A Simple Model for the Underwater Noise Source Level of Ships

Dietrich Kurt Wittekind

DW-ShipConsult GmbH, Lise-Meitner-Str.1-7, Schwentinental D-24223, Germany

Underwater noise becomes a field of growing concern because of the possible interaction with sound vocalization of marine mammals. Modeling the effect of shipping noise being a predominant contribution worldwide requires more than statistics of measured ships in the field. This article is an attempt to characterize the underwater radiated noise level of a ship by relating spectral components of noise to naval architectural features of the ship.

Keywords: underwater noise; propeller noise; low frequency shipping noise

1. Introduction

Underwater radiated noise of commercial shipping becomes a growing concern in view of its effects on marine life.

It is observed that in most regions of deep water oceans, the low frequency range below approximately 300 Hz of the underwater sound spectrum is caused by ships, thus masking natural background noise and communication calls of marine mammals such as the baleen whales. The level of this noise appears to increase with the number of ships, size, and propulsive power, which are growing with global trade (Andrew et al. 2002; McDonald et al. 2006).

Approaches to describing underwater acoustic levels radiated from ships are traditionally generated from field measurements of incidentally passing ships (Wales & Heitmeyer 2002; Hatch et al. 2008). Frequency ranges considered vary as do descriptions of measuring conditions, measuring setup, and geometry. Operating conditions of the ships are not described. Existing empirical acoustic ship models (Ross 1976; Wales & Heitmeyer 2002) and others are limited in frequency range and ship parameters considered. All do not model the familiar hump at approximately 50 Hz of the ship underwater noise spectrum.

However, it is known from research around naval ships and work done in full and model scales on merchant vessels that radiated noise from ships shows great variations depending on certain design parameters (Wittekind 2009). Systematic investigations into the relationship of design parameters and radiated noise are missing. It can even be assumed that these parameters are not yet known.

This article is an attempt to describe the underwater source level based on observations in the field and rational relationships between mechanical and geometrical parameters. Findings are related to ship design parameters familiar to naval architects.

Besides literature sources, this article is based on work funded by the Okeanos Foundation, the German Federal Environment Agency, and the German Federal Agency for Nature Conservation.

2. Contributions to radiated noise of ships

There are no field measurements made under controlled conditions that relate naval architectural features to spectra and noise levels. A speed dependence of radiated noise has been described in detail by Arveson and Vendittis (2000) on which much of the following work relies.

Full-scale and model tests reveal features of background noise recognizable when measured in close vicinity of the propeller (Bark 1985; Heinke 1991; Baiter 1992; Wittekind 2009). It could also be shown that important features of the spectrum appear reliably in model tests with good match to the full-scale ship (Bark 1985; Heinke 1991).

1. Propeller noise (fixed pitch propellers and controllable pitch propellers at design pitch)

a. Tonals at blade rate

These are a consequence of the individual propeller blade passing through the uneven wake field behind the ship. The areas with the highest wake (smallest axial flow velocity into the propeller) in a single-screw ship are observed in the upper region (around the 12 o’clock position) of the propeller disk. Under these conditions, the angle of attack on the blade is highest and therefore the pressure on the suction side (facing into forward direction) lowest. For all propellers of seagoing ships at their service speed, this
pressure will be below evaporation pressure. The forming of steam-filled bubbles is referred to as cavitation. The cavitation bubbles form only around the upper position. They will appear and vanish with the rhythm of blades passing. In a spectrum, these appear as tonals at multiples of blade rate (shaft speed × number of propeller blades). Depending on shaft speed (e.g., 90 rpm for a large ship, 150 rpm for a small ship) and number of blades (typically four, sometimes five, for high-power container ships sometimes six), the first harmonic is below 10 Hz for large ships and slightly above for small ships.

These tonals are often subject to investigation during ship design because they influence comfort on board. Vibration levels are limited by standards and are related to the pressure acting on the hull above the propeller. Typical pressure maxima are 2 to 10 kPa for a first harmonic usually (but not always) decreasing with the higher harmonics. Values below 1 kPa can be assumed as a possible minimum even for a noncavitating propeller. These contributions can be measured at the hull above the propeller if this part of the ship is submerged. Model scale results are reliably used to predict full-scale values. Accuracy decreases with the number of harmonics.

b. Broad band, low frequency

This contribution is the least understood. Background noise attributed to shipping at long distances as well as measurements in close vicinity of the ship and the propeller show a broad band spectrum peaking at approximately 40 to 50 Hz in most ships. It is unknown how this spectrum is formed and why it seems that the peak is increasing with speed but does not move in frequency (Arveson & Vendittis 2000).

The broad band, low-frequency contribution is not a subject to consider in ship and propeller design because its effect on vibration is negligible compared with that of the blade rate tonals. On the other hand, it also does not contribute critically to the acoustic frequency range, partly because it fades away fast in the structure of the ship with distance to the propeller and because it is already strongly reduced by the A-weighting of the human ear such that other noise sources (machinery, ventilation) mask the contribution from the propeller.

c. Broad band, high frequency

This is the contribution that is observed first when a propeller exceeds cavitation inception speed. It first appears as an increase of level at high frequencies, which then dominates lower frequencies with increasing ship speed. The reason is the high-frequency part of small bubbles appearing and vanishing, often interacting with the blade structure. It also contains continuous noise such as hub vortex cavitation. The frequency where this contribution appears first is not subject to consideration here. If cavitation inception speed is considered, this is defined as the speed where the tonals of blade rate harmonics start to increase with speed at a high rate. This will occur later than the rise of the high-frequency part of the spectrum.

2. Machinery noise

a. Diesel generators

Large ocean-going ships typically have three generators, either driven by dedicated medium-speed four-stroke-cycle diesel engines or by the propulsion diesel. Diesel generators are often resiliently mounted because they are strong contributors to noise after it propagated through the structure and being radiated into rooms aboard. The noise of these diesels is characterized by tonals at multiples of half rotational speed. Rotational speed is linked to electric mains frequency, which is typically 60 Hz. A typical diesel generator therefore turns at 720 rpm, but there are also aggregates with 600 or 900 rpm. A diesel with 720 Hz has tonals at 720/60/2 = 6 Hz and multiples up to kilohertz range.

b. Low-speed propulsion diesels

The low-speed two-stroke-cycle engine is the standard engine type for ship propulsion. It drives the propeller directly without gear and therefore has the same rotational speed. As a result of low revolution, a high torque is required, which leads to an impressive size of these engines (up into the 1000 tons mass). They are always rigidly mounted in the ship. As a result of their low speed, they are relatively quiet compared with a four-stroke-cycle engine but may contribute to radiated noise resulting from their sheer size. The spectrum of these engines has no clear signature; therefore, it is difficult to identify a possible contribution to radiated noise.

c. Medium-speed propulsion diesels

These are used for propulsion of smaller ships. A typical rotational speed is 514 rpm. This has to be reduced to propeller shaft speed by means of a gear box. In a standard design, the engine also drives a generator making use of the low fuel consumption of the engine compared with a diesel generator and saving one diesel as a generator drive. The generator requires constant speed. A standard feature for this propulsion system is therefore a controllable pitch propeller to allow ship speed variations by adjusting blade pitch independent of shaft speed.

These diesel engines can be resiliently mounted quite easily. For this, the shaft is decoupled by a rubber coupling making the contribution of these diesels about equivalent to diesel generators. However, still very often these engines are hard-mounted for cost reasons and will therefore have a high noise output to the environment. Controllable pitch propellers at normal service speed are acoustically equivalent to fixed-pitch propellers. However, at lower speed when pitch is reduced, they may appear considerably noisier, because the inflow to the blades is far off the optimal performance they were designed for. These ships become noisier at low speed. The exact relationship between noise output and speed still is to be investigated in the future.

3. Basic thoughts on an acoustic ship model

For simplicity we further look only at three components of shipping noise, which are observed to dominate in almost all ships:

- Low frequencies from propeller cavitation;
- Medium to high frequencies from propeller cavitation; and
- Medium frequencies from four-stroke diesel engines.
One of the prerequisites for a universal acoustic ship model is the possibility to place it in an arbitrary environment and determine received levels in a given environment. This would be ideally possible if the model can be reduced to a monopole and be placed in a known position relative to the water surface.

Noise of the propeller can be viewed as a monopole because the cavitation bubbles are very limited in size and actually act as a monopole as a result of their variation in volume during expansion and contraction. However, their relative position to the surface is difficult to assess. For determination of the exact position, we would need the draft of the ship, the size of the propeller, the position where cavitation occurs, and the height of the stern wave created by the ship itself. The consequence of the presence of the water surface as a pressure release surface manifests itself in the Lloyd Mirror effect, essentially an interference effect of two sound propagation paths, one directly from the source and the other through reflection at the surface. At low frequencies, this behavior merges into a dipole radiation with a pronounced directivity in the vertically downward direction. The Lloyd Mirror effect for point sources can easily be described analytically with great accuracy for practical applications (Urick 1983).

For machinery noise, the source has a finite dimension consisting of the hull shell in way of the source such as a diesel engine. This cannot be modeled as a monopole but there is an integration effect resulting from the distributed source with a large surface. In addition, because the contribution from machinery is not particularly of very low frequency, it is acceptable that the Lloyd Mirror effect does not affect radiation.

The numerical model presented here is primarily based on Arveson and Vendittis (2000) and our own measurements on a container vessel and field measurements. The container ship was a new 3400-TEU vessel built by the Nordseewerke yard in Germany. One of the three ships built carried a set of acoustic sensors on the hull above the propeller for several weeks and recorded low-frequency noise at various operating conditions (drafts and speeds).

Arveson reports on noise measurements of a small bulk carrier in ballast at several speeds in well-defined conditions. Measurements of comparable quality for this kind of ship are not available to the author.

4. The main ship parameters influencing noise and their spectral behavior

The main parameters considered here are:
- Displacement;
- Speed relative to cavitation inception speed;
- Block coefficient as an indicator for wake field variations;
- Mass of diesel engine(s); and
- Diesel engine resiliently mounted yes or no.

Propulsive power is not explicitly addressed but it relates to displacement, speed, and the block coefficient.

The block coefficient is the ratio of the displacement to length × breadth × draft of the ship.

Considerations are valid for fixed-pitch propellers and controllable pitch propellers at design pitch.

These parameters are now related to the three main contributors to underwater irradiated noise low-frequency cavitation noise, hereafter denoted \( F_1 \), high-frequency cavitation noise \( F_2 \) and diesel engine noise \( F_3 \). Each of these contributions shall be viewed as an averaged sound pressure level \( L_{eq} \) in third octaves. The intensities of these contributions are then added to yield the overall source level (SL).

\[
SL = 10 \log \left( \frac{10}{10} F_1 + \frac{10}{10} F_2 + \frac{10}{10} F_3 \right)
\]

The low-frequency contribution \( F_1 \) is formulated in a way that it represents the monopole level, i.e., the level as it would appear in an unbounded medium. The monopole level is higher as the dipole level at low frequencies. At higher frequencies, the dipole level is higher (theoretically by 3 dB) because noise spreads hemispherically as a result of the presence of the nonpenetrable surface.

The transition between high and low frequency is approximately

\[
f = \frac{c \cdot r}{8 \pi z_r z_s}
\]

with
- \( c \) = speed of sound
- \( r \) = slant distance between source and receiver
- \( z_s \) = source depth
- \( z_r \) = receiver depth

The 3-dB lower level at higher frequencies for the monopole is ignored in the following avoiding too much complexity. Modeling the low-frequency part as a monopole is very important because there the propagation loss when moving away from the source parallel to the surface follows 40log(distance) rather than 20log (distance). If the source level as presented in the following is based on an input for a propagation loss calculation using an approximation of the Helmholtz equation, it will only yield correct results if described as a monopole. For the higher frequency part, there is an error of 3 dB but 20log(distance) remains a correct assumption.

5. Components of the acoustic model

5.1. Low-frequency propeller noise

In a noncavitation condition, the dominating noise is from blade vibrations, which yield a very low noise contribution neglected here as compared with, e.g., machinery noise.

As soon as the propeller cavitates, its low-frequency contribution quickly becomes dominant. Considering the cavitation bubble(s) developing on the blades predominantly around the 12 o’clock position, these grow in size with decreasing pressure on the suction side and size of the propeller. The pressure on the suction side will decrease with rising angle of attack on the blade, which in turn follows the wake. The higher the wake (i.e., the smaller the inflow velocity to the propeller), the higher the angle of attack and the more pronounced is cavitation. Size of the propeller scales with the length of the ship and area increases therefore with the scale squared. However, our own measurements show that the relationship between ship size and noise level is not as strong as might be expected as follows from publications (Ross 1976; Wales & Heitmeyer 2002) and our own measurements.

Furthermore, we have to consider that not in all cases the propeller can be designed for highest efficiency, which relates to relative thrust loading of the propeller. For container vessels in most cases, the highest efficiency propeller can be designed; however, for a slow big block ship, this may not be the case. It is
technically not feasible to accommodate a propeller of the diameter required or buy an engine, which could operate with the resulting low speed.

The quality of propeller/hull interaction can be judged by looking at cavitation inception speed (CIS). This speed depends on inflow speed variation, propeller loading, propeller submergence, and quality of the propeller design. This would suggest that big block ships like a tanker have less favorable conditions compared with a slender containership, i.e., CIS is higher in a containership. However, looking at individual ships, CIS can vary greatly. Table 1 shows the characteristics of five ships and Fig. 1 the amplitude of the first harmonic of blade rate with increasing shaft speed. The point where the level increases more rapidly indicates the shaft speed where cavitation has a measurable effect on pressure fluctuations and supposedly radiated noise. Note that cavitation may have started at considerably lower speed but may have first an effect only at higher frequencies, which may explain the high CIS compared with traditional experience.

From Arveson and Vendittis (2000) we now curve fit the low-frequency contribution with the function and account for speed, block coefficient, and size:

\[
F_1 = 2.2 \cdot 10^{-10} \cdot f^5 - 2 \cdot 10^{-7} \cdot f^4 + 6 \cdot 10^{-5} f^3 - 8 \cdot 10^{-3} f^2 \\
+ 0.35 \cdot f + 125 + A + B \\
A = 80 \cdot \log \left( \frac{v}{v_{CIS}} \right) \cdot 4 \cdot c_B \\
B = 10 \cdot \log \left( \frac{\Delta}{\Delta_{ref}} \right)^2
\]

with

\[ f = \text{frequency in Hz} \]
\[ A = \text{factor modeling speed and block coefficient} \]

![Fig. 1](image_url) Effect of shaft speed (about linear with ship speed) on level of first harmonic of blade rate for five ships. CIS is approximately 21 knots for ship 2, 13 knots for ship 3, 13 knots for ship 4, and 12.5 for ship 5. Ship 1 does not show cavitation. Dots are measured points, lines are interpolation. CIS, cavitation inception speed

**Table 1** Data are based on measurements by the Hamburg Ship Model Basin (HSVA) taken at the hull above the propeller on modern ships in full scale

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Propeller Diameter D (m)</th>
<th>Number of Blades Z (1)</th>
<th>Rotational Speed N (RPM)</th>
<th>Ship Speed V (knots)</th>
<th>Delivered Power PD (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Research</td>
<td>3.5</td>
<td>5</td>
<td>150</td>
<td>13.8</td>
<td>3.300</td>
</tr>
<tr>
<td>2</td>
<td>RoRo-Ferry</td>
<td>6.1</td>
<td>4</td>
<td>123</td>
<td>22.4</td>
<td>20.000</td>
</tr>
<tr>
<td>3</td>
<td>Tanker 1</td>
<td>5.8</td>
<td>4</td>
<td>130</td>
<td>15.8</td>
<td>7.860</td>
</tr>
<tr>
<td>4</td>
<td>Tanker 2</td>
<td>5.8</td>
<td>4</td>
<td>134</td>
<td>16.0</td>
<td>7.930</td>
</tr>
<tr>
<td>5</td>
<td>Tanker 3</td>
<td>5.7</td>
<td>4</td>
<td>130</td>
<td>15.3</td>
<td>7.062</td>
</tr>
</tbody>
</table>
Fig. 2 Radiated noise of a bulk carrier in ballast at different speeds as received by a hydrophone vertically down and converted to source level using $20 \log(\text{distance})$ from Arveson and Vendittis (2000) compared with prediction for 14 knots. White line represents formula from Wales and Heitmeyer (2002).

B = factor modeling displacement  
\( v \) = speed through water in knots  
\( v_{\text{cav}} \) = cavitation inception speed in knots  
\( c_B \) = block coefficient  
\( \Delta \) = displacement in t  
\( \Delta_{\text{ref}} \) = reference displacement in t = 10,000

The resulting curve is displayed in a graph of source level in third octaves in dB re 1 \( \mu \text{Pa} \) against frequency and will peak at 40 Hz.

5.2. High-frequency propeller noise

The high-frequency part is known to rise from the high-frequency end of the spectrum and covering the spectrum of machinery noise down to lower frequencies with increasing speed. The physical law to describe this behavior is not known; therefore, this behavior is just curve fit to Arveson and Vendittis (2000). A stronger dependence on ship shape is assumed for this contribution representing the observation that it is observable in the radiated spectrum before the low-frequency contribution

\[
F_2 = -5 \cdot \ln(f) - \frac{1000}{f} + 10 + B + C
\]

\[
C = 60 \cdot \log \left( \frac{v}{v_{\text{cav}}} \cdot 1000 \cdot c_B \right)
\]

with

C = modeling effect of speed and block coefficient

The diesel engine is taken from own observations and measurements. It is assumed to be a medium-speed four-stroke engine.
resiliently mounted. Its noise output will increase with power and hence with weight assuming a roughly constant power-to-weight relationship. This would mean an increase in noise with 20log (power); however, as correlation of forces transferred to the ship decreases with the size of the engine, we assume a 15log law. In addition, we include the number of engines in operation. A rigidly mounted engine will have a 15-dB higher level describing the insertion loss of a resilient foundation of moderate quality.

$$F_3 = 10^{-7} \cdot f^2 - 0.01 \cdot f + 140 + D + E$$

$$D = 15 \cdot \log(m) + 10 \cdot \log(n)$$

with

- $D$ = factor modeling engine mass and number
- $E = 0$ engine resiliently mounted, = 15 engine rigidly mounted
- $m = $ engine mass in t
- $n = $ number of engines operating at the same time

6. Other parameters influencing radiated noise

It is observed in various publications (Ross 1976; Wales & Heitmeyer 2002) that noise from ships seems not to vary beyond a band of 10 to 15 dB, at least if looking at frequencies above 100 Hz. However, their design characteristics can be very different and would imply a larger variation.

Several reasons could be suggested for this observation. All ships are designed according to certain standards defined by classification societies. Propulsive efficiency may vary a lot depending on ship type and design effort. Fast ships are slender and have a good wake field; slow ships have a blunter shape and a worse wake field. Almost all ships operate at their design speed when in open water. It could be expected that the amount of cavitation in each ship differs not so much from most of the others so that a 10-dB difference would result (note that if noise is related to area of noise generation 10 dB mean, a difference in area by factor would be 10).

Of course, this would assume that in all these ships, propeller cavitation dominates the spectrum.

In case of machinery noise, the contribution would very much depend on source level and quality of the resilient foundation, if any.

For low frequencies dominated by broad band cavitation noise, the possible spread is not well investigated because there are too few reliable measurements. It must be observed that the Lloyd Mirror effect has a strong influence on received levels and would need to be considered when deriving a source level. To do so, one would need to know source depth, receiver depth, and distance. These are not indicated in almost all reports.

From cavitation tunnel observations, however, it is observed that levels of tonals at multiples of blade rate can be very much influenced by stern and propeller design and application of appendages improving the wake field. It may be acceptable to assume that the broad band level is related to the narrow band levels at harmonics of blade rate, i.e., tonals and broad band level decrease in unison. This needs to be confirmed by further research.

The model described here leads to a monopole source spectrum at low frequencies in third octaves re 1 μPa. Figure 4 collects all possible representations of the ship source spectrum. Full line is third octaves. The dotted line will be observed when the Lloyd Mirror effect is ignored. It leads to partial cancellation of the low frequencies as a result of destructive interference of the direct propagation path and the one reflected at the surface. The radiation pattern is then equivalent to a dipole. In this case, we assumed a source depth of 2.5 m.

It can also be seen that the typical 50-Hz maximum of radiated noise from ships is becoming more pronounced as a result of the surface influence.

We have not considered the difference between ships with small (ballast condition) and full draft (laden condition). In the few unconfirmed observations, the difference is reported as small (approximately 3 dB). Several effects lead to changes in radiation:

- Resistance is lower, propeller is unloaded, and it becomes quieter. There is a danger of face-side cavitation, which would make the propeller noisier.
- Static pressure is lower, which shifts CIS to lower speeds.
- The propeller is closer to the surface so the Lloyd Mirror effect leads to lower radiation.
- The distance between the propeller and the surface depends on sinkage, trim, and height of stern wave, all not known for a particular operating condition. For a fast container-ship, the water level above the propeller at full speed is several meters higher compared with the still water line.

It requires more research to find and explain the influence of draft. For this model discussed here, a standard source depth of 2.5 m is the recommended compromise for all unknown conditions.

Fig. 4 The source spectrum of the bulk carrier from Arveson in 1/3 octaves. The dotted line is the so-called dipole level, i.e., the source level is not corrected for the effect of the water surface. The full lines is the level corrected for the presence of the surface, i.e., it constitutes the monopole level.
7. Results of modeling

Figures 5 and 6 show modeled results for two ships. Any variations of parameters will lead to continuous changes of the spectrum. Sudden changes with speed as observed in the data of Fig. 2 cannot be modeled.

Considerable deviations might be expected when looking at individual ships. As an example, there is still a large number of general cargo ships underway, which may be very slender but slow and have a low-quality wake field and propeller. Also, their machinery may be outdated and without secondary measures such as resilient foundations.

Also ships with controllable pitch propellers at low speed are not represented by the model.

The model can be applied to get an impression of what the received level of ship is in an arbitrary environment.

During a background noise survey, we measured a tanker in a shallow water environment. Conditions were:

Distance to ship at closest point of approach 0.4 nm;
Water depth 28 m;
Hydrophone depth 26 m;
Ship displacement 50,000 t;
Speed 14.7 knots;
Assumed CIS 11 knots;
Diesel generator 1 × 20 tons; and
Bottom sand.

From these data, the source level of the ship was derived and fed into a sound propagation model based on the parabolic equation approximation of the Helmholtz equation. The calculation was made in 1-Hz spacing, which was then averaged for each third octave in the frequency range considered.

Figure 7 shows results. Noise propagation loss at frequencies below 50 Hz could not be calculated as a result of too low wave length/depth ratio. At frequencies below 150 Hz, the prediction of received level compared with measured level is very good. There is a band of strong tones measured at approximately 250 Hz caused by propeller singing from a nearby ferry, which are, of course, not shown in the model. Above this frequency range prediction yields 4 dB higher values on the average than measured.

Besides the inaccuracies in the model, which are expected in the range of ± 5 dB, there is, of course in addition, the inaccuracy of the propagation loss prediction, which is also expected to be in the range of ± 5 dB as a result of unknown properties of the bottom, which would be required down to a depth of several tens of meters for an accurate prediction.

8. Outlook

With the numerical model presented, a reasonable prediction of radiated noise of common merchant ships is possible based on engineering parameters of a ship. It delivers similar variations as observed in the field.

However, much more research is needed to find more influencing parameters, find the reason why not all ships would fit into the model, and cover ships with controllable pitch propeller in off-design pitch.

Another step would be required to relate the parameters discussed to data from AIS (Automatic Identification System), which do not allow identifying the parameters discussed here directly.
They could possibly be inferred from significant naval architectural parameters such as ship speed, L/B, and B/T, which are part of the AIS protocol.

References


