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Characterization of acoustic diffusion using refracto-vibrometry

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ABSTRACT

Refracto-vibrometry is a relatively new measurement technique that is sensitive to variations in the optical refractive index of a medium caused by changes in acoustic pressure within that medium (the acousto-optic effect). It has so far been employed primarily as a qualitative visualization tool for airborne sound propagation because determining sound pressure level at a point using the technique is difficult and inefficient. Instead, the authors propose that this optical technique is well suited for determining dimensionless quantities, such as coefficients describing scattering uniformity from a surface. A new measurement and analysis process relying on refracto-vibrometry has been developed and used to determine acoustic diffusion coefficients through purely optical means for the first time. A quadratic residue diffuser is used as an arbitrary test surface, and refracto-vibrometry measurements of its polar response have been performed and results compared to a boundary element model. The benefits and limitations of the optical method over the traditional microphone-based approach are discussed.

1. Introduction

The acoustic quality of concert halls, exhibition centres, recording studios, and indeed any enclosed space, is principally defined by their size, shape, and the nature of reflections from the surfaces within that space [1]. Architects and acousticians depend on having accurate information about the absorption, reflection, and scattering properties of surface materials in order to correctly specify and realize their designs [2]. Whilst absorption is often measured in large reverberation chambers, applying statistical assumptions based on an assumed diffuse field, the characterisation of the spatial scattering of surfaces is somewhat more involved. An important property of a surface defined by the latter is the diffusion coefficient – a measure of scattering uniformity with angle [3]. Measuring the scattering properties of surface samples accurately is a laborious and time consuming process because it relies on making a great many measurements with calibrated microphones [3,4] – for diffusion measurements at least 37 microphones are required for simultaneous measurement over a semi-circle, or a bulky goniometer for sequential measurement in 2D or 3D. There is scope for substantial improvement to the speed and accuracy of sample testing if microphone and goniometer based systems can be replaced by optical equivalents.

The use of light to map the distribution of sound in 2D fields has been in existence for more than 300 years, going back to the first experiments in Schlieren imaging and shadowography [5]. A modern equivalent, refracto-vibrometry (which uses a

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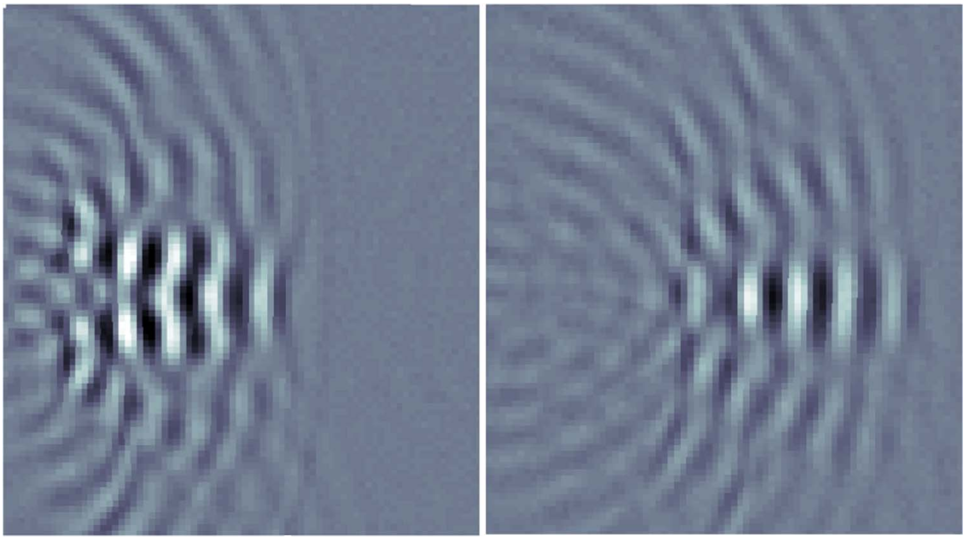

Fig. 1. Full-field scans of a full scale (0.6 m) N=7 QRD diffuser at the left edge of each frame, facing rightwards (not shown) reflecting a 4 kHz tone burst. The two frames are snapshots of the reflected sound field at 2 ms (left) and 3 ms (right) after first reflection, each showing an area of about 1 mx1 m at 1 cm^2 resolution.

laser Doppler vibrometer – primarily developed to study vibrating solid surfaces) allows very rapid and precise optical sampling, and may be used to observe sound propagation in optically transparent media via an interaction known as the acousto-optic effect [6]. From the late 20th century refracto-vibrometry has been used to image ultrasonic waves in water [7], and over the last 15 years it has been successfully applied to image sound propagation in air [8]. Two frames showing sound propagation (reflected from a diffuser) constructed using refracto-vibrometry are presented in Fig. 1 to illustrate one qualitative application of the technique.

The acousto-optic effect describes how the optical refractive index of a medium, n, is dependent on the pressure, and is therefore influenced by sound pressure, p, in a deterministic way (Eq. 1).

$$n \cong n_0 + \frac{n_0 - 1}{\gamma p_0} p \tag{1}$$

Where n_0 is the static refractive index (close to 1 in air), p_0 the static pressure, and γ the ratio of specific heats. The ratio p/p_0 and the difference $(n_0 - 1)$ confirm that this is an incredibly weak effect in air, and therefore high sound pressures are required for it to be observable.

The change to refractive index alters speed of light through that region, which is detected through refracto-vibrometry as an apparent Doppler velocity, v. This velocity is proportional to the rate of change of the line integral of acoustic pressure along the laser's path, **L**, as described by Eq. (2).

$$v(t) = \frac{n_0 - 1}{\gamma p_0 n_0} \frac{\mathrm{d}}{\mathrm{d}t} \left(\int_{\mathbf{L}} p(\boldsymbol{x}, t) \mathrm{d}l \right) \tag{2}$$

A limitation of the technique is immediately apparent: the line integral of acoustic pressure provides no direct way to determine sound pressure at a point, which is the quantity most commonly sought in acoustic measurements. Tomography has been successfully applied [6,9] to resolve this, although this is very time intensive. Alternatively, for situations where there is a-priori knowledge of the sound field, it is possible to use that in combination with refracto-vibrometry to determine sound pressure at a point [10].

The authors propose in this paper that many of the benefits of refracto-vibrometry can also be directly realized by using it to determine normalized quantities, such as the coefficients describing acoustic reflections (absorption, scattering, and diffusion), where an absolute evaluation of sound pressure is not required. To demonstrate this, an experiment has been conducted on a single plane scattering surface, arbitrarily chosen as a 1D length 7 quadratic residue diffuser (QRD) [11] with well depth sequence [0 1 4 2 2 4 1], and it will be shown that polar responses and directional diffusion coefficients can be derived directly from the optical data.

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