

Interferometric Determination of the Sound-Pressure-Induced Refractive Index Modulation of Ultrasonic Fields in Air

Marius Foith^a, Regina Schuster^a, Jan Helge Dörsam^b, Sören Soennecken^b,
Yannick Schrödel^{cde}, Christoph M. Heyl^{cde}, Mario Kupnik^b, Anne Harth^a

^aCenter for Optical Technologies, Aalen School of Applied Photonics, Aalen University, Aalen

^bMeasurement and Sensor Technology Group, Technische Universität Darmstadt, Darmstadt

^cDeutsches Elektronen-Synchrotron DESY, Hamburg

^dHelmholtz-Institut Jena, Jena

^eGSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt

mailto:marius.foith@hs-aalen.de

Quantitative characterization of high-intensity ultrasonic fields in air remains challenging, particularly in the nonlinear regime. Using an established, fast, contactless, two-dimensional interferometric method, we demonstrate its capability to reveal and quantify higher harmonic components of an acoustic field. Thus the presented method provides a practical tool for the quantitative investigation of nonlinear acoustic wave propagation in air.

1 Motivation

In the field of ultrasonic applications in air, microphones represent typically the standard characterization method. However, in certain applications, such as acoustic levitation [1] or the ultrasonic deflection of high-power laser beams [2], there is a growing demand for rapid, non-contact characterization of the ultrasonic fields used. Optical techniques, including schlieren photography [3], provide a promising alternative but are inherently sensitive to spatial sound-pressure gradients rather than the acoustic pressure field itself.

In contrast, our work is based on an interferometric approach [4], that provides quantitative access to the acoustic field by measuring the optical phase distribution caused by the sound-pressure-induced refractive index modulation. Spectral analysis further reveals higher harmonics of the propagating ultrasonic wave, providing quantitative insight into nonlinear propagation effects. These are essential for characterizing high-intensity ultrasonic fields, yet hard to access with microphones because sensor nonlinearities become difficult to distinguish from intrinsic field nonlinearities at high pressures. Our optical approach avoids this ambiguity.

2 Method

Since nonlinear propagation occurs only at sufficiently high sound pressure levels, the ultrasonic field is generated using a phased array [5] consisting of 64 ultrasonic transducers coupled via an acoustic waveguide to generate a high-intensity ultrasonic field. Microphone measurements yielded a sound pressure level of 145 dB at a distance 0.3 m [5] at a frequency of $f_s = 40$ kHz. The relationship between the generated change in air density caused by the ul-

trasonic field and the refractive index is given by the Gladstone-Dale relation [2]. It must be considered that at large pressure amplitudes > 145 dB, acoustic waves show a nonlinear behavior, which is directly visible in the refractive index modulation. This nonlinearity manifests, among other effects, as a distortion of the ultrasonic wave [6], since a difference in the velocity occurs between compressed and decompressed air. In approximation, this can be represented as a superposition of the fundamental frequency and higher harmonics with decreased amplitudes as follows:

$$n(x, t) = \sum_{m=1}^{\infty} \hat{n}_m \sin(m(\omega_s t - k_s x)).$$

Where $\hat{n}_m$ denotes the harmonic amplitude, with $m = 1$ representing the fundamental wave and $\hat{n}_m \ll \hat{n}_1$ for $m > 1$ (ω_s represents the angular frequency and k_s the acoustic wavenumber).

A Fizeau interferometer as shown in Fig. 1 is utilized for the determination of the refractive index modulation. Therefore the ultrasonic field is placed in front of the slightly tilted sample surface.

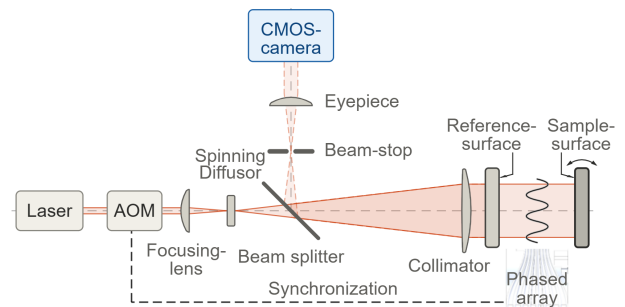


Fig. 1 Schematic of the Fizeau interferometer with an acousto-optic modulator (AOM) synchronized to the ultrasonic source for pulsed illumination at the sound-pressure maximum.

The main advantage of this setup is the common-path arrangement between reference and sample beam, allowing a determination of the 2D phase distribution caused by the ultrasonic field from a single interferogram. This in fact reduces the impact of density fluctuations in air and mechanical vibrations. Accordingly, a slightly tilted sample surface modulates the observed phase shift onto a linear phase (spatial carrier frequency) which allows separation from the DC component in the frequency domain. The phase extraction from the interferogram is performed using a custom build analysis software based on the Takeda method [7].

3 Results and Discussion

Fig. 2 shows the 2D phase distribution (b) as a result of the analysis algorithm using the interferogram (a) as input. The cross section of this phase distribution at $y = 0$ (c) reveals a distorted sinusoidal refractive index modulation which is characterized by an asymmetric steepening of the leading edges. Using an approximate interaction length with the sound field of $l_s = 40$ mm yields to a root mean square value for the refractive index modulation Δn in the order of 10^{-6} .

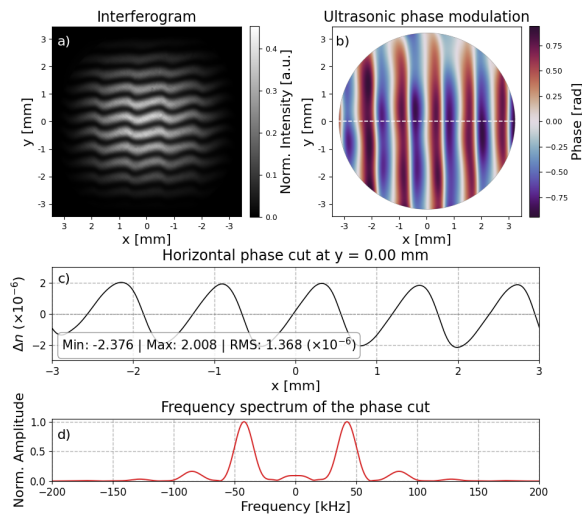


Fig. 2 Interferogram, a) (The propagation direction of the ultrasonic wave is given from left to right). Reconstructed 2D phase, restricted to the region of sufficient fringe contrast, b). Refractive index modulation as cross section of the phase at $y=0$, c). Frequency spectrum of the cross section with a horizontal axis in kHz, d).

The frequency spectrum Fig. 2 d) shows a main peak at $f_1 \approx \pm 40$ kHz, which is in good agreement with the nominal operating frequency of the phased array. The nonlinear behavior is indicated by the second and third harmonics at $f_2 \approx \pm 80$ kHz and $f_3 \approx \pm 120$ kHz reaching 16.5 % and 3.3 % of the main peak amplitude. The frequency axis is given in kHz

to directly represent the ultrasound frequencies contained in the signal. Parameters for the conversion are the pixel size $p = 3.45 \mu\text{m}$, magnification factor $M = 6.7$, and speed of sound $v_0 = 343 \text{ m s}^{-1}$.

The result demonstrates that it is possible to apply the proposed method for a determination of the sound-pressure-induced refractive index modulation and the investigation of acoustic nonlinearities.

While the method enables quantitative characterization of propagating ultrasonic fields, its performance when observing higher ultrasonic frequencies is limited by spatial resolution and reduced irradiance, as shorter laser pulses are required. Furthermore, the output is given as a 2D projection of the 3D sound field because the refractive index changes are integrated along the optical axis.

4 Conclusion

This work demonstrates that a Fizeau interferometer with a pulsed laser source, triggered by an ultrasonic transducer enables the 2D reconstruction of the refractive index modulation caused by an ultrasonic field in air. Furthermore, the results show that frequency analysis can be used to demonstrate the nonlinearity of the observed sound field.

Future work will focus on a setup that enables a stepwise angular rotation of the ultrasound transducer between measurements. The resulting multi-angle projections can then be used to reconstruct a 3D representation of the acoustic field by means of an inverse Radon transform. This allows the local sound pressure amplitudes to be determined quantitatively, without spatial averaging caused by the integral projection.

Refereces

- [1] J. H. Dörsam et al., "Robust Transducer–Reflector Distance Control in Acoustic Levitation," IEEE Open Journal of Ultrasonics, Ferroelectrics, and Frequency Control (2026).
- [2] Y. Schrödel et al., "Acousto-optic modulation of gigawatt-scale laser pulses in ambient air," Nature Photonics (2023).
- [3] F. Wörtche et al., "Characterizing ultrasonic standing wave fields by Schlieren imaging," Elsevier B.V. (2025).
- [4] R. Schuster et al., "Rapid quantitative characterization of ultrasonic fields using Fizeau interferometry," Optics and Laser Technology (2026).
- [5] A. Jäger, "Airborne ultrasound phased arrays," Ph.D. thesis, Technische Universität Darmstadt (2019).
- [6] Deutsche Gesellschaft für Akustik e.V. (DEGA), "DEGA-Empfehlung 101: Akustische Wellen und Felder," Dega-empfehlung (2005).
- [7] M. Groß, H. Müller, and B. Dörband, *Handbook of Optical Systems*, volume 5, metrology of optical components and systems ed. (Wiley-VCH Verlag, 2012.).