PAN
ARCHIVES OF ACOUSTICS
Vol. **38**, No. 3, pp. 351–356 (2013)

DOI: 10.2478/aoa-2013-0041

Underwater Noise Generated by a Small Ship in the Shallow Sea

Grażyna GRELOWSKA[(1),(2)], Eugeniusz KOZACZKA[(2),(1)],
Sławomir KOZACZKA[(1)], Wojciech SZYMCZAK[(1)]

[(1)] *Polish Naval Academy*
Śmidowicza 69, 81-103 Gdynia, Poland; e-mail: g.grelowska@amw.gdynia.pl

[(2)] *Gdańsk University of Technology*
Narutowicza 11/12, 80-233 Gdańsk, Poland

(*received October 24, 2012; accepted April 10, 2013*)

Study of the sea noise has been a subject of interest for many years. The first works in this scope were published at the turn of the twentieth century by Knudsen (Knudsen *et al.*, 1948) and G. Wenz (Wenz, 1962). Disturbances called "shipping noise" are one of the important components of the sea noise.

In this work the results of an experimental research of underwater noise produced by a small ship of a classic propulsion are presented. A linear receiving antenna composed of two orthogonal components was used in the investigation. Identification of the main sources of acoustic waves related with the ship was achieved. In addition, the intensity of the wave was measured. The research was performed in conditions of the shallow sea.

Keywords: signal processing, sound propagation, underwater ship noise, propagation in the shallow sea.

1. Introduction

Problems of generation and noise control in the air are well recognized in general, and in certain cases noise limitation gives satisfying results. Because of direct disadvantageous influence of noise on humans, noise control is topical and stimulates activity of State and NGO organizations. Their main goal is reducing to minimum the impact of undesirable vibroacoustical effects on man.

We are confronted with a considerably worse situation in the water environment (Hildebrand, 2009). Binding laws of particular states or the EU Directives concerning care for the natural environment lack clear rules forcing owners of technical devices to limit the level of underwater noise (Arveson, Vendittis, 2000).

The only exception, however, loosely connected with care for the natural environment, is the limitation of underwater noise produced by warships (Kozaczka, Grelowska, 2004). Military techniques utilize phenomena of generation and propagation in water of the acoustic waves produced by ships (Kozaczka, 1978; Ross, 1976) for monitoring their movement in a fixed sea area (Kozaczka *et al.*, 2007a; 2007b) with the possibility of their classification and identification (Grelowska *et al.*, 2012). This fact forces the users of military equipment to lower the noise produced by their individual ships to the spectral level of the environmental noise (Urick, 1975). Besides, in use also are various manners and methods of changes in time and spectral structure of noise generated by the ships, so as to make their immediate classification and detection difficult or even impossible (Kozaczka, Grelowska, 2004).

Taking into account that this paper does not deal with military utilization of noise produced by ships and other underwater sources, we shall pay our attention mostly to quantitative characterization of this noise with indication of its disadvantageous influence on the natural underwater environment. It is commonly known that impact of noise on organisms living in water is harmful, similarly to that of noise in the aerial environment on any living organism, not only on man (Committee…, 2003, Richardson *et al.*, 1995).

The passing and underwater moving objects produce the noise of variable intensity, which significantly increases the overall level of noise in the sea (Arveson, Vendittis, 2000; Hildebrand, 2009; Kozaczka, Grelowska, 2004; 2011; Ross, 2005). This applies to both the sonic and ultrasonic range. The excessive levels of underwater noise adversely affect the so-called underwater acoustic climate and are the reason why this phenomenon has been intensively investigated for the number of years (Hildebrand, 2009).

The results of experimental work conducted in the sea conditions and connected with the small ship are presented in this paper. Their primary aim is a detailed analysis of the phenomenon of generation and propagation of acoustic waves produced by vessels. The detailed analysis of the acoustic signals illustrated in the form of spectrograms is presented. The influence of the boundary conditions (shallow sea) on the shape of acoustic characteristics will be also considered. The receiving antenna which allows to designate the direction and, in certain circumstances, distance from the sources of acoustic waves was used in the majority of studies.

Elaborated research methods can be applied for diagnostics, identification, and classification of sources of underwater acoustic waves.

2. General features of noise produced by ships

Using the classic classification of noise produced by ships it is possible to segregate them into (Arveson, Vendittis, 2000; Kozaczka *et al.*, 2007a; Ross, 1976):

- noise generated by devices active dynamically, placed inside and on the surface of the hull, mainly by engines, propulsion, and auxiliary, and system of transport of mechanical energy – shafting,
- noise produced by the ship propellers,
- acoustic effects connected with cavitation of the 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 the ship. It radiates tonal components that contribute almost all of the radiated noise power of the ship. They are independent of the ship's speed. Few of components are strong enough to be contributors to the high-speed signature. The tonal levels of ship's service diesel generator are nearly stable in amplitude and frequency (Kozaczka *et al.*, 2007a). The wide-band energy of the noise generated by the ship's service generator is proportional to the square of generated power (Urick, 1975).

Discrete components that could be associated with the mechanical activity of propulsion engines, as well as propellers, appear at a higher speed of the ship in the spectrum of the underwater noise. They are mainly noticed in the frequency range up to 100 Hz (Arveson, Vendittis, 2000).

3. Noise generated by a propulsion engine

The propulsion engine is the main source of the underwater noise for moderate speeds of the ship. In general, the tonal level is not stable because of variations of loading the propeller for different sea states. The radiated power at the fundamental firing rate frequency is related to the engine horsepower and can be estimated up to 0.1% of the total engine power. The tonal components are connected with the firing rate. For the two-stroke x-cylinder diesel engine the firing rate is defined as (Urick, 1975):

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

where FR is the firing rate, x is the number of cylinders, revolutions per minute.

The tonal level is not stable in general because of variations of loading, as it is the case with the propeller for different sea states (Kozaczka, 1978). The radiated acoustic power at the fundamental firing rate frequency F is related to the engine horsepower H as (Urick, 1975):

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

Analyzing the vibration caused by the diesel engine that is converted into acoustic energy one should take into account the possibility of occurring of structural

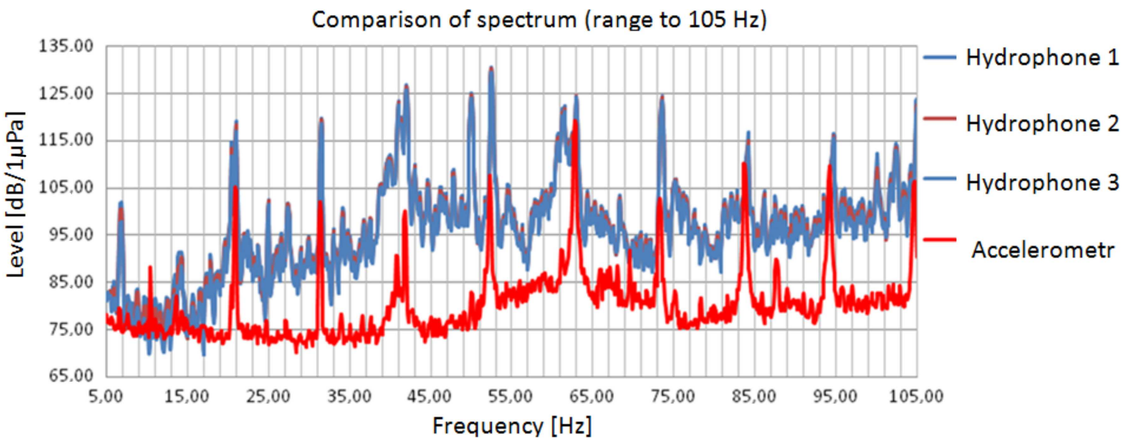

Fig. 1. Spectra of the underwater noise produced by a moving small ship measured by 3 hydrophones (H1, H2, and H3) 2.4 m distant form each other and the spectrum of the vibration of the main engine.

resonances. These may play a great role in determining the radiation efficiency of the ship's engine tones. Comparison of the spectrum of the underwater noise and the spectrum of vibration of the engine allows to determine the components in the underwater noise caused by the engine activity (Fig. 1).

4. Noise generated by a propeller

The most efficient underwater noise source on the ship is the propeller noise. One part of it is the blade rate, which is a signal at the blade passing frequency and its harmonics. This usually gives the dominant contribution to the low frequency tonal level at high speeds of the ship, when the propeller is heavily cavitating (Kozaczka, 1978; 1986).

In view of the fact that the work of the propeller is near the hull, the inflow velocity is reduced significantly near the top of the propeller. A propeller of the surface of the ship operates behind the hull, which creates a nonuniform distribution of the water flow velocity in the screw disk. Additionally, variation of the sea surface due to wind causes that the upper part of the propeller blades during their motion is usually in the area of the lowest pressure. For the high rotation speed a cavity can be formed. It collapses when the pressure increases during the blade movement downwards. Because the collapse of a cavity occurs every time, a blade passes through the region of the low pressure. The noise that appears in this case has fundamental harmonics equal to those of the blade rate.

Estimation of the sound pressure generated by the cavitating area can be done 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, the nearly perfect reflections of the sound waves occur as the second source. As a result, 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 as follows (Ross, 1976):

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

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

In the spectrum of the underwater noise components whose origin can be directly linked to the activity of the mechanisms of the ship can be distinguished. In Fig. 2 the consecutive spectra of the underwater noise of the small ship calculated for particular sections of the track length of 1 kilometer and the averaged spectrum for the track are shown.

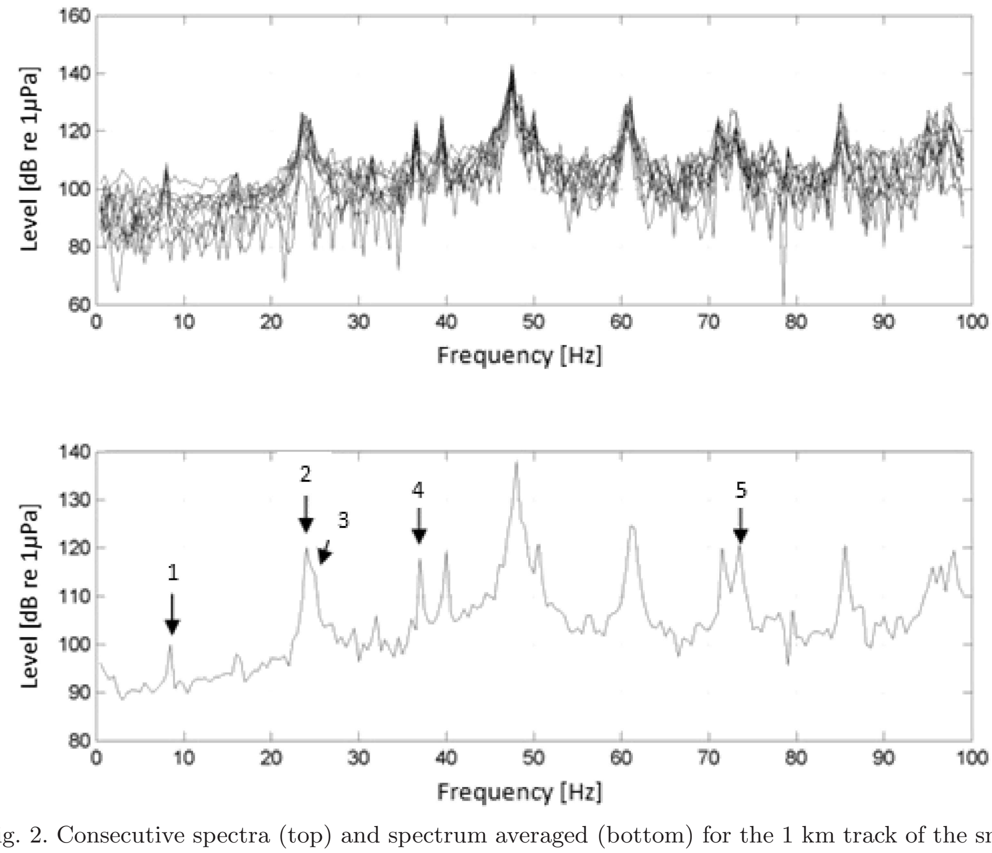

Fig. 2. Consecutive spectra (top) and spectrum averaged (bottom) for the 1 km track of the small ship: 1 – shaft, 2 – proppeler – fundamental frequency, 3 – unbalance of the proppeler, 4 – detonation combustion of fuel in the cylinders, 5 – proppeler – 3rd harmonic.

5. Measurements method and results

As it has been mentioned above, the ship is a broadband underwater source and in the spectrum of the noise generated by her, the low frequency band is of a significant importance. In this case we have to consider propagation of waves with the length comparable to the depth of the sea, according to the theory elaborated for the shallow sea (Brekhovskikh *et al.*, 1992). In such a situation, the transmission losses of waves with the length of λ that satisfy the condition:

$$10\lambda < h, \tag{4}$$

where h is the depth of the sea, has to be calculated under the assumption that the kind of propagation changes with the distance from the source. The kind of bottom sediments has an impact on the phenomenon of wave propagation in the shallow sea (Kozaczka, 2013).

The shape of forming wave mods and the range of propagation of disturbances, in general, is influenced by boundary conditions. Mainly, it refers to the boundary condition at the sea bottom.

Considering the fact that the ship noise is a broadband noise in the low frequency range, in the shallow water conditions the impact of the sound speed distribution, and, thereby, the refraction, is of little importance. However, the influence of the ambient background noise affects the detection range of the target.

In order to minimize the influence of the boundary condition, one can choose the optimal location for measurement, taking into account the depth and the kind of sediments. Nevertheless, the transmission losses for low frequencies were determined according to the shallow sea propagation rules.

The best location for the measurement facility, used in evaluation of hydroacoustic characteristics of noise radiated by classical ships as well as underwater ships, is in places where the ambient noise is the smallest and the depth of the sea is high enough so that the bottom could be treated as reflectionless.

In the measurements of the acoustic pressure vertical and horizontal arrays of hydrophones are used, mounted in such a way so that the impact of the environment motion, especially waved sea surface, is minimized. Signals from the acoustic transducers are transmitted to the registering and analyzing devices. On the basis of the results of these measurements, a set of characteristics that determine individual distinctive features of the examined source is obtained.

Among others, the set of characteristics contains:

- instantaneous spectra of the underwater noise of the ship,
- characteristics illustrating changes in the pressure level with the distance from the ship at a fixed depth,
- a set of correlation and coherence functions and directivity patterns.

Moreover, for each measurement spectrograms that combine features of the spectral characteristics and functions connected with changing of position of the source relative to the receiving antenna are determined.

At the same time, on-board measurement of the vibration of the main engine, as well as the service diesel generator, are carried out. On the basis of the results of these measurements one can determine the bandwidth of the noise produced by the ship, diesel engine cylinder pressure spectra, engine vibration transmis-

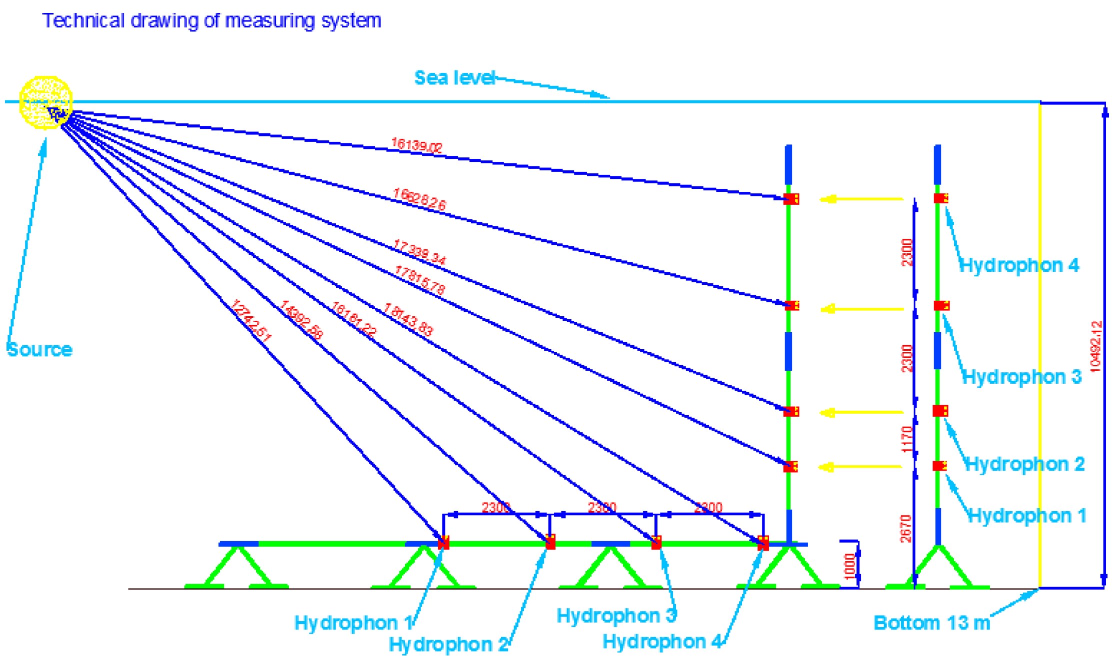

Fig. 3. Technical drawing of the measuring system.

sion paths, the ship hull "beam mode" response, and, at last, the transfer function between the on-board installed sources of vibration and outside radiation level.

Fig. 4. Small ship used in the experiment.

All of these characteristics should reflect individual features of the source that is a moving ship. Knowledge of them gives information about what steps should be taken to obtain the specified characteristics of the source. Besides, the characteristics allow to assess which factors are the most disadvantageous to the surrounding and whether their reduction is possible without changes of operational variables of the ship.

Some measurements carried out during the investigation of the ship noise are illustrated in this text. In Figs. 1 and 2 spectra determined for the frequency range up to 100 Hz, where characteristic components linked to the activity of the main ship's devices are well visible, are shown. The acoustic effects connected with cavitation of the propeller and flow around the underwater part of the hull are observed in the range of higher frequencies, approximately 300–1500 Hz. It depends on the type of ship and its speed. An example of the spectrogram where the mentioned acoustical effects are pointed is shown in Fig. 5. Below is given the spectrum of noise when the ship is over the receiving antenna.

Applying the linear antenna composed both of vertically and horizontally placed hydrophones allows us to determine experimentally the spatial distribution of noise produced by a moving ship. It is a great advantage of the examined measurement set up that distinguishes it from others, typically composed of hydrophones placed on the sea bottom. Moreover, the configuration of hydrophones allows to determine the intensity of the sound (Kozaczka *et al.*, 2007b). An example of the spatial distribution of the sound intensity of noise produced by a moving ship determined experimentally is shown in Fig. 6. This makes it possible to determine the area of a given level of intensity.

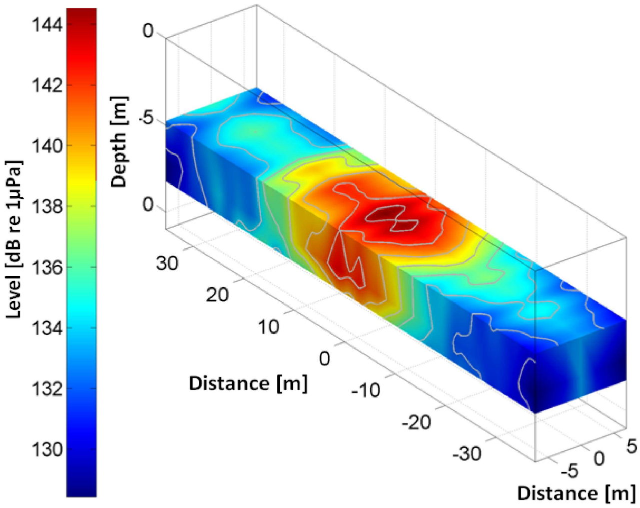

Fig. 6. Distribution of sound intensity of noise produced by a small ship determined experimentally.

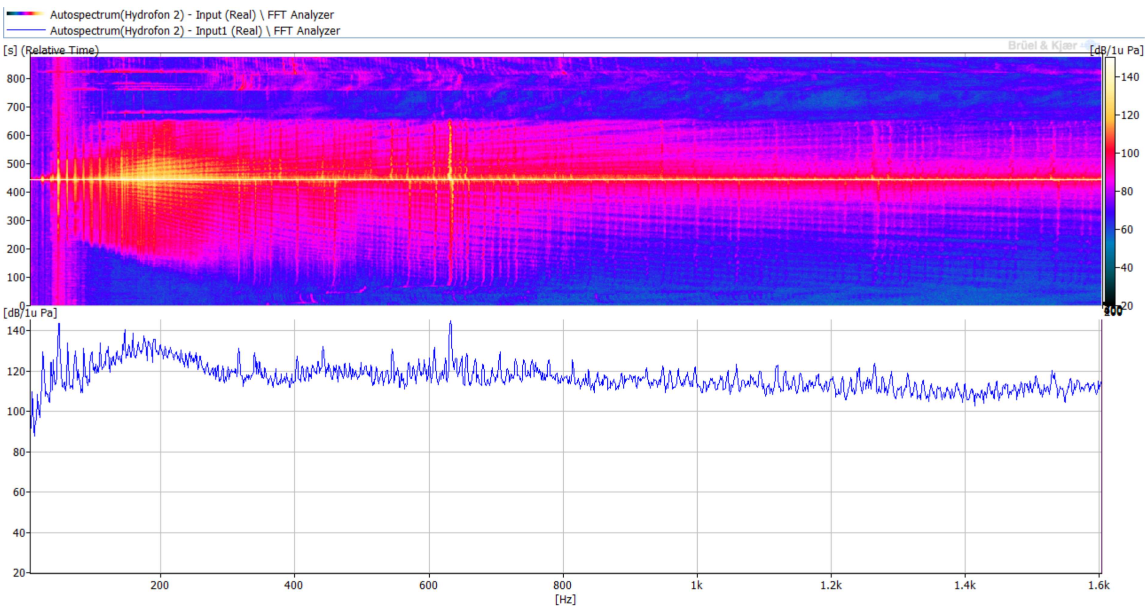

Fig. 5. Spectrogram and spectrum of a small ship.

6. Conclusions

Investigations of the acoustic signature of ships are very expensive and time consuming procedures. These investigations should be carried out at the same time on-board and out-board. This allows to determine connections between sources installed on-board and near the hull (ship propeller) and radiated level, as well as their spectra.

Basing on the measurements of underwater noise generated by a ship it is possible to get information about sources of underwater noise and technical state of ship's mechanisms. The knowledge of the levels and structures of the underwater noise radiated by ships is important for monitoring self-noise and the technical state of their mechanisms.

The noise of a moving vessel is connected with the way of mounting and vibration of the machines and next transmission in various paths into the water as underwater sound.

Applying the sound intensity measuring method, one can carry out the measurements in the near field of a source of acoustic waves. It is very important in the cases when there is a need to measure the ship's noise in the shallow sea. Otherwise, on the basis of intensity characteristics one can determine the direction of movement.

The presented measuring set up composed of linear arrays allows to obtain experimental data about the spatial distribution of the sound field of moving objects. In spectral characteristics of the ship presented in the paper, the following elements can be distinguished:

1) individual components in the band pass up to 200 Hz connected to the activity of the ship's mechanisms;
2) broadband noise in the band from 200 to 700 Hz, as a result of flow of the hull and cavitation;
3) component of frequency 500 Hz, independent of the speed of the ship.

The results of measurements are influenced by the ambient noise, especially in the low band frequency range. This was due to the vicinity of a harbor and shipyard, as well as marine traffic.

Acknowledgments

The investigation was partially supported by the National Centre for Research and Development, Grant No. O R00 0089 09 and Grant No. 0007/R/IDI/2011/01.

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