A STUDY ON PASSIVE SOUND SOURCE DEPTH ESTIMATION BASED ON BROAD-BAND SIGNAL MODELING IN THE DEEP SEA

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1 INTRODUCTION

Studies on estimating underwater sound source localization using acoustic signal characteristics have mainly been conducted in shallow waters. Recently, technologies are being studied to understand the stable and efficient estimation of underwater sound source localization using the underwater sound propagation characteristics of the Reliable Acoustic Path (RAP) in the deep waters. The underwater surveillance technologies in the deep water are known to have the advantages of low variability of detection performance due to time-varying underwater environment (underwater sound speed structure) and a small shadow zone, making it easy to stably detect underwater sound sources and estimate their location even from relatively long distances[1,2]. In this study, we present a study on passive sound source depth estimation based on the broadband signal modelling in the deep water.

2 UNDERWATER SOUND SOURCE DEPTH ESTIMATION TECHNIQUE

2.1 Sound source depth estimation based on broad-band interference pattern

When a receiver exists on the seabed in the deep sea, the direct and sea surface-reflected path are ideally dominated by Lloyd-mirror sound fields because the sound wave transmission loss is lower than that of the seabed-reflected path. The interference pattern by the direct and sea surface-reflected path are periodically modulated according to the sound source frequency, as shown in Fig. 1.

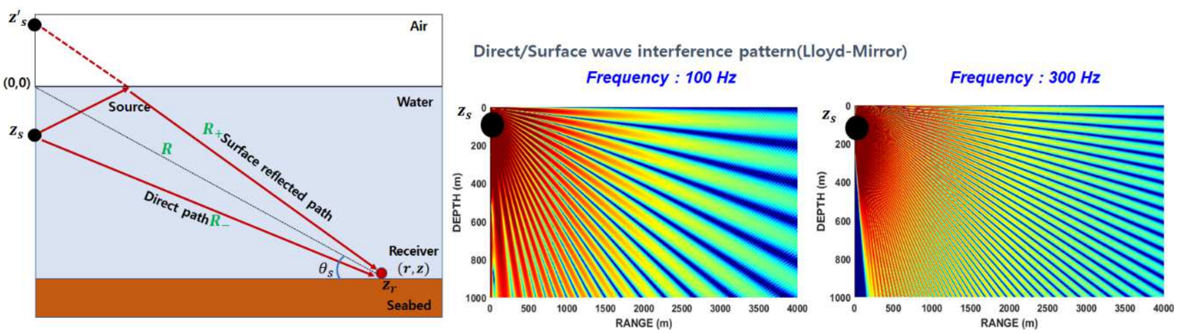

Figure 1. An illustration of direct and surface reflected wave interference pattern (Lloyd-Mirror)

According to the image source theory, the received sound pressure of the direct and sea surface-reflected wave at the receiver is expressed as the following equation (1)[3]

$$P(\mathrm{r,z,w}) = P_1(r,z,w) + P_2(r,z,w) = S(w)\left[\frac{e^{ikR-}}{R-}\gamma\frac{e^{ikR+}}{R+}\right] \quad (1),$$

where $P_1(r,z,w)$ and $P_2(r,z,w)$ are pressure of the the direct and sea surface- reflected wave, the wave number in the environment with sound speed c is given by $k = w/c$, $S(w)$ is the source complex spectral amplitude, and $R-$ and $R+$ are the slant ranges of the direct and surface-reflected paths, respectively. Assuming that the distance between the sound source near the sea surface and the receiver on the seabed is large, such as in deep sea ($z_r \gg z_s$). The phase difference between the direct and sea surface-reflected waves can be expressed by equation (2) when expressed as the signal intensity at the receiver.

$$I \approx 2\frac{|S(w)|^2}{\rho c R^2}\left[1 + cos(\pi + 2kz_s sin\theta_s)\right] \quad (2),$$

the interference pattern of the direct and sea surface-reflected wave acoustic arrivals shows periodic modulation in source depth (z_s), wave-number (k) and vertically arrival angle (θ_s).

2.2 Broad-band signal modeling and received angle (θ_s) estimation

For the broad-band signal modeling in the frequency domain, the spatial transfer function for each frequency was derived using a range-dependent acoustic model (RAM). Then, the source spectrum was multiplied, and an inverse Fourier transform was performed. Therefore, the signal was modeled with the characteristics of the broadband sound source[4].
Various studies are being conducted domestically and internationally to apply acoustic vector quantities such as acoustic particle velocity, acceleration, and displacement measured through acoustic vector sensors. In this study, the vertical arrival angle (θ_s) was derived by assuming a single vector sensor. Acoustic particle velocity can also be calculated from Euler's equation with time. If two pressure sensors are close together, the pressure gradient along the axis of two pressure sensors can be approximated through finite difference approximation[5]. Figure 2 shows the results of broad-band signal modeling and the estimation of the vertical arrival angle (θ_s) at the receiver based on acoustic particle velocities.

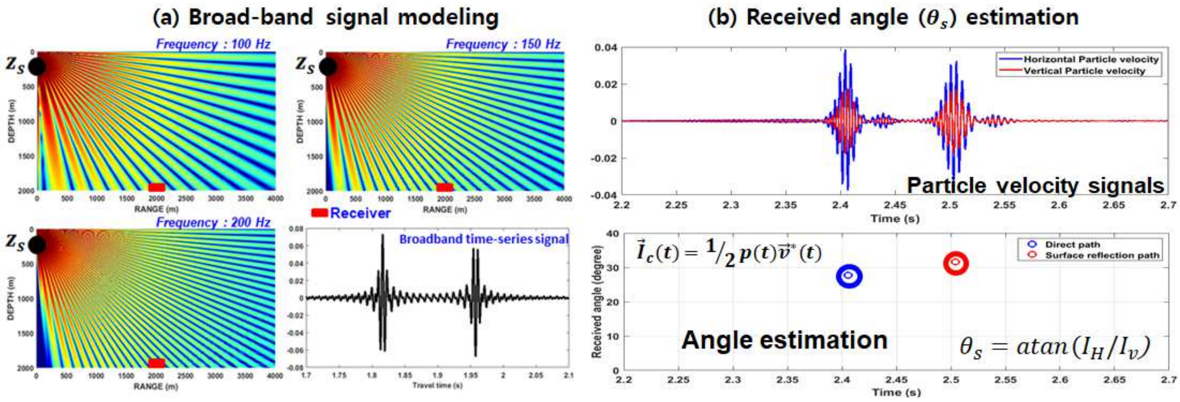

Figure 2. (a) Time series broad-band signal, (b) the received angle estimation

3 PASSIVE SOURCE DEPTH ESTIMATION IN THE DEEP SEA

3.1 Modeling environment

In this study, we utilized CTD (Conductivity, Temperature, and Depth) equipment to measure the seasonal (Spring, Summer, Autumn, and Winter) variation of the sound speed profile in the deep sea region of the East Sea of Korea, with depths exceeding 2,000 m.

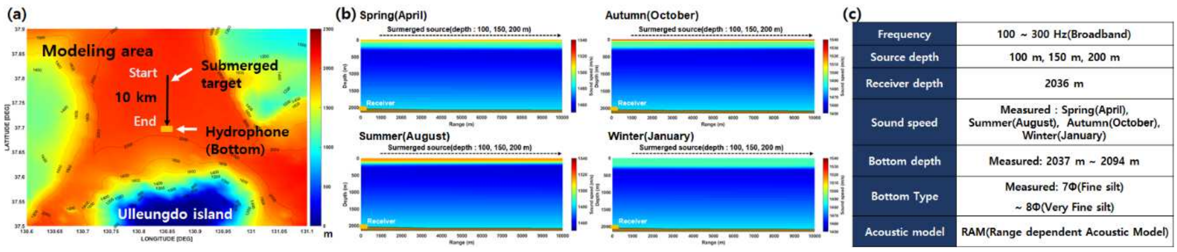

Figure 3. Modeling environment. (a) Target area, (b) environment data, and (c) modeling input parameters

We conducted acoustic modeling and interpreted the low-frequency acoustic transmission characteristics based on these measurements. Additionally, the underwater topography and sediment components between the acoustic source and receivers were utilized as input parameters for acoustic modeling, which information was obtained using a Multi-beam echosounder and a Grab sampler.

3.2 Source depth estimation results

To confirm the depth estimation performance of underwater sound sources with seasons in deep sea areas, the acoustic modeling based on broadband signal modeling was performed. It is assumed that the underwater sound source exists at a depth of 100, 150, and 200 m, and the horizontal distance between the sound source and the vector sensor located on the seabed is 0 to 10 km. The angle of arrival was estimated using a broad-band modeling signal received by a vector sensor located close to the seafloor, and depth estimation modeling of underwater sound sources was performed by applying a broadband interference pattern-based depth estimation technique.

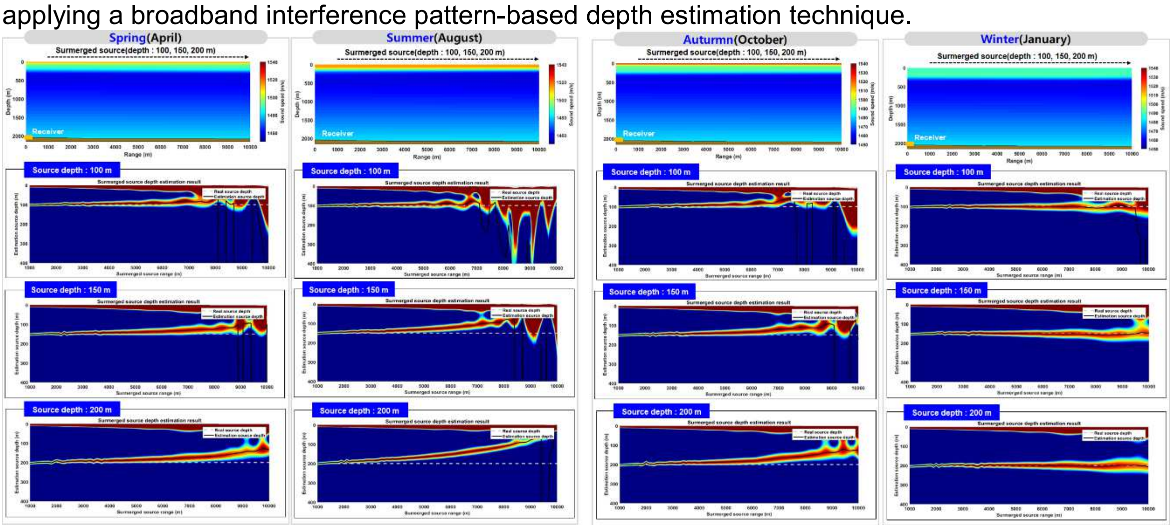

Figure 4. Source depth estimation results in a modeling environment

Figure 4 shows the depth estimation of underwater sound sources based on the characteristics of sound wave transmission according to the sound velocity structure in the Spring (April), Summer (August), Autumn (October), and Winter (January). The solid black line represents the maximum value of the estimated depth for each horizontal distance. In spring (April) and autumn (October), the depth of the sound source estimation results is similar because they have a similar sound velocity structure except for the thickness of the layer depth. However, in summer (August), the effect of sound wave downward refraction near the depth of the sound source was greater due to the high sound velocity of the surface layer. In addition, it can be seen that the broadband interference pattern is irregularly disrupted, leading to a higher depth estimation error as the horizontal distance between the sound source and the receiver increases.

4 SUMMARY AND CONCLUSIONS

In this study, low-frequency broadband signal modeling was performed using actual observations of marine environment data. It verified sound transmission models in the deep sea of the East Sea of Korea (water depth of approximately 2,000 m or more). A study was conducted to derive and characterize underwater sound sources' seasonal depth estimation performance assuming a vector sensor receiver. As a future study, based on this proposed technique and results, we plan to conduct a test of the ocean environment in the deep sea to verify.

5 ACKNOWLEDGMENTS

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