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1pUW7. Inversion of seabed acoustic parameters in shallow water using the warping transform

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In this paper, a method is described for inverting geoacoustic parameters of the seabed from short range field data recorded by single hydrophone. The original data in time domain are processed by a warping operator at first, and then the dispersion curve and the mode amplitude ratios are extracted separately from the warped data. The velocity and the density in the bottom are inverted from the dispersion curve, and the attenuation from the mode amplitude ratios, respectively. The performance of the method is examined using simulated data and then experimental data from the North Sea of China. The source used in the experiment was a small explosive charge that provided good signal to noise ratio over the frequency band from 200 Hz to 1 kHz. The depth of the water was about 30m, and the water sound speed was nearly constant with depth. The seabed geoacoustic parameters are inverted from the data received at different ranges from 2 to 14 km. The results from the different ranges are consistent with a simple half space model of the bottom. The seabed velocity is about 1600 m/s.

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Ⅰ. INTRODUCTION

In shallow water, the geoacoustic properties of the seabed have a significant impact on sound propagation, and the inversion of the seabed acoustic parameters has been a serious research focus. Researchers have developed many methods to estimate the sound speed, density and attenuation of the seabed. Some methods try to estimate the seabed acoustic properties as precisely as possible and construct a true picture of the seabed layering and composition, others focus on a simpler effective seabed model that is adequate for predicting the acoustic field. Since the seabed properties have great affects on the pressure field, transmission loss (TL), group speed, mode amplitude ratios, vertical coherence of reverberation etc., the seabed acoustic parameters can be inverted from measurements of these quantities. In this paper, the dispersion of low frequency broadband signal propagation is exploited to invert the geoacoustic model parameters.

The dispersion effect can be observed by time-frequency analysis of the acoustic pressure signal recorded at sufficiently large distance from the source. The dispersion curve can be extracted directly from these time-frequency energy relationships. Time-frequency analysis can be performed using many methods, such as wavelet transform, windowed Fourier transform and so on. The main disadvantage of these methods is the nonlinear relationship of time and frequency of the time-frequency spectrogram, so it is complicated to extract the dispersion curve from them. The technique used here for analysis of non-linear T-F structures is based on the use of warping operators. In time-frequency analysis, warping produces a linear relationship of the time-frequency behavior of the signal, and simplifies extraction of the dispersion curve. There have been many successful applications in the analysis of the underwater signals. Iaona and Quinquis used the warping operator to analyze the signals emitted by marine-mammals[1,2]. Bonnel and Gervais used it to extract the arrival time of different modes at different frequencies and the mode function from the received pressure signal emitted by an air-gun source [3]. Wang and Gao used the invariant based warping operator to remove the dispersion effect from the close range received data [4] [5].

In this paper, a warping operator in the time domain used to process the pressure signal emitted by an explosive charge deployed in shallow water. The dispersion curve and the mode amplitude ratios are extracted from the spectrum of the warped signal, respectively. The former is used to invert the sound speed and density of the seabed, and the attenuation coefficient of the seabed is inverted from the latter.

Ⅱ. THE DISPERSION CURVE AND MODAL AMPLITUDE RATIO IN SHALLOW WATER

In the shallow water waveguide, the propagation at low frequency is described by normal mode theory. For an impulsive source at depth z_s in a range independent waveguide, the pressure received at depth z_r and range r is given by

$$P(\omega, z_r) \approx AS(\omega)\sum_{m=1}^{M}\psi_m(\omega, z_s)\psi_m(\omega, z_r)\frac{e^{jk_m(\omega)r-\beta_m(\omega)r}}{\sqrt{k_m(\omega)r}}, \tag{1}$$

where M is the number of propagating modes, $k_m(\omega)$ is the mth mode horizontal wavenumber, ψ_m is the mode function of the mth mode, β_m is the mth mode attenuation coefficient, which depends on the seabed attenuation. $S(\omega)$ is the spectrum of the source and A is a constant factor.

Just as mentioned above, in a shallow water waveguide, low-frequency broadband propagation exhibits a dispersion effect. The dispersion curve of mode m satisfies

$$t_m(\omega) = \frac{r}{v_g^m(\omega)} , \tag{2}$$

$t_m(\omega)$ is the arrival time of the mth mode, $v_g^m(\omega)$ is the group speed of the mth mode, which satisfies[6]

$$\frac{1}{v_g^m(\omega)}=\frac{\omega}{k_m(\omega)}\int_0^\infty\frac{\rho(z)}{c^2(z)}\left|\psi_m(z)\right|dz. \tag{3}$$

According to (1), the ratio of the amplitude of the mth mode to the amplitude of the first mode can be written as

$$R_{m1}(\omega)=\sqrt{\frac{k_1(\omega)}{k_m(\omega)}}\left|\frac{\psi_m(z_s)\psi_m(z_r)}{\psi_1(z_s)\psi_1(z_r)}\right|e^{(\beta_1-\beta_m)r}. \tag{4}$$

From (2) and (4) it can be seen that both $t_m(\omega)$ and $R_{m1}(\omega)$ include the environment information, so these two quantities can be used in an inversion algorithm. But because $t_m(\omega)$ is not sensitive to the attenuation of the seabed, and $R_{m1}(\omega)$ is more sensitive, so the sound speed and density of the seabed are inverted from $t_m(\omega)$ whereas the attenuation coefficient is inverted from $R_{m1}(\omega)$.

Ⅲ. THE ESTIMATION OF THE DISPERSION CURVE AND MODAL AMPLITUDE RATIOS

In order to estimate the dispersion curve and mode ratios sufficiently well, it is necessary to improve the modal separability in the time-frequency domain. The improvement can be performed using the warping operation. Bonnel and Gao have demonstrated successful separation of the different modes even for close range data, which is difficult to perform using traditional methods.

Suppose the warping function is $h(t)$, after using the warping operation, a signal $y(t)$ will be transformed into a new signal $y_w(t)$

$$y_w(t)=\sqrt{\left|h'(t)\right|}\,y\left[h(t)\right]. \tag{5}$$

The above transformation is invertible and conserves energy between the original and warped signal. Choosing $h(t)$ correctly allows warping to adapt to a given situation. The goal of the transformation is to transform each mode into a pure frequency. For an ideal waveguide consisting of an isovelocity water column between a pressure release upper boundary and a rigid bottom, the below warping function $h(t)$ has the form

$$h(t)=\sqrt{t^2+t_r^2}, \tag{6}$$

where $t_r=r/c_w$, c_w is the sound speed in the water column. Although (6) is defined for an ideal waveguide, it is a robust transformation, and can be applied to most low-frequency shallow-water scenarios.

The relationship between the warped frequency and the original time has the form [2]

$$\omega_w=\omega_0\sqrt{1-\left(t_r/t\right)^2}, \tag{7}$$

where ω_0 is the center frequency of the original signal. From (7), it can be seen that the frequency of the signal has been changed after transformation, and is a function of the time. Similarly, for the impulsive source of a given frequency, the different modes arrive at different time, so after warping transformation, the different modes will have different warped frequency, which is almost equal to the airy frequency. According (7), it is straightforward to get the relationship between the arrival time of the mth mode and the warped frequency ω_w^m corresponding to the mth mode, which follows

$$t_m(\omega)=t_r\Big/\sqrt{1-\left(\omega_w^m/\omega_0\right)^2}. \tag{8}$$

According to (8) the dispersion curve can be extracted directly from the spectrum of the warped signal without the need to go back into the original domain. Thanks to the energy conservation of the warping transformation, the mode ratio also can be extracted from the spectrum of the warped signal.

Figures 1 and 2 describe the simulated result of the dispersion curve and modal amplitude ratio extracted from the spectrum of the warped signal, respectively. The environment model is the Pekeris waveguide. The depth of the water is 30m, the sound speed is 1580m/s, the density is 1.8g/cm^3, the attenuation coefficient is 0.3dB/wavelength. The central frequency of the signal is 500 Hz, the bandwidth of the signal is 397- 630Hz, the receive range is 5 km, the depth of the source and the receiver is 7 m and 29 m respectively.

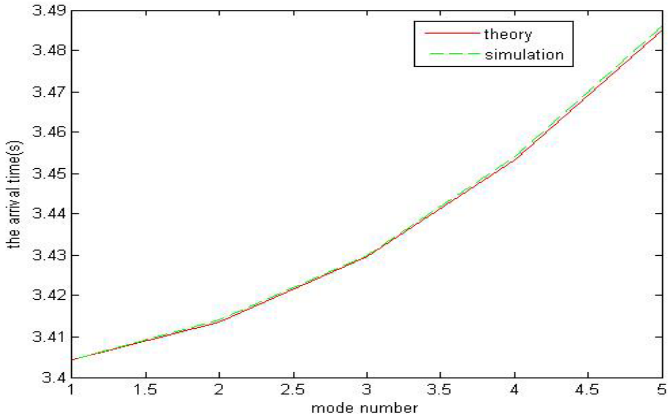

FIGURE 1. The dispersion curve extracted from the spectrum of the warped signal

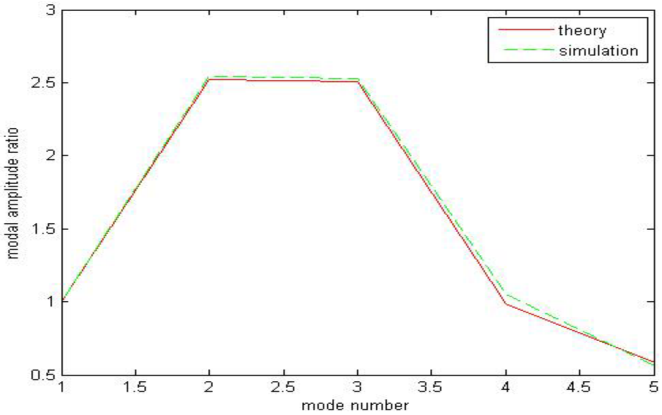

FIGURE 2. The mode amplitude ratio curve extracted from the spectrum of the warped signal

After getting the dispersion curve and mode amplitude ratio, the acoustic parameters of the seabed can be inverted using the classical inversion algorithm. The cost function for the inversion of the sound speed and density is

$$C_v(A)=\sum_{m,n=1}^{M,N}\left[\hat{v}_g^m(\omega_n)-v_g^m(\omega_n,A)\right]^2 . \tag{9}$$

The cost function for the inversion of the attenuation of the seabed is

$$C_r(\beta_\omega)=\sum_{m=1}^{M}\left[\widehat{R}_{m1}(\omega_n)-R_{m1}(\omega_n,\beta_\omega)\right]^2 . \tag{10}$$

In (9) and (10), M is the number of modes, N is the number of the frequencies, vector A is the set of inversion parameters, $\hat{v}_g^m(\omega_n)$ is the estimated group speed from the experimental data, and $v_g^m(\omega_n,A)$ is the calculated group speed according to (3). $\widehat{R}_{m1}(\omega_n)$ is the mode amplitude ratio estimated from the experimental data, and $R_{m1}(\omega_n,\beta_\omega)$ is the calculated mode amplitude ratio. In this paper, $v_g^m(\omega_n,A)$ is calculated according to (2) and (3), $R_{m1}(\omega_n, \beta_\omega)$ is calculated according to (4). The mode function and the wavenumber are calculated by KRAKENC [7].

From the seabed data obtained from the sub-bottom profiling system, there is no obvious sediment layering in this experimental area, so the halfspace seabed model is used in the inversion. The ASSA algorithm [8] is used to minimize (9) and (10).

As above, the inversion procedure can be outlined as follows

(1) Warp the receiving signal $r(t)$
(2) Calculate the spectrum of the warped signal
(3) extract the dispersion curve from the spectrum of the warped signal
(4) Extract the mode amplitude ratios from the spectrum of the warped signal
(5) Invert the sound speed and density of the seabed using the dispersion curve
(6) Using the result of (5) as input, invert the attenuation of the seabed using the mode amplitude ratios.

Ⅳ. INVERSION RESULT FOR THE EXPERIMENT DATA

The experiment was carried out at a site in the north sea of China on 19 Jan. 2002. The depth of the water was about 30 m, the sound speed profile of the water was almost constant at 1475 m/s. The bottom between the source and the receiver was almost the flat. The source was a small impulsive charge and the receiver was a vertical line array of 30 sensors and the interval between the sensors was 1 m. The vertical array was suspended at the side of the research boat.

The data received by the deepest sensor (about 29 m) at 2 km, 5 km, 10 km and 14 km are used in the inversion. Before the warping transformation, a bandpass filter was applied to the original signal, the bandwidth was varied according the receiver range. For the 2 km data a one octave band was used, and for the other ranges a one half octave band was used.

Figures 3 and 4 are the spectrogram of the original signal and the warped signal at 5 km respectively. The white lines on the spectrogram of the original are the dispersion curves extracted from the spectrum of the warped signal.

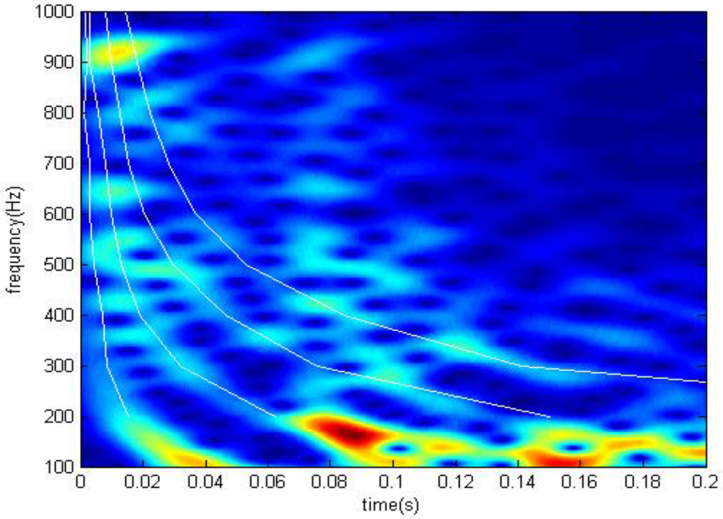

FIGURE 3. The spectrogram of the original signal and the extracted dispersion curve

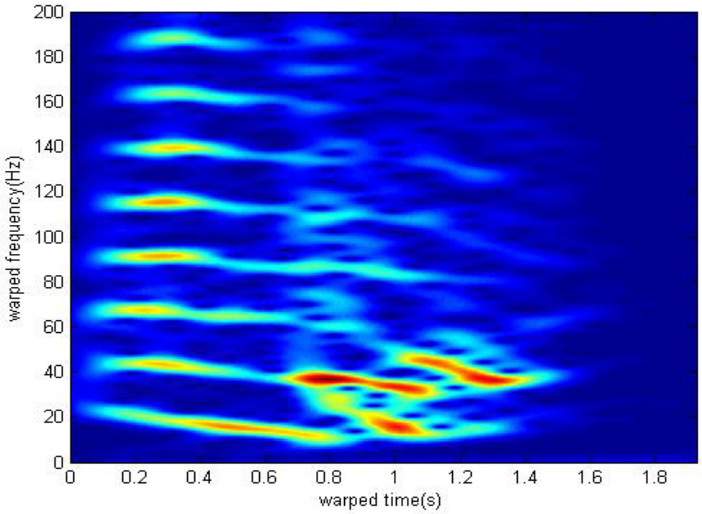

FIGURE 4. The spectrogram of the warped signal

Table 1 lists the search ranges of the model parameters. Table 2 is the inversion result of the sound speed, density and the depth of the water at the different ranges. Table 3 is the inversion result of the attenuation of the seabed at range 14 km.

TABLE 1. The search range of the parameters

Parameter	Unit	Range
Water depth	m	[28 32]
Sound speed	m/s	[1500 1800]
Density	g/cm^3	[1.0 2.0]
Attenuation	dB/ λ	[0.05 2.0]

TABLE 2. The inversion result of the sound speed, density and the depth of the water

Range(km)	Sound speed(m/s)	Density(g/cm^3)	Water depth(m)
2	1620	1.38	30.4
5	1602	1.25	29.7
10	1560	1.05	29.1
14	1588	1.35	28.5

TABLE 3. The inversion result of the attenuation

Frequency(Hz)	200	300	400	500	700
Attenuation(dB/ λ)	0.17	0.35	0.51	0.63	0.77

From the inversion results, it can be seen that the inversion of the sound speed is consistent for the different ranges. The relationship between the attenuation of the seabed and the frequency is not linear, just as most of the researchers have pointed out [9].

Ⅴ. SUMMARY

In this paper, an inversion method for the geocoustic parameters of the seabed is described that exploits the signal dispersion effect in shallow water. The dispersion curve is extracted directly from the spectrum of the warped signal and there is no need to go back into the original domain.

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