Lisheng Zhou · Wen Xu
Qianliu Cheng · Hangfang Zhao *Editors*

水下声学与海洋动力学

——第四届环太平洋国际声学会议论文集

Underwater Acoustics and Ocean Dynamics

Proceedin[illegible]cific Rim Underwater Acoustics Conference

ZHEJIANG UNIVERSITY PRESS
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Preface

The 4th Pacific Rim Underwater Acoustics Conference (PRUAC) was held in Hangzhou, China during 9–11 October 2013. Thanks to all the participants, it turned out to be one of the most exciting conferences around the Pacific focused on the ocean, with the theme "Underwater Acoustics and Ocean Dynamics."

This conference was jointly hosted by Hangzhou Applied Acoustics Research Institute and Zhejiang University. The sponsors also included Acoustical Society of China, Science and Technology on Sonar Laboratory, China, Acoustical Society of America, Canadian Acoustical Association, and Acoustical Society of Korea. The objective of this conference was to provide a forum for active researchers to discuss state-of-the-art developments in underwater acoustics. It brought together scholars, scientists, and engineers from numerous countries to exchange ideas and stimulate future research.

The proceedings is a collection of most of the scientific papers and reviews that were presented at the 4th PRUAC. The volume is composed of 16 presented lectures covering a variety of topics in 3 sessions, including acoustical oceanography, underwater acoustic communication, and vector sensors and target detection. These lectures were made by distinguished researchers from a variety of countries, including the United States, China, Canada, Korea, and Russia.

We extend our sincere gratitude to all the attendees of the conference, with special thanks to the invited speakers, conference committee members, and those who have provided support for the conference and proceedings.

Contents

1 Inference of Sound Attenuation in Marine Sediments from Modal Dispersion in Shallow Water

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Abstract: Attenuation of sound in the seabed plays an important role in predicting transmission loss in shallow water waveguides. Methods to invert the attenuation from low-frequency acoustic field data include time-frequency techniques that make use of modal dispersion. Since modal separation improves as a sound signal that propagates to longer ranges, most of the inversion methods based on modal dispersion were carried out with long range data. Recently a time-warping signal processing technique was introduced that enables high resolution of modes at relatively short ranges. Time-warping involves an axis transformation that transforms the original time-frequency relationship of the modes to a new domain in which the modes are approximately tonal and are well resolved. This paper shows that the inversion can be carried out directly in the time-warped domain, and extends the work to estimate low-frequency seabed attenuation.

Keywords: Geoacoustic inversion; Time-warping transform; Seabed attenuation; Modal dispersion

1.1 Introduction

In shallow water, it is well known that the geoacoustic properties of the seabed have a significant impact on sound propagation at low frequencies (<1 kHz). Inversion methods for estimation of seabed model parameters from acoustic field data have been developed by many researchers, and benchmark exercises to compare the inversion performance have shown that they provide realistic results for the sound speed profile in marine sediments[1]. However, estimation of low-frequency sound attenuation in marine sediments remains a significant experimental challenge.

The most comprehensive summaries of attenuation measurements at low frequencies are due to Holmes and Carey[2] and Zhou et al.[3] who compiled results from many different types of experiments. Inversion methods for attenuation can be divided into three categories according to the type of experimental data that were used in the inversions: (1) modal techniques that use dispersion or wave number analysis to separate propagating modes[4-8], (2) transmission loss (TL) techniques that use TL versus range measurements at multiple frequencies with narrowband or broadband impulsive sources[8], and (3) reflection coefficient techniques that measure the angle-dependent reflection coefficient at different frequencies[9].

Because of the strong dispersion of propagating modes in shallow water, the techniques based on modal dispersion offer significant promise for estimation of seabed attenuation. However, most of the inversion methods based on dispersion phenomena made use of long range data (> ~100 water depths), because modal separation improves with range and the dispersion curve and modal amplitude ratios can be extracted directly by time-frequency analysis of the received signal[6-7]. The disadvantage of using long range data is the impact of the range-dependent environment, including variations of water depth and changes in the type of sediment material.

For close range data, special signal processing techniques known as warping have recently been introduced that enable high resolution of the propagating modes, and there have been many successful applications in the analysis of the underwater signals. Iaona et al. used the warping operator to analyze the signals emitted by marine mammals[10]. Bonnel and Gervais used it to extract the arrival times of different modes at different frequencies and the mode functions from the received pressure signal emitted by an air-gun source[11]. Gao et al. used an invariant-based warping operator to remove the dispersion effect from close-range received data[12].

The warping operation transforms the original signal into a new time and frequency space in which the modes are well-resolved tones. Previous work by Bonnel and Chapman has shown that time-warping of broadband signals in shallow water provides estimates of modal dispersion curves that can be used effectively for inverting sound speed and density in marine sediments[13]. However, the inversion required transforming the resolved modes back into the original time-frequency domain.

This research shows that the inversion can be carried out in the time-warped domain, and extends the initial work to estimate low-frequency seabed attenuation. The group velocities and modal amplitudes that are used in a two-stage inversion are extracted directly from the spectrum of the warped signal. Sound speed and density of the seabed are inverted from the dispersion curve in the first stage, and then the estimated values are used as prior information to invert attenuation from the normalized modal amplitudes. The method is applied to invert attenuation using short range data from an experiment with impulsive broadband sources carried out in the Yellow Sea off the east coast of China.

The paper is organized as follows. The theory of inversion of modal dispersion in the warped domain is briefly reviewed in the next section, and a simulation is carried out to demonstrate the feasibility of the approach. The experiment is described, and the results of the two-stage inversion are presented. The estimated values of attenuation are compared with results from other experiments in the Yellow Sea. The last section summarizes the paper.

1.2 Inversion by Time-Warping

1.2.1 Mode Relationships

The theoretical development of the time-warping transform has been reported previously[13-14] and only an outline of the main points will be given here. In a shallow water waveguide, low-frequency sound propagation is dispersive. The dispersion relationship of mode m satisfies

$$t_m(\omega) = \frac{r}{v_g^m(\omega)} \tag{1.1}$$

where t_m is the arrival time of the component at frequency ω of mode m at range r, and v_g^m is its group velocity. The group velocity is related to the geoacoustic properties of the ocean waveguide by[15]

$$\frac{1}{v_g^m(\omega)} = \frac{\omega}{k_m(\omega)} \int_D^\infty \frac{\rho_b(z)}{c_b^2(z)} |\Psi_m(z)| \mathrm{d}z + \frac{\omega}{k_m(\omega)} \int_0^D \frac{\rho(z)}{c^2} |\Psi_m(z)| \mathrm{d}z \tag{1.2}$$

where k_m and Ψ_m are the horizontal wave number and mode function of mode m, respectively, D is the water depth, ρ_b, ρ and c_b, c are the densities and sound speeds in the ocean bottom and the water, respectively. The normalized amplitude of the *m*th mode can be expressed as

$$A_m(\omega) = 1 \Bigg/ \sqrt{\sum_{n=1}^{M} \left| \frac{\Psi_n(z_s)\Psi_n(z_r)}{\Psi_m(z_s)\Psi_m(z_r)} \right|^2 \left| \frac{k_m}{k_n} \right|^2 \mathrm{e}^{-2(\beta_n - \beta_m)r}} \tag{1.3}$$

where M is the total number of modes, β_m is the mode attenuation that is given by[15]

$$\beta_m = \frac{\omega}{k_m(\omega)} \int_D^{\infty} \frac{\alpha_b(z)}{c_b(z)} \rho_b(z) \left| \Psi_m(z) \right|^2 \mathrm{d}z + \frac{\omega}{k_m(\omega)} \int_0^D \frac{\alpha}{c} \rho \left| \Psi_m(z) \right|^2 \mathrm{d}z \tag{1.4}$$

where α_b and α are the attenuations in the ocean bottom and water, respectively.

From Eq. (1.2), it is clear that the group velocity is sensitive only to the density and sound speed in the bottom, and from Eq. (1.4), the mode attenuation and thus the normalized mode amplitude is sensitive to all three bottom parameters, namely attenuation, sound speed and density. Our inversion is therefore staged in two parts: the sound speed and density of the sediment bottom are obtained first from inversion of the modal group velocity, and then the sound attenuation in the bottom is obtained by inversion of the normalized mode amplitude, using the results of the first inversion as prior knowledge of sound speed and density.

1.2.2 Time-Warping

Application of the time-warping transform follows the development in Refs. [13] and [14]. We assume an ideal waveguide, for which the warping function has the form

$$h(t) = \sqrt{t^2 + t_r^2} \tag{1.5}$$

where $t_r = r/c$, the travel time from the source to the receiver, which is conveniently the travel time of the highest frequency component of the first mode. Although Eq. (1.5) is defined for an ideal waveguide, it is a robust approximation, and can be applied to most low frequency shallow water environments.

The relationship between the warped frequency ω_w and the original time is[10]

$$\omega_w = \omega_0 \sqrt{1-(t/t_r)^2} \tag{1.6}$$

where ω_0 is the center frequency of the original signal. According to Eq. (1.6), the frequency of the signal has been changed after the warping transform, and is a function of time. The relationship between the arrival time of the mth mode $t_m(\omega_0)$ and the warped frequency ω_w^m corresponding to the mode is thus

$$t_m(\omega_0) = t_r / \sqrt{1-(\omega_w^m / \omega_0)^2} \tag{1.7}$$

Substituting Eq. (1.7) into Eq. (1.1), the group velocity can be obtained directly,

$$v_g^m = c\sqrt{1-(\omega_w^m / \omega_0)^2} \tag{1.8}$$

Using Eq. (1.8) the group velocity curve is extracted directly from the spectrum of the warped signal without the need to transform back into the original time-frequency domain. The relationship is exact for an ideal waveguide, and is approximately true for a real waveguide. Since the warping transform conserves energy, the modal amplitude ratios can also be extracted from the spectrum of the warped signal. In the inversion, the modal amplitudes can be normalized over all the resolved modes to generate a more stable cost function that is robust to errors in the amplitude of any single mode[14].

A simulation using the shock pulse of the shot as the sound source was carried out to demonstrate the feasibility of the approach. The centre frequency of the simulated signal was 500 Hz and the band was 397–630 Hz. The model parameters of the Pekeris waveguide environment are shown in Fig. 1.1. The comparison of the calculated group velocities and modal amplitude ratios (calculated using KRAKENC[16]) with those determined from the spectrum of the warped signal is shown in Fig. 1.2. The left panel shows the warped signal spectrum for the centre frequency, the middle panel shows the mode amplitude ratios (with respect to mode 2) and the right panel shows the group velocities. Fig. 1.2 indicates that the estimated values determined from the warped signal spectrum (open circles) agree closely with the expected values for the Pekeris waveguide (closed circles). Note that the modal amplitude ratios are calculated with respect to mode 2.

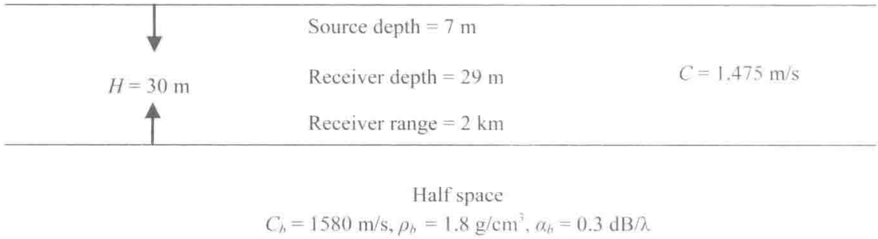


Fig. 1.1 Model parameters of the Pekeris waveguide. H: water depth; C: sound speed; C_b: sound speed in the bottom half space; ρ_b: the density; α_b: the attenuation

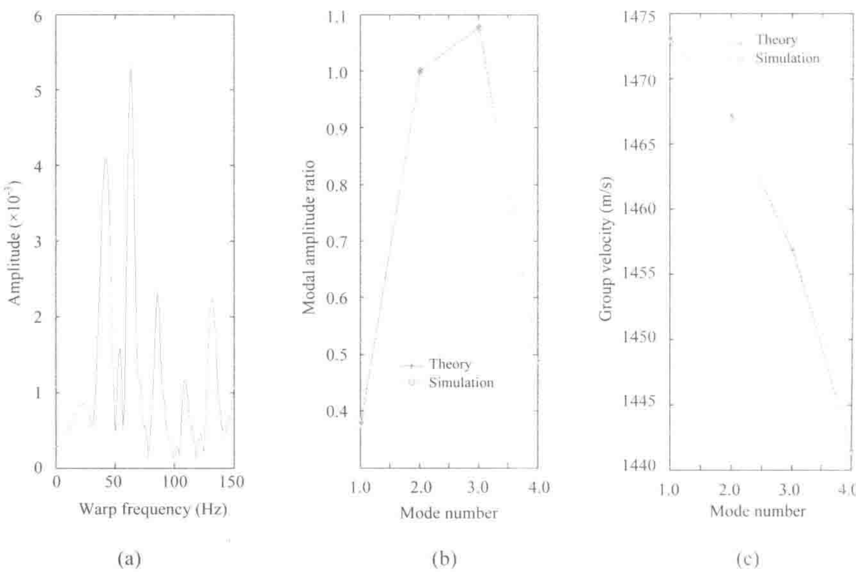


Fig. 1.2 Spectrum of the warped signal (a), modal amplitude ratios (b) and group velocities (c)

1.2.3 Inversion in the Warped Space

With the estimated group velocities and modal amplitude ratios, the inversion can be carried out using standard methods. The cost function for the inversion of the sound speed and density is

$$C_v(\theta) = \sum_{m,n=1}^{M,N} \left[\hat{v}_g^m(\omega_n) - v_g^m(\omega_n, \theta) \right]^2 \tag{1.9}$$

and the cost function for the inversion of sound attenuation in the seabed is

$$C_A(\alpha) = \sum_{m=1}^{M} \left[\hat{A}_m(\omega_n) - A_m(\omega_n, \alpha) \right]^2 \tag{1.10}$$

In Eqs. (1.9) and (1.10), M is the number of modes, N is the number of the frequencies in the broadband sound signal, the vector θ is the set of inversion parameters, $\hat{v}_g^m(\omega_n)$ is the group speed estimated from the experimental data, and $v_g^m(\omega_n, \theta)$ is the calculated group speed according to Eq. (1.2). $\hat{A}_m(\omega_n)$ is the normalized mode amplitude estimated from the experimental data, and $A_m(\omega_n, \alpha)$ is the calculated normalized mode amplitude from Eqs. (1.3) and (1.4). To summarize, the inversion procedure is outlined as follows:

- Time-warp the received signal;
- Calculate the spectrum of the warped signal;
- Extract the group velocity at specific frequencies from the spectrum of the warped signal;
- Extract the mode amplitudes from the spectrum of the warped signal;
- Invert the sound speed and density of the seabed using the measured group velocities over the signal band;
- Using the estimated seabed sound speed and density, invert the attenuation of the seabed using the normalized mode amplitudes.

1.3 Inversion of Sound Attenuation

The inversion is applied to broadband data from an experiment carried out at a site in the Yellow Sea in the winter of 2002. The water depth was about 30 m, the sound speed profile of the water was almost constant at ~1475 m/s, and the ocean bottom between the source and the receiver was essentially range independent. The sound sources were small explosive charges (38g) that were detonated at ~7 m, and the shot signals were received at a vertical line array of 30 sensors with an interval between the sensors of 1 m. The sediment bottom at the site was a mixture of sand-silt-clay.

The data received by the deepest sensor (about 29 m) at a range of 2.1 km were used in the inversion. The spectrogram of the shot signal over the band

100–700 Hz shown in Fig. 1.3 indicates that there is significant intra- and inter-mode interference, and clearly the modes are not well resolved. In addition, the bubble pulse of the charge arrives about 62 ms after the onset of the signal, and contaminates the data at longer time. For this reason, the warping transform was applied to a portion of the signal that was time-windowed at 60 ms.

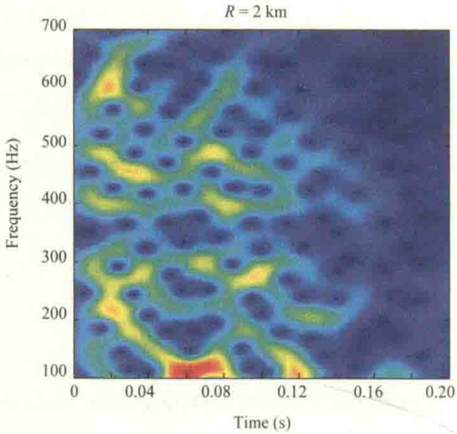
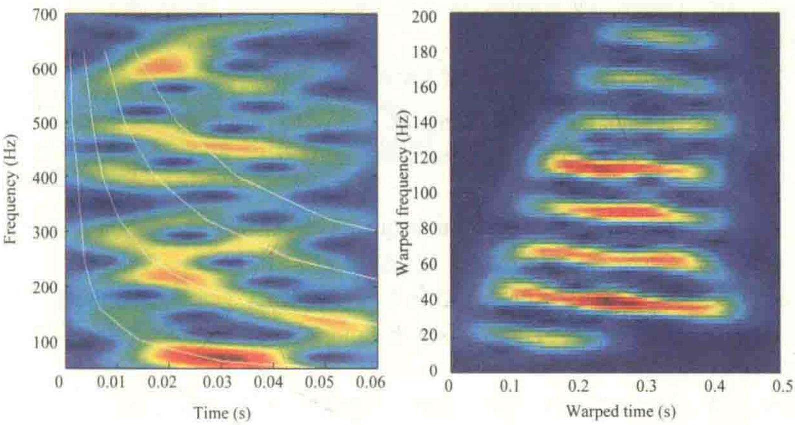


Fig. 1.3 Spectrogram of the 38*g* shot signal received at the deepest array hydrophone at a range of 2 km. The bubble pulse of the charge contaminates the signal after ~60 ms

The spectrograms of the time-windowed signal before and after time-warping are shown in Fig. 1.4. There are eight modes resolved by the warping transform and these were used in the first stage of the inversion to estimate sound speed and density in the bottom sediment. A Pekeris waveguide model was assumed, based on the results of sub-bottom sonar surveys that indicated no significant layering in the sediment in the vicinity of the experimental site. Since the number of unknowns was small, the inversion was cast as a grid search for three unknown model parameters: the water depth, the sound speed and density of the sediment bottom, and all other parameters were assumed to be the values measured in the experiment. The search ranges and estimated values of the unknown parameters are listed in Table 1.1. For the estimated sound speed, the ratio of sediment/water sound speed is 1.07. The curves shown in Fig. 1.4(a) represent the calculated modal arrival time for the first four modes using the estimated model parameters.

Sound attenuation was inverted from Eq. (1.10) over the band 125–500 Hz using the estimated values of sound speed and density from Table 1.1. The inversion was a grid search over the range [0, 1.6] dB/λ with a step size of 0.1 dB/λ. The results listed in Table 1.2 are consistent with a nonlinear frequency dependence of attenuation given by $\alpha(f) = \alpha_0 (f/f_0)^\beta$ with $\alpha_0 = 0.55$ and β = 1.9. These values are slightly higher than those reported previously[3,17]. The significant aspects of our results are: they were obtained using more information from higher order modes at short range (~60 water depths), and thus represent an average over about the first 10 m of sediment below the sea floor. The results from other experiments were obtained from lower order modes (modes 1 and 2), and from very long range data (> 500 water depths)[3,6,7].



(a) (b)

Fig. 1.4 Spectrograms of the time-windowed shot signal in the real time-frequency (a) and warped (b) domains. The curves through the first four modes in the original time-frequency spectrogram are calculated based on the estimated model parameters

Table 1.1 The search range and inverted results of the geoacoustic model parameters

Parameter	Unit	Range	Step	Inverted result
Water depth	m	[28, 32]	0.2	29.7
Sound speed	m/s	[1500, 1800]	5.0	1580.0
Density	g/cm^3	[1.0, 2.2]	0.1	1.7

Table 1.2 Estimates of the seabed attenuation

Frequency (Hz)	125	160	200	250	320	400	500
Attenuation (dB/m)	0.0134	0.0334	0.0352	0.0522	0.0567	0.109	0.174

1.4 Conclusion

This paper presents an application of time-warping for inversion of sound attenuation in marine sediments. The estimated geoacoustic model parameters are consistent with those expected for the sand-silt-clay sediment material, and the attenuation displays nonlinear frequency dependence over the low-frequency band below 500 Hz.

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