Characterization of ships as sources of underwater noise

C.A.F. de Jong

TNO Science and Industry, Delft, The Netherlands, Email: christ.dejong@tno.nl

Introduction

There is a growing interest in the possible impact of anthropogenic underwater noise on marine life [1]. One of the concerns is the increasing contribution of shipping noise, with the growing number and size of commercial ships. Traditionally, underwater radiated noise control was only of interest for naval [2,3] and fishery research vessels [4]. Due to the potential environmental impact, it becomes also relevant for commercial shipping. The challenge is to bring the expertise from the naval area to the maritime industry. One of the issues is the measurement of ship radiated underwater noise. The definition of the ship as a noise source, the measurement set-up and the environment in which the measurements are taken all have a large impact on the results of ship underwater noise measurements. In this paper these aspects are reviewed and an attempt is made to derive quantitative requirements for the measurement geometry and the resulting accuracy of the results on the basis of numerical simulations and some results from experiments.

Surface ship underwater noise

Surface ships radiate underwater noise due to machinery noise, to the noise generated by the propulsor (propeller, water jet, etc) and to hydrodynamic noise from the flow around the ship hull and appendages [2,3,5]. Particular vessels produce unique sound spectra, known as acoustic signatures, usually composed of a broadband component a set of tonals. Noise characteristics of individual vessels can be roughly related to ship size and speed, but there is a significant variation among vessels of similar classes. The noise depends on a large range of parameters, related with ship design, current state of maintenance, operational settings and sometimes even with environmental conditions, e.g. wave height and direction. Recently, Trevorrow et al. [6] have shown that manoeuvring a vessel leads to a significant increase of radiated noise.

Surface ship underwater noise is usually measured when the vessel passes a stationary hydrophone or hydrophone array. That means that the distance between the ship and the hydrophones changes during the measurements. The propagation loss will change accordingly. On the other hand, the noise generated by surface ships is subject to variations, e.g. due to varying propeller loading in sea way and waves. Hence, the assessment of underwater noise requires averaging of the received sound over a certain time.

'Source Level' definition

The measured underwater noise is an effect of the ship and the environment in which the noise propagates. The measure for characterising sources of underwater noise, independent of the environment in which the measurements are taken, is the source level *SL* [2,3]. This expresses the mean square sound pressure p_{rms}^2 [Pa^2] at a distance r [m] in a certain direction in the far field of the source (where the sound pressure and particle velocity are in phase and decrease inversely proportional to the distance from the source), scaled back to a reference distance r_{ref} = 1 m from the acoustic centre of the source. The acoustic centre is the fictitious point from which the far field sound appears to be radiated. Note that the source level cannot be directly measured at the reference distance of 1 m if that point is not in the far field. The definition of *SL* can be written as:

$$SL = SPL(r) + 20\log_{10}\left(r/r_{ref}\right) \quad \text{[dB re 1 μPa}^2\text{m}^2\text{]} \qquad (1)$$

where $SPL(r) = 10\log_{10}\left(p_{rms}^2(r)/p_{ref}^2\right)$ [dB re 1 μPa^2] is the mean square sound pressure level measured at distance r [m] in a certain direction and p_{ref} = 1 μPa is the reference pressure for underwater sound. The second term in eq.1 provides the scaling to the 1 m reference distance.

This definition is for a monopole in free space, i.e. a point source that radiates sound uniformly in all directions, in a homogeneous, isotropic medium (with equilibrium density ρ [kg/m^3] and speed of sound c [m/s]), without absorption and free from boundaries. In that case, there is a simple relation between the source power W [W] and the mean square sound pressure p_{rms}^2 [Pa^2] at a distance r [m] from the source:

$$W = \frac{4\pi r^2}{\rho c} p_{rms}^2(r) \quad \text{[W]} \qquad (2)$$

In practice, this equation does not apply to surface ships. Ships exhibit directional radiation patterns and a local hydrodynamic field in their vicinity. The underwater environment in which the noise is measured is complex, due to effects of reflections at the water surface and sea bed and of variations of the sound speed across the water depth. Especially the reflections at the water surface, often referred to as *Lloyd's Mirror effect* [2,3], have a large impact on the sound radiation by surface ships. When comparing published ship 'source levels', one must be alert for the definition, the measurement conditions, experimental procedures and environmental parameters, as well as for inconsistencies in reference distances, units and bandwidths, which are all given in various ways in the literature. Some present ship 'source levels' based on the correction given in eq.(1), without taking the free-surface and bottom interference effects or absorption losses into account [3,5]. Others [7,8] determine the 'true' monopole source level, using a propagation model and an assumption for the effective location of the acoustic centre. The latter is required when the resulting 'source level' is to be used as input for propagation models. The first approach can be sufficient for comparison with the appropriate requirements.

Hence, the choice for the 'source level' definition and the associated measurement and analysis procedure, depends on the intended use of the results.

Navies operate fixed and mobile noise ranges to measure underwater radiated noise of ships. Measurement procedures for naval vessels are aimed at an assessment of the susceptibility to detection by acoustic sensors. This concerns detection by passive sonar systems at long range, but also by sensors in torpedoes and mines in the vicinity of the vessel. If the underwater noise levels are to be used for the assessment of mine threat, near the vessel and in shallow water, an averaged single point 'source level', not properly corrected for propagation loss, is clearly insufficient.

There is limited experience with underwater radiated noise of ships outside the navies. The International Council for the Exploration of the Sea (ICES) has proposed an underwater noise requirement for fishery research vessels [4]. The report describes how to measure vessel noise, but it is not clear about source level definition and analysis procedure [9]. The Working Group 47 of the S12 Committee on Noise Standards of the Acoustical Society of America [10] is now developing a commercial standard for the measurement of underwater noise from ships.

With this paper, an attempt is made to quantify the effects of the procedure on the resulting 'source level', by means of simple numerical simulations.

Numerical simulations

For the relatively short ranges at which the surface ship 'source level' measurements are usually taken, the underwater propagation can be conveniently modelled by means of rays, emanating from the source and its images in the surface and the bottom [3]. Effects of variations of the velocity of sound across the water depth can be ignored. In the simulations described here, the sea surface is modelled as a perfect reflector. Reflections at the sea bed are more complex to model. Here the sea bed is taken to be a plane interface with a homogeneous absorptive fluid, described by its density ρ_b [kg/m^3], sound velocity c_b [m/s] and attenuation coefficient α_b [dB/m]. The ship is represented by a point source at a certain depth below the surface.

Source level of a point source in beam aspect

Consider a point source, travelling at a depth $z_s = 4$ m along a straight track (x_s = -100 to +100 m, $y_s = 0$). Measurements are taken at a horizontal distance $y_h = 100$ m from the track, with the closest-point-of-approach (CPA) at $x_s = 0$ m. Three hydrophone positions are defined at depths z_h which correspond with depression angles of 15, 30 and 45° relative to the CPA [10] (z_h = 26.8, 57.7 and 100 m). The water density is $\rho = 1027$ kg/m^3 and the sound velocity $c = 1480$ m/s. Absorption is ignored. The water depth is very large so that sea bed interference can be ignored. Fig.1 presents the received signal at the mid hydrophone. It shows the typical Lloyd Mirror interference pattern due to surface reflections. This pattern depends on the source depth and on the hydrophone position, which means that it is not a source property only.

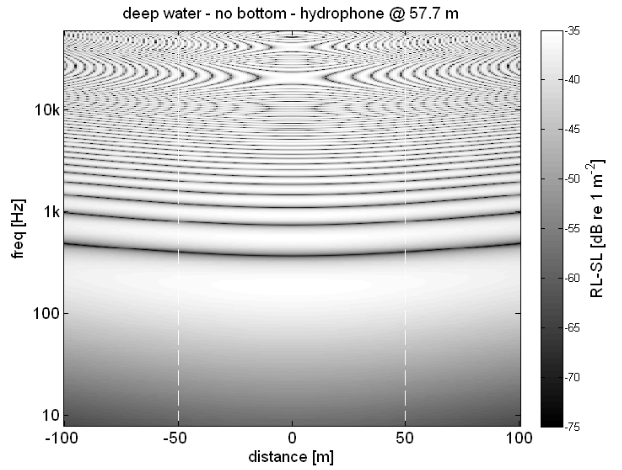

Figure 1: Difference between the received sound pressure level at the mid hydrophone and the monopole source level, versus narrowband frequency and source position. The white dashed lines indicate the ±30° track angle over which the signals are averaged.

In theory, the interference effects between the direct and surface reflected paths can be calculated and measured pressures corrected to free-field values. However, when measuring surface ship noise, one seldom knows depths or distances with the precision required [3,5]. Hence, it is proposed [5,9,10] to present an equivalent averaged '*affected source level*' for a given solid angle, usually in 'beam aspect', i.e. at a ±30° horizontal aspect angle relative to the closest-point-of-approach (CPA) between the source on track and the vertical hydrophone chain, and at a 15-45° depression angle relative to the water surface. This 'source level' is affected by reflections at the water surface.

Fig.1 shows that the received spectrum does not change very much during the passage of the source. Averaging along the track does not effectively mitigate the interference pattern, but is necessary to provide a sufficient bandwidth-time (*BT*) product for a reliable estimation of the levels.

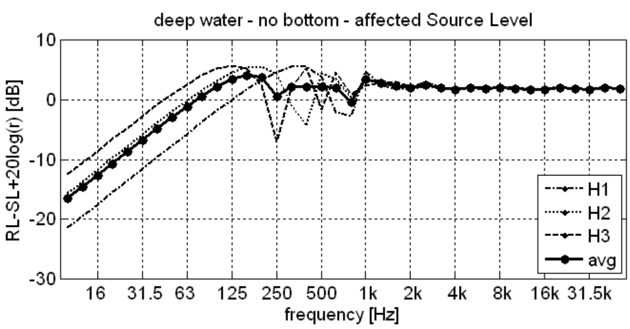

Figure 2: The difference, in one-third-octave bands, between the affected source level for a point source of unit strength at 4 m depth and the true monopole source level. Results for the three individual hydrophones and averaged.

Fig.2 shows the difference between the affected 'source level' and the free field source level of the monopole. The distance correction is for a source at the water surface. The summation in one-third-octave bands reduces the interference effects in the individual hydrophone results in the 250 Hz to 1 kHz bands. The averaging over three hydrophones further reduces the minima, though some effects remain. The averaged level at frequencies below 125 Hz is close to that of the mid hydrophone (H2). Surface reflections enhance the affected source level at frequencies above 1 kHz. This effect will be smaller under influence of surface waves. The received levels at high frequencies (> 10 kHz) will also be lower under influence of the absorption in sea water, which is ignored here.

Source level of a point source in keel aspect

The same point source is now observed in keel aspect, i.e. with the hydrophones straight below the track line. The shortest distance between the track and the individual hydrophones is kept the same as for the beam aspect simulations (y_h = 0; z_h = 104, 116 and 141 m). Applying the same analysis as for the beam aspect measurements, averaging over a ±30° track angle, leads to differences in the affected source level up to 9 dB (Fig.3).

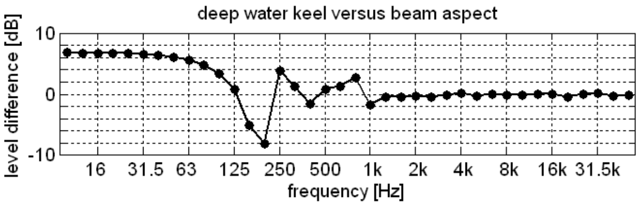

Figure 3: The difference, in one-third-octave bands, between the affected source level in keel aspect and that in beam aspect (Fig. 2), both in deep water.

In keel aspect, the averaging over the hydrophone depths does not effectively mitigate effects of surface image interference at frequencies below 1 kHz.

Effect of the water depth

Reflections at the sea bed may influence the measurements. If the local water depth is twice the CPA distance, i.e. 200 m and there is a 'rock' sea bed (modelled as a fluid with density 2500 kg/m^3 and sound velocity 5090 m/s). Fig. 4 shows the effect of the sea bed on the affected source level. The sea bed reflection effects are smaller in keel than in beam aspect, especially at those frequencies where the deep water keel aspect levels are higher (see Fig.3). Sea bed reflection effects will be larger in shallower waters.

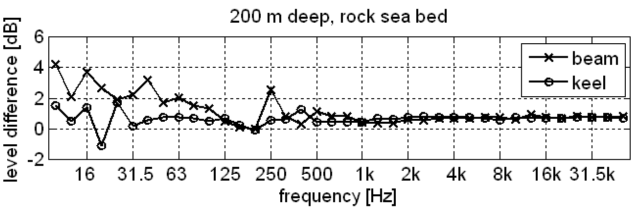

Figure 4: Difference between the affected source level, in beam and keel aspect, observed with a rock bottom at 200 m depth and in deep water.

Requirements for measurement distance

The averaging over a track length that corresponds with a ±30° horizontal aspect angle relative to CPA implies that the measurement distance should be of the order of the ship length or larger, to include all possible source locations along the ship hull in a single point description. The spherical spreading loss between the hydrophone and a non-directive source at CPA+30° is $20\log_{10}(1/\cos(30°)) \approx 1$ dB larger than that for the source at CPA. That means that a correction for propagation loss variations during the averaging time will not lead to a large increase in accuracy.

If the 10 Hz one-third-octave band is the lowest band of interest, the averaging time should be at least 4 seconds to get an bandwidth-time product BT=10. In the example of Fig.1, the track distance within the ±30° opening angle is about 115 m. Hence, the CPA distance of 100 m is sufficient for speeds less than 29 m/s (56 knots). It may be necessary to choose a measurement distance much larger that the ship length to achieve sufficient averaging time for small ships at high speed.

For measurements at distance shorter than the source length, the characterisation by a single (affected) point source is not necessarily valid. The consequences of ignoring this will be illustrated in the next section. For near-field applications, the source description should be redefined. One possibility is to describe the ship in terms of multiple point sources along its length. New procedures can be developed to determine the associated source parameters for a distributed source.

Point source measurements

Measurements were carried out, by the Netherlands' Naval Establishment, with a towed point source at the GE/NL/NO navy deep water range (sea bed at 380 m) near Bergen in Norway. The source produced a broadband noise spectrum in the range between about 10 Hz and 80 kHz. It was towed by a small boat at a speed of about 3 knots (1.5 m/s), at 4 m below the water surface and 108 m behind the boat. The noise was measured in keel aspect at various hydrophone depths (between 11 and 80.5 m). One-third-octave band spectra of the received sound pressure at the hydrophones with a 1 s averaging time.

Fig.5 and Fig.6 show the received sound pressure in one-third-octave bands at 80.5 and 27.5 m depth respectively, as a function of the position of the source along the track. The response clearly shows the Lloyd Mirror interference pattern, with the first interference minimum at CPA in the 160 Hz band. This frequency changes along the track. If the 'affected source level' in keel aspect were to be used to predict the underwater noise of the vessel in the approach to the hydrophone, this would lead to significant errors around these interference frequencies. For such purposes, the actual monopole source level and the position of the acoustic centre have to be known.

It can be seen that the tow boat produces more underwater noise than the towed source in the 25 Hz band and at frequencies above 500 Hz. Fig.7 shows the affected source strength of the towed source, averaged over a ±30° angle around the CPA of the source. Although the CPA of the towing boat is well outside the averaging area, the influence of its radiated noise on the calculated 'affected source level' increases with increasing measurement distance. This again illustrates the difference between measurements in the near field and the 'source level', which is determined from measurements in the far field and scaled back to a reference distance.

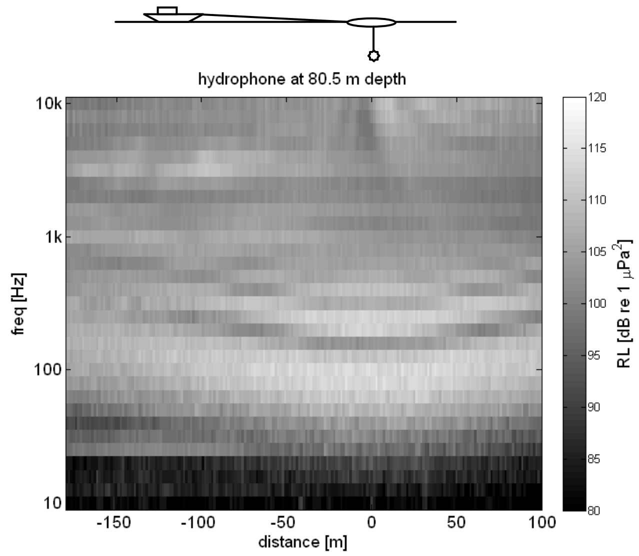

Figure 5: The one-third-octave band sound pressure level due to a towed point source, received at a 80.5 m deep hydrophone, versus the horizontal distance between the towed source and the hydrophone. The source is towed at 4 m depth at a distance of 108 m behind a small boat.

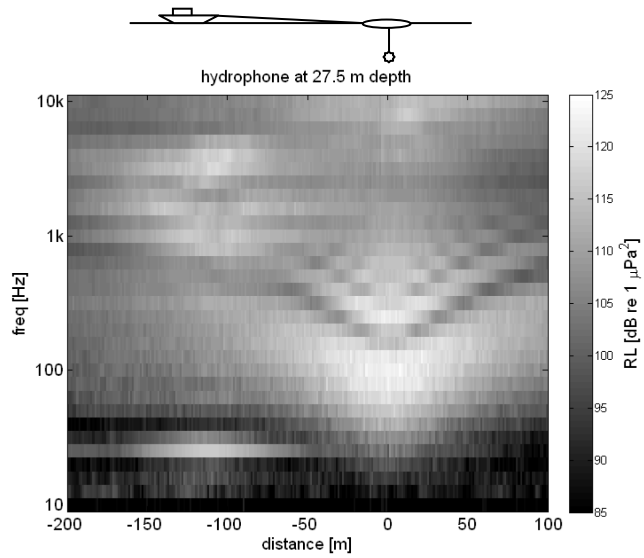

Figure 6: The one-third-octave band sound pressure level due to the same source point source, received at a 27.5 m deep hydrophone.

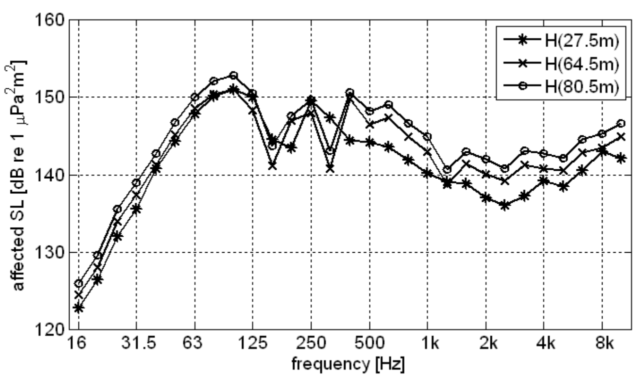

Figure 7: The affected source level of the towed source in keel aspect, estimated from three hydrophone depths, averaged over a ±30° angle around the CPA of the towed source.

Conclusions

- Surface ship underwater radiated noise depends on many parameters. Attempts to characterize the underwater noise by a single 'source level' or 'source level spectrum' per ship class are subject to a large uncertainty.
- Surface ship underwater radiated noise is generally directional, due to the distribution of sources along the hull, scattering at the underwater hull and reflections at the sea surface.
- Different 'source level' definitions may be required for different applications.
- Different definitions require different measurement and analysis procedures.

Acknowledgements

This work has mainly been carried out within projects for the Netherlands' Defence Material Organisation. The insights are based on many discussions with colleagues within TNO, in the Netherlands Navy, in international naval exchange programs and in the ASA-WG47.

References

[1] W.J. Richardson, C.R.J. Greene, C.I. Malme & D.H. Thomson: *Marine Mammals and Noise*, Academic Press, San Diego, 1995

[2] D. Ross: *Mechanics of underwater noise*, Pergamon Press, New York, 1976

[3] R.J. Urick 1983 *Principles of underwater sound.* Los Altos (CA): Peninsula Publishing

[4] R.B. Mitson: International Council for the Exploration of the Sea. report 209 *Underwater noise of research vessels. review and recommendations*, 1995

[5] P.T. Arveson & D.J. Vendittis: *Radiated noise characteristics of a modern cargo ship*, J.Acoust.Soc.Am. **107**(1), 118-129, 2000

[6] M.V. Trevorrow, B. Vasiliev and S. Vagle: *Directionality and maneuvring effects on a surface ship underwater acoustic signature*, J.Acoust.Soc.Am. **124**(2), 767-778, 2008

[7] P. Scrimger & R.M. Heitmeyer: *Acoustic source-level measurements for a variety of merchant ships*, J.Acoust.Soc.Am. **89**(2), 691-699, 1991

[8] S.C. Wales & R.M. Heitmeyer: *An ensemble source spectra model for merchant ship-radiated noise*, J.Acoust.Soc.Am. **111**(3), 1211-1231, 2002

[9] M. Bahtiarian & R. Fisher: *Underwater radiated noise of the NOAA ship Oscar Dyson*, Noise Control Engineering Journal **54**(4), 224-235, 2006

[10] Reference to ASA-WG47. URL: `http://www.noise-control.com/wg47`