Localization of marine seismic vibrator via hyperbolic Radon transform

双曲型ラドン変換を用いたマリンセイスミックバイブレータの定位

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概要：音波を用いた海底資源探査では，海底下の層の間で反射または屈折された音波から海底下の構造を推定する．観測された音波から海底下の構造を推定するためには，音源位置および音速の情報が必要である．探査に用いる音源の一つであるマリンセイスミックバイブレータには，周波数や位相の制御性が高く，高深度で音波を発振できるなどの利点がある．しかし，音源位置が海面から遠い場合，正確な位置を特定することが困難になる．本研究では，音源位置と音速を推定する問題を双曲線ラドン変換を用いて最大化問題として定式化することにより，観測された信号から推定する手法を提案する．シミュレーションにより，推定誤差が理論上の下限をほぼ達成することを確認した．

キーワード：海洋地震探査，音源定位，クラメル・ラオの下限

Keywords: marine seismic survey, sound source localization, Cramér-Rao lower bound

1. Introduction

For exploring seafloor resources, seismic surveys using sound waves are performed. In the surveys, sound waves are emitted from a seismic sound source, and receivers obtain returned waves which are reflected or refracted between the layers below the seafloor. Then, the structure below the seafloor is estimated from the obtained data based on positional relations between the sound source and receivers, and sound speed.

Recently, marine seismic vibrators (MSV) [1], which can control frequency and phase of sound with high reproducibility, are studied as another marine seismic source. MSV can oscillate at the position closer to the seafloor since MSV can adjust an internal pressure to sea water pressures, which can reduce attenuation of sound waves due to propagations between the sound source and the seafloor. However, as the MSV position is deeper and more far from the sea surface, it is more difficult to specify the exact position.

In this paper, a method to estimate the position of MSV and the sound speed from obtained marine seismic data of receivers is proposed [2]. The effectiveness was confirmed by applying the proposed method to simulated data.

2. Problem establishment

Let us assume that the MSV and receivers are disposed as shown in Fig. 1, and sound waves are propagated with the constant speed c. When sound waves oscillated from the MSV are assumed to be spherical waves, travel times of direct waves from the MSV to m-th receivers are formulated by

$$t(h_m, \boldsymbol{\theta}) = p\sqrt{(s_{\xi_1} - h_m)^2 + s_{\xi_2}^2}, \qquad (1)$$

where $\mathbf{s} = [s_{\xi_1}\ s_{\xi_2}]^T$ is the position of MSV, h_m is the horizontal position of m-th receivers (the vertical positions of receivers are assumed to be zero), p is the slowness (reciprocals of the sound speed c), $\boldsymbol{\theta} = [\mathbf{s}^T\ p]^T$ is the parameter to be estimated, and A^T denotes the transpose of A.

3. Proposed method

I propose a method to estimate the parameter $\boldsymbol{\theta}$ via hyperbolic Radon transform. Let $d(t, \xi_1)$ be the deconvoluted data obtained from the receiver at horizontal

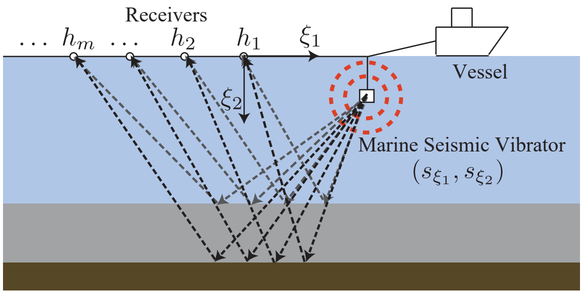

Fig. 1 The positional relationship of MSV and receivers.

position ξ_1. The hyperbolic Radon transform $\mathcal{R}$, which maps the data $d(t, \xi_1)$ to $(\mathcal{R}d)(\boldsymbol{\theta})$, is formulated by

$$(\mathcal{R}d)(\boldsymbol{\theta}) = \int_{h_M}^{h_1} d\Big(t(\xi_1, \boldsymbol{\theta}), \xi_1\Big)\, d\xi_1. \qquad (2)$$

When the data are obtained from M channel receivers, Eq. (2) is approximated by

$$(\mathcal{R}d)(\boldsymbol{\theta}) \simeq (Rd)(\boldsymbol{\theta}) = \sum_{m=1}^{M} d_m\Big(t(h_m, \boldsymbol{\theta})\Big), \qquad (3)$$

where $d_m(t) = d(t, h_m)$ is the deconvoluted data obtained from m-th receiver.

When the parameter $\boldsymbol{\theta}$ is close to the true parameter, the value $(Rd)(\boldsymbol{\theta})$ becomes large. Therefore, the estimation problem of a proper parameter $\hat{\boldsymbol{\theta}}$ is formulated as solving the following maximization problem:

$$\hat{\boldsymbol{\theta}} \in \arg\max_{\boldsymbol{\theta}}\ (Rd)(\boldsymbol{\theta}). \qquad (4)$$

In order to calculated $(Rd)(\boldsymbol{\theta})$ from the discrete signals, the reconstruction of the continuous signal from the discrete signal by the interpolation is performed. Signal interpolation by the spherical Bessel function denoted by $j_\nu(t)$ is used in the proposed method.

A continuous signal $d_m(t)$ reconstructed from a discrete signal bandlimited to the Nyquist frequency is formulated by

$$d_m(t) \simeq \mathbf{d}_m^T \mathbf{j}_0(t), \qquad (5)$$

where $\mathbf{j}_\nu(t) = \big[j_\nu(\pi f_s t)\ \dots\ j_\nu\big(\pi(f_s t - N + 1)\big)\big]^T$, $\mathbf{d}_m =$

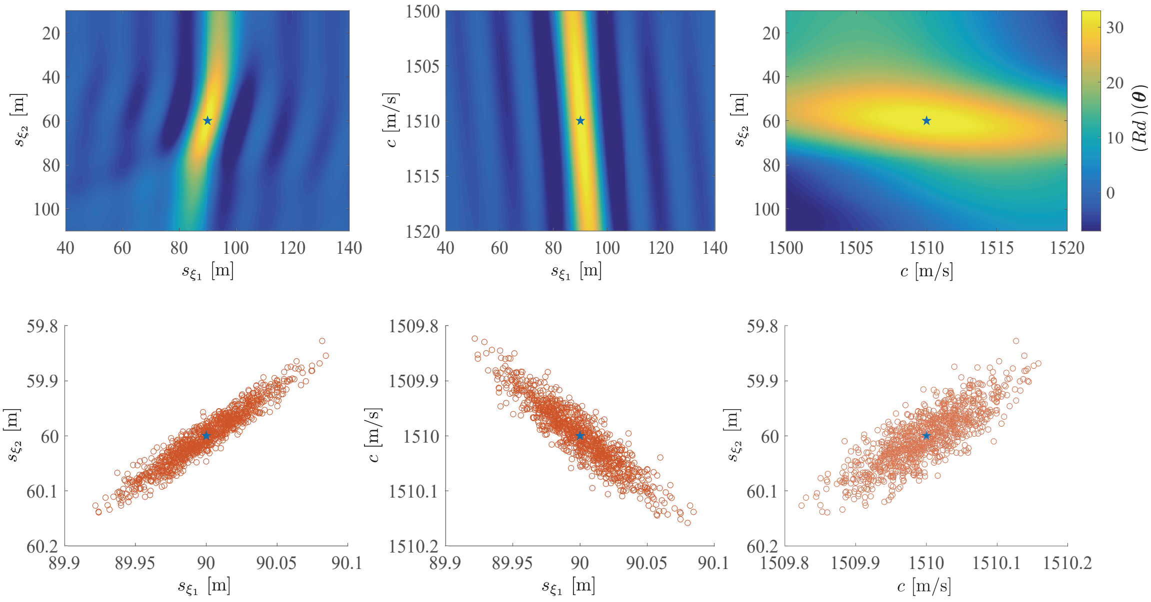

Fig. 2 (top) Value $(Rd)(\boldsymbol{\theta})$, (bottom) distributions of the estimated parameter for each plane (★: target, ○: estimated).

Table 1 Simulation setting.

Number of receivers M	100
Interval of receivers [m]	12.5
Target estimation parameter	$[90\ 60\ 1510]^T$
Recording time [s]	7.0
Sampling rate f_s [Hz]	1000
Output signal	linear chirp (10–100 Hz)
Length of signal [s]	4.0
$\mathrm{SNR}_{\mathrm{signal}}$ [dB]	$-20, -15, \ldots, 50$
Number of trials	1000 for each $\mathrm{SNR}_{\mathrm{signal}}$

$\left[d_m(0) \ldots d_m\big((N-1)/f_s\big)\right]^T$ and f_s is the sampling frequency. When Eq. (5) is substituted into Eq. (3), $(Rd)(\boldsymbol{\theta})$ becomes

$$(Rd)(\boldsymbol{\theta}) = \mathbf{d}^T \boldsymbol{\jmath}_0(\boldsymbol{\theta}), \qquad (6)$$

where $\boldsymbol{\jmath}_\nu(\boldsymbol{\theta}) = \left[\mathbf{j}_\nu\big(t(h_1,\boldsymbol{\theta})\big)^T \ldots \mathbf{j}_\nu\big(t(h_M,\boldsymbol{\theta})\big)^T\right]^T$, $\mathbf{d} = [\mathbf{d}_1^T \ldots \mathbf{d}_M^T]^T$. Therefore, $(Rd)(\boldsymbol{\theta})$ can be calculated from the discrete data using Eq. (6).

In the proposed method, Eq. (4) is solved by the gradient based optimization method using the gradient calculated from Eq. (6). The gradient of $(Rd)(\boldsymbol{\theta})$ is can be culculated from Eq. (6).

4. Experiments

To confirm the effectiveness of the proposed method, it was applied to simulated data. The root mean square error (RMSE) of estimations was calculated and compared with the Cramér-Rao lower bound (CRLB).

The simulation setting is shown in Table 1. Signal to noise ratio (SNR) of received signals was defined by

$$\mathrm{SNR}_{\mathrm{signal}} = 10 \log_{10} \frac{\sum_{m=1}^{M} \|\mathbf{x}_m\|^2}{\sum_{m=1}^{M} \|\mathbf{w}_m\|^2}, \qquad (7)$$

where $\mathbf{x}_m$ is the data obtained from m-th receiver with no noise, $\mathbf{w}_m$ is additive white Gaussian noise with variance σ^2, and $\|\cdot\|$ is the Euclidean norm. Value $(Rd)(\boldsymbol{\theta})$ calculated by Eq. (6) and distributions of the estimated parameter of each plane when SNR is 0 dB is shown in Fig. 2. The RMSE of estimated parameter $\hat{\boldsymbol{\theta}}$ and the CRLB for each SNR is shown in Fig. 3. It is confirmed that the proposed method is unbiased, and almost achieved theoretical lower bounds for the variances of the estimations.

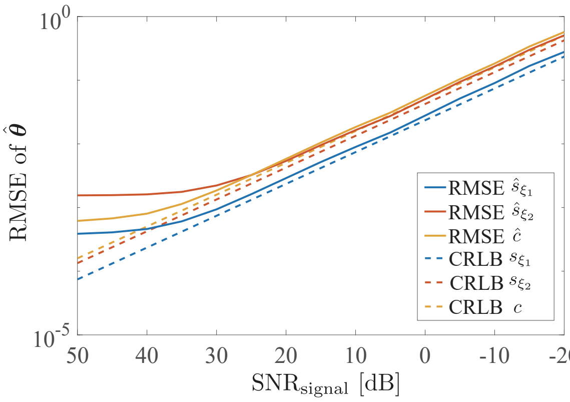

Fig. 3 RMSE of estimated parameter $\hat{\boldsymbol{\theta}}$ versus SNR of obtained signals. Each color represents elements of parameter vector. The solid lines indicate the RMSE of the estimations, and the dashed lines indicate the CRLB.

5. Conclusion

In this paper, the sound source localization method from obtained seismic data via hyperbolic Radon transform was proposed. The proposed method is applied to simulation data, and its estimation accuracy was shown. Future works include reductions of initial value dependence of the estimation method.

References

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