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Acousto-optic back-projection: Physical-model-based sound field reconstruction from optical projections

Kohei Yatabe*, Kenji Ishikawa, Yasuhiro Oikawa

Department of Intermedia Art and Science, Waseda University, 3-4-1 Ohkubo, Shinjuku-ku, Tokyo 169-8555, Japan

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ABSTRACT

As an alternative to microphones, optical techniques have been studied for measuring a sound field. They enable contactless and non-invasive acoustical observation by detecting density variation of medium caused by sound. Although they have important advantages comparing to microphones, they also have some disadvantages. Since sound affects light at every points on the optical path, the optical methods observe an acoustical quantity as spatial integration. Therefore, point-wise information of a sound field cannot be obtained directly. Ordinarily, the computed tomography (CT) method has been applied for reconstructing a sound field from optically measured data. However, the observation process of the optical methods have not been considered explicitly, which limits the accuracy of the reconstruction. In this paper, a physical-model-based sound field reconstruction method is proposed. It explicitly formulates the physical observation process so that a model mismatch of the conventional methods is eliminated.

1. Introduction

For measuring sound in air, microphones are commonly used as the sensors. Highly developed measurement microphones can measure the sound pressure quite accurately when the type of the sound field (pressure-, free- or diffuse-field) is known. However, every microphone has essential difficulties in measuring the exact acoustical quantity owing to the existence of the microphone inside the field. Since a microphone's body inside the sound field causes extra reflection and diffraction, the measured quantity is contaminated by them when the size of the microphone is relatively large comparing to the wavelength of the sound. In fact, a 1/2-inch microphone can have measurement error more than 10 dB at 20 kHz due to the reflection and diffraction [1]. Such measurement error increases when the number of microphones increases, which might be problematic for a many-channel microphone array [2]. The only way of avoiding this physical limitation is to make the size of the microphone infinitesimally small.

As a powerful alternative to microphones, the optical measurement methods have been studied [3–27]. The basic principle of the optical methods is to detect the refractive index of medium which reflects density variation caused by sound[1]. Since light does not affect behavior of sound, these methods can measure a sound field without any physical disturbance. Therefore, the measurement error caused by the existence of equipments inside the field can be avoided. Moreover, their non-contact nature allows us to observe sound fields where microphones cannot be applied. For example,

* Corresponding author.
E-mail address: k.yatabe@asagi.waseda.jp (K. Yatabe).

[1] Note that there are several optical methods based on the other principles [28,29]. In this paper, we only focus on the optical methods based on the acousto-optic effect [30] for simplicity.

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sound inside strong airflow is difficult to measure owing to the aerodynamic noise generated around the measuring instruments. Sound inside a very high-temperature field or a strong magnetic field is also difficult to measure by microphones. They must be measured in a contactless manner, which can be achieved by the optical methods.

Although the optical methods have such attractive properties, they have a fundamental disadvantage which restricts their applications. Since sound affects light at every points on the optical path, the observed quantity is spatial integration of sound pressure (see Section 2). This integration principle conceals the point-wise information of a sound field. Therefore, some post-processing is necessary for reconstructing the information at a point in the three-dimensional field. Ordinarily, the computed tomography (CT) technique based on the back-projection of the Radon transform has been applied for the reconstruction [3–16]. However, there is an assumption mismatch which limits the accuracy. Usual CT methods assume that quantity to be reconstructed is concentrated within a small area. This assumption does not match with sound because sound spreads widely. Then, the assumption mismatch results in artificial noise. Furthermore, CT methods do not assume any physical property related to sound. That is, any causes of changing the refractive index including heat and flow can be remained in the reconstructed results. If physical model of sound is considered within the reconstruction process, these problems can be resolved. Nevertheless, to the best of our knowledge, such method has not been investigated until now.

In this paper, a physical-model-based reconstruction method of a sound field from optical observation is proposed. It assumes that observed data is obtained from a sound field, which is modelled by the Helmholtz equation whose effectiveness for optical methods has been confirmed [31–34]. Thus, the physical behavior of sound is imposed as the prior knowledge within the reconstruction process. Numerical simulations and measurements of actual sound fields were performed, and the conventional CT method and the proposed method are compared.

2. Optical observation of sound field

Observing acoustical quantity using optical techniques is based on the well-known acousto-optic effect [30]. For an audible sound field which satisfies the linear acoustic theory, the acousto-optic effect is modelled by the phase modulation of light as follows [35].

The sound is a physical phenomenon that fluctuate the density of the medium. The refractive index of air can be expressed as a function of density, and it is also related to sound pressure. Therefore, by assuming adiabatic conditions, the refractive index of air $n(x, t)$ can be interpreted as a function of sound pressure $p(x, t)$:

$$n(x, t) = (n_0 - 1)\left(1 + \frac{p(x, t)}{p_0}\right)^{\frac{1}{\gamma}} + 1, \tag{1}$$

where $x = (x_1, x_2, x_3) \in \mathbb{R}^3$ denotes a position vector, $t \in \mathbb{R}$ is time, n_0 and p_0 respectively represent the refractive index and pressure under static conditions, and γ is the specific heat ratio of air. When the sound pressure p is much smaller than the static pressure p_0, the above equation can be linearized as

$$n(x, t) = n_0 + \frac{n_0 - 1}{\gamma p_0} p(x, t), \tag{2}$$

whose validity was confirmed for audible sound[2] [35].

Let us consider a situation that light is passing through a sound field. Since the refractive index varies according to sound pressure, the light is affected by the sound. With the assumption for Eq. (2), geometrical optics approximation gives the medium dependent part of the phase of the light:

$$\begin{aligned} \phi(x, t) &= \phi_{\mathrm{light}}(x) + \phi_{\mathrm{sound}}(x, t) \\ &= k_{\mathrm{light}}\left[n_0 \int_{L(x)} dy + \frac{n_0 - 1}{\gamma p_0} \int_{L(x)} p(y, t) dy \right], \end{aligned} \tag{3}$$

where ϕ_{light} and ϕ_{sound} are respectively medium dependent phases of the light without and with contribution of the sound field, ϕ is the total phase, k_{light} is the wavenumber of the light, and $L(x)$ denotes the optical path from the light emitting point to x. By fixing the position of optical devices including an emitter and detector, the optical path is also fixed, that is

$$\phi_{\mathrm{detect}}(t) = k_{\mathrm{light}}\left[n_0 |L| + \frac{n_0 - 1}{\gamma p_0} \int_L p(y, t) dy \right], \tag{4}$$

where L is the optical path from the light emitting point to the detector, $|L|$ is its length, and ϕ_{detect} is the medium dependent phase of the light at the detector. Thus, information of the sound field can be acquired by measuring the degree of modulation of the phase of the light:

[2] Here, the term *audible* refers to the range of not only frequency but also sound pressure that human can perceive without pain.