Empirical prediction of peak pressure levels in anthropogenic impulsive noise. Part I: Airgun arrays signals

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Abstract: This paper presents an empirical linear equation to predict peak pressure level of anthropogenic impulsive signals based on its correlation with the sound exposure level. The regression coefficients are shown to be weakly dependent on the environmental characteristics but governed by the source type and parameters. The equation can be applied to values of the sound exposure level predicted with a numerical model, which provides a significant improvement in the prediction of the peak pressure level. Part I presents the analysis for airgun arrays signals, and Part II considers the application of the empirical equation to offshore impact piling noise.

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Date Received: June 6, 2015 **Date Accepted:** December 8, 2015

1. Introduction

Anthropogenic sound is increasingly present in oceans as a result of rapidly growing offshore industrial operations. These operations can generate sounds of high level, which has a potential impact on marine fauna with short and long term effects,[1] especially at short ranges from the noise source. Jurisdiction, policies, and other initiatives developed over the last years require assessing these effects.[2]

Offshore seismic surveys and impact pile driving for offshore installations are operations producing the highest levels of underwater noise, along with explosions, ships, and active sonars. The measures more commonly used in the context of impact assessment of underwater noise are the sound pressure level (SPL), the sound exposure level (SEL), and the peak pressure level (SPL_{peak}).[3] SPL, which is the root-mean-square (rms) pressure expressed in dB re 1 μPa, is not an appropriate measure to characterize the impact of impulsive signals because it varies rapidly with time and depends strongly on the length of the time window chosen for averaging. SEL is calculated by integrating the square of the pressure over the time interval containing 90% of signal energy, and thus it is a more appropriate measure of the potential impact. For short transient signals, SPL_{peak} is also a critical measure of the potential impact as high levels of it can result in a significant damage to hearing ability of marine animals even if the SEL values are below the critical value.[4]

The SEL and SPL_{peak} values and their variations with range need to be predicted prior to commencement of any activity generating impulsive underwater noise to avoid potential impacts. The prediction of SEL can be achieved with good accuracy using the existing underwater sound propagation models, if the environmental parameters are known. However, accurate modeling of the peak pressure at long ranges is a much more complex ploblem.[5] Predictions based on numerical modeling of the signal

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waveform often result in an overestimation of the peak pressure value in comparison with measurements[6] (see also, for example, Refs. 7 and 8).

An analysis of the correlation between SEL and SPL_{peak} of impulsive signals from different seismic surveys with airgun arrays resulted in a linear dependence between these two measures with similar regression coefficients for all tracks and locations regardless of water depth and other environmental parameters, leading to an analysis of all signals combined from all tracks to derive global coefficients for predicting SPL_{peak} from SEL.[9] This result suggested that the regression formula depends primarily on properties of the acoustic source rather than characteristics of the environment. Thus the source signals from airgun arrays were analysed to validate this observation.

2. Prediction of SPL_{peak} from SEL

2.1 Seismic data

For this part of the study, measurements of airgun array signals from ten different tracks of three different seismic surveys were used. The first set of measurement data were recorded over the continental slope off Cape Leeuwin in Western Australia, using the HA01 hydroacoustic station of the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty. Signals from one seismic survey track recorded from approximately 17 to 94 km from the airgun array were analyzed in the station's frequency band of 1–100 Hz. The sound propagation path was highly range-dependent with water depth varying from about 1130 to 1740 m. The top layer of sediment along the acoustic path consisted primarily of sand.[7] The second data set were obtained from the seismic survey off Dongara in Western Australia, where airgun signals were recorded in a frequency band of 3–230 Hz. This is a nearly range-independent environment in shallow water of 40 m depth on average over a calcarenite seafloor with a limestone basement. Six tracks were run spanning distances from 1 to 15 km from the recording system. The third set of recordings made in a frequency band of 5 Hz to 3 kHz was taken from a survey in Bass Strait. This area is characterized by a calcarenite seafloor with a range-dependent bathymetry and mean water depth of about 130 m.[10] Airgun signals from three tracks were recorded at ranges from 2 to 13 km from the source.

2.2 Empirical analysis

All airgun signals from these ten seismic tracks were analysed with respect to the linear dependence between SPL_{peak} and SEL. Ten specific linear equations were derived and regression coefficients Ai and Bi were calculated for all the tracks using a least-square fit, with Ai being the slope, Bi the offset, and i the track number [Eq. (1)],

$$\{\mathrm{SPL}_{\mathrm{peak}}^{\exp-i} = A_i \cdot \mathrm{SEL}^i + B_i\}_{i=1,\ldots,10} \mathrm{dB\ re 1}\mu\mathrm{Pa}. \quad (1)$$

The least-square fit resulted in similar values of the regression coefficients in most cases, despite the different environmental characteristics. This finding motivated a joint correlation analysis using all measurements. The best linear fit of the variation of SPL_{peak} with change in the SEL value (left panel in Fig. 1) resulted in global regression coefficients $A_G = 1.21$ dB re 1 μPa/dB re 1 μPa^2 s and $B_G = -20.1$ dB re 1 μPa, which

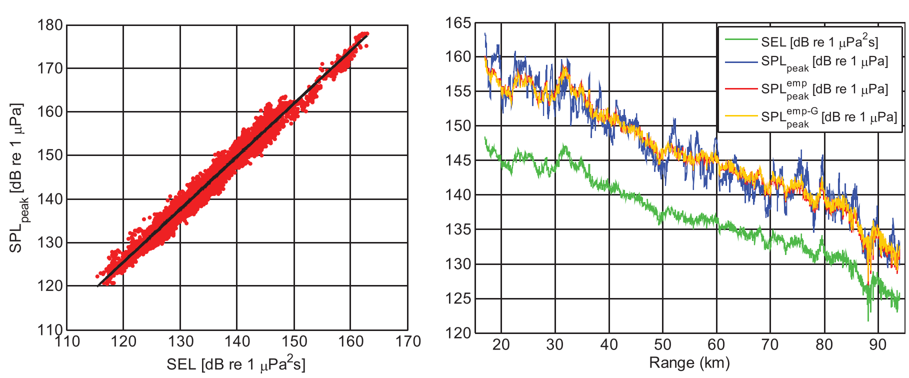

Fig. 1. Left: Experimental SPL_{peak} vs SEL and best linear fit (black line) for data from all three surveys. Right: Empirical prediction applied to the Cape Leeuwin data set: Measured SEL (green), measured SPL_{peak} (blue), empirical prediction of SPL_{peak} with the specific regression coefficients (red), empirical prediction of SPL_{peak} with the global regression coefficients (yellow line).

are not specific for each individual site. The rms residual of the linear fit is 1.6 dB re 1 μPa.

To test the accuracy of the linear regression with the global coefficients, the SPL_{peak} values measured for each individual track were compared with those predicted from the SEL measurements using the empirical equation [Eq. (1)] with the global coefficients and those specific for each track. In all cases, the prediction of SPL_{peak} with the global coefficients is nearly as accurate as the prediction with the coefficients specific for each environment. The right panel in Fig. 1 shows the prediction results for the Cape Leeuwin track using both global and track specific coefficients, with the latter being $A_S = 1.24$ dB re 1 μPa/dB re 1 μPa^2 s and $B_S = -24.0$ dB re 1 μPa.

Let us notice that the linear dependence and regression coefficients found from this analysis are valid for measurement ranges from about 1 km to nearly 100 km. At a shorter distance, where multipath and/or scattering effects are not determinative, the correlation between SPL_{peak} and SEL can be somewhat different. Additional measurements and analysis are needed to examine this correlation at shorter distances.

2.3 Semi-empirical prediction

The ultimate aim of this study is to develop methods for predicting the peak pressure level of impulsive noise produced by offshore industrial activities before they occur. In contrast to SPL_{peak}, which is more affected by interference and scattering effects, the SEL can be well predicted by the existing underwater sound propagation models, if the environment parameters are known. Therefore, given an accurate numerical prediction of SEL with an appropriate model and the correlation between SEL and SPL_{peak} with known regression coefficients that are independent of the environment, SPL_{peak} can be estimated in a semi-empirical way.

This semi-empirical method was tested for the Cape Leeuwin data set. The numerical simulation of the waveform of signals propagated along the acoustic path was made with RAMGeo, a model based on a parabolic equation approximation in the Range-dependent Acoustic Model developed by Collins.[11] This model provided numerical predictions of SEL which were fairly consistent with the measurements (left panel in Fig. 2). The right panel in Fig. 2 shows the measurements of SPL_{peak}, the prediction obtained with the numerical model of the signal waveform and the semi-empirical prediction obtained from the numerically predicted SEL and the linear equation for SPL_{peak} [Eq. (1)] with the global coefficients. The prediction with RAMGeo differs from the measurements by more than 10 dB within some sections of the acoustic path and varies from 2.5 to 14.6 dB at ranges between 70 and 94 km. The semi-empirical method predicts the variation of the SPL_{peak} values with range much closer to the measurements than the direct numerical simulation of the waveform. Statistics of fluctuations of SPL_{peak} around the value predicted by the empirical equation is currently under analysis.

3. Analysis of source properties

For the analysis of airguns as acoustic sources, a model developed at the Centre for Marine Science and Technology (CMST) of Curtin University was used to model sound emission by single airguns and airgun arrays.[12] This model is based on a variation of an airgun bubble model[13] and verified using data from short-range measurements. The source signal was modeled for six single airguns with volumes of 10, 20,

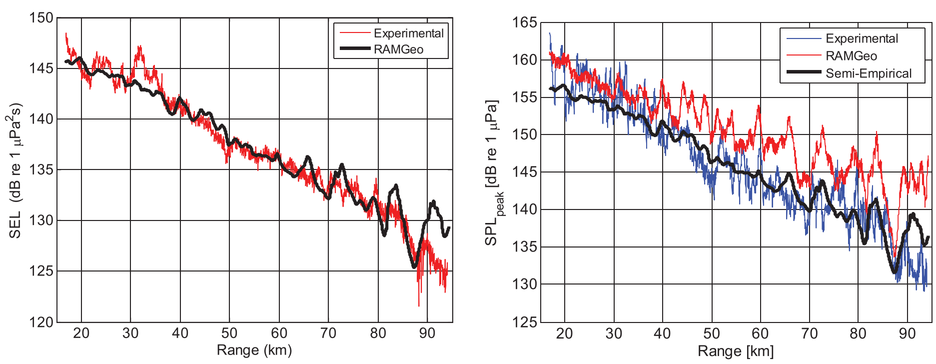

Fig. 2. Left: SEL vs range: Measured values (red) and numerical prediction from the sound propagation model RAMGeo (black). Right: Comparison of SPL_{peak} measurements and predictions: Measured values (blue), prediction from the waveform numerically modeled using RAMGeo (red), and semi-empirical prediction obtained by applying the global equation to the predicted SEL (black).

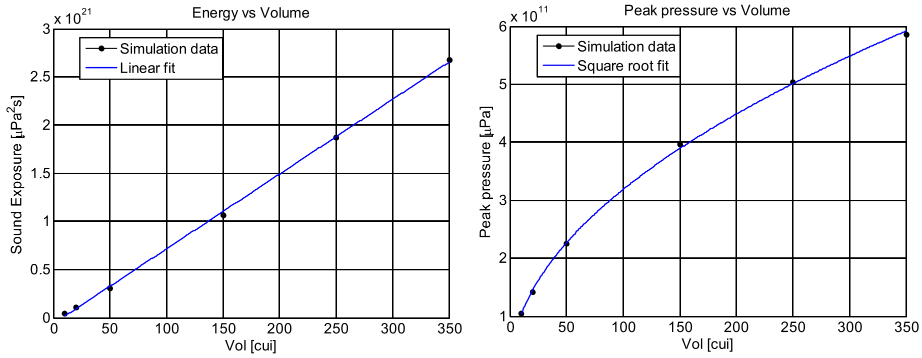

Fig. 3. (Color online) Left: Sound exposure vs airgun volume for six single airguns. Right: Peak pressure vs airgun volume for the same single airguns (both characteristics modeled at 1 m from the source).

50, 150, 250, and 350 cui. The airguns were assumed to be fired at a typical depth of 7 m and internal chamber pressure of 2000 psi. Five airgun arrays used or proposed for real seismic surveys were also modeled, with the total volume varying from 2660 to 6300 cui, rectangular flat and V-shaped, and towed at depths of 6 to 10 m.

The sound energy and consequently the sound exposure are expected to increase linearly with the product of the volume and chamber pressure.[14] This is also predicted by the CMST model, which is illustrated in Fig. 3 (left panel) for constant chamber pressure. In an ideal airgun, where a pressurized ideal gas is instantaneously discharged from the chamber, the peak acoustic pressure is theoretically proportional to cube-root of the airgun volume.[13] However, in more physically realistic airgun models the peak pressure is rather proportional to the square-root of the volume, as predicted by the CMST model and illustrated in Fig. 3 (right panel). Therefore the dependence of the squared peak pressure on airgun volume can be well approximated by a linear function, like the sound exposure does at fixed chamber pressure. This means that the correlation between SEL and SPL_{peak} of airgun signals does not change significantly with volume variation. This is demonstrated in Fig. 4 which shows the values of SPL_{peak} versus SEL for five single airguns and five airgun arrays and the linear dependence given by Eq. (1) with the global regression coefficients. For single airguns, the slope of the modeled dependence is slightly smaller than that of the regression line; however, within the range of standard volumes, the difference from the global regression is relatively small. The SPL_{peak} and SEL values predicted from the sound emission model of airgun arrays follow the same global regression, with a small variation in the offset. Therefore the correlation between SPL_{peak} and SEL, particularly the offset B in Eq. (1), is intrinsically governed by the source characteristics (airgun array in this case). All signals analyzed in this study were produced by airguns with the same chamber pressure and therefore no correction was needed in the global equation to account for changes in the pressure in contrast to the analysis in Part II (Ref. 15) for pile driving noise, where an extra term is added to allow for the effect of variation in piling parameters.

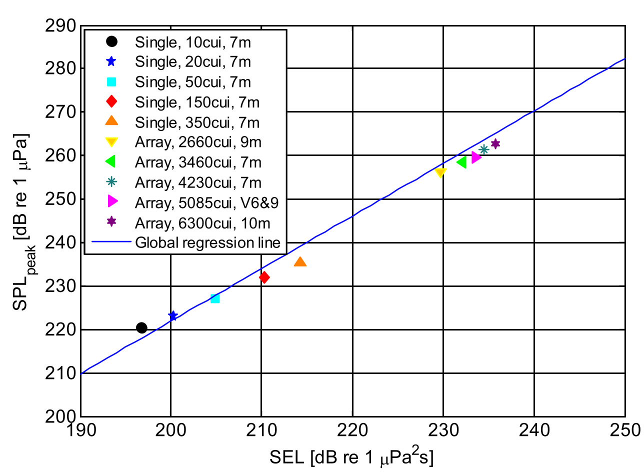

Fig. 4. (Color online) Peak pressure level vs SEL modeled for five single airguns of different volumes and five different airgun arrays.

4. Conclusions

An empirical equation was presented in this paper (Part I) to predict the peak pressure level of impulsive signals from airgun arrays based on its correlation with the SEL. Part II (Ref. 15) considers the application of the empirical equation to offshore impact piling noise.

The regression coefficients in the empirical equation derived from all measurements of airgun array signals do not depend much on environmental characteristics of seismic surveys and thus they can be used to predict peak pressure levels in different marine environments at distances from about 1 km to nearly 100 km analyzed in this study. At shorter distances the correlation between the peak pressure and SELs can be somewhat different, depending in particular, on water depth. The values of the coefficients are shown to be determined by the source parameters, which has been confirmed via modeling of source signals from different single airguns and airgun arrays.

The empirical equation can be used to predict peak pressure levels of airgun array signals from numerical predictions of the SEL using an appropriate sound propagation model. Such a modeling approach can be referred to as semi-empirical prediction.

A comparison of the modeling and measurement results showed that the use of the semi-empirical method for predicting the peak pressure level of impulsive signals provided significantly more accurate results than the method based on numerical prediction of the signal waveform over the distances analyzed in this study.

Acknowledgments

The authors want to thank Geoscience Australia for providing the experimental data collected off Cape Leeuwin, RocOil Pty. Ltd. for the data from Dongara, and Origin Energy for supporting measurements in Bass Strait.

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