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Acousto-optic sensing – spatial reconstruction of the sound field enclosed in a room

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Abstract

Measuring the sound pressure field over medium and large volumes, such as rooms, can be cumbersome. Conventional sensing methods acquire the sound pressure (or other field quantity) at a single point. Therefore, to acquire the three-dimensional sound filed in a room, a large number of measurement points must be distributed throughout. In this study, we propose a method to capture the sound field in a volume based on the acousto-optic effect. The acoustic pressure field is captured along beams of laser light. As the light (the sensing element of this method) travels through the sound field, it captures information of the sound pressure along its travel path. In this study, the spatial reconstruction of the sound field in a room from acousto-optic measurements is presented and compared with conventional point-wise measurements. The results show a first approach to the spatial characterisation of the sound field in a room using the acousto-optic sensing principle.

Keywords: Acousto-optic, microphone arrays, sensing methods, signal processing

1 INTRODUCTION

Capturing the spatio-temporal properties of the sound field enclosed in a room is crucial in many applications; from architectural and room acoustic design (1, 2), to 3D audio recording and reproduction (3, 4). Pressure measurements at a discrete set of positions (either using microphone arrays (5) or sequential measurements (6)) have conventionally been used to sample sound fields over space. However, sampling large three-dimensional domains, such as rooms, using point-wise pressure measurements is impractical. Firstly, a large number of measurements (that increases with frequency and room size) is required. Secondly, the measurements have to be distributed across large regions of the room that are often inaccessible. Alternative sensing methods, better suited for sampling the sound field over large volumes, are lacking.

In this study, *acousto-optic tomography* is examined as an alternative (or complementary) sensing method to conventional pressure measurements. The acousto-optic effect describes the interaction between sound and light. Pressure fluctuations in a medium caused by a sound field produce changes on the medium local density. Such density changes, in turn, change the speed of light, i.e. light travel faster or slower depending on the medium density. The small changes of the speed of light can be captured along beams of laser light using a laser Doppler vibrometer (LDV). In other words, laser light can be used to measure acoustic pressure fluctuations. LDVs can capture the projected sound field along laser beams, and if enough projections are measured, tomographic images of the sound field can be obtained.

Acousto-optic tomography has been applied to the visualisation of sound fields, both in ultrasonics (7–13), and more recently in the audible frequency range (14–30). The use of acousto-optic tomography has been limited to laboratory conditions partly due to the reconstruction methods (inherited from classic computerised tomography (31)) that are usually employed. For example, the commonly used filtered back-projection algorithm requires measuring projections of the sound field from every direction along a set of parallel beams. As a result, sensing methods based on the acousto-optic effect have not yet been employed to characterise large, complex sound fields such as those that are found inside rooms.

In this study an acousto-optic tomography method, suitable for capturing complex sound fields, is introduced. The proposed method formulates the problem as an algebraic reconstruction, therefore it does not require a specific configuration of the measurements.

In a previous study (32) the authors examined the proposed tomographic reconstruction method from numerical data. In this paper, we present a first experimental study that explores the acousto-optic effect as a sensing principle for capturing the sound field in a real room.

2 THEORY

2.1 Acousto-optic effect

Let us consider a pressure field $p(\mathbf{r})$ enclosed in the domain Ω (such as $\mathbf{r} \in \Omega \mid \Omega \subset \mathbb{R}^3$). We assume that the domain boundary $\partial\Omega$ is an impenetrable surface (not porous), and that points on the boundary $\mathbf{r}_{\partial\Omega}$ vibrate with velocity $\mathbf{u}$. The vibration velocity of surfaces can be measured by a LDV: a laser beam is sent through Ω, back scattered at $\mathbf{r}_{\partial\Omega}$, and collected again. The phase of the beam is determined by its optical path (15)

$$\phi = k_\ell \int_0^L n(\mathbf{r};l)\mathrm{d}l, \tag{1}$$

where n (defined as the ratio between the speed of light in vacuum and in the medium) is the refractive index within Ω , l is an integration variable along the beam path, L is the length of the path, and k_ℓ is the wavenumber of the laser light. Laser Doppler vibrometers determine the velocity of a surface by measuring the phase shifts induced by changes in the optical path. Therefore, the velocity v measured by a LDV is proportional to the rate of change of ϕ

$$v = j\omega\phi \frac{1}{k_\ell n_0}. \tag{2}$$

Generally, it is assumed a constant n across the measurement domain, $n(\mathbf{r}) = n_0 \ \forall \ \mathbf{r} \in \Omega$. In this case, Eq. 2 reduces to changes in the length of the path L, i.e. the velocity of the surface in the direction of the laser beam $v = u_\Psi(\mathbf{r}_{\partial\Omega})$. However, acoustic pressure fluctuations in a medium induce changes on n as

$$n = n_0 + \frac{n_0 - 1}{\gamma p_0} p, \tag{3}$$

where n_0 is the refractive index of the unperturbed medium, p_0 is the static atmospheric pressure, and γ is the heat capacity ratio. Equation 3 describes the relation between the refractive index and the acoustic pressure – i.e. the *acousto-optic effect*. The expression in Eq. 3 is obtained by combining the Gladstone-Dale relation $n = \rho K + 1$ (33) (where K is a constant characteristic of the medium), and the assumption that the pressure fluctuations p are an adiabatic process

$$\frac{p}{p_0} = \gamma \frac{\rho - \rho_0}{\rho_0}, \tag{4}$$

where ρ_0 and ρ are the densities of the static and perturbed medium. Equation 4 relies on a first order approximation, as generally made in linear acoustics.

The actual measurement of a LDV is obtained combining Eqs. 1, 2 and 3

$$v = j\omega L + j\omega \frac{n_0 - 1}{\gamma p_0 n_0} \int_0^L p(\mathbf{r};l)\mathrm{d}l. \tag{5}$$

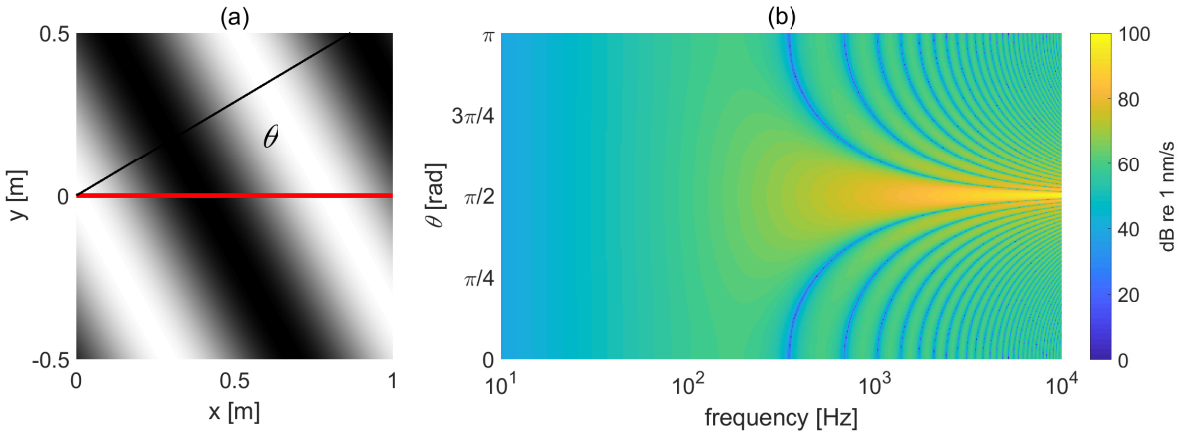

Figure 1. a: laser beam of length 1 m on the x-axis and a single plane wave with direction defined by θ. b: magnitude of the acousto-optic term along the 1 m laser beam for unit amplitude plane waves propagating in directions $\theta = 0 : \pi$ and frequencies 10Hz to 10kHz.

Equation 5 shows that LDV measurements are the combination of the surface vibration velocity $u_\Psi = j\omega L$, and the acousto-optic effect $j\omega \frac{n_0 - 1}{\gamma p_0 n_0} \int_0^L p(\mathbf{r}; l) \mathrm{d}l$. We can identify three cases. If u_Ψ is much larger than the acousto-optic effect term, the LDV only measures the velocity of the surface at which the laser is directed (which is the original purpose of LDVs). If the surface is rigid, the acousto-optic effect term dominates, and we obtain measurements of the sound field projected along the beam path. In case that the two terms are of the same order, the LDV measures a combination of the two phenomena.

The magnitude of the acousto-optic effect term for simple sound fields is examined in Fig. 1. Figure 1(a) represents a laser beam of length 1 m placed in the x-axis. The sound field is a single unit-amplitude plane wave propagating in the direction defined by θ. Figure 1(b) shows the magnitude of the acousto-optic effect that would be measured for plane waves propagating in different directions (θ from 0 to π) and frequencies (from 10 Hz to 10 kHz). For $\theta = 0$, the acousto-optic term is zero for frequencies with wavelengths that are an integer of the laser beam length. At other directions, this zero term is shifted to higher frequencies. For $\theta = \pi/2$, the integral in Eq. 5 is done over a constant. At frequencies below 100 Hz the wavelength is much larger than the length of the laser beam, thus the measurement magnitude is constant regardless of the direction of propagation. The loss of sensitivity at low frequencies constitutes an inherent limitation of the acousto-optic sensing method: sampling at low frequencies require the use of longer beams. Between 100 Hz and 1 kHz, the magnitude of the acousto-optic effect generated by unitary amplitude plane waves is of the order of $\approx$ 60 dB with reference to 1 nm/s.

3 METHOD

3.1 Tomographic reconstruction of sound fields

The reconstruction method proposed in this paper is based on the plane wave expansion of the pressure field

$$p(\mathbf{r}) \approx \sum_{n=1}^{N} X_n e^{-jk\mathbf{w}_n \cdot \mathbf{r}}, \tag{6}$$

where $\mathbf{w}_n$ indicates the direction of propagation of the n^{th} plane wave, and the complex coefficient X_n contains its amplitude and phase. Only propagating waves are considered, i.e. $k = 2\pi f/c$, where f is the frequency of

the sound field and c is the speed of sound. Neither sound sources nor absorption within Ω are considered. An expression that links the plane wave complex coefficients X_n to LDV measurements is obtained combining Eqs. 5 and 6

$$v = \sum_{n=1}^{N} X_n j\omega \frac{n_0 - 1}{\gamma p_0 n_0} \int_0^L e^{-jk\mathbf{w}_n \cdot \mathbf{r}} dl. \tag{7}$$

Equation 7 assumes that the surface at which the LDV is directed is rigid, so the measurement v is mainly due to the acousto-optic term ($u_\Psi \ll j\omega \frac{n_0-1}{\gamma p_0 n_0} \int_0^L p(\mathbf{r};l)\mathrm{d}l$). The validity of this assumption will be tested section 4. Measuring with M beams with various paths l_m leads to a system of equations that can be written algebraically as

$$\mathbf{v} = \mathbf{H}\mathbf{x}, \tag{8}$$

where $\mathbf{v} \in \mathbb{C}^M$ are the LDV measurements, $\mathbf{x} \in \mathbb{C}^N$ are the plane wave complex coefficient, and $\mathbf{H} \in \mathbb{C}^{M \times N}$ is a matrix with elements $\mathbf{H}_{mn} = j\omega \frac{n_0-1}{\gamma p_0 n_0} \int_0^{L_m} e^{-jk\mathbf{w}_n \cdot \mathbf{r}} dl_m$. Estimating the coefficients $\mathbf{x}$ from the measurements $\mathbf{v}$ poses an inverse problem that can be solved via common regularised inversion (34). The pressure field can then be estimated at any point $\mathbf{r}_s$ within Ω by multiplying the estimated coefficients $\tilde{\mathbf{x}}$ with the corresponding propagation terms $e^{jk\mathbf{w}_n \cdot \mathbf{r_s}}$. In contrast to classic reconstruction methods (such as filter back projection) used in previous studies (20, 23, 28), the method proposed in this paper does not require a specific regular sampling scheme.

4 EXPERIMENTAL STUDY AND RESULTS

An experimental study was conducted in a room to examine the suitability of using the acousto-optic sensing principle in a real scenario. Vibrometer measurements over one plane were acquired using a compact LDV placed on a tripod (see Fig. 2a). The LDV was sequentially moved to 8 positions inside the room, and the laser beams were directed to two of the room walls, covering the plane of height 1.25 m (the beam paths are shown in Fig. 4b). An accelerometer was used to monitor the vibration of the walls at the sampled positions (Fig. 2b), making it possible to asses the assumption of rigid boundaries. The vibration of the LDV head was as well monitored with an accelerometer. Rubber pads were placed under the tripod feet to minimise the vibrations of the LDV head. In order to assess the quality of the reconstruction, extensive pressure measurements were performed in the room. A robotic arm (shown in Fig. 2c) was used to move a microphone and sequentially measure the room frequency response on $S = 1734$ positions, covering one plane (1.6×2.4 m, height 1.5 m) in the room. This plane constitutes the reference sound field.

The room, with bare concrete wall, has dimensions $3.29 \times 4.38 \times 2.97$ m and an approximate reverberation time of 2.5 s. The excitation was a logarithmic sine sweep played through a loudspeaker at one of the corners. The overall sound pressure level was ≈ 95 dB.

Figure 3 shows the velocity measured by the LDV, by the accelerometer placed on the wall, and by the accelerometer placed on the LDV head. At low frequencies (below 300 Hz), the LDV mainly captures the vibration of the wall. Above 300 Hz, the velocity measured by the LDV and the wall vibration start to deviate. At frequencies higher than 500 Hz, the LDV measures a velocity at least 10 dB larger than the accelerometer. This discrepancy cannot be explained by vibrations of the LDV head, although the head does resonate at certain frequencies. The results in Fig. 3 and Fig. 1 are not directly comparable since the amplitude of the sound fields and the length of the beams are different. However, a qualitative assessment of Fig. 1 suggests that the acousto-optic effect term becomes significant above approx. 300 Hz. This result indicates that the discrepancy observed in Fig. 3 above 300 Hz can be due to the acousto-optic effect.

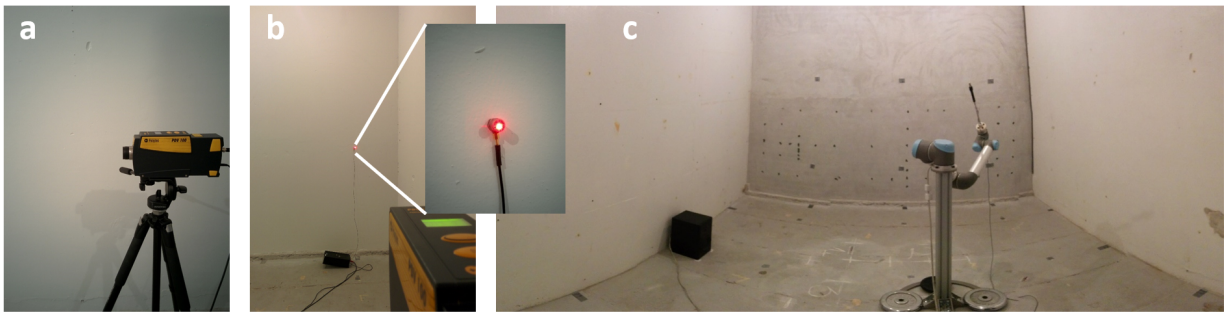

Figure 2. Experimental setup. a: LDV mounted on the tripod. b: accelerometer used to monitor the wall vibration. c: robotic arm used for the extensive pressure measurements that serve as reference.

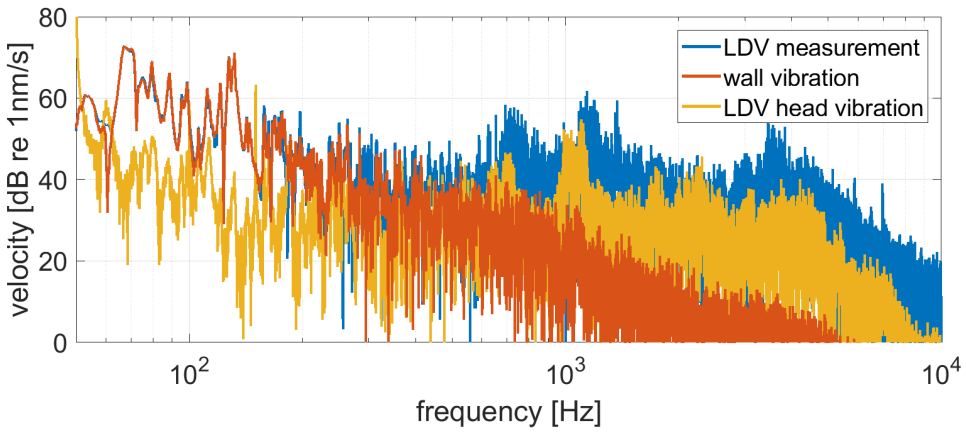

Figure 3. Blue: Velocity measured by the LDV. Red: velocity measured by the accelerometer placed on the wall (same position at which the laser is pointing). Yellow: velocity measured by the accelerometer placed on the laser head.

The sound field is reconstructed following the method presented in section 3. In this first experimental study, the reconstruction was performed using the $M = 8$ LDV measurements, from which the velocity of the walls (measured by one of the accelerometers) was subtracted. The subtraction is done to be able to reconstruct the sound field at low frequencies (where the wall vibration dominates). Reconstructions at frequencies above 300 Hz (where the acousto-optic term is larger that the wall vibration) would require a larger number of measurements.

Figures 4a and b show the magnitude of the reference measured and reconstructed sound fields across the reference plane at 55 Hz. The general features of the sound field (corresponding to an axial mode in the x-direction) are correctly recovered. The way beams were distributed favours the reconstruction of the 55 Hz axial mode: projections both perpendicular and parallel to the waves that compose the mode are measured. The lower half of the reference plane was practically unsampled (see Fig. 4b), which might explain the inaccurate reconstruction in that area.

Figure 4c shows the modal assurance criterion (MAC) (35) across frequency. The MAC, defined as $\mathrm{MAC} = \left|\mathbf{p}^H\tilde{\mathbf{p}}\right|^2/(\mathbf{p}^H\mathbf{p})(\tilde{\mathbf{p}}^H\tilde{\mathbf{p}})$, is a measure of the spatial correspondence between the reference field $\mathbf{p}$ and the reconstructed field $\tilde{\mathbf{p}}$. The MAC takes values between one (when reference and reconstruction are consistent) and

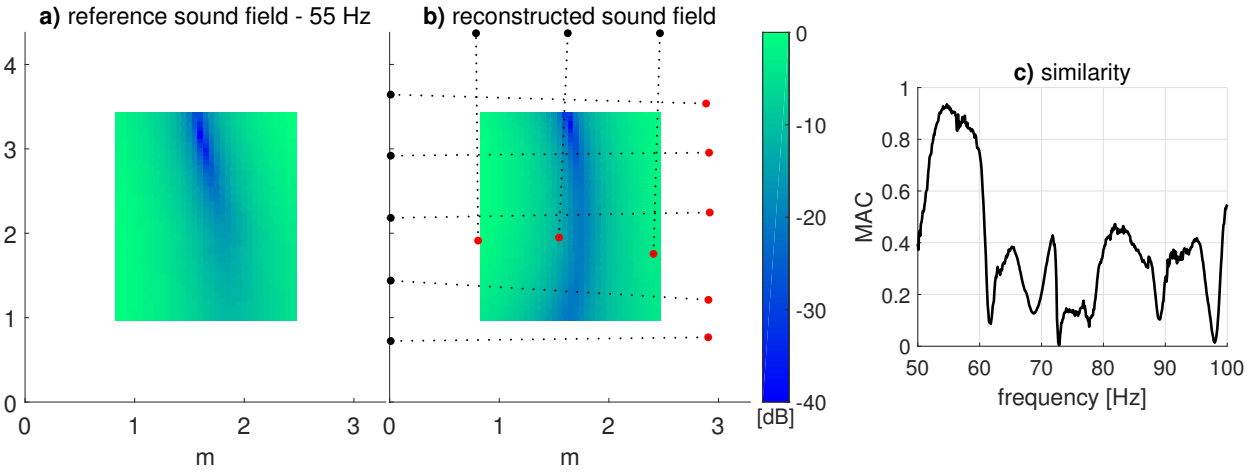

Figure 4. a: normalised pressure level of the measured reference sound field at 55 Hz. b: reconstructed sound filed from LDV measurements. Red dots: positions of the LDV. Dashed lines: laser beam paths. c: Modal Assurance Criterion indicating the degree of similarity between reference and reconstructed sound fields across frequencies.

zero. Figure 4c shows a good agreement at low frequencies, although above 60 Hz the reconstruction degrades. At higher frequencies the sound field becomes more complex. The number of waves increases, and they propagate with different directions. The simple scheme used (with just 8 beams along the x and y directions) cannot properly sample this complex sound field. Therefore, additional beams measuring projections from other directions would be required at higher frequencies.

This first experimental study indicates that it is possible to recover a simple mode in a room from measurements of the acousto-optic effect. However, we have identified technological limitations (the vibration of the LDV system) and case-specific limitations (the vibration of the room walls). In this study, the vibrations have been monitored using accelerometers, making it possible to obtain ideal acousto-optic effect measurements non-biased by wall vibrations. Other compensation methods to separate the acousto-optic effect from unwanted vibrations will be investigated in the future. Another possibility is the use of the measured wall velocity as additional information to solve the reconstruction problem (instead of regarding it as unwanted noise), for which the coupling between the wall vibration and the sound field inside the room has to be studied.

It is important to differentiate technological and case-specific constrains (which can eventually be overcome) from the loss of sensitivity at low frequencies. The loss of sensitivity is a fundamental limitation inherent to the sensing principle, and it cannot be compensated for. Finally, the authors will study alternative sensing principles for sampling sound fields over large volumes.

5 CONCLUSION

In this study we have proposed a method to capture the sound field over large volumes from projection measurements of the acousto-optic effect. The method is based on the algebraic formulation of the reconstruction problem, which makes it possible the use of arbitrary measurement arrangements.

The experimental study has shown that the acousto-optic effect inside a room is detectable by means of vibrometry measurements. One axial mode of the room has been recovered by means of 8 acousto-optic measurements. At the same time, we have identified the limitations to the applicability of the acousto-optic sensing principle.

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