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TOWARDS THE REAL-TIME MEASUREMENT OF ULTRASOUND FIELDS BY COMBINING SCHLIEREN TOMOGRAPHY AND WAVEFRONT SENSING

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ABSTRACT

Recent advances in ultrasound generation such as ultrasonic holography and acoustic tweezers require methods for the fast characterization of pressure fields. Typically, this can be achieved by using a hydrophone, but the measurement of the three-dimensional (3D) pressure distribution in a few cm region is extremely time-consuming, with typical times ranging from hours to even days. Alternatively, visual methods like Schlieren techniques offer a rapid assessment of the pressure field, but they remain largely qualitative. In this work, we combine Schlieren tomography with wavefront sensing to fill this void and quantitatively reconstruct 3D ultrasonic fields within seconds. Our method is based on the simultaneous acquisition of intensity images with a Schlieren setup and phase maps with a Wavefront Sensor. Because optical phase differences are related to changes in refractive index in the medium and, at the same time, to changes in pressure, we can convert phase values into pressure maps. By feeding this information into the Schlieren sinograms, we obtain quasi-real-time 3D pressure fields with sub-millimetric resolution. This new optical method is a significant step forward toward the real-time and precise characterization of ultrasound.

Keywords: *Ultrasound characterization, Wavefront sensing, Schlieren technique, Tomography.*

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1. INTRODUCTION

A number of techniques are now available for characterizing ultrasound (US) fields in water with sub-millimeter resolution. The classical strategy consists of point by point scanning a needle hydrophone throughout the volume of interest. While allowing for a precise three-dimensional (3D) pressure reconstruction, this method is intrinsically invasive and time-consuming, with typical measurement times of hours or even days. Alternatively, optical methods exist capable of fast 3D US measurement based on the acousto-optic effect [1], where the presence of a changing pressure distribution deviates the light passing through it. Techniques that exploit this effect include Schlieren imaging [2], Laser Doppler Vibrometry (LDV) [3], or Fabry-Perot interferometry [4]. Unfortunately, these methods are normally restricted to gathering qualitative information about the US field. Attempts to extract quantitative pressure values usually come at the cost of increased complexity or limited applicability.

In this work, we propose a new methodology that preserves the core advantages of optical methods in terms of speed while allowing precise and simple quantification of 3D pressure patterns. Named Schlieren-WFS, it is based on combining a Wavefront Sensor (WFS) [5] device with Schlieren tomography. The WFS is used to retrieve, over a small region, the phase differences originated in a collimated light beam when traversing a pressure-modulated fluid. These phase values are then converted into pressure maps provided the piezo-optic coefficient of water is known. Such quantitative information serves as an on-the-fly calibration step for large field-of-view images obtained with a parallel Schlieren tomography setup. Thus, the simultaneous capture of phase information with qualitative images leads to US field reconstructions with optical resolution in just a matter of seconds.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The light coming from a pulsed light-emitting diode (LED) is first homogenized using a diffuser (DF) and collected by a lens (CL), which focuses the beam down to a 1 mm pinhole (PH). Then, the first field lens (FL_1) collimates the beam into the water tank (WT). There, the light interacts with the pressure field and reaches a beam splitter (BS) which divides the beam into two. Half of the light is magnified by a factor of 3.3 by means of L_1 and L_2 and sent to the WFS. The other half is focused on a horizontal knife-edge (KE) using the second field lens (FL_2) and sent to the camera with a magnifying factor of 1/3.

The WFS consists of an array of 80x50 lenses, each with a diameter of 150 μm, placed in front of a camera sensor and allows for direct measurement of the phase differences originated by the interaction of the collimated light beam with the pressure waves, obtaining a projected phase map. Instead, the camera measures Schlieren projections of the US field. These projections carry information about the first derivatives of the refractive index. By integrating them through the vertical direction, qualitative projections of the refractive index changes are obtained. Note that the field of view is significantly bigger in the camera than in the WFS. The Schlieren projections depend on the gradient of the refractive index in the direction of the knife edge [2], while the WFS projections values are directly proportional to the refractive index [5]. Moreover, the projections on both methods scale linearly with the pressure. Therefore, by integrating the Schlieren projections along the direction perpendicular to the knife edge (vertical axis *z*, in our case), the resulting projection is essentially the same as the one obtained with the WFS observing the same window, as it is depicted in Fig. 2, so that the former is qualitative (light intensity, a.u.) and the latter is quantitative (phase difference, m).

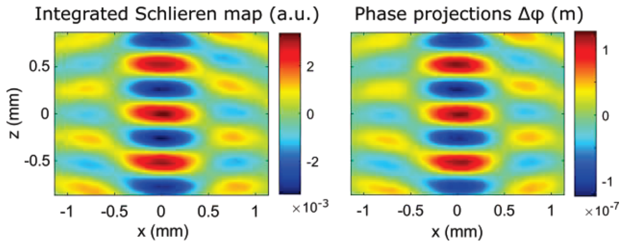

Figure 2. Comparison of an integrated Schlieren intensity image in a.u. (left) and a WFS phase map projection in m (right) of the US pattern to be tested using the same observation window.

By rotating the US source, several projections can be measured at different angles. To reconstruct a 3D phase pattern, we apply the inverse Radon transform (IRT), an algorithm used in tomography. The phase obtained at each voxel is the optical phase difference (OPD) caused by the disturbance, which is related with the refractive index change Δn by:

$$OPD = \Delta n \cdot L \qquad (1)$$

Where L is the voxel length. Therefore, the projected refractive index changes can be obtained by dividing the phase values over the pixel distance. Finally, the pressure values P are calculated using the piezo-optic coefficient C_{PO} for water at 20ºC [6], which is $1.51 \cdot 10^{-10}$ MPa^{-1}.

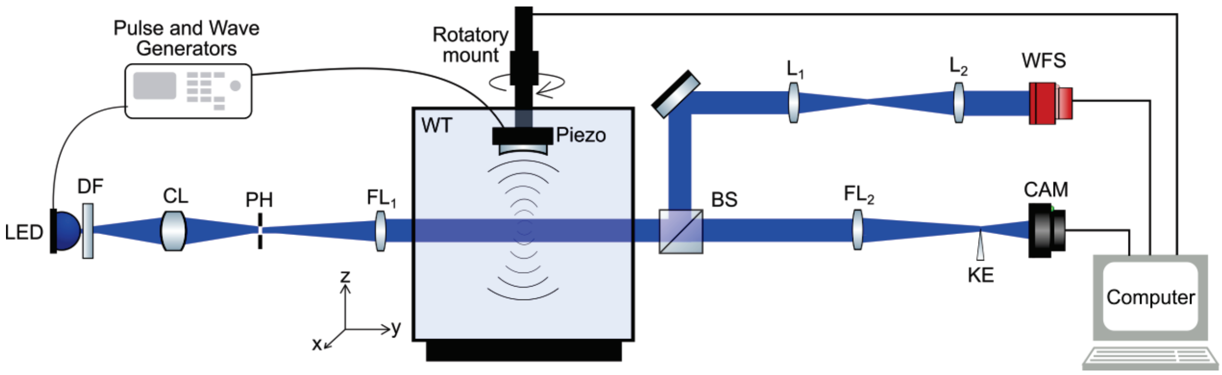

Figure 1. Experimental setup of the combined Schlieren and wavefront sensing system.

The piezo-optic coefficient is considered constant as the refractive index – the pressure relationship behaves linearly even at extremely high pressures ($\Delta n = C_{PO} \cdot P$).

Importantly, the LED pulse (about 50 ns) and the US emission are synchronized using a pulse generator and a waveform generator. Thus, the LED is turned on after some delay of several microseconds to allow the pressure waves to reach the illuminated region. As a result of such stroboscopic illumination, the instantaneous US field projections appear frozen in time at the detectors. By adjusting the time delay, different time snapshots of the projections can be observed, providing the Schlieren-WFS system with high temporal control – down to nanoseconds. The WFS field of view and resolution determine the upper limit of the measurable US frequency, a threshold that can be improved using a different magnifying system. Hydrophone scanning is used to compare and verify the results obtained by our method. The hydrophone is fixed at the bottom of the tank and an XYZ stage allows the scanning by moving the US source through the three axes.

3. RESULTS AND DISCUSSION

To test the feasibility of the WFS-Schlieren system for 3D-pressure field measurements, we measured the US pattern generated by a bowl-shaped piezoelectric transducer, with a focus position of 14.5 mm. We compared the results of our methods with numerical simulations using a MATLAB open-source toolbox called *k-Wave* [7], which enables simple and efficient simulation of time domain wave propagation. Moreover, as a benchmark, we also performed measurements using a needle hydrophone over the same US region, a procedure that took 4 h to complete. Fig. 3 shows the results obtained when driving the US transducer at 3 MHz. We plot the XY and XZ orthogonal slices of the pressure field obtained using our method, using the needle hydrophone, and using simulations. The XY orthogonal slice of the reconstructed US pattern at z = 0 mm features an axisymmetric ring pattern, with a high-pressure central lobe of 1.5 MPa surrounded by low-pressure rings. Along the *z* direction, the pressure field exhibits an axisymmetric distribution, covering a range of pressures from -1.5 to 1.5 MPa.

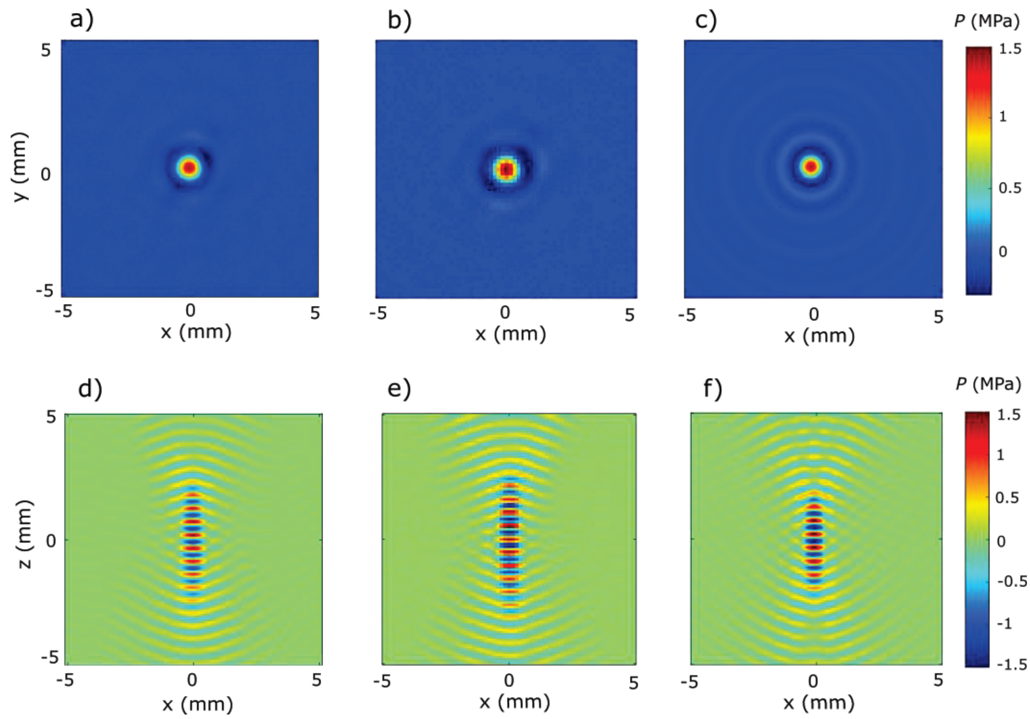

Figure 3. XY (a) and XZ (d) reconstructed pressure maps obtained using our method. XY (b) and XZ (e) pressure maps obtained with hydrophone scanning. XY (c) and XZ (f) simulated pressure maps.

From this pressure map we can calculate the US wavelength, which is 0.49 mm, as expected for the acoustic frequency used in this experiment. For a more quantitative comparison between the WFS-Schlieren system and the needle hydrophone, we plotted the central pressure profiles along the x and z directions, respectively (Fig. 4). Note the exceptional agreement between the two techniques. Still, there is a significant difference between the two methods. The acquisition with the needle hydrophone took 4 hours. Instead, considering the rotation velocity of 18º/s that we used for the tomography measurements, the Schlieren projections were acquired in just 10 seconds. Therefore, our technique allowed a speed improvement of over 3 orders of magnitude compared to the state-of-the-art hydrophone scanning system.

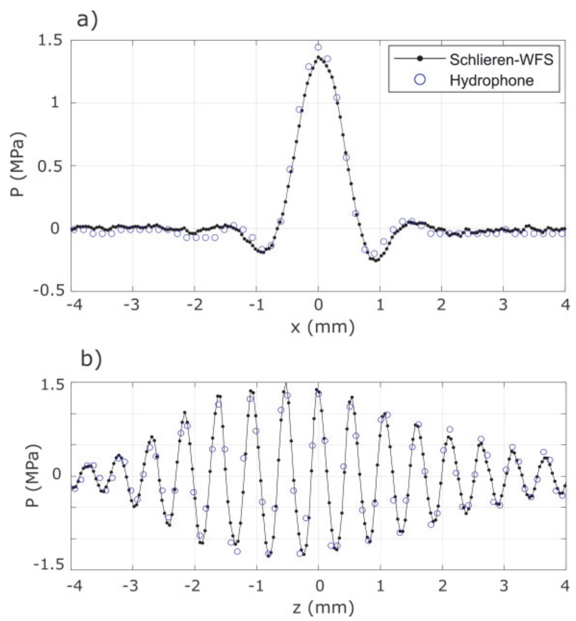

Figure 4. Central pressure profiles along the x-axis (a) and y-axis (b). The Schlieren-WFS results are shown in black, while the hydrophone values are plotted in blue.

4. CONCLUSIONS

The combination of Schlieren tomography with wavefront sensing enables the direct and rapid quantification of 3D pressure fields at sub-millimeter resolution. The method does not require any calibration step and can be implemented in most systems at ease, and not only in water but also for US measurements in any other transparent medium like a fluid or a solid crystal. As our results demonstrate, the reconstructed US field generated by a focused transducer is in excellent agreement with needle hydrophone scanning and numerical simulations. We anticipate that this technique will help to democratize the use of optical systems for real-time quantitative pressure measurements.

5. ACKNOWLEDGMENTS

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