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Pulsed Optical Phase Contrast Microscopy to Measure the Absolute Pressure Amplitudes of Ultrasonic Fields

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Abstract: We apply pulsed optical phase contrast microscopy to measure the absolute pressure amplitudes of complex ultrasonic fields generated by planar and focused transducers at frequencies up to 20 MHz.

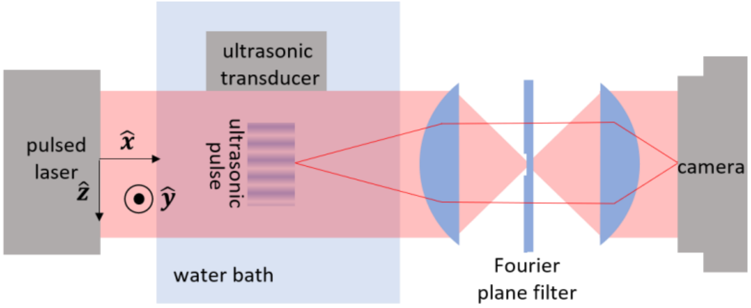
1. Background

Quantitative measurements of 3D ultrasonic fields in water typically involve scanning a calibrated piezoelectric hydrophone through the ultrasonic field to measure the local pressure vs. time waveform at many points [1]. However, this method has limitations; it is slow due to mechanical scanning of the hydrophone, and the field being measured is perturbed by ultrasonic wave reflections from the hydrophone. Furthermore, accurate characterization of non-planar pressure waves at high ultrasonic frequencies is difficult because the ultrasonic wavelength becomes smaller. If deviations from planarity are comparable to or larger than the ultrasonic wavelength, the hydrophone's calibration is no longer valid, and the measurement accuracy is compromised. Here, we present a pulsed optical phase contrast microscopy (POPCM) technique capable of measuring complex ultrasonic fields with high accuracy. POPCM is faster than the hydrophone scanning method, does not perturb the pressure field, and measures pressure wavefronts of arbitrary shapes, including wavefronts generated by focused and planar transducers. We demonstrate the high measurement accuracy of POPCM by comparing measurements of ultrasonic fields made with POPCM to those made with a calibrated hydrophone. POPCM could serve as a primary method for pressure calibration of various ultrasonic transducers at high frequencies.

2. Methods

Fig. 1. is a schematic of our POPCM setup. Collimated, strobed laser light (470 nm, 130 ps, 80 mW peak power, Hamamatsu PLP10-047) is synchronized with the ultrasonic pulse from a piezoelectric transducer. The laser pulse traverses the propagating pressure field to capture a snapshot of the ultrasonic field. Wide-field images of the ultrasonic pulse, recorded with different homemade Fourier plane filters (π/2 filter, 3π/2 filter, and aperture filters) in the illumination beam path, record changes to the local refractive index (RI) of the ultrasound propagating medium due to the pressure field. The imaging optics are focused at the center of the ultrasonic field to help minimize diffraction effects [2]. The 2D spatially resolved phase shift is calculated from the recorded images by procedures described elsewhere [3, 4]. The 3D refractive index perturbation is reconstructed using the inverse Abel transform [5] and the piezo-optic coefficient, a material property of the medium, relates the refractive index perturbation to the absolute pressure amplitude of the ultrasonic field.

Fig. 1. A schematic of the POPCM technique to image a propagating ultrasonic field generated by an ultrasonic transducer. Note that the x, y, z coordinates are indicated.



3. Results and discussion

Fig. 2. (Left panels) POPCM images of a pressure fields recorded with three different Fourier plane filters (π/2 filter, 3π/2 filter, and aperture filter, from top to bottom, respectively). (Right panels) Phase shift image calculated from these recorded images (top) and the reconstructed pressure field.

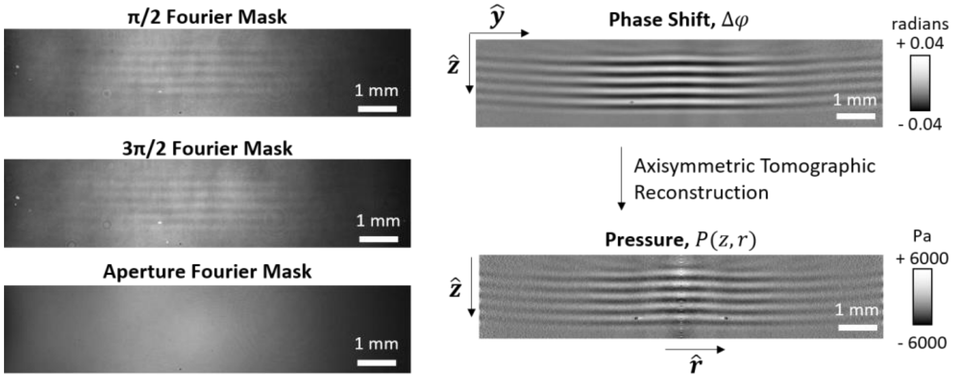
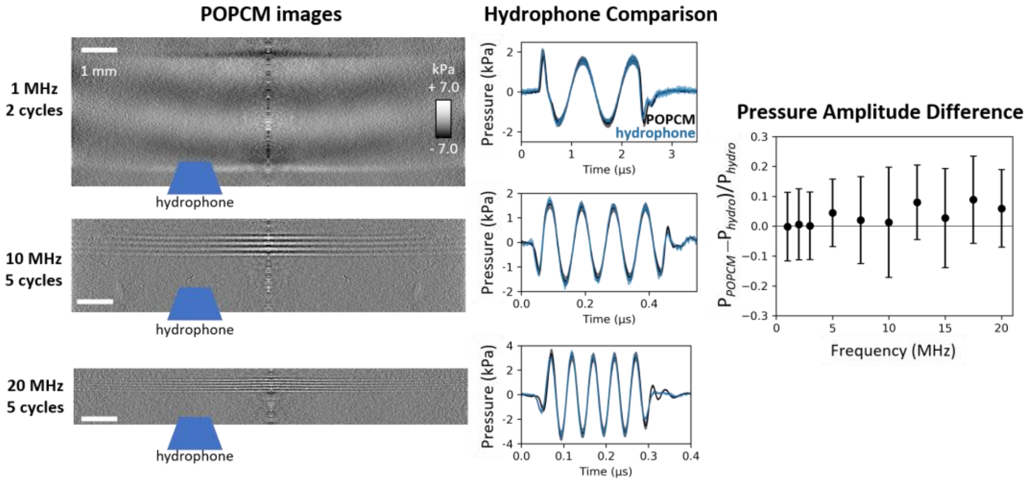


Fig. 2. shows POPCM images of the pressure fields generated from a flat transducer driven by a 5 MHz sinusoidal tone burst wave packet. Images recorded with each Fourier filter, as well as the calculated phase shift and reconstructed axisymmetric pressure distribution are displayed in Fig. 2. The field of view is about 25 mm from the transducer's surface.

Fig. 3. (Left Column) Axisymmetric, 1 MHz, 10 MHz, and 20 MHz tone burst pressure wave distribution reconstructed from phase contrast images. (Middle column) Plots of the pressure vs. time measured with the hydrophone (blue) and POPCM (black) methods. The curves are measured at the locations shown in the left panels. The thicknesses of the curves represent the measurement uncertainty. No fitting parameters are used in overlaying the curves except a constant offset in time. (Right) Differences between the pressure amplitudes measured with the POPCM and hydrophone methods as a function of frequency for planar tone bursts.



The local pressure field amplitudes obtained by the optical method are compared to measurements with a commercial calibrated hydrophone (Onda HNP-1000, 1 mm diameter aperture). The hydrophone is oriented perpendicular to the ultrasonic wavefronts and voltage vs. time curves due to the propagating ultrasonic field are recorded at different locations in the y-z plane that intersects the transducer's axis of symmetry. The voltage is converted to pressure using manufacturer-provided calibration data (traceable to the National Physical Laboratory in the United Kingdom) of the hydrophone's frequency-dependent voltage vs. pressure. The POPCM technique (black curves) and hydrophone measurement (blue) compared in Fig. 3. show good agreement with tone burst waveforms at frequencies up to 20 MHz. The calculated ratio, $(P_{\mathrm{POPCM}} - P_{\mathrm{hydrophone}})/P_{\mathrm{hydrophone}}$, quantifies the difference at the fundamental frequencies of the tone burst as shown in Fig. 3. The measurement differences, consistent with zero within the measurement uncertainty, confirms that the results of the two methods agree well, while the POPCM measures a somewhat higher amplitude at high frequencies.

In Fig. 3, center column, the plotted uncertainty in the hydrophone measurements represents the calibration uncertainty of the hydrophone. The uncertainty in the POPCM measurements is due to the standard deviation of 5 repeated measurements and the uncertainty of the piezo-optic coefficient of water [6]. In Fig. 3, right, the plotted uncertainty in the pressure amplitude difference accounts for the above-mentioned factors as well as the standard deviation in the measurement difference at five measurement points within the field of view.

We have also applied POPCM to measure ultrasonic fields generated by different types of piezoelectric ultrasonic transducers (planar or focused) driven by various tone burst waveforms at frequencies up to 20 MHz, and by a broadband pulse. We have demonstrated quantitative measurements of ultrasonic fields with the POPCM method at frequencies up to 20 MHz. In some situations, differences between high-frequency measurements made with POPCM and a calibrated hydrophone become apparent, and we will discuss potential reasons for these differences.

POPCM enables quick characterization of ultrasonic fields with complex wavefront shapes, such as near field waves. The capability of absolute pressure measurements opens the possibility of using POPCM as a primary calibration method for hydrophones or transducers. In particular, it may be instrumental in calibrating hydrophones and transducers with non-planar elements, which is difficult with current calibration methods.

3. Acknowledgement

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

4. References

[1] C. R. Hill, "Detection and Measurement of Acoustic Fields," In C. R. Hill, J. C. Bamber, and G. R. ter Haar (Eds.), Physical Principles of Medical Ultrasonics Second Ed. John Wiley & Sons Ltd, pp. 69–91 (2004).

[2] H. Hanayama, et al., "Simulation of optical propagation based on wave optics for phase retrieval in shadowgraph of ultrasonic field," Jpn. J. Appl. Phys. 56, 07JC13 (2017).

[3] T. Nakamura, et al., "Quantitative measurement of ultrasonic pressure field using combination of optical phase contrast and nonlinear acoustic holography methods," Jpn. J. Appl. Phys. 57, 07LB13 (2018).

[4] T. A. Pitts, et al., "Optical phase contrast measurement of ultrasonic fields," IEEE Trans. Ultrason. Ferroelectr. Freq. Control 48, 1686–1694 (2001).

[5] N. H. Abel, "Auflösen einer mechanischen Aufgabe," J. Reine Angew. Math. 1, 153–157 (1826).

[6] L.S. Shraiber, "Experimental investigation of the thermal dependence of the piezo-optical coefficient of water between 5 and 90°C," Isr. J. Chem. 13, 181–184 (1975).