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2pUWa13. Modeling of underwater piling noise mitigation using an array of soft spheres in the ocean  

Keunhwa Lee, Kyungmin Baik and Woojae Seong*  

*Corresponding author's address: Dept. of Ocean Eng., Seoul National Univ., Seoul, 151-744, Seoul, Korea, Republic of Korea, wseong@snu.ac.kr

The ocean noise generated by marine piling affects severely fish, other marine life, and fishery activities. Accordingly, a few kind of noise mitigation system are presented. Among them, the noise mitigation system using soft scatterers such as air bubbles or rubber spheres is reported to show higher noise reduction than the classical cofferdam system composed of mass-absorbing materials. In this proceeding, a numerical scheme is developed to model and design the noise mitigation system using an array of soft spheres. This scheme is originally based on self-consistent equation of Zhen Ye for multiple scattering [Z. Ye and A. Alvarez, Phys. Rev. Lett. 80, 3503 (1998)]. We generalize the original self-consistent equation for the oceanic waveguide using the waveguide green function. This generalized self-consistent equation is useful to model the noise propagation through an array of soft spheres in the ocean and assess the ability of the noise mitigation system. The effect of the oceanic waveguide on the noise reduction is studied and the validity of effective medium approach for a bubbly layer is also analyzed numerically.

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INTRODUCTION

The underwater noise generated from the pile driving at the ocean wind turbine construction site belongs to a successively intermittent noise to have the broad bandwidth of 10 Hz to 3 kHz, and its sound exposure level (SEL) is usually higher than the disturbance level of marine mammals of 140 dB re 1 μPa. Thus, a serious threat to marine life and fishery activities is posed by the underwater piling noise, which often causes legal conflicts among stakeholders.

The mitigation of underwater piling noise has been worked by the direct reduction of noise source level or the modification of the noise transmission paths. The former is made from the enhancement of hammer housing system and the latter uses the enclosure and the barrier such as air bubble curtain, encapsulated gas bubble curtain, pile sleeve, and enclosed cofferdam. Among them, it is known that the screen of soft bubble array has the superior cost performance ratio. By previous experimental studies, the bubble screen showed the noise reduction ability of approximately 5 - 20 dB near the bubble resonance frequency.

Some studies have dealt with the underwater noise propagation modeling in the waveguide considering the enclosure or the barrier. In the study of Lee, Wocher, and Wilson, the encapsulated bubble screen is regarded as an effective continuum medium based on Commander and Prosperetti model, and also put to the finite element (FE) model. Reinhall and Dahl considered a Temporary Noise Attenuation Pile (TNAP) consisting of the two pipes, the sound absorbing material, the bubbly water layer, and the appendage. They modeled each element of TNAP to be an effective continuum, and the detailed finite model of the TNAP is applied to the FE model for the acoustic wave propagation.

In this proceeding, we present new simulation study for the low frequency acoustic wave propagation in the waveguide when the noise source is surrounded by the screen of soft spheres. This approach is based on the multiple-scattering formulation of self-consistent form. The original formulation of Foldy and Lax in the free-field is generalized for the oceanic waveguide using a waveguide Green function. The coupled equation can be rigorously solved by the procedure of Ye and Alvarez. The noise reduction screen used in the calculation is assumed to be a cylindrical array of soft spheres (Fig. 1).

FORMULATION

In the free field, a unit point source surrounded by soft spheres radiates the continuous wave with the angular frequency of $\omega$. The sphere radius is $a$ and the void fraction is $\beta = 4\pi a^3 n / 3$ with the numerical density of the bubble of $n$. Then, the scattered wave from the $l$th sphere at the position of $\vec{r}$ can be composed as

$$ p_s(\vec{r}; l) = f_l \left( p_0(\vec{r}) + \sum_{m=1,m\neq l}^N p_s(\vec{r}; m) e^{i|\vec{r} - \vec{r}_l|} \right) $$

(1)

where $f_l$ is the isotropic scattering function of the $l$th sphere, $\vec{r}_l$ is the position vector of the $l$th sphere, and $p_0(\vec{r}) = e^{i\vec{k} \cdot \vec{r}} / r$ with the wavenumber of $\vec{k}$. Here it is assumed that $f_l = a_j / (\omega_{0j}^2 / \omega^2 - 1 - j\delta_j)$ with the sphere radius $a_j$ and the angular resonance frequency of $\omega_{0j}$ and the damping factor of $\delta_j$ for the $l$th sphere.

By observing the hierarchy of Eq. (1), the above equation can be generalized for the waveguide environment as follows.

$$ p_s(\vec{r}; l) = f_l \left( G_0(\vec{r}_0, \vec{r}_l) + \sum_{m=1,m\neq l}^N p_s(\vec{r}; m) G(\vec{r}_l, \vec{r}) \right) $$

(2)

where $G(\vec{r}_l, \vec{r})$ is the waveguide Green function satisfying the Helmholtz equation and the waveguide boundary conditions, and $G_0(\vec{r}_0, \vec{r}_l)$ is the waveguide Green function for the incident wave with the point source position vector of $\vec{r}_0$.

When $p_s(\vec{r}; l) = A_l G(\vec{r}, \vec{r})$ and setting $\vec{r}$ at another scatterer’s position, Eq. (2) is modified as a matrix equation as follows.
where $X_{lm} = \{ f_l G(\vec{r}_m, \vec{r}_i) \ (l \neq m) \} \ or \ -1 \ (l = m) \}$, $Y_i = -f_l G_0(\vec{r}_0, \vec{r}_i)$, and $A$ is a column vector composing of $A_i$.

From Eq. (3), the scattered amplitudes of $A_i$ are calculated, and then the total wave field can be obtained as the sum of the incident wave field and the scattered wave field,

$$p(\vec{r}) = G_0(\vec{r}_0, \vec{r}) + \sum_{i=1}^{N} A_i G(\vec{r}_i, \vec{r})$$

In the above equation, the waveguide Green function is obtained by the combination of the image method and the normal mode method. These methods give the exact solution in the ideal waveguide with the pressure released surface and the hard bottom even for near field.

**FIGURE 1.** Arrangement of soft spheres in the numerical experiment. The circle symbol indicates soft spheres and the asterisk symbol means the position of unit point source.

**FIGURE 2.** Comparison of the noise reduction loss as a function of $ka$ for the free-field, the half-space, and the ideal waveguide. (a) $r = 3.9$ m, (b) $r = 3.9$ km.

**NUMERICAL EXAMPLES**

Numerical experiments are performed respectively in the free field, the half-space, and the ideal waveguide. The water depth of the waveguide is 10 m. This depth is same to that of the wind turbine construction site located in Yellow sea, southwest off Korea Peninsular. The water sound speed is 1500 m/s and the water density is 1000 kg/m$^3$. The unit point source is located at the depth of 5 m below the ocean surface. The cylindrical array of soft sphere has the configuration of the center radius of 1.25 m and the height of 9.23 m. The total number of spheres is 130. All
spheres have same size and are regularly arranged on the surface of transparent cylinder as shown in Fig. 1. The sphere radius is 5 cm and the void fraction is approximately 0.009. The resonant frequency of single sphere is obtained using Minnaert formula\textsuperscript{10}, and then $ka$ at the resonant frequency is 0.0136. The damping factor of the scattering function is set to be 0.01 for all frequencies. Note that the value of damping factor in these examples is arbitrarily chosen since our objective focuses on the observation of the multiple-scattering effect and the waveguide effect. For the realistic modeling of soft sphere, the use of the improved physical models such as Church model\textsuperscript{11} is recommended.

In the present study, the noise reduction loss (NR loss, dB) is defined that NR = SL – TL – Lp, where SL is the source level, TL is the transmission loss of the noise source, and Lp is the sound pressure level (SPL) at the receiver. In all examples, the SL is set to be 0 dB. Fig. 2 shows the noise reduction loss as a function of $ka$. The results of Fig. 2 are respectively measured at the range of 3.9 m and 3.9 km and the depth of 5 m. Here, the noise reduction clearly happens at the range between 0.013 and 0.25 in $ka$. The highest noise reduction occurs that $ka$=0.0158. We note that this critical point can be changed, dependent on the sphere arrangement. Some peaks at the early part of curve are clearly different from the single resonant frequency of sphere. These peaks are the results of the collective motion of spheres and the cutoff phenomenon in the waveguide. In Eq. (2), if we eliminate the multiple-scattering terms and consider only single scattering term, the noise reduction loss gets totally different. Fig. 3 exhibits the result of single scattering approximation at the range of 3.9 m. Compared to Fig. 2, Fig. 3 shows no acoustic localization. The single peak of Fig. 3 is attributed to the single resonant frequency.

![FIGURE 3. Noise reduction loss obtained from single scattering terms as a function of ka.](image)

The regular spikes shown in Fig. 2 (a) occur due to the transition of evanescent mode to propagation mode for increasing the frequency. In the realistic oceanic waveguide, such eccentric trends may be weak due to energy penetration through ocean bottom. In Fig. 2 (b), the noise reduction curves of the free field and the half-space become same while the ideal waveguide case shows more complex fluctuation due to the highly oscillation of horizontal phase term. Also, it is observed that the energy inhabitation occurs below $ka=0.0079$. This frequency coincides with the first cutoff frequency of this waveguide.

![FIGURE 4. Sound pressure level with and without the bubble screen as a function of the range for three frequencies of 75, 150, and 300 Hz. (a) 75 Hz, (b) 150 Hz, (c) 300 Hz.](image)
Fig. 4 plots the sound pressure level in the ideal waveguide for the range at the depth of 5m and three frequencies of 75 Hz, 150 Hz and 300 Hz. At the lower frequency where the acoustic localization occurs, it is clear that the screen of soft sphere reduces the sound pressure level. Moreover, two curves in each figure show the similar interference pattern. This is because the number of propagation modes is few and the interference structure is simple. In case of 300 Hz, the effect of noise reduction is negligible or worse for the range.

**FIGURE 5.** Depth versus sound pressure level with and without bubble screen for three frequencies of 75, 150, and 300 Hz. (a) 75 Hz, (b) 150 Hz, (c) 300 Hz.

Fig. 5 plots the sound pressure level for the depth in the ideal waveguide. In Fig. 5 (a), two curves show same behavior except the amplitude difference in SPL. In this case, only one propagation mode exists. As the frequency increases, the depth-interference pattern of SPL varies gradually and Fig. 5 (c) clearly shows the depth-dependency of the noise reduction loss. At the depth of 1.5 m, the noise reduction loss is approximately 4 dB. But, this ability of the bubble screen disappears at the depth of 3.5 m with the noise reduction loss of -10 dB.

**CONCLUSION**

The self-consistent equation for multiple scattering in the free field is generalized for the oceanic waveguide. The derived equation is used to solve the forward wave propagation in the waveguide for the noise source surrounded by the screen of soft spheres. As the study of Ye and Alvarez in the free field, the acoustic localization also occurs in the waveguide. The positions of the peaks in the NR loss are different in each case of the free field, the half-space and the ideal waveguide, but the highest inhabitation occurs near which $ka = 0.0158$. The value of this magic point is closely related to the use of Minnaert formula. Using other formula of the single resonant frequency such as Church model, this value can be changed. In this acoustic localization region, the multiple-scattering wave from the bubble screen has out-of-phase with the noise source and the acoustic propagation energy is trapped inside the screen. The modeled results show the range and depth dependency of the noise reduction loss. The mode propagation in the waveguide makes the noise reduction curve more dynamic. The proposed scheme is useful to predict the ability of the screen damper of bubbly type and can be applied to the optimization design of the screen damper.

**REFERENCES**


