A PARAMETRIC STUDY OF THE ENVIRONMENT AND THE ARRAY CONFIGURATION FOR UNDERWATER NOISE MEASUREMENT FROM SHIPS IN SHALLOW WATER

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In 2016, a standard describing the experimental procedure to measure the underwater sound from ships has been published (ISO17208-1). A second part has been written to correct the measured data from the reflection on the sea surface, effect known as the Lloyd’s mirror effect (not published yet). For these procedures, deep waters are required, i.e. a minimum depth of 150 m or 1.5 times the overall ship length. In some maritime areas, this requirement can be difficult to fulfill and the measurements can only be done in shallow waters. It is well known that in a shallow water environment, it is difficult to assess the level of a sound source, because of the multiple reflections on the bottom and on the sea surface. The aim of this study is to understand which parameters influence the sound measured by a hydrophone array in such a configuration, assuming the source level is known. The sound level measured by the hydrophone array is simulated using open source underwater propagation models for propagation distances up to a few hundred meters. The influence of different parameters is successively investigated: source depth, water depth, source range, number of hydrophones, sea bottom properties, speed of sound profile. At low frequencies, the radiation of the source is similar to a dipole because of the Lloyd’s mirror effect. At high frequencies, the third-octave bands level tends to a constant number with respect to frequency, which depends on the ratio of water depth to distance to source, and to the sea floor properties. Observations of the results show also that the gap between these two frequency domains is at a fixed value of the acoustic wavenumber multiplied by the source depth. Based on the simulations, empirical formulas are suggested in order to correct the effect of the shallow water environment.

Keywords: radiated noise, shallow water, shipping noise, standardization, underwater noise

1. Introduction

With the global increase of commercial traffic in every sea around the globe, concerns are arising about the impact on the environment. More especially, the underwater noise radiated by ships can disturb and harm fish and marine mammals. Nowadays, there is no regulation limiting underwater noise from ships but only non-mandatory guidelines [1,2] or incentives to reduce their radiated noise. For instance, the port of Vancouver has a programme aiming at saving the whales’ habitat by giving discounts to quiet ships, the ECHO project [3]. In this context there is a need for reliable measurement procedures able to determine the underwater radiated noise of a ship. The first part of the ISO standard 17208 describes the experimental procedure aiming to measure the noise in a deep water environment [4]. The second part aspires at correcting the measured level from the reflection on the sea surface. In a shallow water environment (typically less than 150 m depth), the measured level needs also to be cor-
rected from the reflections on the sea bottom, and from the multiple reflections at the bottom and at the surface (see Figure 1). The correction can be influenced by several measurement parameters: source depth, water depth, source range, number of hydrophones in the array, sea bottom properties, speed of sound profile. In this paper, a parametric study is conducted in order to understand which parameters influence the measured level.

![Figure 1: Sketch of the underwater radiated noise measurement from a ship in a shallow environment](image)

### 2. Methodology

As presented on Figure 2, a reference situation is being considered. In order to model this problem, several assumptions are made:
- The problem is 2D, i.e. propagation loss depends only on distance and depth,
- The ship is modelled as an equivalent omnidirectional point source. It is placed at a fixed position,
- The speed of sound in water is constant,
- The sea floor is flat and composed of a homogeneous material, of semi-infinite extent and modelled as an equivalent fluid.
- The hydrophones are equally spaced on a vertical hydrophone array.

Numerical values for the reference case are given in Table 1. The values corresponding to the grey lines will be modified in the parametric study presented in the next section.

![Figure 2: Definition of the situation for the parametric study](image)
### Table 1: Reference case’s parameters

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth</td>
<td>H</td>
<td>60 m</td>
</tr>
<tr>
<td>Source depth</td>
<td>d_s</td>
<td>4 m</td>
</tr>
<tr>
<td>Speed of sound in water</td>
<td>c_0</td>
<td>1500 m/s</td>
</tr>
<tr>
<td>Density of water</td>
<td>( \rho_0 )</td>
<td>1024 kg/m³</td>
</tr>
<tr>
<td>Speed of sound in the sea floor</td>
<td>( c_{SF} )</td>
<td>1749 m/s</td>
</tr>
<tr>
<td>Density of the sediment</td>
<td>( \rho_{SF} )</td>
<td>1941 kg/m³</td>
</tr>
<tr>
<td>Absorption in the sediment</td>
<td>( \alpha_{SF} )</td>
<td>0.9 dB/λ</td>
</tr>
<tr>
<td>Number of hydrophones</td>
<td>N</td>
<td>3</td>
</tr>
<tr>
<td>Depth of the first hydrophone</td>
<td>H_{top}</td>
<td>15 m</td>
</tr>
<tr>
<td>Depth of the last hydrophone</td>
<td>H_{bottom}</td>
<td>55 m</td>
</tr>
<tr>
<td>Distance between two hydrophones</td>
<td>( \Delta H )</td>
<td>20 m</td>
</tr>
<tr>
<td>Distance between the ship and the hydrophone array</td>
<td>( D )</td>
<td>100 m</td>
</tr>
</tbody>
</table>

Numerical simulation is used to determine the transfer function between the sound source representing the ship and the hydrophone array. The transmission loss (TL) between the source and a hydrophone is calculated for each hydrophone position. For each hydrophone, the TL is multiplied by the distance between the source and the hydrophone. This correction corresponds to the losses in the case of a point source in a homogeneous and infinite medium. Then, the quantities for each hydrophone are quadratically summed up to yield the relative level between the source and the measured quantity.

A Matlab interface to classical propagation codes is used to calculate the TLs [5]. In the low frequency range (between 10 Hz and 1 kHz), the problem is solved using the wavenumber integration (Scooters&Fields). In the high frequency range (between 1 and 20 kHz), the problem is solved using the beam-tracing code Bounce&Bellhop. These codes have been previously compared to experimental data in shallow water and have shown good accuracy [6]. The results are given on third-octave bands with 11 frequencies on each band.

### 3. Results

#### 3.1 Influence of source depth

Three source depths are chosen: 2 m, 4 m (reference case) and 6 m. On Figure 3, the results are plotted as a function of the dimensionless variable \( kd_s \) with \( k = \frac{\omega}{c_0} \) being the acoustic wavenumber at the circular frequency \( \omega \). The dipole effect due to the free surface is seen at low frequencies (also called the Lloyd’s mirror effect), while at high frequencies the relative level tends to a constant value around 5 dB. Plotting these values as a function of \( kd_s \) shows that the limit between the low and high frequency behaviors is at a fixed \( kd_s \) (around 2) for each and every source depths.
Figure 3: Relative pressure level (dB) as a function of $kd_s$ for different source depths

3.2 Influence of the distance between the source and the hydrophone array

Let us chose the source depth at 4 m. The calculations are then performed for 6 different values of $D$: 50, 100, 150, 200, 250 and 300 m. The results are plotted on Figure 4. First, it can be seen that for each distance, the low and high frequency behaviors are still clearly distinct, with a limit around $kd_s = 2$, as shown in the previous section. It can be noticed that the low frequency behavior ($kd_s \leq 2$) does not depend on D. At higher frequencies, we note that the larger the distance, the higher the level. This can be explained by the fact that the relative level is calculated using a spherical correction on each hydrophone ($20 \log_{10} R$ with $R$ the distance between the source and the hydrophone). We find that the further the hydrophone array is, the more reflections with the sea bottom and surface appear, so that it is often considered in practice that the level of waves propagating in a channel decreases with $10 \log_{10} R$ when far from the source. The difference between the spherical correction and the actual propagation explains why the relative level increases with D.
3.3 Influence of water depth

All other parameters being fixed, four different values are chosen for the depth of the water column H: 20, 40, 60 and 100 m. As described on Figure 5, water depth has an influence on the configuration of the hydrophone array (the hydrophones being represented by the red dots). On Figure 6, the relative level for these four different configurations is plotted as a function of $kd_S$. At low frequencies, the curves for the water depths of 40, 60 and 100 m are the same. For 20 m water depth, the hydrophones are at smaller immersions: the first hydrophone is 5 m deep, while it is at 15 m for the other configurations. When the hydrophones are closer from the pressure-release surface, the dipole effect is stronger. It explains why at low frequencies the red curve deviates from the others.

At high frequencies, the level is lower when the water channel is deeper. It can be explained by the fact that the acoustic power from the source radiates through a larger surface (or solid angle), resulting in a lower pressure at the hydrophones locations.

![Figure 5: Sketch of the hydrophone array configurations for different water depths](image)
Figure 6: Relative pressure level (dB) as a function of the frequency for different water depths, a source depth of 4 m and a distance of 100 m

4. Empirical model

4.1 Formulation

The previous simulations analysis highlights the following trends:

- It is relevant to plot the relative level as a function of the reduced wavenumber $kd_s$ to compare configurations with different source immersions. It shows a dominant low and high frequency behavior, with a frequency limit around $kd_s = 2$.
- At low frequencies, there is a dominant Lloyd’s mirror effect, corresponding to a dipole-like behavior with high propagation loss.
- At high frequencies, the relative level tends towards a constant value, depending on the water depth and the distance between the source and the hydrophone array. Note that if $H \gg D$, the asymptotic value should be 3 dB [7].

Except for $d_s$, D and H, every other parameters are set to the values given in Table 1. In that case the following formula is suggested:

$$\Delta L = \begin{cases} 20 \log_{10}(kd_s) & \text{if } f < f_0 \\ \alpha & \text{if } f > f_0 \end{cases}$$

(1)

with

$$f_0 = \frac{c_0}{2\pi d_s} 10^{(\alpha/20)}$$

(2)

and

$$\alpha = 5 \log_{10}\left(\frac{\max(D,H)}{H}\right) + 3$$

(3)
4.2 Comparison of the model with the simulations

Let us compare the empirical formula given in Eq. (1) to the results of the simulation for H=60 m and D=100 m, as shown on Figure 7. It can be noticed that for the three source immersions the offered model (dashed lines) fits the simulations (solid lines) well.

![Figure 7: Relative pressure level (dB) as a function of the frequency, comparison of model and simulations for water depth H=60 m and D=100 m, depending on different source depths.](image)

5. Conclusions and perspectives

Numerical simulations using open-source propagation codes have been used to calculate the relative level of a ship depending on different measurement configurations. The relative level shows a dipole-like behaviour in the low frequency range, and a constant value in the high frequency range. The influence of source depth, water depth and distance between the source and the hydrophone array has been studied. Results show that these three parameters have an influence on the measured level. The source depth changes the location between the low and high frequency domains, while the two other parameters modify the relative level at high frequencies. An empirical formula has been suggested regarding the relative level and demonstrates good agreement with the simulations. The main limitation of this work is that the formula is only valid for a given set of the parameters representing the sea floor properties. Further study consists in conducting parametric studies over the configuration of the hydrophone array and the sea bottom parameters in order to offer a model taking into account all the relevant variables.

REFERENCES

1. Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life, IMO MEPC.1/Circ.833, April 2014.


