to experimental test results. The investigation was supported by the Ministry of Science and Higher Education (grant No O R00 0089 09).

References

[1] E. Kozaczka, *Arch. Acoust.* **13**, 133 (1978).

[2] E. Kozaczka, G. Grelowska, *Arch. Acoust.* **29**, 169 (2004).

[3] D.E. Weston, *J. Sound Vibrations* **18**, 271 (1971).

[4] P.T. Arveson, D.T. Vendittis, *J. Acoust. Soc. Am.* **107**, 118 (2000).

[5] E. Kozaczka, J. Domagalski, *Pol. Maritime Res.* **17**, 64 (2010).

[6] E. Kozaczka, J. Domagalski, *Pol. J. Env. Studies* **14**, 31 (2005).

[7] E. Kozaczka, G. Grelowska, J. Domagalski, I. Gloza, *Pol. Maritime Res.* **14**, 40 (2007).

[8] E. Kozaczka, J. Domagalski, I. Gloza, *Pol. Maritime Res.* **17**, 26 (2010).

[9] L. Milanowski, in: *Proc. VI Symp. on Hydroacoustics*, Polish Naval Academy Press, Gdynia 1989, p. 215 (in Polish).