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Localization of random acoustic sources in an inhomogeneous medium

Shahram Khazaie*, Xun Wang, Pierre Sagaut

Aix Marseille Univ, CNRS, Centrale Marseille, M2P2, 13451 Marseille Cedex 13, France

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ABSTRACT

In this paper, the localization of a random sound source via different source localization methods is considered, the emphasis being put on the robustness and the accuracy of classical methods in the presence of uncertainties. The sound source position is described by a random variable and the sound propagation medium is assumed to have spatially varying parameters with known values. Two approaches are used for the source identification: time reversal and beamforming. The probability density functions of the random source position are estimated using both methods. The focal spot resolutions of the time reversal estimates are also evaluated. In the numerical simulations, two media with different correlation lengths are investigated to account for two different scattering regimes: one has a correlation length relatively larger than the wavelength and the other has a correlation length comparable to the wavelength. The results show that the required sound propagation time and source estimation robustness highly depend on the ratio between the correlation length and the wavelength. It is observed that source identification methods have different robustness in the presence of uncertainties. Advantages and weaknesses of each method are discussed.

1. Introduction

Sound source estimation using recorded signals by various active or passive sensors is one of the main problems in acoustical engineering, oceanic engineering and seismology. Modeling the wave propagation requires the knowledge about the properties of the propagation medium along with the source parameters. The spatial variation of the medium properties is one of the main factors which plays an important role on the applicability of the localization method. In elastic media for instance, geological processes, experimental observations, and well log data are among the direct evidences of the existence of spatial variations [1,2]. In ocean acoustics, the sound propagation speed varies with depth, pressure, salinity and temperature [3]. Typical sound speed profiles show drastic variations especially near the sea surface. Hence, the environmental parameters are spatially varying and only their statistical information might be provided [4]. Another source of uncertainty comes from the randomness of the source position. In acoustics, Grosveld [5] investigated the acceleration response and noise reduction of plates which are excited by random acoustic sources. In seismology, Husen et al. [6] combined a probabilistic earthquake location and a 3D velocity model to more precisely identify the hypocenter location. In this

* Corresponding author.
E-mail addresses: shahram.khazaie@univ-amu.fr (S. Khazaie), xun.wang@univ-amu.fr (X. Wang), pierre.sagaut@univ-amu.fr (P. Sagaut).

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presentation, spatial variations of the medium properties are taken into account using a single realization of a random function of space. The source position is modeled via a random variable.

A comprehensive review of the source localization techniques along with the advantages and drawbacks of each method is introduced in [7]. Classical beamforming [8–10] and Near-field acoustical holography (NAH) [11–13] are two approaches dedicated to the source localization problem, which assume that the medium is homogeneous, i.e., Green's function of wave equation has an analytical solution. NAH back-propagates the acoustic field in the wavenumber domain from the measurement plane to the source plane. This approach has a high spatial resolution for source identification but works only for near-field source. The beamforming method estimates the sound source location via the delay of signal arrival measured by the microphones. As already mentioned, in many real applications such as in geophysical media or ocean environments, the homogeneous assumption does not hold and would cause large errors in the source localization result. In heterogeneous media, however, the wave equation has no analytical solution so that the sound propagation process has to be numerically simulated. To this end, a variant of the classical beamforming is employed to estimate the sound source, in which the closed form of Green's function is replaced by a numerical version. Another source localization method in the time domain that is frequently used in both acoustic and elastic media is time reversal [14–19]. It is based on the symmetric nature of the wave equation with respect to the time variable in non-dissipative media. The received sound waves are reversed in time and reinjected into the same medium to refocus on the initial source location within a resolution. An experimental comparison between time reversal and beamforming methods has been recently done in aeroacoustics [20]. Mimani et al. [21] introduced an improved version of time reversal in aeroacoustics and made the same comparison. One of the main differences between our work and the last two cited papers lies on the fact that we consider a randomly heterogeneous propagation medium and we discuss the influence of two different scattering regimes.

In this paper, the localization of random sound source propagating through randomly-generated inhomogeneous media is discussed. The emphasis is put on the robustness of the methods and the number of samples required to get a converged solution of random sound source. The sound source location is chosen randomly following a given probability distribution. Each realization of the random sound source emits the sound waves and the generated wave field is measured by a linear array of microphones. Then, the source location is estimated via beamforming and time reversal methods. The estimates of both approaches reconstruct the probability density functions (PDF) of the random sound source position and a comparison between the results is done. The present analysis has relevance to nondestructive testing of materials, structural health monitoring, ultrasonic medical imaging and underwater communication, among others. In all these applications, one can consider the random nature of the source position with an aim of identifying the propagation of the initial uncertainty on the direct and then on the source localization problem.

The organization of this paper is as follows. Section 2 begins with a description of the proposed model. In particular, the inhomogeneous medium and random source are explicitly introduced. Then, in Section 3, the source localization methods used in this paper (time reversal and beamforming) are presented and compared. In Section 4, numerical simulations are presented, in which two media with different correlation lengths are investigated. The estimation efficiency of the sound source using the proposed approaches is justified. Finally, Section 5 concludes the paper.

2. Acoustic wave propagation in randomly inhomogeneous media with randomly-generated source position

The acoustic wave equation for the pressure and velocity fields (p and $\mathbf{v}$, respectively) propagating in a non-dissipative medium is considered as:

$$\rho(\mathbf{x})\frac{\partial \mathbf{v}(\mathbf{x},t)}{\partial t}+\nabla p(\mathbf{x},t)=\mathbf{0}, \tag{1a}$$

$$\frac{1}{\kappa(\mathbf{x})}\frac{\partial p(\mathbf{x},t)}{\partial t}+\nabla\cdot\mathbf{v}(\mathbf{x},t)=0, \tag{1b}$$

in which $\rho(\mathbf{x})$ and $\kappa(\mathbf{x})$ are, respectively, the local density and bulk modulus of the heterogeneous medium, and $\mathbf{x}=(x,y)$ stands for the 2D spatial coordinate. The local angular frequency and the wavenumber are related via the dispersion equation $\omega(\mathbf{x})=c(\mathbf{x})|\mathbf{k}|$, in which $c(\mathbf{x})=\sqrt{\kappa(\mathbf{x})/\rho(\mathbf{x})}$ is the local velocity of propagation. The corresponding wave equation for the velocity potential field $\Phi_{\mathbf{v}}$ reads

$$\left[\Delta-\frac{1}{c^2(\mathbf{x})}\partial_t^2\right]\Phi_{\mathbf{v}}(\mathbf{x},t)=S(\mathbf{x}_0,t), \quad (\mathbf{x},\mathbf{x}_0,t)\in\mathbb{R}^2\times\mathbb{R}^2\times\mathbb{R}^+, \tag{2}$$

in which the term $S(\mathbf{x}_0,t)$ represents the acoustic source. Note that the velocity field $\mathbf{v}$ and its potential $\Phi_{\mathbf{v}}$ are related via $\mathbf{v}=\nabla\Phi_{\mathbf{v}}$. The experimental estimation of the medium parameters, i.e., $\kappa(\mathbf{x})$ and $\rho(\mathbf{x})$, is highly limited and in general can be done locally on some limited points. The source parameters such as position $\mathbf{x}_0=(x_0,y_0)$ and amplitude are also *a priori* unknown and are often considered as the parameters to be identified. In this paper, the medium properties are considered as a single realization of a sufficiently large (compared to the wavelength) randomly heterogeneous medium and the source position is modeled using a random variable. In the next two sections we will deal with the probabilistic description of the medium and source parameters.

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