IDENTIFICATION OF THE SHIP'S UNDERWATER NOISE SOURCES IN THE COASTAL REGION

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The results of the investigations of underwater noise radiated by ships at the background of the ambient sea noise in the coastal region are presented. Sounds in shallow water are inherently modified by the local environment. Based on the results of the measurements of both the ambient noise and the noise radiated by ships the investigations of the influence of the ship's motion on the ambient sea noise were carried out. What more the noise field at the sea in the coastal region is notably influenced with the technical noise, especially connected with the human's activity.

INTRODUCTION

Much information is required about the local seabed structure to determine accurately the acoustic signature of a ship in the shallow water. The radiated ship noise in shallow water creates a stationary acoustic field. While you examine spectra you must take into account some important facts such as: sea surface and bottom roughness, water velocity profile, wave propagation in the sediment, bottom velocity profile and noise source depth; because the stationary acoustic field in a two plane parallel medium is characterized by the thickness of the water and the reflectivity of the boundary surfaces. Maxima and minima of pressure are generated at some given depths depending on the radiated frequency and distance.

Few detailed studies of the underwater radiated noise of surface ships have been reported, in spite of the fact, that shipping constitutes a main source of noise in the sea. "Trends in Merchant Shipping (1969-1980)" by Donald Ross described radiated noise of many ships of that period. Sophisticated numerical and experimental research on propeller cavitation has been conducted by many researchers in Germany, Poland, Norway and other European countries in recent years. Propeller noise is a hybrid character of noise having features and an origin of both cavitation and hydrodynamic pressure. Except when the ships are running at very slow speeds radiated spectra of surface ships are dominated by propeller cavitation noise. A main engine noise originates as mechanical vibration of many rotating, unbalanced, and reciprocating parts, also repetitive discontinuities, turbulence and cavitation in pipes, valves and pumps and mechanical friction in bearings. A Diesel generate creates 25 Hz, 37.5 Hz and a series of harmonics which amplitudes and frequencies are independent of ship speed.

1.SOUND RANGES AND MEASUREMENT CONDITIONS

The measurements were carried out in the Gulf of Puck region and at Naval Test and Evaluation Hydroacoustic Range. The underwater sound measurement was performed both for anchored and sailing conditions. Planning was done to maximize the information from the ship noise measurements, because of the high cost of ship's running.

During the ship measurements the ambient noise level was low, the mean wave height was less than 0.5 m, and the wind speeds were less than 5 m/s. We had the typical summer sound speed profile, it means a smooth, regularly decreasing gradient without a mixed layer.

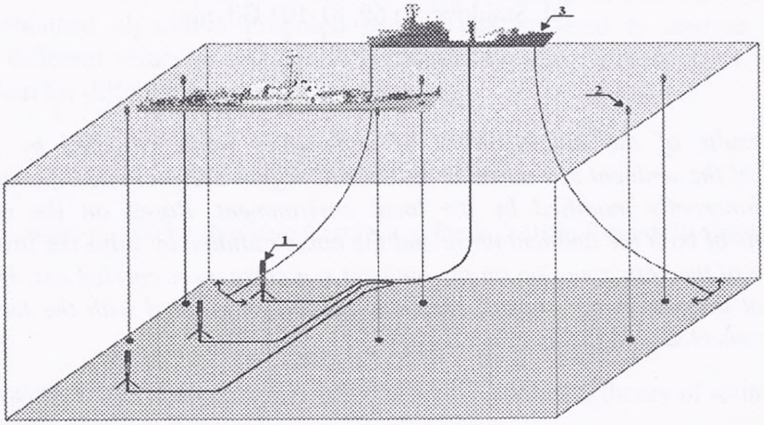

Fig.1. Plan of ship's field measurement range for running vessels
1-hydrophones, 2 - buoys, 3 – measuring vessel

The ship under test ran at a constant speed and course in order to pass the measurements hydrophones at a know distance. During the run analogue and digital recordings were made, and late subjected to analysis in different frequency bands. Radiated-noise measurements must be made at a distance from the radiating vessel, usually from 10 to 100 m.

2. SOURCE LEVEL AND NOISE SPECTRA

The source levels for radiated noise are suitably spectrum levels relative to the 1 μPa reference level, and specified in a 1 Hz band, and must be reduced to 1 m by applying an appropriate spreading or distance correction.

The radiated noise of a ship consists of a mixture of tonal noise having a continuous spectrum and line components happening at discrete frequencies. These two spectral types are illustrated diagrammatically in Fig. 6.

We used for acoustic and vibration measurements real-time digital frequency analyzers and a computer. Suitable used bands are from octave to 1/24-octave and 0.125 Hz narrow-band bandwidth filters. The 0.125 Hz bandwidth was achieved by uniform sampling of an 8-s noise record at 8192 Hz. This was an advanced acoustic analysis system enables data to be analyzed on-line so that effects were quickly available. We decided to use such advanced techniques in order to achieve results as fast as possible.

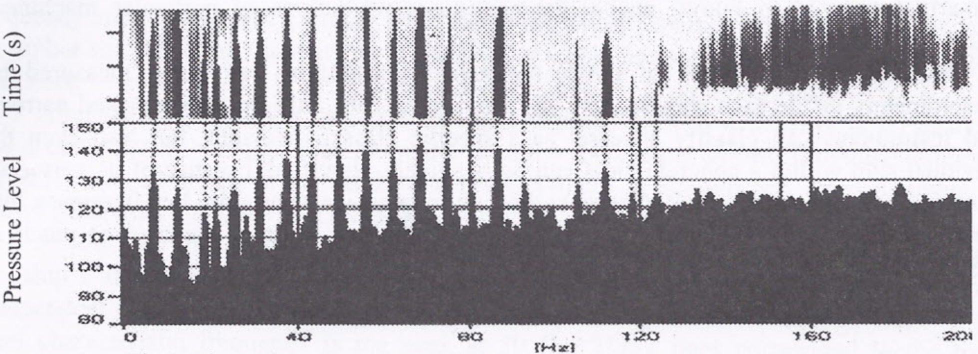

Fig.2. The underwater noise spectrogram and spectrum of a moving vessel.

The recordings were carried out by means of the array of hydrophones. On the basis of these results we determined the maximum values of the sound pressure levels for different speeds of a ship. A sound spectrogram of the radiated ship noise moving away from the array of hydrophones in the shallow water shows the parallel lines at low frequencies. This frequency spectrogram is generated by the stationary acoustic field set up in a two plane parallel medium surface and bottom of the sea. The hydrophones were located at 12 m.

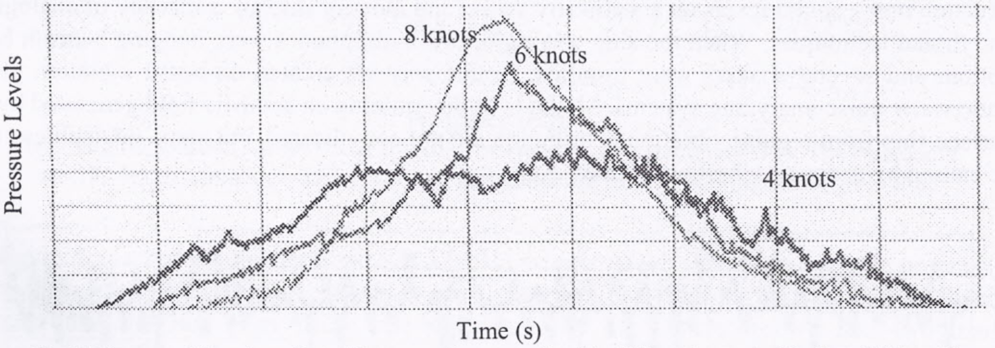

Fig.3.The sound levels radiated by a moving vessel with different speeds (4 , 6 and 8 knots).

One of the methods of identification of underwater noise of a ship is by investigation of its spectrum. Basing on the conducted analysis it is possible to isolate discrete components in the spectra associated with the work of mechanisms and equipment on board along with the broad band spectrum reflecting the work of the cavitating propeller, turbulent flow in piping and ventilators or bearing frictions. In practice the noise identification is difficult. The own noise is combined with technical environmental noise coming from remote shipping, ship-building industry ashore or port works. There exists also the noise of natural origin: waves, winds or rainfalls. Additional obstruction in the process of spectral component identification may be the fact that various ship's equipment may be the source of hydroacoustic waves of similar or same frequencies. The propeller is the dominant source of the hydroacoustic waves at higher vessel speeds. It generates the driving force that is balanced by the resistance force of the hull. It also stimulates the vibrations of the hull's plating and all elements mounted on it.

Control and evaluation of noise signature is an important determinant of ship survivability in a stealthy naval environment. Specialists conduct vessel trials both statically and dynamically, sometimes over their full speed ranges. Stationary trials, with ships or submarines moored to buoys, enable the acoustic contributions of particular machinery systems to be estimated.

To identify the source of noise, the level of vibration was also measured by accelerometers inside each ship section. In many cases, not only the sophisticated narrow-band instruments can classify a vessel as a specific class of warship, but also even the individual ship within a concrete class can be positively identified, because of its very own distinctive acoustic signature. Radiation at discrete frequencies, caused by low frequency hull vibrations, excited by the machinery is easily detected and must be reduced as much as possible.

3. RESULTS

Identification of underwater noise generated by a moving ship equipped with diverse mechanisms is a complex task. The energy of vibration resulting from the main engines, shafts, propellers, auxiliary plants, compressors, ventilators, pumps, piping and of other pieces of equipment installed on board is transferred via the construction elements into the water environment in shape of hydroacoustic waves. In these elements the vibration energy spreads out and interferes with the acoustic waves coming from many sources what additionally makes identification of the spectral components difficult.

The methods to measure the rotational and translation components of the vibration or structure borne sound levels on a stationary vessel and moving ship are a mixture of analogue and digital techniques. When the ship was rigid, two hydrophones were hanging beneath her bottom and several shakers were installed; in this way we created on-board vibration plus underwater noise-analyzing systems. Methods of determining an acoustic field generated by a surface ship from regular vibration distribution are not complicated, but some difficulties can be caused by irregular vibration sources.

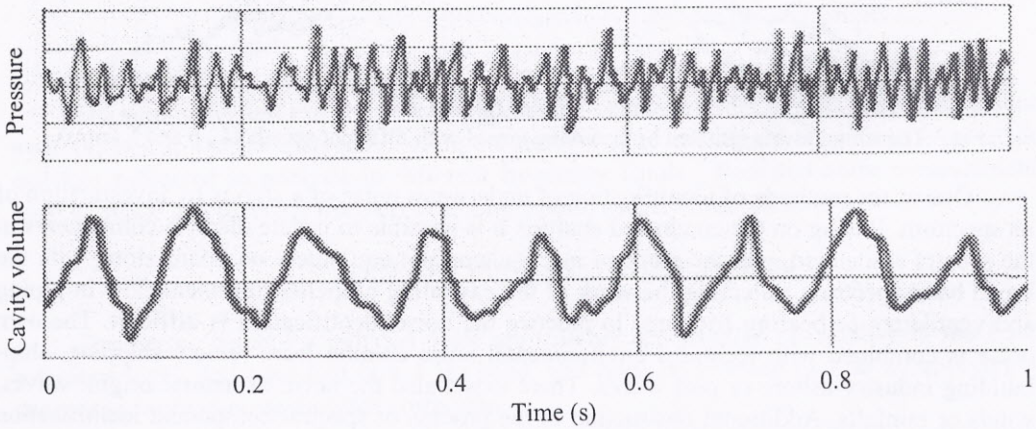

Fig.4. Waveform of radiated noise pressure from a vessel (a) dipole pressure waveform, and (b) cavity volume in cubic meters.

Dipole pressure waveforms were recorded from the Naval University of Gdynia hydrophones. The waveforms shown in Fig.4 (a) was measured near the keel aspect, the sample rate was 8192 Hz, that's why the upper frequency in the data was 3200 Hz. At this ship speed the blade rate noise plays a role of most of the power with some noise from the main engine, Diesel generator and other sources. We had here samples 1-seconds long. This waveform was asymmetrical and was strongly amplitude modulated at the blade rate frequency and its harmonics. Figure 4 (d) shows the cavity volume variation in cubic meters. At higher sea states the fluctuations in underwater sound pressure levels are certainly higher than here.

After that, the resulting spectra were made digitally both by a Bruel & Kjaer analyzer and a computer. A simultaneous on-board vibration monitoring system provided additional measurements of tonals from inside our vessel (where accelerometers were mounted on Diesel generators and other machinery).

At low ship speeds, discrete lines of the spectrum nearly almost always originate from the ship's diesel generator. Tonal components radiate a series of harmonics that are independent of ship speed. The main component is a strong discrete line at 25 Hz; also the most characteristic frequency is the peak at 50 Hz. These lines correspond to the basic frequencies of the European ships electric generators.

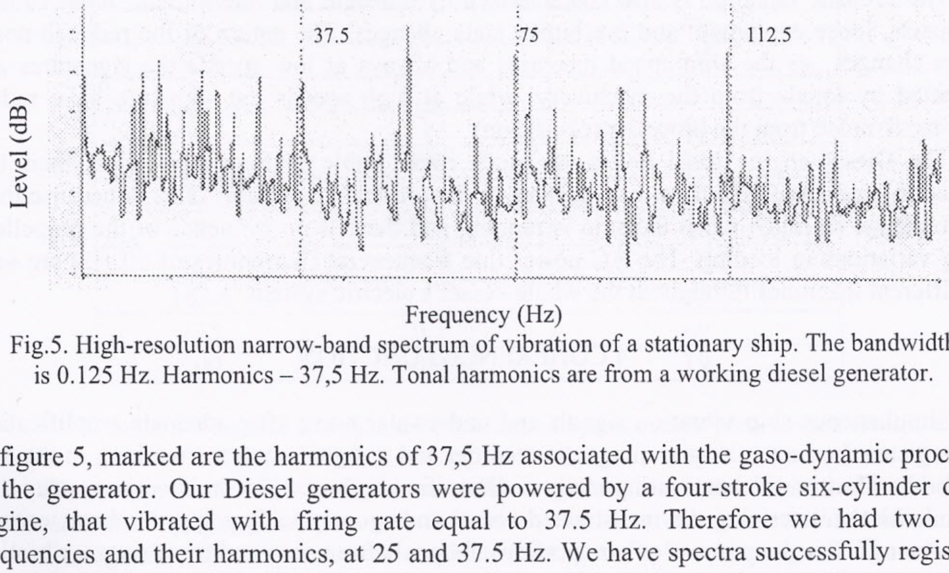

Fig.5. High-resolution narrow-band spectrum of vibration of a stationary ship. The bandwidth is 0.125 Hz. Harmonics – 37,5 Hz. Tonal harmonics are from a working diesel generator.

In figure 5, marked are the harmonics of 37,5 Hz associated with the gaso-dynamic processes in the generator. Our Diesel generators were powered by a four-stroke six-cylinder diesel engine, that vibrated with firing rate equal to 37.5 Hz. Therefore we had two main frequencies and their harmonics, at 25 and 37.5 Hz. We have spectra successfully registered up to several harmonics of basic frequencies. Some of these harmonics are strong enough to be contributors to both the low- and high-speed signatures. These main lines are strong enough to exist even in the high-speed signature. Here, the frequency spectrum has a continuous – discrete character. The Diesel firing rate is defined as:

$$FR = \frac{6 \cdot rpm}{60} = \frac{rpm}{10} Hz \tag{1}$$

The next tonal components, which are in high-resolution narrow-band power spectrum of low-frequency noise, are multiples of these lines, or in other words, harmonics of the basic frequencies.

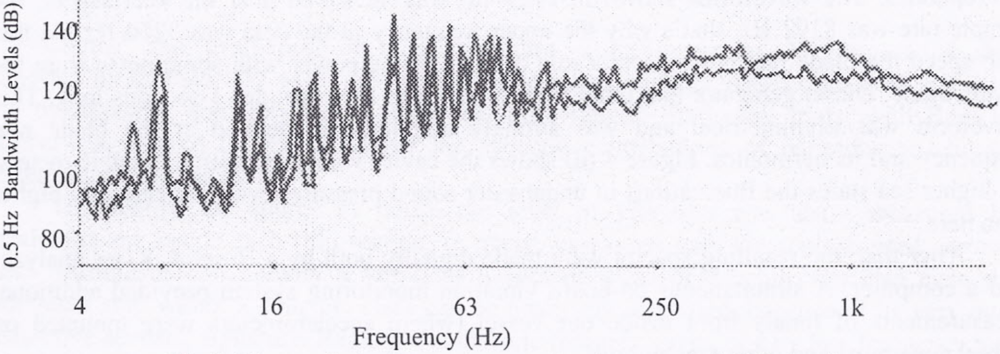

Fig.6. Changes in keel-aspect narrow-band spectra in 0.5 Hz bands after two years in service of a surface ship

During their service life, ships wear out and their mechanisms become old and often unbalanced, so their underwater noise levels grow; after two years serving in the Navy on average by 3 – 4 dB.

The acoustic radiation is also characterized by transient and intermittent noise caused by impacts, loose equipment and machinery state changes. The nature of the radiated noise spectra changes as the ship speed increases and always at low speeds the signatures are dominated by tonals from the machinery, while at high speeds the signature have rather broad-band noise from the propeller (cavitation).

The Diesel engine tonal levels are much more stable in frequency (less than 1% fluctuation) and amplitude than the lines due to the propulsion system. This is because they do not change so much when the ship is running and there is no influence of the propellers during variations in loading. The AC power line frequencies (harmonics of 50 Hz) are sent into different machines throughout the whole vessel's electric system.

4.COHERENCE FUNCTION

Simultaneous ship vibration signals and underwater noise after adequate amplification were registered on an analogue magnetic recorder and a digital analyzer working in the real time mode. The assumed measuring method allows finding in the power density spectrum the components characterizing the investigated vessel analogously to fingerprints characterizing human beings. For the purpose of comparison of signals from ship and from water, vibration and hydroacoustic pressure coherence function was arranged, defined for the two signals v(t) and p(t) in the following way [1]:

$$\gamma_{pv}^{2}(f)=\frac{\left|G_{pv}(f)\right|^{2}}{G_{p}(f)G_{v}(f)} \tag{2}$$

where Gp and Gv denote the corresponding spectral densities of signals p(t), v(t) and Gpv denotes the mutual spectral density.

Coherence function is a real function accepting arguments from the interval:

$$O\leq\gamma_{pv}^{2}(f)\leq1 \tag{3}$$

Therefore, the zero value occurs for signals that do not have the cause association and the one value for signals coming from the same source. Using the dependence (1) we determine the coherence function between the signals. The components in the coherence spectrum determined this way reflect qualitative correlations associated with particular frequencies coming from a working piece of equipment.

5. RESULTS OF RANGE MEASUREMENTS FOR STATIONARY VESSELS.

The interpretation of the underwater noise of a vessel was conducted by analyzing the spectra of consecutively powered up machines and comparing them with the corresponding underwater noise. In the first phase the measurements of vibration velocities and aggregate noise (primary engines not working) were carried out. Then, the measurements were continued for the left, right and both main engines.

Frequency Hz	Coherency function	Vibration on the hull (μm/s)
16.5	0.8	13
25	1	80
37.5	0.8	69
50	1	42
62.5	0.9	8.4
75	1	72
87.5	1	64
100	0.8	23
112.5	1	55
125	1	28
150	1	66
162.5	1	35
175	0.7	69
200	0.9	19

Table 1. Vibration and coherence function of hydroacoustic pressure and vibration.

The comparison of vibrations velocities registered at the ship's hull and at the fundament of the power generators with the underwater noise were presented in table 1.

Analogically, the research was conducted for the ship's main engine. The results of narrow-band spectral levels and the coherence function were shown on figure 7.

Vibration	Frequency		Harmonics
	Formula	Hz	
Unbalanced parts	$f_n = kf_o$	25	50, 75, 100, 125, 150, 175, 200,…
Diesel firing rate	$f_s = \frac{kz_c f_o s}{4}$	12.5	25, 37.5, 50, 62.5, 75, 87.5, 100,112.5, 125, 137.5, 150, …

Table 2. Basic frequencies and harmonics of vibration.

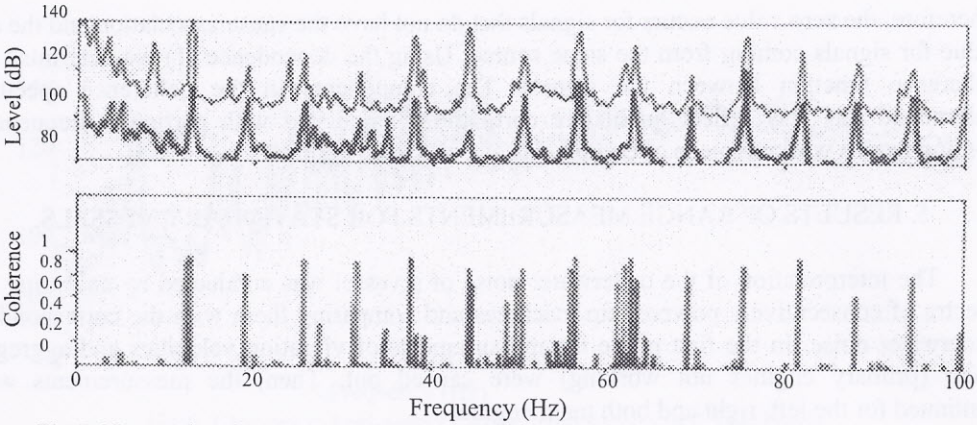

Fig.7. Narrow-band spectra and coherence function of underwater acoustic pressure and vibration of a stationary ship

The dependence between the vibrations and their response (underwater noise) are determined by the energy transfer coefficient α. With the assumption that the vibrating hull generates a flat wave, the relationship between the speed of vibration and the acoustic pressure level is as follows:

$$\alpha = \frac{L_{1m,1Hz}}{\rho c v} \qquad (4)$$

where: L1m,1Hz – the acoustic pressure level ref. to 1m and 1Hz, v – vibration speed (m/s), ρ – water density (kg/m^3), c – sound speed (m/s)

$$L_{1m,1Hz} = L + 20 \log R - 10 \log \Delta f \qquad (5)$$

where: L – acoustic pressure level under ship (dB re μ*Pa*),
R – the distance between a ship and a sensor (m),
Δ*f* – the width of an applied filter (Hz)

The results of the acoustic levels, vibration speeds and coefficient α are shown in tab. 3.

f (Hz)	L (Pa)	v (m/s)	α
12.5	3.14	0.001	2.2 10^{-3}
25	6.3	0.00032	1.4 10^{-2}
37.5	14.1	0.00028	3.4 10^{-2}
75	56.2	0.0005	7.7 10^{-2}

Table 3. The energy transmission coefficient calculated for consecutive frequencies.

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