THE ENVIRONMENTAL COST OF MARINE SOUND SOURCES

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Abstract: *Cumulative acoustic exposure is used as an indicator for the risk of negative impact to animals as a consequence of exposure to underwater sound. The free-field energy of a single source, defined as the total acoustic energy that would exist in the source's free field, is shown to be closely related to the total cumulative exposure added over a population of animals. On this basis, the free-field energy of an underwater sound source, referred to as its "energy cost", is proposed as an indicator of its environmental risk. For otherwise the same conditions, the environmental cost so defined of a multi-beam echo sounder (frequency 100* kHz*) is about 40 000 times less than that of a search sonar (1* kHz*) of the same source level. In turn, the cost of the same sonar is about 300 times less than that of a pile driver of the same energy source level, implying that source level (or energy source level) alone is a poor indicator of environmental risk. The main reason for this is that source level takes no account either of the amount of space occupied by the sound once in the water, or of the time required for the sound to dissipate. The free-field source energy, which includes the effects of source directivity and decay time, is therefore useful as an indicator of the environmental cost of a marine sound source.*

Keywords: *Acoustic exposure, source level, environmental cost*

1. INTRODUCTION

Anthropogenic sound in water is a growing source of concern because of its possible detrimental effect on aquatic animals such as marine mammals [1, 2] and fish [3, 4]. The European Commission now includes underwater noise explicitly in its Marine Strategy Framework Directive for achieving good environmental status (GES).[5]

A measure of the strength of underwater sound sources known as the „source level“ (or „energy source level“, which is the source level scaled by the duration of the sound) is widely used to assess their performance as underwater sensors [6, 7]. The same metric has been adopted by the European Commission as part of an underwater noise indicator [8] for achieving good environmental status [5]. For environmental impact, the sound as received by marine life will determine whether a negative effect will occur. In this paper we investigate the extent to which source level or „energy source level“ may be used as a suitable indicator for underwater noise. This question is addressed by developing a framework within which the cost of different sound sources can be compared, taking into account their temporal and spatial footprints as well as their source level.

In Sec. 2, the concept of an environmental cost associated with a continuous source of underwater sound is introduced, and defined as the total cumulative sound exposure on all animals exposed to the sound. The concept is applied to a point source with spherical spreading. The concept of „free-field acoustic energy“ is introduced in Sec. 2.2, and defined as the total acoustic energy of the sound field that would exist if the same source (and radiating the same acoustic power) were placed in an infinite uniform medium of the same speed of sound and same absorption coefficient as the true medium. The free-field acoustic energy is proposed as a proxy for environmental cost. The properties of various sources are considered in Sec. 3, with a view to examining variations in their cost for either the same source level or the same energy source level. Finally, the effect of departures from spherical spreading is considered in Sec. 4.

2. ENVIRONMENTAL COST

2.1. Cost as cumulative exposure

Anthropogenic underwater noise can have many different effects on marine animals. Negative effects include physiological damage, masking, and avoidance of the sound source [1-4]. In principle there might also be other effects. For example, ambient sound might give navigation cues [9] or provide a source for acoustic imaging [10]. For the purpose of the present article it is assumed that all effects of human-induced noise in a marine ecosystem are negative and that these negative effects increase with increasing levels of noise. Although wave form and frequency also play a factor, these are not separately addressed here.

These negative effects not only increase with increasing levels of sound, but also with increasing duration of exposure. For injury, dual criteria are proposed in Refs. [2] and [11] involving peak pressure and cumulative sound exposure. In practice, the cumulative acoustic exposure, denoted here by the symbol E, is seen as a good indicator for assessing the risk of hearing injury to marine mammals (p438 of [2]; [12]). There are some indications that exposure duration might be an additional risk factor [13], but in this paper we use the assumption that SEL alone is suitable for quantifying the risk of negative impact. Similar to the approach in life cycle assessment [14, 15] the total potential exposure of a population is proposed as a measure of environmental impact. Our measure could be compared to the toxicity potentials of emitted substances, which are calculated using environmental fate models. In these fate models, substance concentrations depend on emission, spreading and decay - in essence not different from what acousticians do when using a sound propagation model. Although a concentration is not an impact, knowing (or estimating) the concentration is a prerequisite for predicting impact, and the concentration can be used as a measure for quantifying possible impact [14]. The impact (hereafter called „cost") is assumed to be additive in the sense that, for a population of size M, the total cost χ is the sum of exposure E_i over all receivers, where E_i is the time integral of the square of the acoustic pressure $p_i(t)$ at the ith receiver. To avoid the complication of a discrete sum, χ can be approximated by assuming a continuous distribution of recipients with volumic population density N. If, further, the population is distributed uniformly such that N is a constant, equal to N_0, for exposure of duration T to RMS acoustic pressure $p(\mathbf{x})$, this becomes [16].

$$\chi = N_0 T \oint p^2(\mathbf{x}) \mathrm{d}V \tag{1}$$

The „exposure cost" of a sound source, defined in this way, is the cumulative potential exposure on animals due to that source, without regard for possible differences in sensitivity to, or dependence on sound between species. The actual environmental impact, taking into account such sensitivity or dependence, as well as possible further discrimination on ecological grounds, is outside the present scope.

Adding (1) over all sources, and dividing by the total volume of space into which the sound spreads, it follows that the exposure cost is proportional to the mean square ambient noise pressure averaged over that volume. This means that the exposure cost is not only relevant to physiological effects resulting from high exposure on individual animals, but also to masking as a consequence of increased ambient noise levels.

An important advantage of the chosen approach, focussing on exposure (or energy) as cost, is that it enables like comparison between completely different types of source. On the other hand, it takes no account of levels of natural noise, which in some situations might already be high enough to drown the contribution from anthropogenic sources.

Initially using spherical spreading, consider a single directional source, of radiant intensity (power per unit solid angle) J, in an infinite uniform medium with absorption coefficient α, density ρ and sound speed c. (The term "free space" is used henceforth to describe such a medium, implying also – in the context of a source in a real medium – that the values of density, sound speed and attenuation in the infinite uniform medium are those of the true medium evaluated at the source position). The mean square pressure (MSP) at distance r from the source is

$$p^2 = \rho c J \frac{\exp(-2\alpha r)}{r^2} \tag{2}$$

and therefore, for a source of total power W

$$\oint p^2(\mathbf{x}) \mathrm{d}V = \rho c \oint_{4\pi} J(\Omega) \mathrm{d}\Omega \int_0^\infty \frac{\exp(-2\alpha r)}{r^2} r^2 \mathrm{d}r = \rho c \frac{W}{2\alpha}. \tag{3}$$

Substituting this result into (1), it follows that the exposure cost associated with a directional source in free space is proportional to the product of the source power and the exposure duration and inversely proportional to the absorption α:

$$\chi = \rho c \frac{N_0 T W}{2\alpha} . \tag{4}$$

The increasing attenuation of sound with increasing frequency means that high frequency sources are likely to have a lower environmental impact than low frequency sources of the same acoustic power. Further, high frequency sources might require less power to achieve the same radiant intensity because high frequency sound is more easily focussed where it is most needed.

2.2. Free-field acoustic energy as proxy for exposure cost

Let the free-field energy of an underwater sound source (denoted H_0) represent the total acoustic energy of that source, integrated over all space in an infinite uniform medium of the same impedance and absorption coefficient as the true medium at the source position. If the source has acoustic frequency f, it follows from (3), for a broadband directional source of power spectral density $U(f)$, that [16]

$$H_0 = \frac{1}{2c} \int \frac{U(f)}{\alpha(f)} \mathrm{d}f . \tag{5}$$

This quantity is closely related to exposure cost. Specifically, if the potential cost χ_0 is defined as the exposure cost that the same source would have if placed in free space (and operated with the same power and frequency), this potential cost is related to the free-field energy according to [16]

$$\chi_0 = \rho c^2 T \, N_0 H_0 . \tag{6}$$

The actual exposure cost χ, as approximated by (1), is never greater than the potential cost χ_0, making the free-field energy, which depends on propagation conditions only through the absorption $\alpha(f)$ (and sound speed c), suitable as a worst case indicator.

The acoustic exposure on a single animal at $\mathbf{x}_i$ is related to the energy density $H_V(\mathbf{x}_i)$ via [16]

$$E_i = \rho c^2 T \, H_V(\mathbf{x}_i) . \tag{7}$$

Comparing (6) and (7), the free-field source energy H_0, multiplied by the animal population density N_0, is seen to be related to potential cost, χ_0 in the same way as the local energy density $H_V(\mathbf{x}_i)$ is to the exposure cost on a single individual, E_i. This means that H_0 reflects the essential sensitivities of exposure cost without the main complications. It is adopted here as a proxy for exposure cost.

3. IS THE SOURCE LEVEL A USEFUL MEASURE OF ENVIRONMENTAL COST?

3.1. Source level, energy source level and 'footprint'

For the reasons outlined above, the total free-field energy (H_0) is used in this section as a proxy for exposure cost, and referred to in the following as „energy cost". Four different types of source are considered: an air gun, a search sonar transmitter operating at 1 kHz (duration 1 s), a cargo ship and a multi-beam echo sounder operating at 100 kHz (duration 1 ms). One purpose is to show that sources of identical source level, but otherwise different characteristics (see Table 1), can have a very different cost. To achieve this, the parameter values are constrained artificially to ensure that the air gun and search sonar have identical energy source level (denoted L_E), and that the search sonar and multi-beam echo sounder have identical source level based on the mean square pressure in the far field during transmission (denoted L_{MSP})

$$L_{\mathrm{MSP}} = L_E - 10\log_{10}\frac{t_{\mathrm{dur}}}{1\,\mathrm{s}} . \tag{8}$$

	air gun	search sonar (1 kHz)	cargo ship	multi-beam echo sounder (100 kHz)
energy source level L_E [re µPa² m² s]	**210 dB**	**210 dB**	**243 dB**	**180 dB**
duration t_{dur}	n/a	1 s	780 ks	1 ms
repetition time t_{cyc}	2 s	10 s	860 ks	10 ms
directivity index DI	0 dB	0 dB	3 dB	20 dB
source level L_{MSP} [re µPa² m²]	**n/a**	**210 dB**	**184 dB**	**210 dB**
decay time τ	2.5 ks	39 s	3 ks	100 ms
energy cost (free-field source energy) H_0	**10 MJ**	**31 kJ**	**28 kJ**	**820 mJ**

Table 1: Energy source level L_E, duration t_{dur}, repetition time t_{cyc}, directivity index DI*, source level L_{MSP}, (8), free-field decay time τ (9) and energy cost H_0 (10) for selected sound sources of underwater sound. The value of L_{MSP} is included only for sources with a well defined duration.*

An important parameter, in addition to the source level, in determining the impact of a sound source, is its spatial „footprint", by which is meant the size of the region of space affected by that source. Variations in the size of the footprint for sources with the same source level will lead to variations in the energy cost of these sources, and also in their impact. The footprint is determined partly by decay time τ, which is the time it takes for the sound from the source to die out after the source has been switched off or removed.

The decay time depends on absorption, and therefore on acoustic frequency, and is equal to the ratio of energy cost to source power [16]

$$\tau = H_0 / W \,. \tag{9}$$

For sound of a single frequency the footprint has radius $c\tau$. Other factors affecting the footprint of a source are its directivity index (a logarithmic measure of the width of the transmitted beam, abbreviated DI) and its duty cycle (the ratio of duration t_{dur} to cycle time t_{cyc}).

3.2. Comparison between energy cost and source level

The energy cost H_0 of a source, the energy source level L_E, and various parameters associated with the footprint are related via the equation [16]

$$H_0(L_E) = \frac{4\pi\tau}{\rho c t_{\mathrm{cyc}}} 10^{(L_E - \mathrm{DI})/10} \ \mu\mathrm{Pa}^2\ \mathrm{m}^2\ \mathrm{s} \tag{10}$$

making explicit the dependence of the energy cost on terms other than source level (directivity index DI, decay time τ and repetition time t_{cyc}). The costs of the three sources included in the table are now compared, starting with the search sonar and echo sounder.

Despite having identical source level, the energy cost of the search sonar exceeds that of the echo sounder by a factor 40,000. The difference arises because of the large difference in extent of the sources‟ spatial footprints. There are two main contributing factors, namely the small decay time of the echo sounder and its narrow beam (large DI), both of which are associated with the high frequency.

The search sonar and air gun are considered next. These have the same energy source level, and yet the energy cost of the air gun exceeds that of the search sonar by a factor 300. Here the difference is mainly a consequence of the lower absorption (longer decay time) of the broadband sound originating from the air gun.

One cannot conclude from this that air guns necessarily have a higher environmental impact than search sonar, nor that search sonar has a higher impact than echo sounders – there are many other factors that need to be considered before such a conclusion can be drawn. For example, the impact would depend on the number of such sources, their actual characteristics (bearing in mind the artificial nature of some of the values chosen for Table 1, such as the idealised DI values of the air gun and search sonar, which are unlikely to be representative of real systems), the number of times each one is used, possible harm associated with peak acoustic pressure due to a sound of impulsive nature and the sensitivity of local species to the type of sound, which depends, for example, on its frequency spectrum. The local propagation conditions and ambient noise are also relevant. The point is that, if differences in energy cost exceeding four orders of magnitude can arise for the same source level, use of source level as an indicator of impact, unless corrected for the spatial footprint of the source, risks poor prioritisation of limited resources for risk mitigation and management. For example, for the investigation of suitable mitigation measures, it would make more sense to start at the left of the table and work across to the right, and not vice-versa.

A final comparison is made between the energy cost of two very different sources: a cargo ship and the 1-kHz sonar transmitter. The cargo ship radiates broadband sound almost continuously, while the sonar transmitter radiates at a single frequency intermittently and with a relatively high source level. Despite having very different source level (and energy source level) they have approximately the same energy cost, which means that they make roughly equal contributions (ca. 30 kJ) to the total sound energy in the sea, added over all space and averaged over time, or at least that they would make equal contributions if both were operated in free-field conditions.

4. DEPARTURES FROM SPHERICAL SPREADING

Ref. [16] shows that, in conditions of cylindrical spreading (CS) with critical angle ψ, the total source energy is $(W/2c\alpha)\ \psi$, which is identical to the free-field energy apart from an extra factor ψ. This means that, when comparing the energy cost of different sources at the same location, the free-field energy is suitable for use as a proxy for total energy in the CS regime as well as in a free-field situation. For mode stripping [17] conditions the energy is proportional to $\alpha^{-1/2}$, instead of α^{-1} for the free-field case, resulting in qualitatively the same effect (decreasing decay time with increasing frequency, albeit less quickly than in the free field).

5. CONCLUSIONS

Conclusions of this work are:

- The environmental cost of a marine source, defined as the total cumulative exposure, is closely related to the free-field energy H_0; the free-field energy is referred to as the „energy cost‟.
- The energy cost of different sources of the same source level can vary by more than four orders of magnitude, suggesting that source level is a poor indicator of environmental cost in the form of acoustic exposure. The estimated variations in energy cost arise almost entirely through differences in the source‟s footprint, i.e., its spatial extent, determined by seawater absorption and source directivity.
- Source level can be converted to environmental cost by supplementing it with information about the spatial footprint of the source (size of the region of impact) using (10). If not in this way, use of source level alone as a measure of cost might lead to an inappropriate prioritisation of mitigation resources. The free-field source energy, which includes the effects of source directivity, duty cycle and decay time, is proposed as a complementary indicator [18].

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