GEOACOUSTIC PARAMETERS INVERSION IN THE SOUTH CHINA SEA USING MODAL DISPERSION CURVES

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Abstract: *This paper presents an inversion scheme that uses two wideband explosive sources based on modal dispersion characteristics to synchronously obtain sound speed profile and bottom parameters. The signal received on a single hydrophone in a vertical line array is decomposed into a series of propagation modes within the framework of normal mode theory, and the dispersive characteristics of the modes are analyzed using time-frequency analysis. Time-warping transform is applied to resolve the propagation modes of explosive sources from the South China Sea in 2007. The relative travel time differences of the propagation modes are used to invert the environmental parameters, including empirical orthogonal function coefficients, sediment thickness, sound speed, density, basement sound speed and density. Sediment density and basement density are constrained by Hamilton's empirical relationship. An adaptive simplex simulated annealing algorithm is used for the inversion. The transmission loss calculated using the deduced parameters matches the experimental data well.*

Keywords: *Geoacoustic inversion, modal dispersion curves, time-frequency analysis*

1. INTRODUCTION

Acoustic propagation in shallow-water areas of the ocean is strongly influenced by environmental parameters [1-6]. Indirect methods for estimating environmental parameters have elicited considerable attention in underwater acoustics because direct measurements are extremely difficult [7-10]. Therefore, an area of considerable interest in ocean acoustics is inverse methods for determining environmental parameters. Geoacoustic inversion estimates ocean environmental parameters, such as water column sound speed profile (SSP) and seafloor parameters, including sediment thickness, sound speed, density, attenuation, basement sound speed, density and attenuation. Recently, several single receiver and single sound source inversion methods have been developed [11-17]. When a wideband acoustic source is used in a shallow waveguide, the acoustic propagation shows dispersion effects [18,19]. High frequencies generally arrive earlier whereas low frequencies, which interact strongly with the bottom and hence are more important in geoacoustic inversion, arrive later. Low and high frequencies both interact with the seabed to the same extent on the scale of wavelengths. The longer wavelengths associated with low frequencies penetrate more deeply into the seabed and hence provide information to greater depths. The group speeds, i.e., the speeds at which energy is transported, differ for different frequencies and modes. Modal dispersion curves of wideband acoustic sources have time delay information of the propagating modes, and energy information can be extracted from modal dispersion analysis.

This study uses the explosive source data from the South China Sea in 2007 to estimate the geoacoustic parameters. As the distance of explosive source increases, the effect on mode travel time caused by the variation of the SSP in the water column also increases. Therefore, the SSP in the water column must be included in the inversion because it has a significant influence on the mode travel time. In this paper, an inversion method based on modal dispersion curves using a single hydrophone with two explosive sources is presented for estimating environmental parameters. This method is roughly divided into two steps. Each frequency of each mode travels at its own speed, and the group speed used in modelling the travel times is independent of attenuation. Therefore, in the first step, the relative modal travel time differences are extracted to invert the environmental parameters, including empirical orthogonal function (EOF) coefficients, sediment thickness, sound speed, density, basement sound speed and density. Considering that the bottom density is not very sensitive to the modal travel time, the sediment density and basement density are constrained by Hamilton’s empirical relationship [20]. In the second step, the parameter values inverted in the first step are used, and the relative energy ratio of two explosive sources is applied to estimate the bottom attenuation.

2. BASIC THEORY

The use of EOFs is a reasonable way to fully parameterize the SSP. EOFs are the basis functions that can be obtained from a measurement database and are efficient in reducing the size of the parameter vector to be estimated. Therefore, SSP inversion is to invert the EOF coefficients.

In a shallow-water waveguide, if a source emits a broadband pulse at depth z_s and time $t = 0$, then the received signal $y(t)$ on a receiver at radial distance r and depth z_r is expressed as $y(t)=\sum_{m=1}^{M} A_m(t)e^{j\phi_m(t)}$, where M is the number of propagation modes, $\phi_m(t)$ represents the time-evolving phase, and $A_m(t)$ represents the instantaneous mode m amplitude. The amplitude is considered a slowly varying function of time (compared with the phase dependence). In an ideal waveguide of depth D in which sound speed is c, the time-evolving phase is defined by $\phi_m(t)=2\pi f_{cm}\left[t^2-(r/c)^2\right]^{1/2}$, where $f_{cm}={mc}/{2D}$ is the cut-off frequency for mode number m. Mathematically, a time-warping transformation is mainly a substitution. Thus, in the case of an ideal waveguide, the warped version $W_h y(t)$ that uses the time-warping function $h(t)=\left[t^2+(r/c)^2\right]^{1/2}$ is given by

$$W_h y(t)=\left[\left|dh(t)/dt\right|\right]^{1/2} y\left[h(t)\right]=\sum_{m=1}^{M}\left[h'(t)\right]^{1/2} A_m\left[h(t)\right]e^{j2\pi f_{cm}t} \tag{1}$$

where $h'(t)$ is the derivative of $h(t)$, Equation (1) shows that the warped signal is a single-frequency signal. It allows us to conduct classical processing (such as filtering) in the time-warping domain, and then return to the initial domain. Time-warping is invertible because the time-warping function $h(t)$ is a bijective function. The inverse function $h^{-1}(t)=\left[t^2-(r/c)^2\right]^{1/2}$ allows the inverse time-warping transform to be defined. Time-warping defined using an ideal waveguide model is a robust transformation. It can be applied to most low-frequency shallow-water scenarios. The choice of r/c is not a critical step [11-13], and it can be determined empirically without knowing r or c. For example, r is the distance between the source and the receiver, and $c=1530$ m/s in the following experiment. In the present study, two explosive sources with the same parameters at distance r_1 and r_2 in a straight line are used to determine the environmental parameters. The group speed $V_g^{(m)}$ of the mth mode satisfies $\frac{1}{V_g^{(m)}}=\frac{dk_m}{d\omega}=\frac{\omega}{k_m}\int_0^{\infty}\frac{\psi_m^2(z)}{\rho(z)c^2(z)}dz$, where ψ_m is the mth mode eigenfunction, k_m is the mth mode eigenvalue, and $\rho(z)$ is the water density at the source depth. Generally, directly measuring the group speed of the normal mode is difficult. However, the relative travel time differences between two wideband explosive sources of different frequencies for the mth mode can be easily derived

$$\Delta T_m(f)=\left[1/V_g^{(m)}(f)-1/V_g^{(m)}(f_H)\right]r_1-\left[1/V_g^{(m)}(f)-1/V_g^{(m)}(f_H)\right]r_2 \tag{2}$$

where f_H is a reference frequency and $f_H>f$. For the same frequency, the relative travel time differences between mode m and mode n of the two wideband signals are given by

$$\Delta T_{mn}(f)=\left[1/V_g^{(m)}(f)-1/V_g^{(n)}(f)\right]r_1-\left[1/V_g^{(m)}(f)-1/V_g^{(n)}(f)\right]r_2 \tag{3}$$

Equations (2) and (3) provide the basis for the inversion by matching the theoretically calculated $\Delta T_m^c(f,G)$ and $\Delta T_{mn}^c(f,G)$ with experimentally derived $\Delta T_m^e(f)$ and $\Delta T_{mn}^e(f)$. Since the influence of the two terms on cost function is different, the relative weighting of the two terms is different. And the inversion is expressed as

$$\left[\hat{G}\right]=\min_{G}\left\{\sum_{m}\sum_{f}\left|\Delta T_{m}^{e}(f)-\Delta T_{m}^{c}(f,G)\right|^{2}+\sum_{m,n(m\neq n)}\sum_{f}\left|\Delta T_{mn}^{e}(f)-\Delta T_{mn}^{c}(f,G)\right|^{2}\right\} \tag{4}$$

where G represents the set of unknown model parameters, $\hat{G}$ is the inversion results. In this study, the parameters are the first three EOFs, which can represent the complete variation of the SSP, sediment sound speed, density, basement sound speed and density. Since sound speeds and densities are commonly correlated parameters in geoacoustic inversion, in this study, sediment density and basement density are constrained by the Hamilton's empirical relationship, which is expressed as

$$c_{ave}=2330.4-1257.0\rho+487.7\rho^{2} \tag{5}$$

where c_{ave} is the average sound speed and ρ is the corresponding density.

3. EXPERIMENTAL VERIFICATION

The experiment was conducted in the South China Sea in September, 2007. A vertical line array (VLA) was placed at 19°26.92′N, 111°44.961′E, and the ship sailed away from the array. The VLA consisted of 32 hydrophones, but only one hydrophone was used for this study. Its depth was 48.3 m. Explosive sources at a detonation depth of 50 m were used in the experiment. The explosive sources and expendable bathythermographs (XBTs), which were used to record water temperature, were deployed at regular time intervals during the experiment. A total of 62 groups of effective XBT data were obtained in this area. Figure 1(a) shows the SSPs of experimental area. The figure indicates that the sound speed fluctuation is large below 20 m. Given the sound speed fluctuation caused by marine mesoscale phenomenon (eg. internal wave and fronts), the average SSP is regarded as an unknown parameter along with the bottom parameters in the inversion. Figure 1(b) shows the first four EOFs, and Fig. 1(c) shows the percentage of energy disturbance for the first 10 EOF coefficients. Figure 1(c) shows that the first three EOF coefficients can represent > 90% of the energy disturbance, so the inversion of the SSP is the inversion of the first three EOF coefficients.

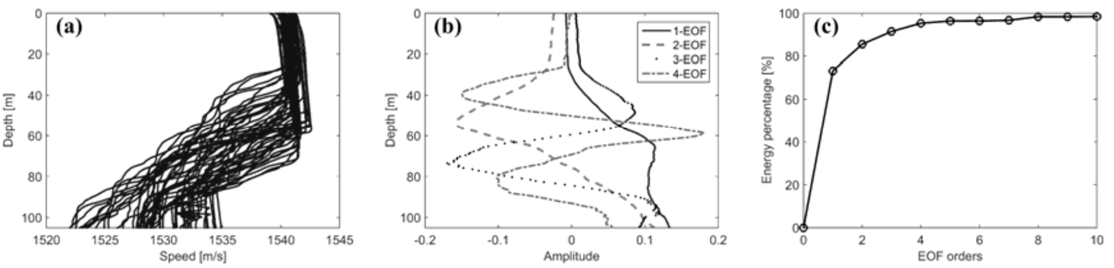

Fig.1: EOFs of the SSPs. (a) SSPs of the experimental area. (b) First four EOFs. (c) Percentage of energy disturbance for first 10 EOF orders.

This study uses two 50 m depth explosive sources at distances of 49.6 km and 63.4 km from the receiver. The two explosive sources had the same parameters. This paper assumes that the two explosions generate the same signal. From the results obtained, there are only small differences in the various inversions, so the impact of small errors in explosion depths is likely very small. Figure 2 shows the time domain waveforms and the time-frequency diagrams of the two signals.

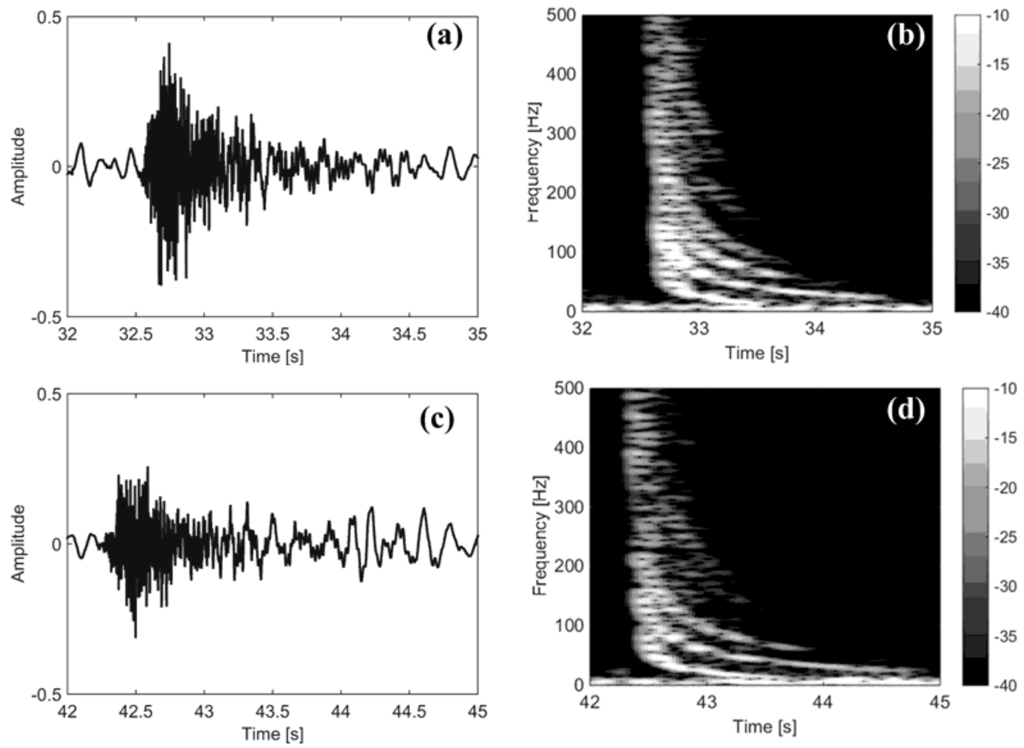

Fig.2: Time domain waveforms and time-frequency diagrams of the received signals. (a) Time domain waveform at 49.6 km. (b) Time-frequency diagram at 49.6 km. (c) Time domain waveform at 63.4 km. (d) Time-frequency diagram at 63.4 km.

The relative mode travel time differences of the low-frequency band are used to invert the first three EOF coefficients, sediment thickness, sound speed, density, basement sound speed and density. The mean water depth along the line is approximately 105 m. The sediment attenuation and basement attenuation are both set to 0.15 dB/λ. The search is carried out by an adaptive simplex simulated annealing (ASSA) algorithm [21] with an objective function defined by Eq. (4). ASSA algorithm combines local (downhill simplex) and global (simulated annealing) methods to exploit the advantages of both methods, thereby achieving efficient optimization without becoming trapped in local minima. Table 1 provides the parameter search bounds and summarizes the results. Since sediment density and basement density are constrained by Hamilton's empirical relationship, these parameters are not searched as unknowns in the inversion.

Parameters	Search bounds	Inversion results	95% HPDI
1-EOF	[-15, 15]	-3.342	[-3.668, -3.024]
2-EOF	[-20, 20]	14.5732	[11.0912, 16.5872]
3-EOF	[-12, 12]	8.121	[7.3257, 9.8777]
d [m]	[0, 20]	13.3965	[9.8729, 15.0527]
c_{sed1} [m/s]	[1500, 1700]	1618.1	[1599.2, 1648.9]
c_{sed2} [m/s]	[1500, 1700]	1631.8	[1603.7, 1652.7]
c_{sub} [m/s]	[1650, 2200]	1697.2	[1633.5, 1855.6]
ρ_{sed} [g/cm^3]		1.7405	

ρ_{sub} [g/cm^3]		1.8907	

Table 1: Search bounds and inversion results of relative travel time differences. 95% *HPDI indicates the interval of minimum width containing 95% of probability.*

Figure 3 shows the comparison of the experimental and theoretical normal mode relative travel time difference results. The calculated relative travel time differences of modes 1, 2, and 4 are consistent with the experimental data for almost all of the frequencies. Small differences are observed between the theoretical travel time differences of mode 3 and the experimental data for frequencies larger than 200 Hz.

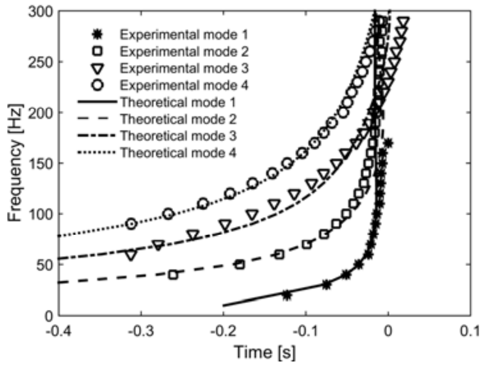

Fig.3: Comparison of experimental and theoretical normal mode travel time differences.

4. CONCLUSION

An inversion method based on modal dispersion curves is developed to estimate the environmental parameters using two explosive sources. This approach can reduce the system error, because it uses the relative travel time differences and the relative energy ratio of two explosive sources. Modal group speeds can be extracted without knowledge of the environment from a single receiver, even when modes are overlapped in time and frequency. Such extraction is carried out using time time-warping. The first three EOF coefficients, sediment thickness, sound speed, density, basement sound speed and density are estimated by matching the relative travel time differences of the propagation modes. It should be pointed out that sediment density and basement density are constrained by Hamilton's empirical relationship in the inversion.

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