underwater TECHNOLOGY

Technical Paper

Estimation of underwater noise – a simplified method

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Abstract

A set of procedures has been developed to allow preliminary estimates to be made of underwater noise and its effects on marine species. They do not require detailed acoustic survey data, either of the site or of the proposed plant. However, they still facilitate the comparison of different project proposals to assist in the optimisation of equipment layout and routing. Noise may be due to specific sources, such as ships and marine equipment, or assessed as a general background level. Some aspects of acoustic analysis applicable to more detailed environmental impact assessments are also described, particularly relevant when comparing noise spectra with audiometry data appropriate to different species of wildlife.

Keywords: Environmental impact assessment, marine equipment noise, noise power levels, shallow water transmission, mixed layer duct, underwater audiometry, masking bandwidth

1. Introduction

The issue of subsea noise emanating from marine developments has become more prominent in recent years as the sensitivities and behavioural responses of various species have become better understood. Working for the developer of a submarine power cable between the UK and Holland, Metoc were presented with the task of describing, within the context of an Environmental Impact Assessment (EIA), the impacts on local species of subsea noise produced by both surface and seabed installation resources.

The investigation process involved looking at the noise sources, the transmission path and the audiometry of the receptors. It was discovered that:

- No data were available for typical cable installation ships and virtually none was available (in the public domain) for equipment of the type used to embed cables in the seabed
- Relatively straight forward transmission models were available for deepwater conditions but none for the shoaling coastal waters in the study area
- Data were available for the small number of receptor species identified as being present in the study area.

Species present in the study area included some of those protected under European Union Habitats Directive.[20] Although impacts were not discounted, intuitively it was felt that those of the installation works would be negligible, particularly set against the local background noise. However, the lack of data and suitable models posed the problem of how to confirm the assumed negligible level of impact without incurring disproportionate costs.

In this collaboration, we therefore returned to first principles to develop an approach that could yield results acceptable as an appropriate assessment within the terms of the EIA process. Our wide ranging discussions, especially with Gerard Duykinck-Dorner of Royal Haskoning in the Netherlands, were very helpful.

2. Estimation of the environmental effects of noise

There are four stages to an estimate of the likely significance of environmental sound pressure levels.

1. Estimate the power of the various sources introduced during the work
2. Estimate how the sound they produce is propagated
3. Estimate the likely background sound levels
4. Relate the sensitivity of the receptors to the background and additional sounds.

3. Estimating the sound power

In many cases, especially those where broadband noise is the issue of concern, the directivity of the sources is not known, or may not be well controlled, and is thus of necessity ignored. This means that the sources will be assessed as omnidirectional, characteristic of a simple monopole point source.

This major simplification means that the total sound output power can be presented in Watts (W), as well as by the source levels which are required to specify the sound power radiated in different directions. The benefits of this aspect of the work have been discussed recently in more detail.[1]

There will still be a need to assess the variations in noise measured in individual frequency bands, which can be added to give the total power in the broad band. However, to simplify this process, we need to use generalised characteristics of the source outputs. Many common noise sources have restricted high frequency noise power, and in any case the output power must be finite. In the case of ship noise (see Figs 1 and 2) the data available show how sound power falls with increasing frequency, with a spectrum described as 'red noise' in analogy to the spectral distribution of red light.

This can be contrasted with 'white noise' or noise with uniform power in every 1Hz band. The total power calculations made by Urick[2] [p344] used this spectral distribution for the lower frequencies. The tonal qualities seen in the lower frequency bands vary from vessel to vessel but their average can be estimated, to characterise noise from an ensemble of ships, as a uniform power in every 1Hz band, the same spectrum as 'white' random noise.

Urick combined the two distributions to give a spectrum which can be described as 'red and white', by specifying a low frequency source spectrum level and a transition frequency to red noise. As he described, this spectral distribution gives a finite integral. A single such spectrum can thus be converted into a power level either given in Watts, or where more convenient, in decibels.

4. Use of decibel levels in air and underwater

Information on noise is usually presented in decibels (dB), a logarithmic scale used to cover the extremely wide dynamic range of human ears, and the brain's perception. After many years of development the method of presenting a broadband sound pressure level in air was standardised by the use of dBA, where the 'A' serves to specify both the reference level and the frequency distribution relevant to human hearing.[Crocker[21] pp11 & 779].

However, the decibel scale is not restricted to sound. For example, a decibel voltage level is given in dBV. It is thus very important that the reference level is given when using decibels, unless clearly indicated by the context. By convention decibel scales are used for measurements which are either of power (W) or can be clearly related to power. A decibel power level, WL, is then found from the power, W, by taking the logarithm of the ratio W/W_o, where W_o is the reference level

$$WL = 10 \log (W/W_o)$$
$$= 10 \log W \quad \text{dB re 1 Watt} \quad (\text{when } W_o = 1\text{Watt}) \quad (1)$$

The reference should be specified unless comparing two measured powers. For example, an increase in the power by a factor of 10 is a rise of 1 bel or 10 dB (no reference required).

By convention, sound power levels measured in air are referred to 1 pico Watt (10^{-12} W). This system is used to specify the L_{WA} sound output of white goods such as refrigerators, where the direction of emission is unimportant, given the uncertainty of the acoustics of the room in which they will be used. Whilst it is not common for ships to be so rated, there is no technical reason why not, and the 24W example given by Urick (a typical 20th century destroyer moving at 20 knots) becomes 13.8dB re 1 W, or 133.8 dB re 1 pW. This 120dB difference reflects the change in the reference level by a factor 10^{12}. It is often simpler to quote sound power in Watts, and this would be more widely understood by non-specialists.

Closely related parameters are the sound intensity I, and sound pressure P. Provided there are not too many echoes, so that the sound energy flows away from the source uniformly in all directions, these can be simply linked to the sound power W. The result also depends on the range, r, from the source to the point of measurement of P and I. If P is given as the root mean square (rms) value of the pressure fluctuations, then:

$$I = \frac{P^2}{\rho.c} = \frac{W}{4\pi r^2} \quad (2)$$

As can be seen here, the intensity I is the power W divided by the area through which it is passes, $4\pi r^2$ (the area of a sphere radius r). This can be given in Watts/m^2, or dB re 1 pW/m^2. The link to pressure P depends on the fluid characteristic impedance, the product of its density ρ, and sound speed c, within the medium.

Because the power is given by the square of the acoustic pressure P^2, the decibel pressure level "PL" is given by:

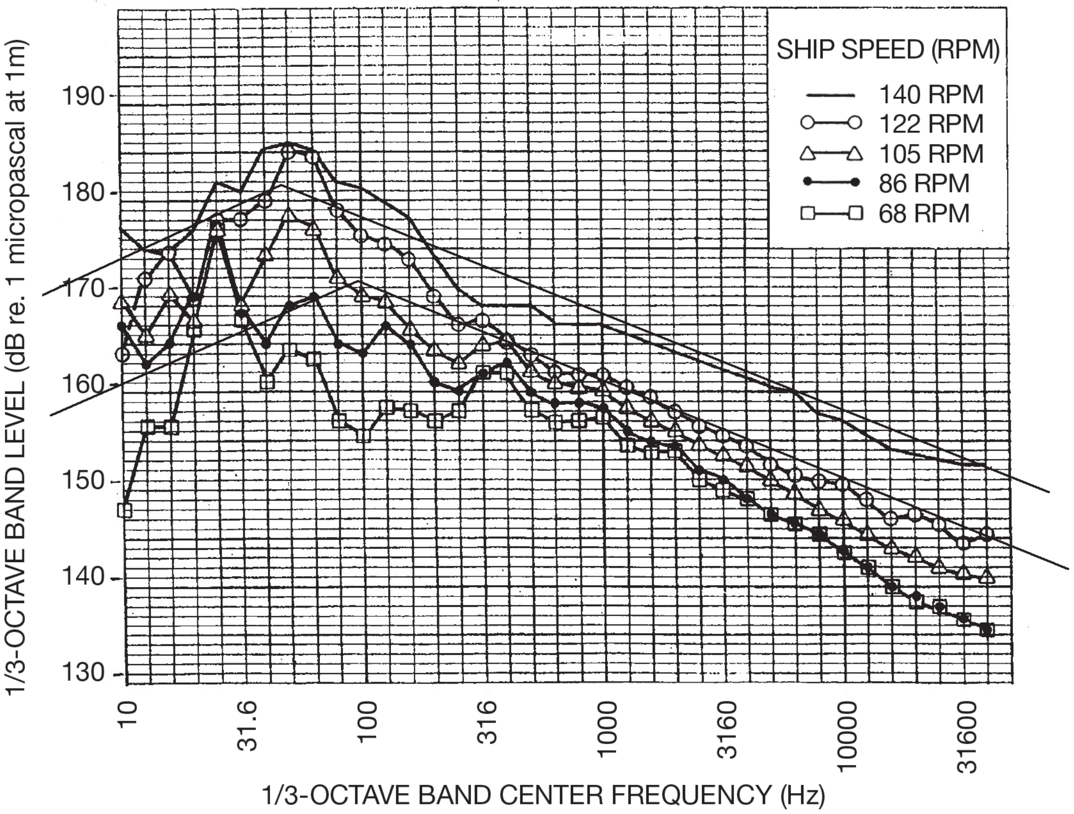
$$PL = 10 \log (P^2/P_o^2)$$
$$= 20 \log (P/P_o) \quad \text{dB re 1Pa} \quad (\text{when } P_o = 1 \text{ Pascal}) \quad (3)$$

In air the reference level P_o is, by convention, 20 μPa, but in water the convention is 1 μPa.

These differences show how easy it can be to create errors if the decibel levels are not used with care. Physical parameters such as pressures or voltages require the '20 log' of equation (3), whereas power and frequency bandwidth, for example, use the '10 log' of equation (1).

In air, with P_o=20μPa, Eq2 shows that $I_o \approx$ 1pW/m^2, because the characteristic impedance for air is close to 400kg/(m^{2}s). This is the minimum detectable sound level for a typical human, at an optimum frequency. This means that at around 1kHz, a pressure level of 0dB re 20 μPa is a convenient measure of a barely detectable sound level for humans in otherwise silent conditions.

However, this does not apply to humans or other creatures when underwater. The characteristic impedance of water is about 1.5 10^6kg/(m^{2}s), so that a much larger pressure around 1225μPa would be required to give the same intensity of 1pW/m^2 in water.



Figs 1: Noise measured for the MV *Overseas Harriette* plotted over a frequency range 10-40kHz

Whilst the benefits of decibels, to those familiar with their use, are substantial, their use is fraught with potential error. Wherever there is scope for misunderstanding, critical information should also be quoted in linear SI units, such as the Watt and the Pascal.

5. Frequency distribution of noise and the masking bandwidths

The data shown in Fig 1 shows the noise measured for the MV *Overseas Harriette*,[3] plotted over a frequency range from 10Hz to 40kHz. Note that the frequency scale is logarithmic, with fine divisions of 1/10th decade (10 to the power 0.1), a ratio close to 1.26, and to a 1/3rd octave.

Each measurement includes the sound in a 1/3rd octave band, and together they cover the broadband shown, 10-40,000Hz. This choice of presentation contrasts with the spectrum levels given in Fig 2, but has the advantage of roughly matching typical masking bandwidths for biological receptors. If the threshold detection by an animal (perhaps human) is being measured by reducing the intensity of a tone until it cannot be heard, other sounds within the same bandwidth will raise the threshold, whereas interference at different frequencies outside the band will not. Creatures such as dolphins need a low background level to give a good system response for hunting their prey, and tonal audiometry data is available for a number of species. However their masking bandwidths are harder to measure.

The development of the critical or masking bandwidth concept, reviewed by Buus [in Crocker[21] p1150], has been extended to other mammals. A coarse approximation can be made using 1/3rd octave masking bandwidths as discussed by Richardson.[5] This assumes that only the noise within a 1/3rd octave band around the frequency of interest will be effective in masking. For example, only noise between 891Hz and 1122Hz will be confused with a 1kHz tone.

The use of 1/3rd octave masking bandwidths is a significant simplification, but it should be con-

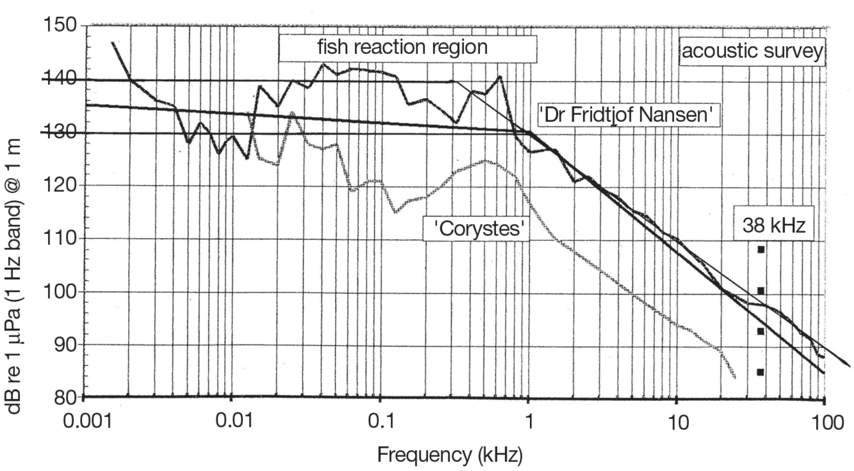


Fig 2: Noise data for two fishing vessels

trasted to the use of measurements made in a fixed bandwidth such as 1Hz, as in Fig 2. Whilst these are very useful for the analysis of mechanical systems, they are much less suitable for consideration of biological system responses.[1] The important issue to note is that $1/3^{rd}$ octave band noise data can usefully be directly compared with the tonal audiometry data for different wildlife.

In Fig 2 data for two fishing research vessels[4] is shown. The frequency scale is again logarithmic, but the fine divisions correspond to a linear scale. Whilst the data points (seen as changes in slope) are again spaced at $1/10^{th}$ decade (1/3rd octave), data has been scaled for a 1Hz band. This alters the shape of the spectrum.

This source spectrum data, quoted per 1Hz band, must be distinguished from that measured over a $1/3^{rd}$ octave band, and differs by a factor of over 10 000 (40dB) at high frequencies. Sadly, this distinction is not always made clear in quoted data, with the potential for serious errors.

6. The red/white distribution and total power output

In both Figs 1 and 2 additional lines have been superimposed over the data as published. These show possible fits of the data to a red/white distribution. The quality of fit of the higher frequencies is seen to be good when based on red noise, with the power per Hz (Fig 2), falling as $1/f^2$. The bold lines form the International Council for Exploration of the Sea (ICES) threshold criterion[4] for suitability of research fishing vessels to be able to survey fish populations accurately. Although differing slightly from the red/white spectrum, their concept is similar.

The vertical axes use a decibel source level presentation, where every 10 dB increase is a factor of 10 in output power. Ship data is usually directional (quoted as keel aspect for Fig 1) so cannot strictly be converted to power in Watts without integration of similar graphical data for all azimuth angles. However, for our purposes we need to assume that this data is for an omnidirectional source, since the orientation of shipping cannot be specified in the assessment. This is likely to produce a small over estimate of the total output power.

If omnidirectionality is assumed, a 1W source radiating into typical seawater will give a source level of 170.9dB re 1 μPa at 1m.[2,1] This applies either to the total power and the source level in the broadband, or to both measurements when made in a specified bandwidth.

In Fig 2, the higher power fitted line at 140dB is equivalent to 0.81mW/Hz. When this white noise is integrated up to the transition at 316Hz this gives a total of 0.26W. Urick showed that the same power is radiated by the upper band red noise, a result which is easier to see[1] when the data is presented as in Fig 1. The total then becomes 0.52W. For the ICES specification (bold line) the integral is about 0.2W, a threshold power level over which vessels are deemed too noisy for fisheries research.

For the presentation of Fig 1 each $1/3^{rd}$ octave band is treated separately. The higher of the two fitted lines peak at 180dB re 1μPa at 1m, or 8.1W in the band centred on 50Hz. If we make the same conversion for the other 37 bands shown, the total is about 70W for this bulk carrier. This figure is simple to understand, and immediately conveys the fact that the underwater acoustic output is only a very small fraction of the total power consumed.

7. Radiated noise as a fraction of available power

This vessel has a rated engine power of 8.4MW, so that if these two figures are compared we see that as an acoustic transducer the ship has an ‘efficiency’ or ‘acoustic leakage’ of only 8 parts per million (ppm). This provides a dramatic indication of the quality of the design, since noise production is undesirable and has thus been minimised. Of course this may not apply to poorly maintained or damaged equipment, with a bent propeller blade providing a notable example.

The earlier analysis of survey data made by Urick[2] and others[6,7] have come to similar conclusions with ‘acoustic leakages’ of a few ppm. This also shows how small the acoustic output from well maintained shipping is, especially when compared with other devices which are designed to make sound, such as sonar projectors and seismic sources such as air guns. A typical airgun rating will exceed 10bar·metres,[8,9] or 1MegaPa·m peak. Even allowing for conversion losses the far-field peak power radiated will exceed 1MW. However, the average over the typical repetition rate is more comparable with continuous sources.

When considering potential physical damage (permanent hearing loss etc), peak directional data is important, and comparisons of intensity in the linear units of W/m^2 are useful. Highly directional sonar sources are designed to produce very concentrated beams. These then give much higher intensities for the same wattage.

A total power analysis has been done over data on noise from underwater machinery such as ROVs. This survey data was collected primarily to predict the effects on acoustic positioning systems.[10-13] Remarkably, the ‘acoustic leakages’ calculated also gave values of a few ppm, even for work class ROVs with large hydraulic power packs. However, the noise output is in general of higher frequency, so that a different transition frequency is usually more appropriate.

For shipping and other well designed mechanical sources, these results allow the available power to be used to make a conservative estimate of the likely acoustic power radiated. Other methods of assessing ensemble averages of ship noise have been made by Ross,[19] and other such as Wales and Heltmeyer,[14] but are in general more complex. Whilst approximate, this

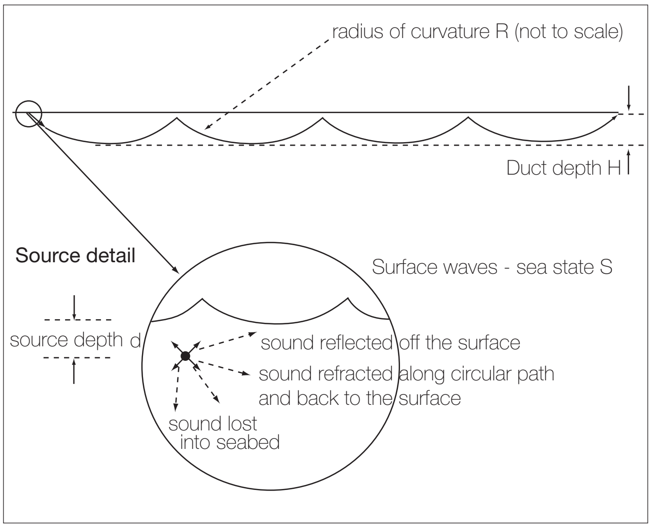


Fig 3: Subsurface ducting

scheme makes use of readily available data, particularly appropriate where the results show a low risk.

8. Transmission of sound through the sea – a useful limiting case

The transmission of sound is another area of great complexity, and the general case requires considerable information about the site, especially if relatively shallow. The energy propagation is highly dependent on oceanographic conditions, particularly water temperature distributions. Indeed the many measurements have been said to be characterised by their variability,[15] making any predictions very difficult unless there is a complete set of data both on the nature of seabed and on current water conditions. The latter can vary by the hour as the sea heats up and variations of 50dB (a factor 100 000 in intensity) have been measured over the same range. Predicting such changes is even more taxing.

However, the prediction of a maximum limit is much less difficult. The absorption of sound (conversion into heat) within the ocean is low. The absorption coefficient α is less than 1dB/km for frequencies below 10kHz. In deep water, with no reflective surfaces nearby, the sound intensity is mainly reduced by spherical spreading, and the acoustic pressure falls as the inverse of the range. The energy then falls as the inverse square, giving a 60dB spreading loss at 1km range (20 log 1000). When reverberation is minimal, the decibel pressure level (PL), is determined from the source level (SL), the range r, and the absorption coefficient, α, given as attenuation per unit length in dB/m. This is given by the well known sonar equation:

$$PL = SL - 20 \log r - \alpha r \qquad (4)$$

Other effects can increase the losses, particularly when sound is absorbed in sediment at the seabed. However, when concerned about the upper limit, the other mechanism to be considered is ducting, which provides a reduction in losses, or ducting gain. Two relatively simple situations give rise to this, the deep ocean ‘sofar’ duct, and the surface duct created when the water is well mixed and thus isothermal.

In an idealised ‘mixed layer duct’ (Fig 3) the sound is trapped between a calm reflective sea surface and the base of the ‘duct’, formed as the sound is repeatedly refracted back toward the surface. Sound which is not captured by the duct is assumed to be lost, so that the characteristics of the seabed can be ignored. The water in the surface duct is assumed to be well mixed and thus of uniform temperature. The base of a surface duct is often quite sharp, defined by a change in temperature or thermocline. In shallow seas the mixed layer often extends to the seabed.

The speed of sound then increases slowly, driven only by the increase in pressure, at about 1/60m/s per metre increase in depth. This gives rise to refraction of the sound along a curved path of radius R = 90km, for a typical speed of sound of 1500m/s at the base of the duct. Note that the centre of this imaginary circle lies in outer space, so the sound cannot return to the source, but if reflected from a calm surface will be channelled as shown.

In these conditions the intensity falls as the inverse of range rather than its inverse square. This is described as cylindrical spreading, with the energy flux density inversely proportional to the circumference of the cylinder, $2\pi r$. For ranges much longer than the depth of the duct this produces a considerable increase in sound intensity of up to 30dB (a factor of 1000 in energy). The sonar equation is modified to:

$$PL = SL - 10 \log r - 10 \log r_o - (\alpha + \alpha_L)\, r \qquad (5)$$

Note that this is equivalent to replacing the second factor r of the square law underlying equation (4), with a fixed transition range r_o. As discussed by Urick[2] [p153], this allows a smooth transition from spherical spreading to the slower losses of cylindrical spreading at $r \approx r_o$. The additional attenuation, α_L, is due to scattering out of the duct, mainly by surface waves.

The value of r_o is related to the depth of the source d and the depth of the duct H.

$$r_o = \sqrt{(R \cdot H/8)}\ \sqrt{(H/(H-d))} \qquad (6)$$

When the source is close to the surface, with $d \approx 0$, this gives $r_o \approx 106 \sqrt{H}$, with R =90km, so if $H \approx 25$m, $r_o \approx 500$m. At greater distances, the duct will noticeably increase the acoustic pressure level over that to be expected from the spherical spreading equation. The sonar equation is then

$$PL = SL - 10 \log r - 5 \log H - 5 \log (R/8) - (\alpha+\alpha_L)\, r \qquad (7)$$

As d increases so the amount of energy captured by the duct decreases until it becomes ineffective when d = H.

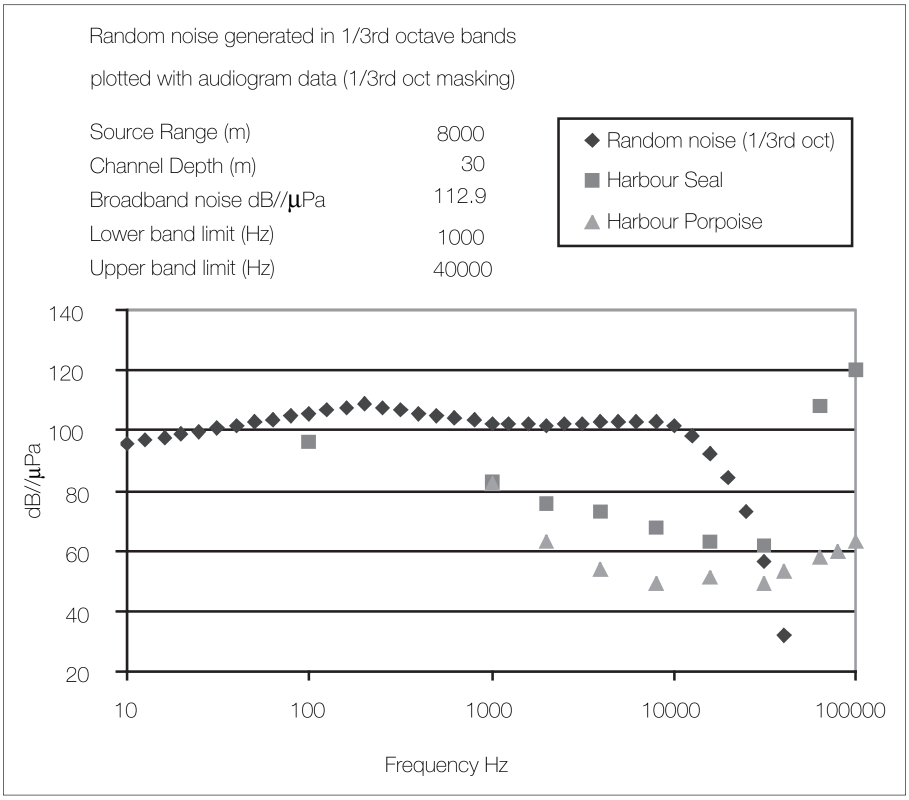


Fig 4: Comparison of predicted 1/3rd octave noise with audiometry data

9. The extent of the region of ducting gain

If the water is calm the additional loss a_L in the equation above is negligible, but as the sea state rises, the waves give rise to scattering of sound out of the duct toward the seabed. This effect can be estimated using empirical data related to the sea state factor, S. Whilst various fits have been made to data, as summarised by Urick, his empirical expression, when converted to SI units with H in metres, and α_L in dB/km for convenience, indicates the trend:

$$\alpha_L = 1.2\, S \sqrt{(f/H)} \tag{8}$$

where f is the frequency of sound in kHz.

For example, this loss coefficient is about 2dB/km for sea state 3 at 10kHz, and 30m duct depth, approximately four times larger than the absorption loss α in the same conditions. Although the strong sensitivity of α to f means that by 30kHz $\alpha > \alpha_L$, the scattering loss is important for lower frequencies and this puts a limit to the extent of any ducting gain when the sea is not calm. For example, at a range of 20km, in the above conditions, the additional 40dB scattering loss will usually dominate any ducting gain.

The use of equation 8 should be treated with caution since it is based on data which has since been extensively reviewed. Ainslie[22] states that the frequency dependence is better assessed as $f^{1.5}$. This discussion has also avoided the complexities of very low frequency transmission which include modal effects, and is thus best suited to higher frequencies where the wavelengths are less than the duct depth. If the sea surface is sufficiently heated during the daytime, the ducting effect may disappear, one reason why the propagation can be so variable. The simple model proposed here is most likely to give the predicted maximum transmission during a calm night.

10. Comparison of estimates with biological data

Fig 4 shows an output from software designed to assist in making preliminary conservative environmental impact assessments without the need to gather specific data on seabed conditions or detailed acoustic output data on equipment.

The source output in Watts has been estimated from ship engine power and ROV power as described earlier.[1] The highest likely pressure level has then been assessed (diamond symbols). This depends on the range (8km entered) and the channel depth (30m), assuming a calm surface.

The noise data has been presented in 1/3rd octave bands to allow comparisons with audiometry data. A small selection of such data is given, taken from Richardson,[5] for the harbour seal (squares) and harbour porpoise (triangles). Here the data shows that significant masking can occur at times of effective ducting.

This method provides predicted sensitivity levels as purely physical parameters, applicable to all species, whose interpretation can be adjusted as improved audiometry data becomes available.[16] Other possible schemes proposed include use of a generic ultimate threshold[17] and the development of many species specific alternatives to the A weighting.[18]

Whilst the accuracy limitations must be borne in mind, this procedure does allow planners to compare different options economically.

11. Influence of background noise level

The prediction of possible masking, and consequent constraints on the behaviour of marine life, will also be influenced by the anticipated background noise levels. As is routine when conducting noise surveys in air, the significance of any noise as an annoyance can be related to the extent to which it exceeds background levels. When considering the effects of subsea operations in areas close to existing shipping lanes then the same principles can be used. Once again the propagation model only provides a likely maximum, but this does indicate levels to which acclimatisation will have occurred, so that comparison of the two data sets becomes more valid than the use of either in isolation.

12. Conclusions

The accurate assessment of the impacts on species of subsea noise may ultimately need to be based on a more detailed study. The multiple parameters of site, source and species will then be required to model the situation satisfactorily. This is particularly likely where highly sensitive species are known to be present.

However, as a first approximation of the significance of the issue, and possibly in situations where no at-risk species are present, the method described offers a developer the opportunity of assessing the issue without commissioning extensive acoustic studies. Where significant impacts are found the method also offers the opportunity of targeting acoustic studies and/or mitigation measures effectively.

The procedures are based on a review of the literature, selecting some simple models of sound sources and the propagation of underwater sound, to achieve these aims and to assist in the understanding of the topic by a wider audience.

References

1. Hazelwood RA. (2005). Presentation of random noise. *Acoustics Bulletin*, Jan 2005. Institute of Acoustics, UK.
2. Urick RJ. (1983). *Principles of Underwater Sound* (3rd ed), McGraw Hill.
3. Arveson PT and Vendettis DJ. (2000). Radiated noise characteristics of a modern cargo ship. *Journal of the Acoustical Society of America* (JASA). 107(1):118.
4. Mitson RB (Ed). (1995). *Underwater noise of research vessels*. Rpt 209 Int. Council for Exploration of the Sea (ICES), Copenhagen.
5. Richardson WJ, Greene CR, Malme CI, Thomson DH. (1995). *Marine mammals and noise*. Academic press.
6. Greene CR. (1987). Characteristics ... of drilling in the Beaufort Sea. *JASA*. 82(4):1315 1987.
7. Malinowski SJ and Gloza I. (2002). Underwater noise characteristics of small ships. *Acta Acustica*. 88:718.
8. Barger JE and Hamblen WR. (1980). The airgun impulsive transducer. *JASA*. 68(4):1038.
9. Goold JG and Fish PJ. (1998). Broadband spectra … of airgun emissions. *JASA*. 103(4):2177.
10. Hazelwood RA and Robinson SP. (Sept 1998). Acoustic power calibration in reverberant tanks. *IoA Proc*. 20(3).
11. Hazelwood RA, Kelland NC and Smedley NJ. (Sept 1998). One man's signal is another man's noise. *Hydro*.
12. Hazelwood RA. (Jan 2002). Measuring machinery noise in the ocean. *Acoustic Bulletin*.
13. Hazelwood RA. (2003). Measuring deep ocean machinery noise. *Proc. IoA* 25(1).
14. Wales CW and Heltmeyer RM. (2002). An ensemble source spectra model for merchant ship-radiated noise. *JASA*. 111(3):1211.
15. Mackenzie KV. Long range shallow water transmission. *JASA*. 33(11):1505 1961.
16. Au WWL. (2004). Harbour Porpoise Acoustics. *Proc IoA*. 26(6).
17. Heathshaw AD, Ward PD and David AM. (2001). The environmental impact of underwater sound. *Proc IoA*. 23(4).
18. Howell DM and Nedwell JR. (2004). A species specific sound level meter. *Proc IoA*. 26(6).
19. Ross D. (1976). Mechanics of underwater noise. Pergamon.
20. European Habitats Directive EU 92/43/EEC.
21. Crocker MJ (Ed). (1998). Handbook of Acoustics. Wiley.
22. Ainslie MA, private communication & UDT 1994 pp489-492