Characterizing Underwater Noise from Industrial Pile Driving at Close Range

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***Abstract*—Acoustic radiation in the water surrounding a ferry terminal pile driving project has been characterized based on 1/3-octave band filtering. The pressure field at approximately 10 meters is shown to be depth dependent based on data captured using a vertical line array. Decibel measurements of underwater sound are often expressed in reference to several non-interchangeable units, a summary of the differences of these references is presented.**

I. Introduction

It is important to measure and understand the underwater acoustic pressure due to impact pile driving in view of the federal and state limitations put on these levels of sound at given ranges from the pile, meant to reduce risk of injury to various species of fish and marine mammals. Although current regulations are based on broadband measurements (RMS, peak-to-peak, or SEL), pile driving produces sound that is frequency dependent. Also, marine life that is potentially affected by pile driving have frequency-dependent sensitivity in hearing. Understanding the frequency spectrum (here based on 1/3-octave band analysis) and where this spectrum is approximately at background level can lead to more informed policy making. Because there are different conventions to describe the frequency content of a signal a brief summary of conversion factors is also provided.

II. Data Collection

Data was collected during two days in November 2009 when a new dolphin installation – a group of four piles to provide guidance for ferries – was being completed at the Vashon Island Ferry Terminal in Vashon, WA. The piles being driven were 0.91 meters in diameter with 2.5 centimeter walls. Each pile was driven to approximately 5 meters short of its final depth with a vibratory hammer, then the rest of the way with a diesel impact hammer that resulted in substantially higher levels of underwater sound. The measurements presented here were all taken while the impact hammer was being used.

The equipment used to measure sound levels included a nine hydrophone vertical line array (VLA) located at distances between 8 and 12 meters from the pile being driven (the VLA was stationary). The second hydrophone from the top of the VLA (depth of 4.2 meters), the middle hydrophone (depth of 6.3 meters), and the second hydrophone from the bottom (depth of 8.4 meters) are selected here as representative of the VLA and will be referred to as Ch2, Ch5, and Ch8, respectively. VLA signals were fed in to the Astro-Med® Dash® 20HF-HS 16-bit analog-to-digital converter sampling at 62.5 kilohertz.

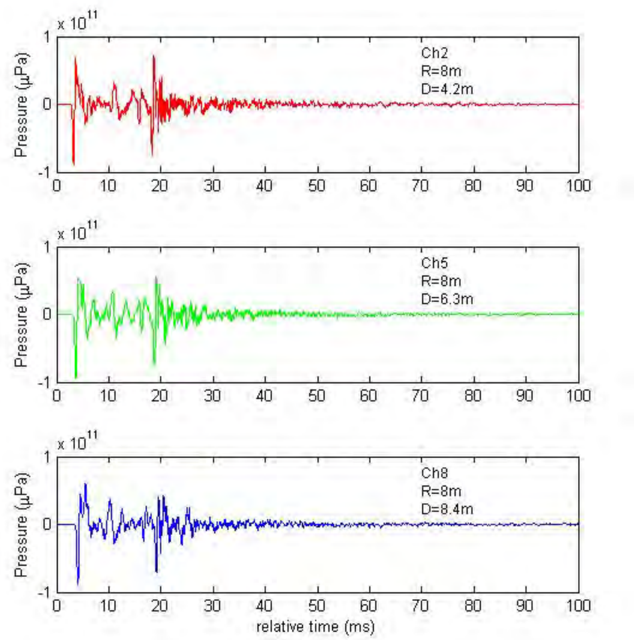

Fig. 1. Time series of pressure incident on channels 2, 5, and 8 of the vertical line array.

III. Data Analysis

A. 1/3-Octave Filtering

The time series (measured in volts) as recorded by the hydrophone elements in the VLA were converted to pressure units of dynes per centimeter squared; this unit was chosen in favor of micropascals because there is precedent in using CGS units in the measurement of pressure waves caused by explosions [1]. The resulting time series (duration of 500 milliseconds) were sent through a 1/3-octave filter bank designed using MATLAB® per the ANSI® standard for

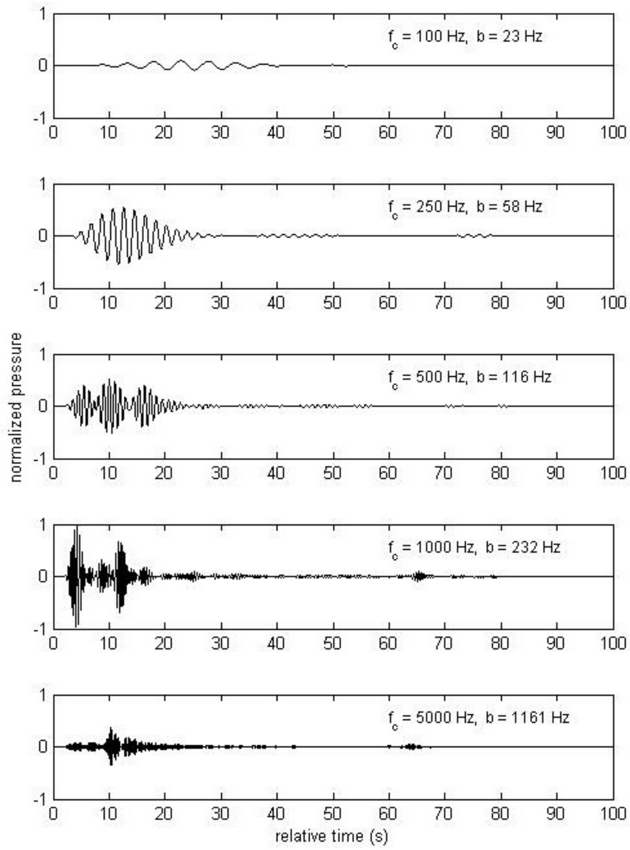

Fig. 2. Sample normalized pressure time series from 1/3-octave filter bank output.

Class 1 filters [2] representing preferred center frequencies from 25 hertz to 25 kilohertz. This resulted in 31 time series that correspond to the contributed signal of each of the 1/3-octave bands to the original signal. The time series output of the i^{th} filter band is then $p_i(t)$ (examples in Fig. 2).

B. Energy Spectral Density

The pressure time series of the i^{th} 1/3-octave band is used to calculate the energy density, given by

$$e_i = \frac{1}{\rho c}\int_0^T p_i^2(t)dt, \qquad (1)$$

where ρ is the density of the sea water, c is the speed of sound in the water, and T is the duration of the signal, all in CGS units.

The energy density per hertz is given by $\frac{e_i}{b_i}$, where b_i is the bandwidth of the i^{th} 1/3-octave band, expressed in decibels this is $E_i = 10\log\frac{e_i}{b_i}$. The average energy density spectrum is displayed for the shallow, middle, and deep water channels in Figs. 3 and 4.

IV. Notes on Units

For reasons mentioned above, Figs. 3 and 4 display the decibel equivalent of energy spectral density in CGS units.

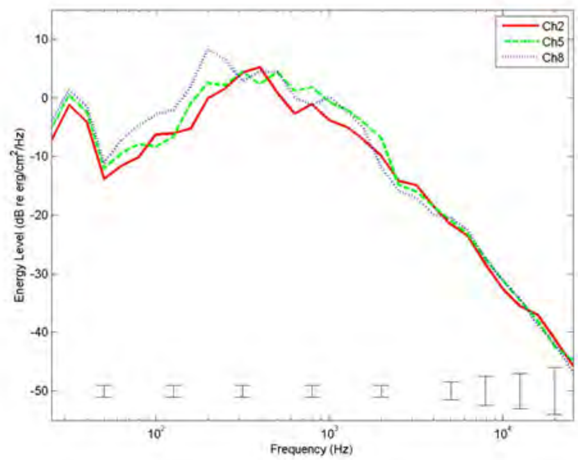

Fig. 3. The energy density per hertz for the Ch2, Ch5, and Ch8 hydrophones averaged over 60 strikes. Range is 12 meters. Nominal error bars for each center frequency are at the bottom.

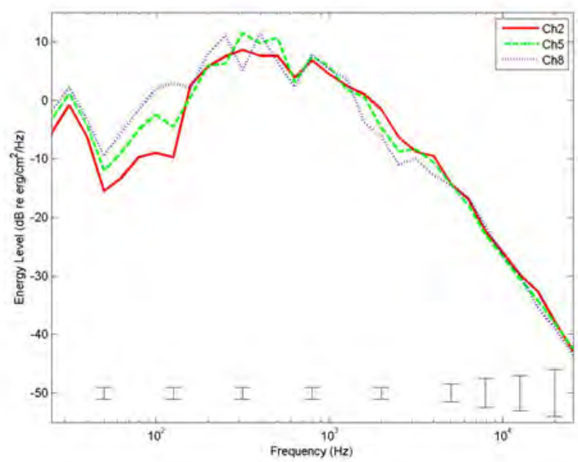

Fig. 4. The energy density per hertz for the Ch2, Ch5, and Ch8 hydrophones averaged over 42 strikes. Range is 8 meters. Nominal error bars for each center frequency are at the bottom.

That is, the pressure, density, and sound speed in (1) are in CGS units. Underwater pressure levels are usually expressed in decibels with reference to 1 micropascal. The integral of pressure squared with respect to time when pressure is in units of micropascals gives micropascals squared seconds. To convert this to the energy density unit of joules per meter squared the value must be divided by the characteristic acoustic impedance of the medium, or ρc [3]. The units are such that 0 decibels reference 1 joule per meter squared is equal to 182 decibels reference 1 micropascal squared seconds, shown in (2) and (3). Note that,

$$1\ \mu Pa^2 s = 1 \times 10^{-12}\ kg^2 m^{-2} s^{-3}, \qquad (2)$$

and

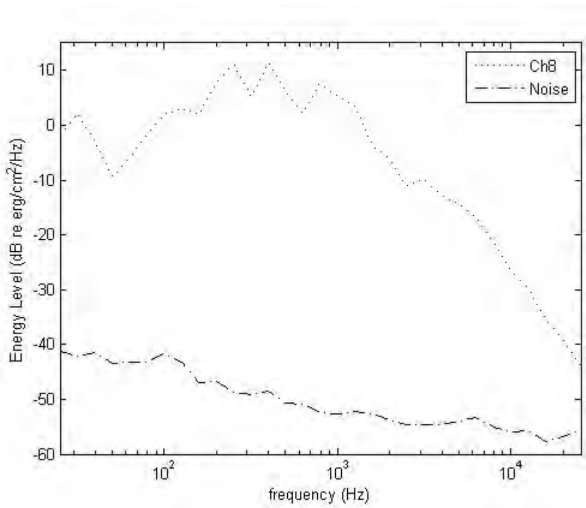

Fig. 5. The energy density per hertz for the Ch8 hydrophone averaged over 42 strikes and the background measured by Ch8. Range is 8 meters

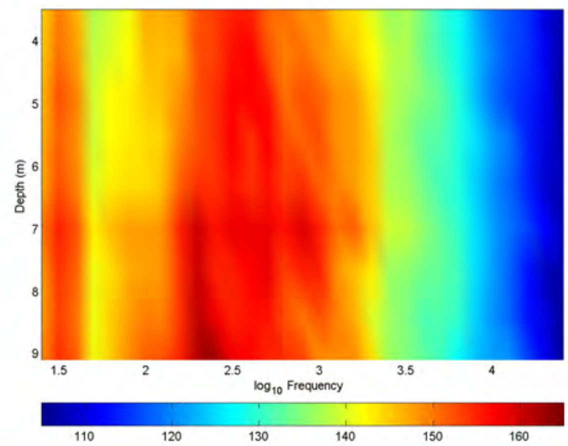

Fig. 6. The time-integrated pressure squared per hertz for all hydrophones in the VLA averaged over 60 strikes. Range is 12 meters. Units of the color-bar are dB re 1 μPa$^2\cdot$s$\cdot$Hz^{-1}.

$$\frac{1 \times 10^{-12} kg^2 \cdot m^{-2} \cdot s^{-3}}{1500\ m \cdot s^{-1} \cdot 1024\ kg \cdot m^{-3}} = 6.5 \times 10^{-19} J \cdot m^{-2}. \quad (3)$$

The resulting energy density may be divided by bandwidth to get energy spectral density. To calculate the energy spectral density in CGS units the following relationship is used,

$$1\ J \cdot m^{-2} = 1000\ ergs \cdot cm^{-2}, \quad (4)$$

where 1 erg is equal to 1 dyne centimeter. Therefore 0 decibels reference joules per meter squared is equal to 30 decibels reference ergs per centimeter squared, or a 152 decibel offset between the two quantities for which spectral density is expressed, ergs per centimeter squared per hertz and micropascals squared seconds per hertz. Note that these specific decibel offsets are only applicable for ρc of seawater. Also note that division by ρc not only changes the magnitude but also the dimension of the value.

V. Discussion

Figures 3 and 4 show the frequency dependence of the radiation of energy from the pile. For all channels there is a local maximum in the 31.5 hertz 1/3-octave band and a local minimum at 50 hertz. The spectrum tends to peak in the 200 hertz to 1000 hertz range, falling off nearly monotonically thereafter at a rate of approximately 10 decibels per octave. Figures 6 and 7 show the frequency content from all 9 channels of the VLA and suggests that while there is minor depth dependence the spectra from each depth are similar in character. At no point in the frequency band analyzed did the measurement of the pile strike reach background levels in a 1/3-octave band, as shown in Fig. 5. The background noise levels (Fig. 5) are upper limits on the true background and are in agreement with analysis of the least significant bit of the data acquisition system. This is an upper bound because the hydrophones in the VLA have a low sensitivity to accurately measure the pressures produced by pile strikes at close range.

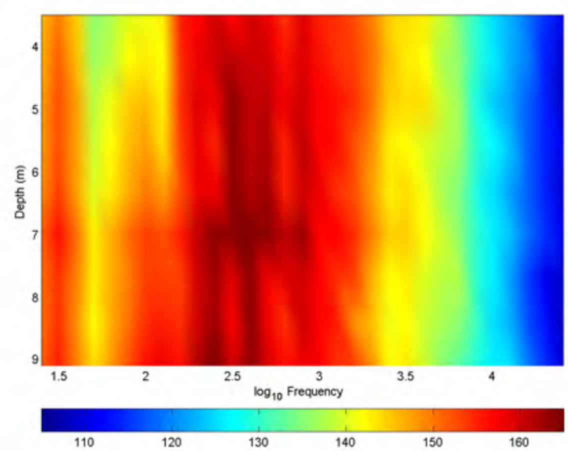

Fig. 7. The time-integrated pressure squared per hertz for all hydrophones in the VLA averaged over 42 strikes. Range is 8 meters. Units of the color-bar are dB re 1 μPa$^2\cdot$s$\cdot$Hz^{-1}.

VI. Conclusions

The pressure field at close range (8 to 12 meters) to pile driving activities was measured and analyzed using 1/3-octave band filters. The vertical field at a constant range was sampled using a nine element vertical line array to evaluate some depth dependence. The time-integrated pressure squared and energy density spectra of the pile strikes were presented in the two most commonly used units in an attempt to make the data more readily comparable to existing data across multiple disciplines. To that aim a summary and a reference on the differences between time-integrated pressure squared and energy density given in MKS and CGS units was provided.

As knowledge increases about the risks of harm to marine life due to anthropogenic sources so must the understanding of those sources and their relationship to background noise levels, not only broadband measurements but also in terms of bandwidths and frequency ranges pertinent to the hearing mechanisms of various species.

VII. Improvements and Future Plans

This data set is relatively new and is still being actively analyzed. Preliminary modeling with both a parabolic wave equation based numerical model and a hybrid model of rays and normal modes has had some success at reproducing the field as measured by the VLA as well as a distant hydrophone (range of approximately 120 meters, depth of 5 meters). The models will need to be improved by accurately characterizing a pile-strike source, of which finite element modeling is well underway [4]. There is an approximate slope of 5° from the location of the VLA to the more distant hydrophone, so a better understanding of the effects of bathymetry on the pressure field needs to be investigated. The estimate of the speed of sound in the sediment is currently a crude one, but a future integration of several parameters and models should be able to increase the confidence level in that estimate.

Many reflections occur shortly after a pile strike – both from the sediment and surface but also from the pile itself – investigation into the 1/3-octave content of each of these reflections could yield a better understanding of the nature of the acoustic radiation from the pile. If the pile strike radiation can be more adequately modeled (especially with inclusion of shallow water effects) there can be improvements made to the information on which policies are based.

Acknowledgment

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