Abstract

In this paper the results of investigations of underwater disturbances radiated by surface ships are presented. The underwater sound measurements were performed both for sailing condition and during anchorage. The series of hydrophones were mounted on tripods 1m above the sea bottom. To identify the source of noise, the level of vibration was measured onboard by accelerometers inside each ship section. At the same time, we performed stationary underwater trials, with a vessel moored to buoys, enable the acoustic disturbances of particular machinery to be analyzed. This research allowed to determine the transmission coefficient for the mechanical vibration energy going through the ship’s hull and the evaluation of influence on the hydroacoustic field of a ship. The values signaling the changes of the technical condition of machinery and propulsion system.

As results of research new solutions have been created useful for improvement of ship’s technical parameters, which is also important for the natural environment and biological life in the sea.

1. INTRODUCTION

For years in the Polish Naval University extensive researches are being made of the noise radiated by different kinds of surface ships and submarines. The underwater ship noise is a subject of interest from several points of view. First of all controlling acoustic signature on vessels is a major consideration for seamen, naval architects and operators. In addition the important application of underwater noise is the underwater warfare; control and evaluation of noise signature is an significant determinant of ship survivability in a stealthy naval environment. High levels of underwater acoustic signatures can be detected by a passive sonar sometimes hundreds of kilometers away from the source of noise. Hostile navies use these signatures for detection and classification of targets. 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 [1].

Last reason is the effect of the noise from naval and merchant ships into the biological environment, because noise from ships elevates the natural ambient by 20 – 30 dB [2]. Marine animals such as gray seals (Halichoerus grypus) and common porpoises (Phocoena phocoena) are present in the southern part of the Baltic Sea They produce a fascinating variety of sounds, that can travel at great distances underwater. Signature sounds of these animals differ between the individual. Vocalizations of these animals are used to communicate with each others.

In many situations, maintenance of the machinery in a ship and details how it is used largely determine the underwater noise 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. This vibration is coupled to the water via the hull of the vessel.

2. THE SOURCES OF ACOUSTIC SIGNATURES

Several sources of noise radiation from a vessel exist; they are dependent on the frequency band, speed and sometimes sea depth. Among the main sources of ship noise are:

- propeller,
- machinery,
- hydrodynamic.

The sources of ship underwater sounds are diverse and a given source changes its sound output with ship speed. Therefore ship noise are variable complex and are distributed through the entire frequency range. The main sources are the hull, that transmits the vibrations of the machinery and engines, and propellers, where hydrodynamics and cavitation produces noise.

Machinery noise originates as mechanical vibration of the many devices inside a moving vessel. It can create underwater noise in the following ways:

- rotating unbalanced shafts,
- repetitive discontinuities,
- explosions in cylinders,
- cavitation and turbulence in the fluid flow in pumps, pipes and valves,
- mechanical friction in bearings.
The first three of these sources radiate discrete spectrum in which the noise is dominated by tonals at the basic frequencies and their harmonics [3]. The harmonic structure of radiated noise is complex, and the discrete component generated by even a single source of noise is irregular and variable. With changing conditions of the ship we have variations of level and frequencies.

There are various paths such as the mounting of the main engine or diesel generator, which connect the vibrating parts to the hull. Radiation at discrete frequencies, caused by low frequency hull vibrations, excited by the machinery is easily detected, it must be reduced as much as possible.

Fig.1. The underwater noise spectrum or so called “acoustic portrait” of a moving vessel

Fig. 1 shows keel aspect narrow-band power spectrum in 0.5 Hz bands of a typical ship going with the speed of 3.8 knots. The radiated noise data show high-level tonal frequencies from the ship’s service diesel generator, main engine firing rate, and blade rate harmonics (directly from propeller cavitation). A ship’s service diesel generator creates a series of harmonics which amplitudes and frequencies are independent of ship speed. Propellers generate cavitation especially at high speeds of a vessel which have continuous component. The production and collapse and cavities created by the action is called propeller cavitation. Cavitation noise consists of a large number of random small bursts formed by bubble collapse; cavitation noise has a continuous spectrum. At the higher speed of the vessel the spectrum of propeller noise increases and shifts to lower frequencies [3].

The sound level frequency of the spectrum constitutes a mixture of the continuous and discrete lines. The former is characterized by a maximum in the area from 50 to 200 Hz, which is a typical feature in ship noise spectra. At frequencies greater than 200 Hz, sound pressure level (SPL) falls by 6 dB, when the frequency is doubled. It means that SPL is inversely proportional to the square of the frequency. The discrete components are the most visible in a ship’s spectra since they are detected even at low speeds (shown in Fig. 1). Moreover these discrete components of noise spectra are called “acoustic portrait”, which is unique for each ship. This acoustic portrait is used to reveal the location and to identify the source of noise.

Some time ago the Navy initiated a new program for accurate and very narrow-band analysis of ship noise. Nowadays, 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 were carried out by means of the array of hydrophones. Several hydrophones at depths from 10 to 60 m were used to acquire the ship’s radiated noise. On the basis of these results, we determine the maximum values of the sound pressure levels for different speeds of a ship; it is shown in Fig.2.

Fig.2. The sound levels radiated by a moving vessel with different speeds (3.8 kn, 8 kn and 11 kn)

3. MEASUREMENT METHODS AND COMPARISON OF SPECTRUM COMPONENTS

During the ship measurements, the average wave height was less than 1 m and wind speeds less than 5 m/s, so the ambient noise level was low. At the time of the measurements the sound profile was typical of the summer. This curve was smooth with gradually decreasing gradient without mixed layers.

Specialists conducted vessel trials both statically and dynamically, sometimes over their full speed ranges. The vessel under test was arranged to run at a constant speed and constant course. Stationary trials, with ships or submarines moored to buoys, enabled the acoustic contributions of particular machinery systems to be estimated. During these trials analogue broadband tape recordings were made, and later subjected to analysis in different frequency bands.

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.
A simultaneous on-board vibration monitoring system provided additional measurements of tonals from inside our vessel (where accelerometers were mounted on the diesel generators and the main engine, near the shaft and the hull).

At low ship speeds, discrete lines of the spectrum nearly almost always originate from the ship’s diesel generator [2]. 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 AC power line frequencies (harmonics of 50 Hz) are distributed throughout the whole vessel [5].

In the Fig. 4 the bandwidth is 0.125 Hz. Tonal harmonics 37.5 Hz are from a working diesel generator.

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. 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 [6]. 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.

In the Fig. 5 the bandwidth is 0.125 Hz. Tonal harmonics are from a working diesel generator. The Diesel generator 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.

**4. TRANSMISSION OF ACOUSTIC ENERGY**

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. Monochrome 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.

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 the 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 \( G_{pv} \):

\[
\gamma_{pv}^2(f) = \frac{G_{pv}(f)}{G_p(f)G_v(f)}
\]

(1)

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 maximum that means from 0.9 to 1.

**Table 1**: Results of measurement: \( f \) - frequency, \( \alpha \) - transmission coefficient of the mechanical vibration

<table>
<thead>
<tr>
<th>( f ) [Hz]</th>
<th>Coherence ( 0.9 \leq \gamma \leq 1 )</th>
<th>Vibration ( v[10^3 \text{ m/s}] )</th>
<th>Pressure ( \text{[Pa]} )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>1</td>
<td>3.14</td>
<td>2.2 ( 10^{-4} )</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.9</td>
<td>4.8</td>
<td>6.3</td>
<td>1.4 ( 10^{-2} )</td>
</tr>
<tr>
<td>37.5</td>
<td>1</td>
<td>3</td>
<td>14.1</td>
<td>3.4 ( 10^{-2} )</td>
</tr>
<tr>
<td>75</td>
<td>1</td>
<td>1.1</td>
<td>56.2</td>
<td>7.7 ( 10^{-2} )</td>
</tr>
</tbody>
</table>

Relations between mechanical vibration and hydroacoustic field of a ship is presented by transmission coefficient of the mechanical vibration \( \alpha \):

\[
\alpha = \frac{L_{1m,1Hz}}{\rho c v}
\]

(2)

where \( L_{1m,1Hz} \) – sound pressure level relative to 1\( \mu \)Pa at 1m for 1 Hz,

\( \rho \) – fluid density for sea water,

\( v \) – velocity of vibration,

\( c \) – propagation velocity of wave.

The proportionality factor \( \rho c \) is the acoustic resistance of the fluid and for sea water is \( 1.5 \times 10^6 \) \([\text{g/cm}^2 \text{s}]\).

Though radiated sound is frequently expressed in spectrum levels, that is, in 1-Hz bands (we show it in – \( L_{1m,1Hz} \)), frequency analyses are more conveniently made in wider bands so the results are reduced to a band of 1 Hz. The results are reduced to a band of 1 Hz by applying a bandwidth reduction factor equal to \( 10 \) log of the bandwidth used. The distance in this case is the horizontal distance, while the actual source-to-receiver range, the radial distance, was used for these measurements. Therefore we calculated here 20 log range (spherical) spreading loss applies in the acoustic field at all frequencies.

## 5. SUMMARY

This paper presents transmission of vibration and its influence into underwater noise created by both a moving and stationary ship. The spectral components may appear as an effect of the change of parameters of vibrating elements or as an effect of non-linear wave deformations due to an increase in pressure amplitude of primary component (higher harmonics). The transmission of the acoustic energy from ship’s hull within which there is a mechanical device in dynamical state is conducted through a relatively complicated path [7]. The observation from analysis of underwater noise give an opportunity for tracing the changes in underwater acoustical disturbances being transmitted to the water. As a result, there are possibilities of monitoring the technical state of ship’s machinery.

It is possible not only to detect a machine like a pump, a generator or a propeller in the background of the shallow sea’s natural noises, but also to show the speed of vessel.

The best solutions to detect a ship are the discrete frequencies in the low frequency portion of the ship’s noise spectrum and that only narrow – band filters can be used. This must be done because there are no discrete lines at frequencies greater than 200 Hz in the modern submarines and surface warships.

In the Baltic’s shallow waters and the conditions under which we are interested, the area of optimal frequencies for the propagation of sound lies in the band from several Hz up to 5 kHz.

There are different methods to minimal acoustic signatures. Noise isolation systems for vessels employ a wide range of techniques, especially double-elastic devices in the case of diesel generators and main engines. Also, rotating machinery and moving parts should be dynamically-balanced to reduce the noise. In addition, the equipment should be mounted in special acoustically- insulated housings (special kind of containers).

## 6. REFERENCES


