Proceedings of Meetings on Acoustics

Volume 19, 2013 http://acousticalsociety.org/

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Noise
Session 3aNSa: Wind Turbine Noise I

3aNSa9. Predicting underwater radiated noise levels due to the first offshore wind turbine installation in the U.S.

Huikwan Kim*, James H. Miller and Gopu R. Potty

***Corresponding author's address: University of Rhode Island, 215 South Ferry Road, Narragansett, RI 02882, hkkim524@my.uri.edu**

Noise generated by offshore impact pile driving radiates into the air, water and sediment. Predicting noise levels around the support structures at sea is required to estimate the effects of the noise on marine life. Based on high demands developing renewable energy source, the United States will begin the first pile driving within one to two years. It is necessary to investigate acoustic impact using our previously verified coupled Finite Element (Commercial FE code Abaqus) and Monterey Miami Parabolic Equation (2D MMPE) models (J. Acoust. Soc. Am. 131(4), p. 3392, 2012). In the present study, we developed a new coupled FE-MMPE model for the identification of zone of injury due to offshore impact pile driving. FE analysis produced acoustic pressure outputs on the surface of the pile which are used as a starting field for a long range 2D MMPE propagation model. It calculates transmission loss for N different azimuthal directions as function of distance from the location of piling with the inputs of corresponding bathymetry and sediment properties. We will present predicted zone of injury by connecting N different distances of equivalent level fishes may get permanent injury due to the first offshore wind farm installation in the U.S..

Published by the Acoustical Society of America through the American Institute of Physics

 [DOI: 10.1121/1.4799983]
Received 22 Jan 2013; published 2 Jun 2013

INTRODUCTION

Offshore wind turbines have been installed throughout Europe and are expected to be built in the United States waters shortly. Compared to onshore wind turbines, offshore wind is an attractive option because more than 40% of the world's population lives within 100 km from the coast, it is possible to construct larger wind turbines, and it takes advantage of steadier and stronger ocean winds, thus allowing turbines to produce more electricity. However, noise generated during construction of offshore wind turbines radiates into and propagates through the air, water, and ocean bottom. Predicting noise levels around these offshore support structures is required to estimate the anthropogenic noise impacts upon marine life. Pile driving during the initial installation produces the loudest source of broadband noise. Our aim is to quantitatively predict the increase in noise level due to installation of offshore wind turbines around Block Island, Rhode Island where the first offshore wind farm in the U.S. will be constructed. This paper is the extension of our previous work presented at the 164th Acoustical Society of America Meeting in Hong Kong [1] and published in the Proceedings of OCEANS, 2012 – Yeosu. [2] In this study, we used the bathymetry recently collected in the proposed wind farm site off Block Island, Rhode Island. We used a Finite Element (FE) model to estimate the vertical acoustic pressure amplitude on the surface of the pile due to marine piling, and the Monterey-Miami Parabolic Equation (MMPE) model [8] to predict long range noise propagation from an offshore wind turbine support structure during installation. Our paper describes the overall approach which ties the FE and MMPE models together. We discuss the bathymetry around the piling site, the FE model with the impact loading on top of the pile, MMPE model with the starting field generated by FE model, and present the expected long range noise levels one would expect to witness due to offshore wind turbine construction.

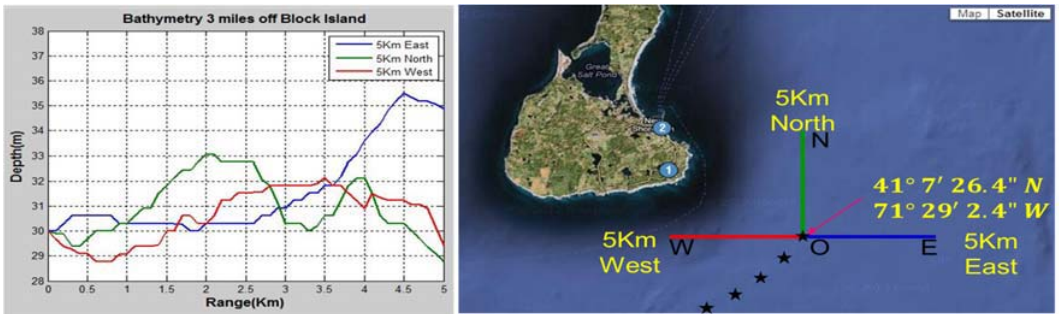
METHOD AND RESULTS

Coupled FE-MMPE Model Approach

Vertical acoustic pressure outputs on the surface of pile produced by a FE steady state dynamic analysis were used as a starting field for the MMPE propagation model. In the FE model analysis, we assume that acoustic pressure is only a function of radial distance and vertical depth, and is independent of azimuthal angle. To accomplish this we used an axisymmetric model available in the ABAQUS 6.11 commercial code. [9] Before implementing the FE-generated vertical pressure starting field into the MMPE, we verified the FE pile driving noise model using implicit dynamic analysis and compared results with the measured and modeled data from Reinhall and Dahl. [3, 4] Once our FE approach was verified [2], we generated the vertical acoustic pressure field due to pile driving upon the offshore wind turbine support structure for the three acoustic media – air, water, and bottom. The FE complex pressure field on the surface of the structure was then incorporated into the MMPE starting field at corresponding frequencies. The main differences between the present and the previous work are that we used the bathymetry off Block Island and extracted vertical acoustic pressure field on the surface of the structure instead of 1 meter from the outer surface of the structure. We used the standard MMPE model simulating water and ocean bottom as acoustic media instead of the modified MMPE specially designed for the previous project because we found that most of acoustic energy from the offshore wind turbine construction propagates in the water and bottom.

Bathymetry off Block Island RI

Bathymetry data off Block Island collected as part of the Rhode Island Ocean SAMP (Special Area Management Plan) has been extracted at the Environmental Data Center located in the University of Rhode Island. [5, 6] An approximate location of offshore wind turbine piling is provided by, Deep Water wind [7] and we set the location of piling 3 miles South-East from Block Island which corresponds to Latitude-Longitude ($41° 7' 26.4" N - 71° 29' 2.4" W$). We extracted bathymetry along 5 Kilometer transect from this location along East, North, and West respectively. FIGURE 1 shows the map around Block Island and bathymetry along these three transects. The stars show the location of five proposed offshore wind turbine construction sites.



(a) (b)

FIGURE 1. (a) Bathymetry off Block Island, Rhode Island along 5 kilometer East (OE), North (ON), and West (OW) from the location "O" $(41^\circ\,7'\,26.4''\,N - 71^\circ\,29'\,2.4''\,W)$. (b) Map view of offshore wind turbine piling locations (★) provided by the website of the developer, Deep Water Wind.

FE (Finite Element) model

FE model overview

To simulate radiated noise from an offshore wind turbine during pile driving using the FE model, an axisymmetric model was used, assuming no variation along the azimuthal angle in the cylindrical coordinate system for a shallow water environment. In FIGURE 2, our axisymmetric model considers 20 meters each of air and sediment with 30 meters of water in-between. The length and radius of the pile are 44 meters and 1.5 meters respectively. In order to provide a vertical starting field for the MMPE, we require the pressure field on the outer surface of the pile in the water and bottom. Elastic properties such as Young's modulus and Poisson's ratio were input parameters which properly characterized the steel pile. Density (ρ) and bulk modulus (K) defined the acoustic medium, with a corresponding speed of sound given by $c = \sqrt{K/\rho}$. Specific details of material properties are shown in the Table 1. Mesh size requirements dictated that at least six elements should exist within the shortest wavelength corresponding to the highest frequency of interest. For this study, we are most interested in radiated acoustic energy between 100 Hz and 1000 Hz for incorporation into the MMPE model. It should be noted that marine piling also causes substantial noise outside of this frequency band. In order to avoid reflection from the geometrical boundary of the model, a non-reflecting boundary condition available in Abaqus 6.11 was applied.

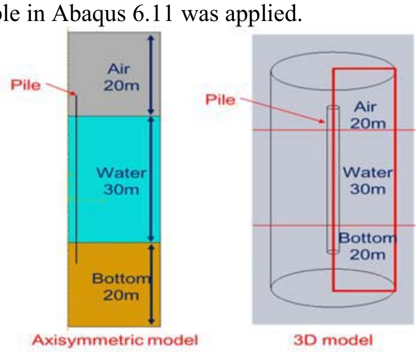


FIGURE 2. Axisymmetric geometry of support structure (left panel) and 3D representation (right panel).

TABLE 1. Material properties for the finite element model

Parameters	Air	Water	Bottom	Steel
Density ($\rho, kg/m^3$)	1.21	1025	1200	7900
Bulk Modulus (K, GPa)	0.000117650	2.306	2.995	-
Young's Modulus (Y, GPa)	-	-	-	200
Poisson's Ratio(ν)	-	-	-	0.3

Vertical acoustic pressure outputs from FE steady state dynamic analysis

For conventional applications (such as a point source or line array), the starting field for the MMPE model can be easily defined. However, the pressure field generated from pile driving is more complicated in terms of its vertical distribution and its frequency dependence. We employed a steady state dynamic analysis which allows us to specify the impact pressure as a function of frequency onto the pile. Our loading condition was calculated by taking the discrete Fourier transform of the time-dependent approximation for impact pressure as specified by Reinhall and Dahl. [3, 4] This approach provides the frequency dependent complex pressure response at a given range as a function of depth, and is particularly well suited for adaptation into the MMPE. Usually this approach imposes steady pressure amplitude over the frequency sweep; however, our loading condition requires varying the pressure amplitude over our frequency band of interest. [8] To adequately model the frequency dependence of the complex pressure in the water and bottom, 175 nodes were defined along a vertical line on the surface of the offshore wind turbine support structure. Each node supplies an acoustic pressure between 1 Hz and 1001 Hz with 2 Hz sampling, generating a 175×501 frequency dependent pressure field matrix. Thus, a frequency-specific vertical starting field can be obtained by extracting the pressure at the desired frequency. FIGURE 3 shows examples of the magnitude of pressure field outputs for two selected driving frequencies. Most of the acoustic energy from the support structure is radiated into the water and bottom.

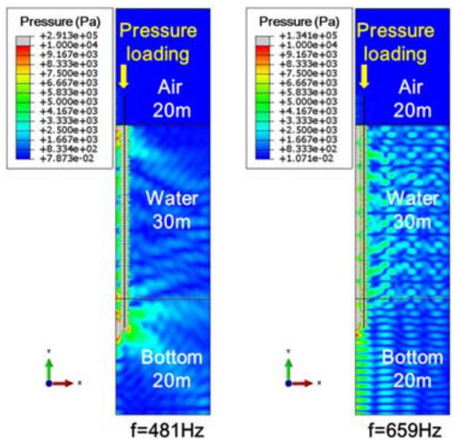


FIGURE 3. Magnitudes of pressure field (Pa) outputs for specific frequencies (481Hz and 659Hz).

To identify dominant frequencies, the mean of the normalized acoustic pressure amplitude on the surface of the structure is calculated by the equation below.

$$\frac{1}{N}\sum_{i=1}^{N}\left|p(z_i,f)\right|, \text{ where, N=175 (number of nodes on the structure in water and bottom)} \tag{1}$$

In FIGURE 4, the mean of the normalized acoustic pressure amplitude is plotted as function of frequency.

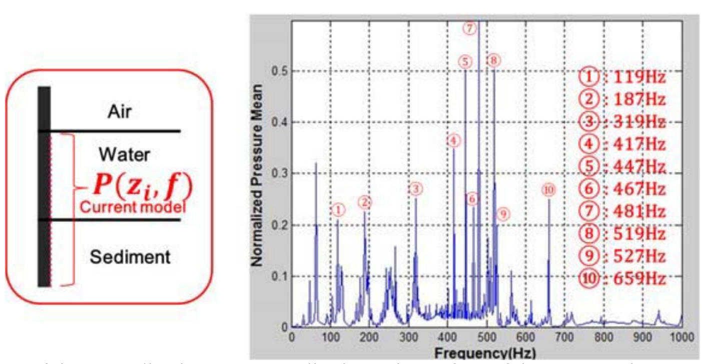


FIGURE 4. Mean of the normalized pressure amplitude on the surface of the structure in water and bottom.

MMPE (Monterey-Miami Parabolic Equation) model

Starting field of the MMPE model

The MMPE model accepts the complex pressure starting field as an initial value problem in depth, and propagates the solution in two acoustic regimes (water, bottom). The numerical domain (vertical extent in depth) is larger than the FE model. Thus it is necessary to interpolate the pressure field results from the FE model to render it suitable for the MMPE model. For our work, the MMPE starting field consists of pressure field gridded into 175 nodes along the depth axis. We used the starting fields of ten most dominant frequencies and this requires a different MMPE model iteration at each frequency. FIGURE 5 shows an example starting field at a frequency of 119 Hz.

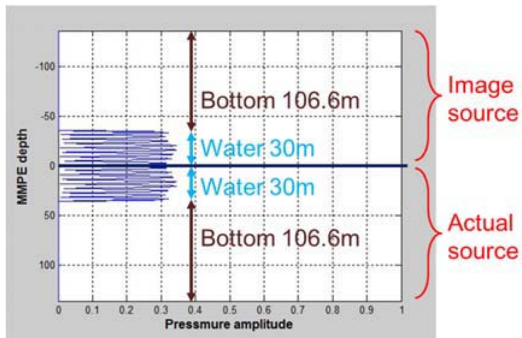


FIGURE 5. Starting field of vertical acoustic pressure amplitude for input into the MMPE model at a frequency of 119Hz.

Results of Coupled FE-MMPE Model

Based on different starting pressure fields at each frequency and using the bathymetry along the tracks OE, ON, and OW as shown in FIGURE 1, transmission loss (TL) in water and bottom were calculated for the ten dominant frequencies between 100Hz and 1000Hz. We ran the MMPE model using the vertical acoustic pressure field at ten dominant frequencies (119Hz, 187Hz, 319Hz, 417Hz, 447Hz, 467Hz, 481Hz, 519Hz, 527Hz, and 659Hz). A few examples of TL outputs along OE are shown in FIGURE 6. Most of the acoustic energy is propagated through the water and some energy penetrates into bottom.

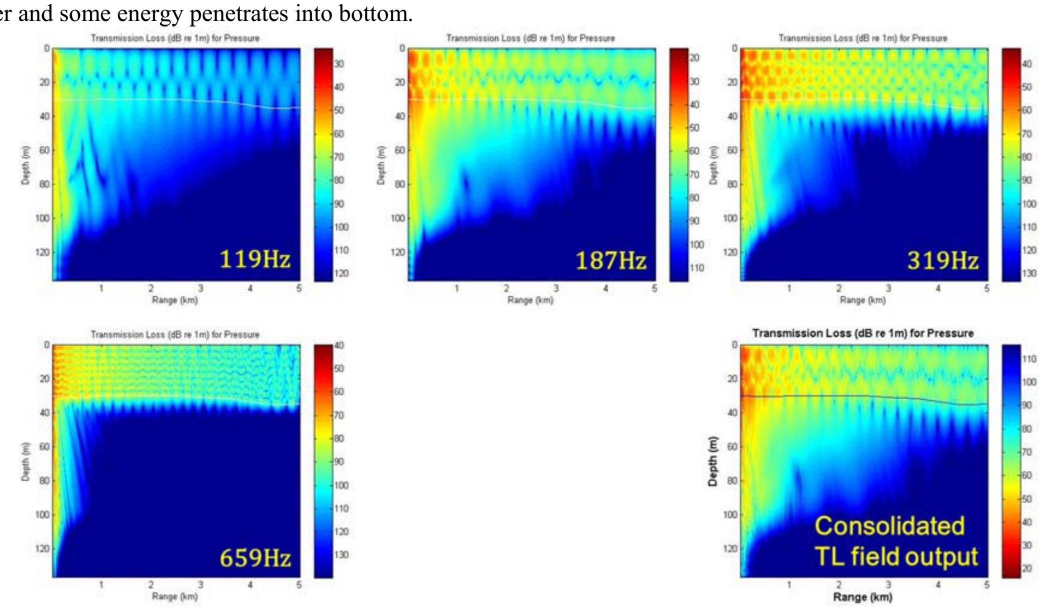
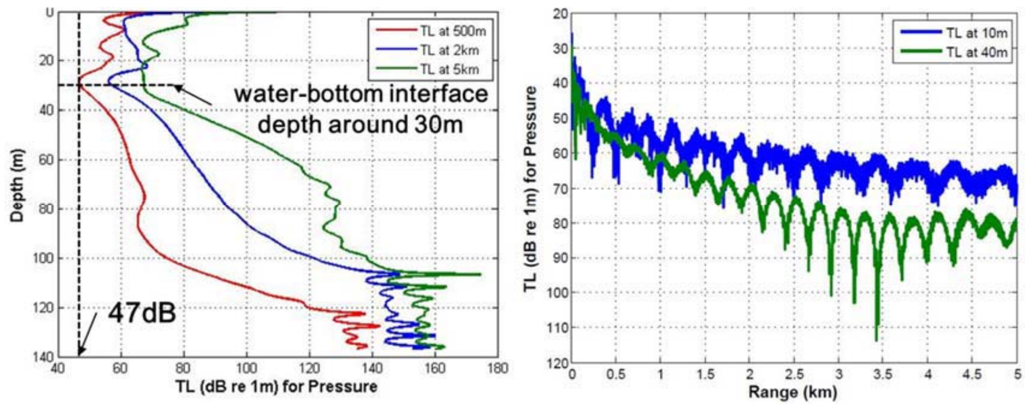


FIGURE 6. MMPE model prediction - TL field output for frequencies (119Hz, 187Hz, 319Hz, 659Hz) and consolidated output.

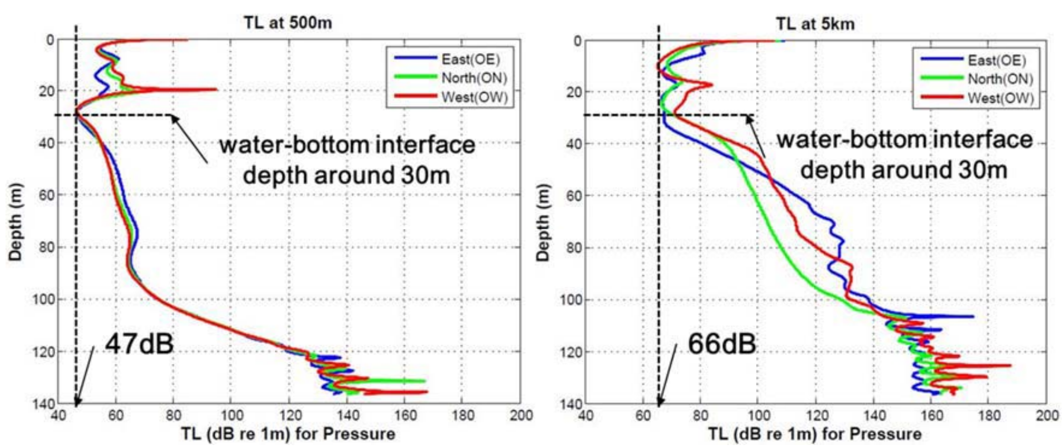
For all examples in FIGURE 6, most of the energy remains in the water column, indicative of trapped modes. To consolidate different frequency runs into a common result, complex pressure output was summed across the frequency band. Extracting total TL as function of depth at three different ranges (FIGURE 7 (a) – red: 500 m, blue: 2 km, green: 5 km), we can observe that TL is increasing with increasing range in the two acoustic media (water and bottom). Attenuation in the bottom causes sound to decay faster than in water. It can be clearly seen from FIGURE 7 that the acoustic wave in the water propagates well and drops 47 dB over a distance of 500 meters. It is also observed that low TL at the depth of 30 m where the water and bottom interface exists. All TL outputs are relative levels compared to a source level at 1m from the offshore wind turbine support structure. TL outputs at specific depths as a function of range were also extracted from the TL matrix at two different depths (blue: 10 m below surface, green: 10 m below the water – bottom interface) are shown in FIGURE 7 (b)



(a) (b)

FIGURE 7. (a) TL as function of depth at three different ranges along OE. (b) TL as function of range at two different depths along OE. The track OE is shown in FIGURE 1.

TL outputs were also compared along OE, ON and OW (FIGURE 8). TL observation at 500m shows good agreement among the results along the three transects as shown in FIGURE 8 (left panel), however, the range dependent characteristics of TL curves at 5km can be observed from FIGURE 8 (right panel) . Finally, the zone of injury can be identified based on the information of source level from offshore pile driving (observed or predicted).



(a) (b)

FIGURE 8. (a) TL as function of depth along OE, ON, and OW at 500m. (b) TL as function of depth along OE, ON, and OW at 5km. The tracks OE, ON, and OW are shown in FIGURE 1.

CONCLUSIONS

We have successfully coupled a finite element model to the MMPE model by incorporating the starting field from the FE model into the MMPE model. This coupled model is advantageous because the FE and MMPE models compliment their strengths. The FE method is ideal for short range calculations of acoustic pressure from a complex structure, but the FE model becomes computationally unsustainable when the size of the model is increased due to the mesh size requirement for longer ranges. In contrast, the MMPE model is ideal for long-range propagation, once a starting field can be adequately defined. Our FE and MMPE analysis shows that the frequency and range dependence is quite important. From our results, we see that pile driving noise propagates quite well in the water medium compared to the bottom. Low TL was observed around the water and bottom interface where many species of animals reside. For practical purposes, we can expect TL levels with inputs of bathymetry off Block Island to be 47dB at 500m and 67 dB at 5 km respectively within the 100 Hz to 1 kHz band. To get more accurate prediction, it is required to model using actual dimension of offshore wind turbine support structure and loading condition.

ACKNOWLEDGMENTS

I would like to acknowledge the financial support of the Link Foundation and the Republic of Korea Navy which enabled me to carry out this work at the University of Rhode Island.

REFERENCES

1. Kim, H., et al., Long range propagation modeling of offshore wind turbine noise using finite element and parabolic equation models. The Journal of the Acoustical Society of America, 2012. 131(4): p. 3392.
2. Huikwan, K., et al. Long range propagation modeling of offshore wind turbine construction noise using Finite Element and Parabolic Equation models. in OCEANS, 2012 - Yeosu. 2012.
3. Reinhall, P.G. and P.H. Dahl, Underwater Mach wave radiation from impact pile driving: Theory and observation. The Journal of the Acoustical Society of America, 2011. 130(3): p. 1209-1216.
4. Reinhall, P.G. and P.H. Dahl. Acoustic radiation from a submerged pile during pile driving. in OCEANS 2010.
5. RI MARINE DATA DOWNLOAD (Physical) from the website: http://www.narrbay.org/physical_data.htm.
6. Environmental Data Center Geospatial Data Analysis Laboratory from the website: http://www.edc.uri.edu/.
7. Deep Water Wind, Block Island Wind Farm from the website: http://dwwind.com/block-island/block-island-project-overview.
8. Smith, K.B., “Convergence, stability, and variability of shallow water acoustic predictions using a split-step Fourier parabolic equation model,” J. Comp. Acoust. 9, 243-285 (2001).
9. Abaqus Analysis User’s Manual 6.3.4 Direct-solution steady-state dynamic analysis, Abaqus 6.11.