Cumulative noise exposure assessment for marine using sound exposure level as a metric

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CUMULATIVE NOISE EXPOSURE ASSESSMENT FOR MARINE MAMMALS USING SOUND EXPOSURE LEVEL AS A METRIC

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Abstract: Sound exposure level (SEL) has been suggested as an important parameter when considering the impact of anthropogenic noise on marine mammals by the US Marine Mammal Criteria Group of the National Marine Fisheries Service (NMFS). This metric allows the cumulative exposure of an animal to a sound field for an extended period to be assessed against a predefined threshold for injury criteria. In many cases, this can become the dominant mechanism by which a marine mammal may suffer injury.

In this paper, the SEL metric has been used to estimate the cumulative exposure of animals using two examples of sound sources: (i) a large tanker vessel; and (ii) sub-sea marine impact piling. The method has been used in a predictive manner using models for noise sources, and also using measured data of the noise radiated by the source. The method can be used to investigate the effect on the cumulative exposure of factors such as source level, transmission loss model and animal behaviour.

Keywords: Sound exposure level, cumulative exposure, injury criteria

1. INTRODUCTION

The impact of anthropogenic noise on marine life is of growing importance with the increasing number of anthropogenic activities in the oceans [1], particularly the increasing number of installations of off-shore wind-farms [2]. Whist the impact on fish species is often an economic concern, the impact on marine mammals is a concern because of the potential to cause injury or disrupt the natural habitat of the species. Disruption of disturbance can be
governed by a number of factors, including the annoyance of the sound, auditory masking and the activity in which the animal is partaking. The annoyance of the sound can be comprised of a number of contributions including the received level (sound pressure level), the temporal and frequency characteristics of the source, the acoustic environment and the duration of the radiating activity. However, injury is simply defined as the on-set of auditory permanent threshold shift (PTS) \cite{3}, which is governed by either a peak level or an exposure level; sound pressure level (SPL) and sound exposure level (SEL) respectively. The fundamental difference between these two parameters is that SPL can be an instantaneous value and SEL is the total noise energy to which the mammal is exposed during a given duration – 1 second is typical or the pulse duration for impulsive source. Due to the very high level required to give rise to instantaneous PTS \cite{3}, the likelihood of PTS occurring due to a prolonged exposure is far more likely. For the case where a sound source is of a prolonged nature, for vessel activity, marine piling etc., cumulative exposure can also be a useful parameter. This considers a summation of the SEL’s to which the animal is exposed.

Cumulative exposure can be considered important for two scenarios; i) an animal close to a sound source might be startled by a high SPL, which is not high enough to cause instantaneous PTS, and proceeds to swim away at a given speed. The time taken for the animal to evade the exposed area is sufficient for the cumulative exposure to exceed that required to cause the on-set of PTS; ii) an animal traversing or entering an area of acoustic activity at a given distance and swim speed might be exposed to an SPL which is not sufficient enough to cause any avoidance behaviour by the animal. The time taken for the animal to traverse the area of acoustic activity might be sufficient for the cumulated exposure to exceed that required for the on-set of PTS.

This paper considers two hypothetical case studies for the use of SEL and cumulative exposure for a marine mammal traversing an area of acoustic activity (a large tanker vessel and sub-sea piling event). The use of a swim-by model enables the closest distance of approach possible without exceeding the SEL criteria for injury to be calculated, or inversely enables the cumulative exposure to be calculated for an animal traversing at a set distance.

2. SOUND EXPOSURE LEVEL AND CUMULATIVE EXPOSURE

Although SPL is routinely used for both the hearing threshold and receive level, other parameters are often used in the literature for impulsive sources such as marine piling \cite{4}. The reason for this is that the SPL parameter is based on the root mean square of pressure and is therefore not strictly suitable for impulsive signals. Other researchers in the literature have suggested the use of peak pressure (dB peak) to provide a more accurate description of the generated acoustic pressure \cite{5}. For a symmetric waveform this is half the value of the peak-to-peak amplitude. However, the waveforms encountered in piling noise measurements can sometimes exhibit significant asymmetry, and so the peak-to-peak values have been used \cite{6}\cite{7}.

Given these problems with using SPL for impulsive signals, calculating the energy in the pulse and expressing it as an SEL is more appropriate for sources such as impact piling events. The SEL for such an event is calculated by integrating the square of the pressure waveform over the duration of the pulse. The duration of the pulse is defined as the region of the waveform containing the central 90% of the energy of the pulse. The calculation is given by:
The value is then expressed in dB re 1 μPa²·s and is calculated from:

\[ SEL = 10 \log \left( \frac{E_{00}}{E_0} \right) \]  

where \( E_0 \) is the reference value of 1 μPa²·s.

The SEL for each impulsive noise event can be aggregated by summation to calculate the total SEL (or cumulative SEL) for the entire exposure duration. This is the main use of the metric, and in the case of a sequence of pulses from marine piling, the total SEL would be calculated for the entire sequence. This cumulative exposure is used to describe the noise dose which considers not only the peak pressure exposed to, but also the duration of the exposure. For injuries such as TTS and PTS, it is this cumulative exposure which is the important parameter to consider.

3. FLY/SWIM BY MODEL

The approach of Southall et al [3] recognises that even if the initial received levels are not great enough to cause injury, harmful effects can result from lower level sounds which last for a longer duration. In this paper, cumulative exposure levels are calculated for animals passing close to the selected noise sources. The source levels and characteristics for which the cumulative exposures are calculated for vessel propeller noise, based on a red/white noise model derived from source levels published by Arveson and Vendettis [8], and a sub-sea impact piling source, based on source levels measured by McHugh et al [9] which are discussed further in section 3. This allows the calculated cumulative exposures to be compared to the thresholds obtained from the literature, for example from the criteria published by Southall et al [3]. To do this, a trajectory is chosen for each animal whereby the animal swims past the source in a straight line at constant speed, heading and depth (it is assumed that no aversion is exhibited), where the trajectory is defined by the position of closest approach.

To calculate the cumulative SEL, the SEL is calculated for discrete intervals of one second assuming a realistic swim speed for the animal, and these are integrated over the entire “journey” (length of the trajectory) or time of exposure. Piling events can be assumed to have a well-defined start and stop time (they are not conducted continuously) which defines the duration. However, the vessel noise source is generally continuous and so a trajectory length has to be chosen over which the integration can take place. This was chosen to be 30 km. It should be noted that the large vessel remains stationary during the exposure, chosen to represent the behaviour of a dynamical positioned vessel maintaining station.

The receive levels at the receptor used in this paper are based on predictions calculated from assumed source levels and modelled transmission loss, which are discussed further in section 3 and 4 respectively.

4. REPRESENTATIVE SOURCE LEVELS
4.1. Vessel propeller noise

For purposes of this paper, a stationary source is considered for cumulative exposure calculation which represents propeller noise for a dynamical positioned vessel whilst maintaining station. Given the lack of availability of such data, the Arveson and Vendettis [8] data for a large vessel at high speed (shaft speed 140 rpm, approximately 16 knots) with substantial cavitation is considered. At these speeds, the higher frequencies are dominated by the cavitation but at lower frequencies the noise arises from different mechanisms. The Arveson and Vendettis [8] low frequency data is typified by peaks showing source levels of up to 182 dB re μPa·m at 38 Hz.

Although the higher frequency cavitation noise and lower frequency tonal noise are generated by different mechanisms, they make a similar contribution in the transition frequencies around 100 Hz. This complicates the identification of the source but allows summary third octave band data to be used to represent the total energy, as in the simple “red/white” model used by Hazelwood and Connelly [10] to estimate the noise power contribution over all frequencies [11]. This model is represented in Fig. 1 and is used for the broadband propeller noise cumulative exposure calculations in section 6.

![Fig. 1: Third octave band source level based on a red/white ship noise model.](image)

4.2. Marine impact piling

Marine impact piling noise is significantly more intense than ship noise, but is typically a short duration source with each operation typically lasting no longer than 40 minutes. For extremely close ranges, the peak levels generated by marine impact piling may actually exceed a level sufficient enough to cause instantaneous injury. However, for most scenarios, the potential for injury will depend on the integrated SEL over the full piling duration. A number of measurements have been made on marine impact piling for offshore windfarm construction [12][13][14][15][16] and the majority of the energy is typically reported [13] in the range 100 Hz to 1 kHz, with a pulse duration of the order of 0.15 seconds. Reported source levels for shallow water piling are very high, with peak source levels of in excess of 230 dB re μPa·m and SEL source levels in excess of 212 dB re 1 μPa²·s @ 1 m (dB re
μPa²·s·m²). Data published by McHugh et al [9] considers a sub-sea piling event (which will be considered for the purposes of this paper) at a depth of 95 m, reporting a source level of 210 dB re μPa·m [9]. Although a source level in terms of energy or SEL is not reported, it has been assumed that the piling pulse energy content and pulse duration has a similar relationship to the peak value as that obtained in shallow water. By this method, the energy (or SEL) source level was estimated as 195 dB re 1 μPa²·s·m² (or approximately 20 Joules).

5. TRANSMISSION LOSS

Single frequency transmission loss was calculated using the parabolic equation method, implemented using the RAM code. This code allows for range-dependent bathymetry to be implemented in the code to calculate transmission loss as a function of range and depth. This approach was used to estimate receive level at range for a single frequency at which the peak source level of a typical sub-sea piling event was believed to have occurred in the spectra – this was taken to be 210 dB re μPa·m at 200 Hz. For this work, it is the peak energy source level (195 dB re 1 μPa²·s·m²) which is of importance so this was also propagated to provide the received SEL.

This propagation model was performed for a sub-surface piling event (bottom source) in deep water >1 km. A number of single frequency source levels were also propagated to represent different harmonic components of propeller noise at the surface. Fig. 2 shows the transmission loss for a 100 Hz surface source as a function of range and depth (the black line on the colour map image indicates the seabed profile for the chosen transect), with a number of selected depth profiles obtained using the RAM code displayed for comparison with geometrical spreading.

![Fig. 2: Transmission loss for a 100 Hz source at a depth of 10 m.](image)

It can be seen from Fig. 2 that beyond a few km’s range, the transmission loss in the water column calculated using the RAM code does begin to settle between the transmission loss for simple spherical and cylindrical spreading. It does in fact approximate to a hybrid 14 log(r), at range for a 100 Hz propagation. This hybrid geometrical spreading was used to estimate the broadband transmission loss for third octave band frequencies which was subsequently used to calculate the broadband cumulative SEL, discussed in the following section, for propeller noise based on the source levels from the red/white ship noise model shown in Fig. 1.
6. CUMULATIVE SEL CALCULATED FOR LOW FREQUENCY CETACEANS

Using the methodology described in section 3, the swim-by model has been used to calculate the cumulative exposure assuming a number of conditions. These conditions are that the mammal, in this case, is a low frequency (LF) cetacean, swims at a constant speed and maintains a constant heading and depth whilst traversing the area of acoustic activity. For the sub-sea piling activity case study, a representative example was selected based on an energy source level of 195 dB re 1 μPa²·s·m² at 200 Hz, being performed in around 2 km’s of water with substantial bathymetry changes in the area and a standard sound speed profile for deep water. Fig. 3 shows this particular example for a LF cetacean swimming directly above the impact piling source at a depth of 500 m with a swim speed of 5 ms⁻¹. For this case where the piling activity takes around 60 mins, with the cetacean directly above the source at 30 mins, the total cumulative SEL is only around 192 dB re 1 μPa²·s. This falls below the criteria for injury suggested by the Marine Mammal Noise Exposure Criteria [3] of 198 dB re 1 μPa²·s for single/multiple pulse sources.

![Figure 3: Calculated SEL received level (upper plot) and cumulative SEL (lower plot) at 200 Hz for a LF cetacean at 500 m depth directly above the seabed source.](image)

Using the broadband approach discussed in section 5 for a ship/propeller noise source (based on the red/white model), the cumulative SEL per third-octave band to which the receptor is exposed whilst traversing the area of acoustic activity (assumed to be 30 km across) can be calculated. An example of this is shown in Fig. 4 for a LF cetacean traversing the area with a constant swim speed of 5 ms⁻¹ at a depth of 10 m and assuming a constant heading. Fig. 4 shows the cumulative SEL results for a number of distances of closest approach between 1 m and 17 km. The maximum total SEL occurs for the 40 Hz band (corresponding with the peak of the red/white noise model) with a value of 184 dB re 1 μPa²·s at 1 m. Even at 1 m, this is substantially less than the criteria for injury
suggested by the Marine Mammal Noise Exposure Criteria [3] of 215 dB re 1 μPa²·s for tonal or broadband sources. However, the ship noise (assuming a stationary ship at maximum noise output representing a large dynamically position tanker holding station) resulted in a higher exposure under the assumed conditions than the sub-sea impact pile which has a much greater source level. It should be noted that the SEL values stated here are weighted according to the animal classifications defined by Southall et al [3], i.e. weighted for a LF cetacean in this instance. The sources have also been categorised as non-pulses and pulse/multi-pulses to maintain consistency with the source classifications used under Marine Mammal Noise Exposure Criteria [3].

Fig. 4: Calculated cumulative SEL per third-octave band for a LF cetacean at 10 m depth traversing the sound source at different distances of closest approach.

7. CONCLUSIONS

A method for calculating cumulative exposure based on SEL using a swim-by model has been outlined and results have been presented for a case study based on two representative noise sources. The first source, sub-sea impact piling, was used to represent a multi-pulse source with a very high source level and the second source, large vessel propeller noise, was chosen to represent a lower source level noise of longer duration. The cumulative exposure was calculated for each for predefined set of conditions. For the conditions considered in this paper, the ship noise resulted in a higher exposure than the sub-sea impact pile which had a much greater source level. However, both sources resulted in cumulated SEL’s below the injury criteria proposed by Marine Mammal Noise Exposure Criteria [3].

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