

UNDERWATER SHIP PASSPORT

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For years in the Polish Navy extensive measurements have been made of the underwater-radiated noise by different kinds of surface ships. To identify the source of noise, the level of vibration was also measured by accelerometers inside each ship section. 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. The radiated noise spectra show high-level tonal frequencies from propellers and main engines. They varied with speed of the vessel in a complex manner. Ship's service diesel generator (SSDG) creates a series of harmonics which amplitudes and frequencies are independent of ship speed. The articles documents series characteristics of the surface ship's radiated underwater noise data. The noise from small vessels elevates the natural ambient noise by 10-40 dB. Third-octave bandwidth analyses are too wide separation of the individual radiated components of ship noise that's why accurate narrow-band spectra (sometimes less than 0,1 Hz) have been made.

INTRODUCTION

Few details studies of the underwater radiated noise of surface ships have been reported, in spite of the fact, that shipping constitutes a major source of noise in the sea.

People who have spent time aboard a small vessel know that vibration and noise is always a major problem there. High noise levels can also distort speech clearness that confuse routine conversations and also reduce a crews' ability to relax during rest periods. Underwater noise influences in the depth weaponry and acoustic torpedoes. Thus, minimizing excessive air and underwater noise can result in better crew performance and increase the stealth against the underwater threat.

Noise levels in accommodation areas of small vessels can range from 60 to 80 dB (A). Other spaces inside a ship have much higher noise levels. The engine rooms are the noisiest areas and have levels ranging from 90 to 120 dB (A). High vibration levels often occur in the aft ship due to propeller cavitation during high speeds and manoeuvring.

Vibrations aft are often local and not measurable in forward part of the ship. Experience has shown great dissimilarities in the vibrations caused by analogous procedures, depending on different combinations of propeller pitch and revolutions per minute used by the officers. It is important to remember that total systems approach must be maintained, all noise sources inside a given space must be considered.

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 can be the fact that various ship's equipment may be the source of hydroacoustical waves of similar or same frequencies. The propeller is the dominant source of the hydroacoustical 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.

1. METHODS OF MEASUREMENT AND RESULTS

Control and evaluation of noise signature is an important determinant of ship survivability in 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.

The underwater-radiated noise and vibration measurements have been carried out in Gdansk Bay area in hot days of spring and during summer (at this time the sound speed profile was typical of the summer, little by little decreasing gradient without mixed layers). In order to correctly predict the acoustics source levels of different kinds of surface ships and submarines, a description of low-frequency sea ambient noise is available. During the ship measurements the weather was good, the average wave heights were less than 1 m and wind speeds less than 5 m/s, so the ambient noise level was low. The vessel under test was running at a constant speed and course. The bottom-mounted hydrophone range is very useful for measuring the noise of surface ships. What more when we use bottom-fixed hydrophones the irrelevant low-frequency wave-induced noise is also eliminated. Throughout this measurement, the signal-to-noise ratio for the spectrum data was greater than 28 dB.

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

During the run analogue and digital recordings were made, and later subjected to analysis in different frequency bands. Radiated-noise measurements must be made at a distance from the radiating vessel, usually in our acoustic ranges from 10 to 100 m.

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.

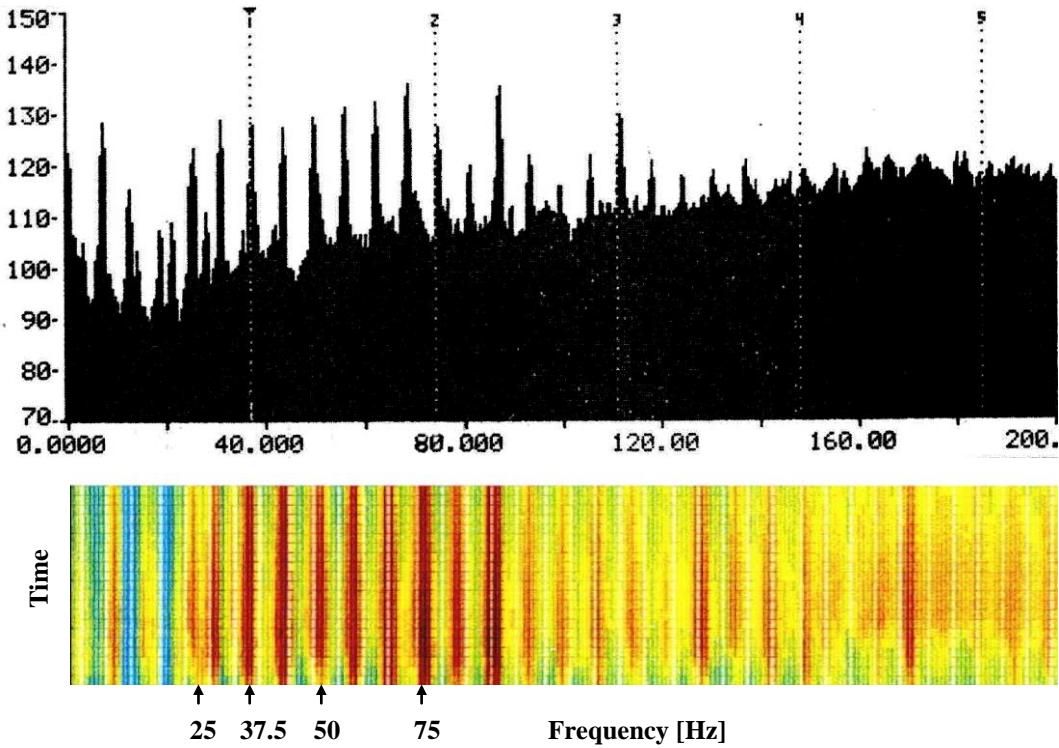


Fig. 1. Sound spectrogram of a moving surface ship at a speed of 8 knots and her high-resolution narrow-band spectrum. The bandwidth is 0.5 Hz.

Figure 1 shows keel aspect spectrogram and narrow-band power spectrum in 0.5 Hz bands of a typical ship going with the speed 8 knots above hydrophones, located in the Naval Test and Evaluation Acoustic Range (NT&EAR). The most important line frequencies (harmonics of 50 Hz) are connected with the AC power generator. These lines are distributed on machinery throughout the ship, and can be seen in all narrow-band power spectra. Radiated spectra of surface ships are at low speeds dominated by the ship's service diesel generator. It radiated a series of harmonics that were independent of ship speed. Two of these harmonics, at 25 and 37.5 Hz, were strong enough to be contributors to the high-speed acoustic signatures. The keel-aspect source levels of these tones are 130 and 132 dB re 1 μ Pa, respectively. The main component is a strong discrete line at 25 Hz and its harmonic at 50 Hz. These frequencies are from rotation speed of auxiliary machinery components. Because our diesel generator was power by a four-stroke six-cylinder diesel engine, that vibrated with firing rate equal to 37.5 Hz. Therefore we have two main lines at 25 and 37.5 Hz and their fundamental harmonics at 50 and 75 Hz.

As usually this research was conducted in two phases. In the first one noise and vibration from a stationary ship was investigated. Here the research included the simultaneous measurements of vibrations onboard the ship and underwater noise near the keel aspect. 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 mixture of analog and digital techniques. When the ship was rigid, two hydrophones hang beneath her bottom and several shakers were installed; in this way we have created on-board vibration plus underwater noise-analyzing systems. Methods of determining acoustic field generated by surface ship from regular vibration distribution are not complicated, but you can have some

difficulties with irregular vibration sources. The total measurement runs were taped using analogue recorders.

In a stationary condition, the ship was anchored above the middle of hydrophones, thus the generated noise of machines operated inside the ship was measured without any interference of hydroacoustic field. In order to identify the noise source, vibration level at the bottom of each ship section was measured using accelerometers, which were utilized to monitor vibration level inside the ship. When the ship was rigid, we created on-board vibration plus underwater noise-analysing systems. The total measurements were taped using an analogue recorder and simultaneously two-channel Brüel & Kjaer digital analyser was applied.

Some time ago we had been undergoing analysis of vessels with third-octave and 3.16 narrow-band bandwidth. Nowadays the Navy initiated a new program for accurate and very narrow-band analysis of a ship's noise. So we can use for acoustic and vibration measurements real-time digital frequency analyzers that have 1/24-octave and less than 0.1 Hz narrow-band bandwidth filters. This advanced acoustic analysis system enables data to be analyzed on-line so that effects are quickly available.

The recordings have been carried out by means of the array of hydrophones or the sound intensity probe. On the basis of these results, we determine the maximum values of the sound pressure or the sound intensity levels for different speeds of a ship.

2. RADIATED NOISE SOURCES

The first ship noise source is ship's service diesel generator (SSDG). At low ship speeds, discrete lines of the spectrum nearly almost always originate from the ship's diesel generator [1]. Tonal components radiate here 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.

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. 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, as can be seen in Fig.1. The diesel engine tonal levels are much more stable in frequency 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 which are always harmonics of 50 Hz are sent into different machines throughout the whole vessel's electric system. Our SSDG-s were powered by a four-stroke six-cylinder diesel engine, that vibrated with firing rate equal to 37.5 Hz. Therefore we have two main frequencies and their harmonics, at 25 and 37.5 Hz. These main lines are strong enough to exist even in the high-speed signature.

Each piece of machinery generates periodic vibration at the fundamental frequencies and that's way generates a series of line components and their harmonics. The harmonic structure of radiated noise is complex because even a single source of noise is irregular and variable. But when many noise sources are present (as it is always in a running vessel), the machinery noise spectra contain discrete components of deeply different levels that are changing under different condition of the ship.

The next main source mechanism is the diesel engine. In this machinery the hit of the piston against wall of the cylinder or so called "piston slap".

Note that Haine [2] proposed a scaling law for ship's diesel engines in which the radiated power W at the basic firing rate frequency F is related to engine horsepower H as:

$$W \sim (HF)^2 \quad (1)$$

The propulsion-related tonals were changing a lot when the vessels were running while the ship's service diesel generator tones showed amplitude stability.

The problem of underwater noise is caused by closely packed high-powered equipment, confined in a small metal or plastic vessel. Shipboard noise is generally created by poor or improper vessel acoustical design. In average speeds, the noisiest piece of equipment on any ship is usually a diesel engine. Being a reciprocating machine, the diesel is very loud and also generates a great deal of vibration. All ships, even quiet ones have noisy or even extremely noise, engine rooms. Problems occur when a vessel's design provides transmission paths for noise to travel from the noisy engine room through the hull into the water. As we mentioned at low ship speeds the ship diesel generates produce discrete lines, which dominate in the spectrum.

Discrete lines in the 2-20 Hz band are caused by rotation of the propellers. This noise can be heard in the sea at a great distance since absorption by sea waters at this low frequency is negligible.

At the low frequency end of the spectrum, propeller noise has discrete spectral blade-rate components occurring at multiples of the rate at which any irregularity in the flow is intercepted by the propeller blades. The main frequency of the blade-rate series of line components is given by the equation:

$$f_m = m \cdot n \cdot s \quad (2)$$

where:

f_m - the frequency [Hz],

m – m -th harmonic of the blade-rate series of lines,

n – the number of blades on the propeller,

s – the propeller rotation speed [rps].

Usually cavitation inception occurs at speed of about 10 knots. Cavitation noise radiated by the implosion of bubbles which can be formed around the edge of the blade, across the low-pressure area of the blade and in the vortex behind the hub of the blade, which is radiated by the thickness of the blade and the loading on the blade when it rotates. This is a broadband high-frequency noise.

The maximum sheet cavity on the propeller covers only small part of the blade surface. The cavity exists here in the area of small wake velocities. The quantity of unsteady cavitation on a propeller in a nonuniform wake is connected with ship vibration, propeller efficiency and its erosion. In order to decrease the intensity of cavitation, the propeller blade region should be enlarged.

The tip cavitation index is defined as:

$$K_t = \frac{p_o - p_v}{\frac{1}{2} \rho U_a^2} \quad (3)$$

where:

- p_o - the ambient pressure at the tip deep,
- p_v - the water vapor pressure,
- ρ - the water density,
- U_a - propeller tip velocity relatively to the surrounding water.

The inflow velocity is reduced significantly near the top of the propeller because of the presence of the hull. A surface ship propeller rotates behind a hull that creates no uniform wake inflow velocity, the pressure on the blade surface varies due to this wake and also due to the change in hydrostatic pressure as a function of its depth below water surface.

Vessel screws are designed to produce a given amount of thrust with a given flow to the propeller. This thrust represents itself as a pressure reduction on the blades. If the pressure reduction on the suction side is adequately harsh, cavitation will occur. A significant irregular thrust component exists due to the fact that the inflow to the propeller is significantly nonuniform over the propeller disk, because we have here a double-screw vessel. The inflow to the propeller disk is affected by the hull boundary layer right away to the screw. Changes in the axial inflow velocity correlated directly to changes in the angle of attack of the propeller blade section. In view of the fact that the lift and the quantity of cavitation on the blade section are proportional to the section angle of attack, the whole amount of cavitation on a blade will change as the propeller progress through the nonuniform wake. At the present time the effects of the cavitation amount fluctuations are the subjects of extensive investigation because of the importance of cavitation-induced pressure in vessel hull vibration excitation. The amount of uneven cavitation on a given propeller in a nonuniform wake is surrounded by considerations of propeller efficiency, wearing away its parts, erosion, and vibration of a ship. With the purpose of reducing the intensity of cavitation on a propeller, its blade area must be increased, which causes a reduction in propeller efficiency and an increase in propeller weight.

3. COHERENCE FUNCTION

We have to determine how much total acoustic power is radiated by a running ship and how it compares with the power used by the vessel for propulsion through the water. This can be done by measuring vibration aboard the ship (inside the engine room) and compare it into the underwater sound. The similarities between the vibration signals of chosen elements within the hull and of ship and the underwater acoustical pressure in the water are represented by the coherence function shown in Tab. 1.

For two signals of pressure $p(t)$ and vibration $v(t)$ spectral densities of these signals are G_p and G_v and their mutual spectral density G_{pv} :

$$\gamma_{pv}^2(f) = \frac{|G_{pv}(f)|^2}{G_p(f)G_v(f)} \quad (4)$$

Coherence function is convenient in this kind of research because it allows to determine the similarity between the spectra of particular signals. In the table you can see a series of discrete components for which the coherence values are from 0.8 to 1.

Tab.1 Results of measurement: f - frequency, α - transmission coefficient of the mechanical vibration

f [Hz]	Coherence $0 \leq \gamma \leq 1$	Vibration v[10^{-3} m/s]	Pressure [Pa]	α
12.5	1	1	3.14	$2.2 \cdot 10^{-3}$
25	0.9	4.8	6.3	$1.4 \cdot 10^{-2}$
37.5	1	3	14.1	$3.4 \cdot 10^{-2}$
75	1	1.1	56.2	$7.7 \cdot 10^{-2}$

4. EQUAL PRESSURE CONTOURS

Radiated noise directionality measurements show that the radiation is usually dipole in form at lower frequencies, as we could expect. There are some departures from this pattern which can show hull interactions.

Ship noise does not transmit acoustic energy uniformly in all directions, but has a characteristic directional pattern in the horizontal plane around the radiating ship. More noise is radiated in the aft direction, because of working the propellers. This is because the hull is screening in the forward direction and the wake at the rear.

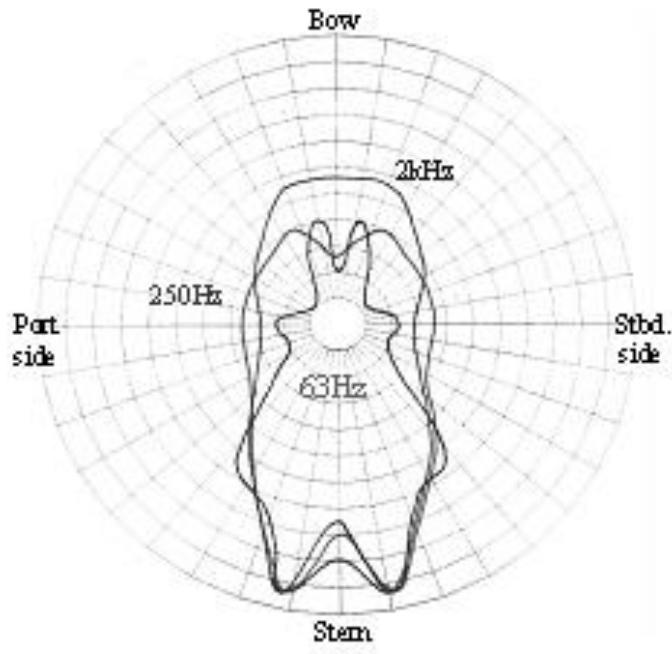


Fig. 2. Equal pressure contours of a ship

A directivity pattern of ship noise is in the 63 Hz, 250 Hz and 2 kHz octave-band for a surface ship moving at 8 knots, sound pressure levels were measured on the button in 20 m of water.

4. SUMMARY

From the analysis of the measurement data it is concluded that at low speed, the acoustic signature of the ship is dominated almost completely by discrete lines from the ship's service diesel generator.

- Above such speed, the ship's signature is dominated by three major sources: main engine diesel firing rate harmonics, blade rate harmonics, and cavitation noise which has a character of wideband noise [3],
- Bad technical state of ship's machinery is associated with the increase of the levels of vibration and underwater noise sometimes about 6 dB,
- The knowledge of underwater noise radiated by ships is important not only for monitoring the technical state and of the military underwater purposes, but also from point of view of noise control in the water environment especially sea animals. So far the effect of ship's noise on the biological environment have not been widely investigated in the Baltic Sea.

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