Tomographic Schlieren Imaging for Measurement of Beam Pressure and Intensity

Todd A. Pitts, James F. Greenleaf, Jian-yu Lu, and Randy R. Kinnick

Biodynamics Research Unit, Department of Physiology and Biophysics
Mayo Clinic and Foundation, Rochester, MN 55905 U.S.A.

Abstract—The visualization of ultrasonic fields via acousto-optic interaction is an old technique. Shadowgraph and schlieren imaging produce data representing a line integral related to pressure and time-average intensity, respectively. These "projections" can be used in computed tomography. We have compared the reconstructed pressure distribution in a plane obtained via tomographic inversion with those obtained by mechanically scanning a 0.5 mm calibrated hydrophone through the same plane. Schlieren methods result in the reconstruction of a time average intensity approximation. Shadowgraph methods reconstruct pressure at a given point in time. The advantage of the tomographic methods is that they can be done quickly. A fully automated system could produce a three-dimensional image of an ultrasound beam in a few minutes.

I. INTRODUCTION

A thorough understanding of the relationship between the three-dimensional fields produced by ultrasound transducers and the structure of the transducers themselves is a topic of both commercial and scientific interest. Efficient measurement of various field parameters is germane to the safe, optimal operation of medical ultrasound equipment. The development of practical methods to accomplish these tasks has been pursued for many decades. Many researchers have sought to exploit the interaction between light and sound as an elegant and efficient means of doing both.

Since the first observations of Debye and Sears and Lucas and Biquard it has been well known that an acoustic field produces variations in the refractive index of its supporting medium [1]. These variations have been shown to be proportional to a physical parameter of the medium called the adiabatic piezo-optic coefficient. As an electromagnetic wave passes through a medium in which such variations are present it diffracts. A rigorous and complete description of this phenomenon has been sought for many decades and is still a topic of much current research. However, if the pressure variations are small and the distance over which the electromagnetic and acoustic fields interact is short, it has been shown that passing a laser (plane electromagnetic wave) through a volume of water in which small refractive index variations are present (due to an ultrasound field) allows one to gather data suitable for tomographic reconstruction of these variations [2]. These data may then be related via the piezo-optic coefficient to the pressure field. It has also been shown that suppression of the energy passing straight through the imaging volume together with a lack of synchronicity between the laser and ultrasound pulses produces data which can be used to tomographically reconstruct the distribution of time averaged power [3,4]. In this series of experiments we compare images obtained from shadowgraph and schlieren projections to investigate the relative utility of each.

II. THEORY

Assume the pressure distribution (Fig. 1) to be accurately modeled by

$$p(x,y,z,t) = \hat{p}(x,y,z) sin(w_a t - k_a z + \phi(x,y,z)). \tag{1}$$

It has been shown that if all but the first two diffraction orders can be neglected, the EM-field intensity in the exit plane of the light is [2,5]

$$I(x,t) = 1 + \hat{v}(x)\cos\left(w_a t + \overline{\phi}(x)\right), \tag{2}$$

1051-0117/94/0000-1665 $4.00 © 1994 IEEE

where

$$\hat{v}(x)\exp\{i\overline{\phi}(x)\} = k_a\frac{\partial n}{\partial p}\int \hat{p}(x,y)\exp\{i\phi(x,y)\}dy. \tag{3}$$

This corresponds to using the shadow stop in Fig. 1.

If all orders *except the zeroth* are retained and the acoustic field is weakly focused ($\phi(x,y) \ll 2\pi$), it has been shown that [4]

$$I(x) = C\left(\int \hat{p}(x,y)dy\right)^2 \tag{4}$$

where C is a constant. This experiment is performed using the schlieren stop shown in Fig. 1.

III. EXPERIMENT

Shown in Fig. 1 is a diagram of the experiment used to gather the data. A laser beam passes through an expanding lens prior to entering the imaging volume. After passing through the imaging volume and diffracting, the light is then focused by another lens. The electromagnetic field intensity distribution in the focal plane of the lens then corresponds to the spatial Fourier transform of the EM-field incident on a plane immediately in front of the focusing lens.

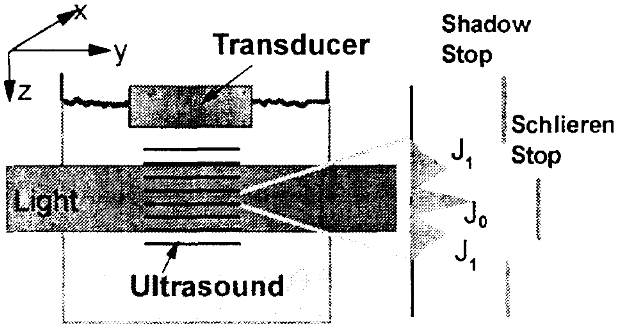

Fig. 1. Schematic of the experiment used to gather both schlieren and shadowgraph data.

When creating schlieren images a *dot* stop is present in the focal plane at the origin of the Fourier space coordinates. Because the energy passing through the focus of the lens corresponds to rays passing straight through the imaging volume, this stop prevents (in an approximate sense) such energy from reaching the image plane. When producing a shadowgraph, the optics are adjusted so as to effectively remove this stop from the light path allowing light passing directly through the imaging volume to be received at the CCD camera shown in Fig. 2.

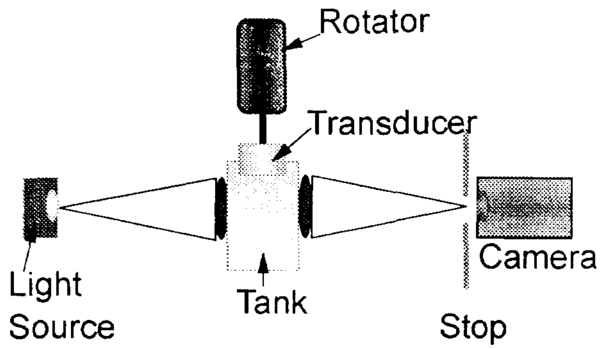

Fig. 2. Schematic of basic tomographic experiment.

In this experiment we used a commercial unit[1] with an expanded IR laser detected with a CCD video camera at 20 samples/micron (Fig. 2). The sound and laser were pulsed up to 100 times per video frame. The video images were stored for background correction and computed tomography. Two hundred equispaced views were taken while rotating the transducer through 180 degrees. Tomographic reconstruction was used to obtain three-dimensional images of the pressure distribution (shadowgraph) and time-average intensity (schlieren) produced by various transducers operating in the 1.0 to 3.5 MHz range. The three-dimensional nature of data collected in this fashion allows the pressure field to be rendered using standard medical imaging rendering techniques.

IV. RESULTS

Here we present several results obtained via the experiment described in the theory section. Figures 3 and 4 show a projection of the classic double-slit experiment using both shadowgraph and schlieren techniques. Figures 5 and 6 compare reconstructions of pressure and time-average intensity with

---

[1] Optison, Intec Research, Sunnyvale, CA.

hydrophone scans of approximately the same physical plane. From these images it can be seen that the shadowgraph reconstructions provide more detail about field structure than those obtained in a schlieren experiment. Figure 7 shows two volume rendered views of a pulse obtained from schlieren data. Schlieren data, due to the high signal-to-noise ratio, are more easily rendered after reconstruction than those obtained via a shadowgraph experiment.

V. CONCLUSIONS

Acousto-optic interaction can be effectively exploited to study and measure parameters of ultrasound fields. Such three-dimensional information is obtained in a noninvasive manner and can provide high resolution as well as high throughput for both commercial and scientific purposes. Further study into the nature of such measurements will be directed at expanding the range of the field parameters that can be measured and developing signal processing algorithms capable of increasing the accuracy and intelligibility of the information obtained via schlieren and shadowgraph imaging methods.

VI. ACKNOWLEDGMENTS

This work was supported in part by grant CA 43920 from the National Institutes of Health.

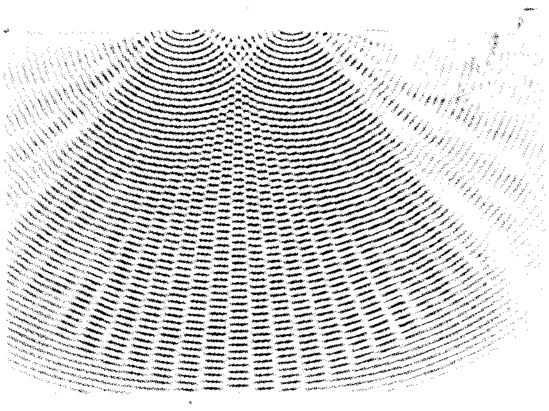

Fig. 3. Projection of the classical double-slit experiment using the shadowgraph configuration.

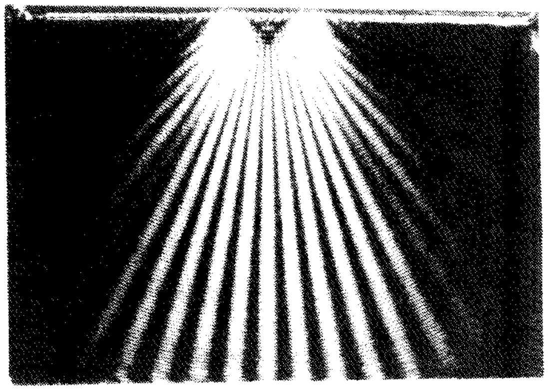

Fig. 4. Projection of the classical double-slit experiment using the schlieren configuration.

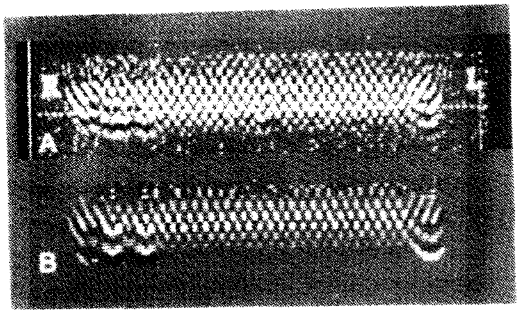

Fig. 5. Comparison of linear array field reconstruction from shadowgraph (A) projections with hydrophone (B) scan of same physical plane.

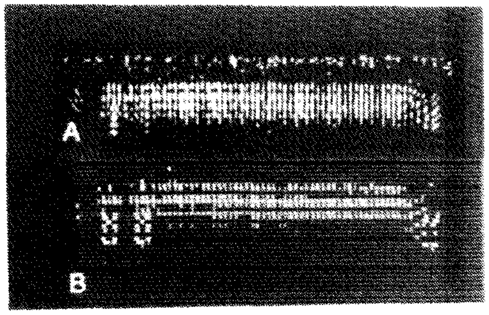

Fig. 6. Comparison of linear array field reconstruction (A) from schlieren projections with hydrophone scan (B) of same physical plane. The hydrophone data have been manipulated to obtain an approximation to time average intensity.

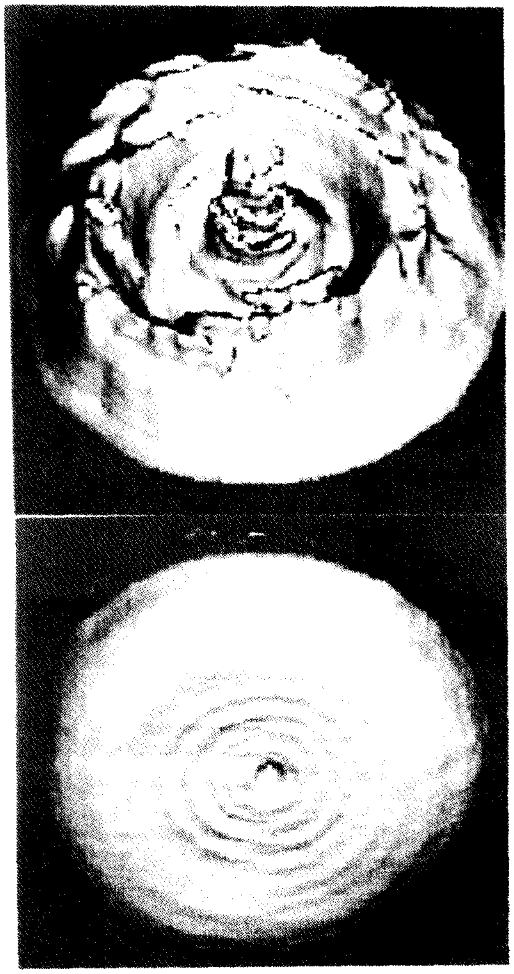

Fig. 7. Rendering of pulse from schlieren data. Top – back side, bottom – front side.

VII. REFERENCES

[1] C. V. Raman and N. S. N. Nath, "The diffraction of light by high frequency sound waves: Part I," *Proceedings of the Indian Academy of Sciences*, vol. 2, pp. 406–412, 1935a.

[2] R. Reibold and W. Molkenstruck, *Ultrasonic Exposimetry*. Boca Raton, FL: CRC Press, Inc., 1993, ch. 5, pp. 143–162.

[3] B. D. Cook, "Measurement from the optical nearfield of an ultrasonically produced phase grating," *Journal of the Acoustical Society of America*, vol. 60, no. 1, pp. 95–99, July, 1976.

[4] A. Hanafy and C. I. Zanelli, "Quantitative real-time pulsed schlieren imaging for ultrasonic waves," *Ultrasonics Symposium*, pp. 1223–1227, 1991.

[5] R. Reibold, "Light diffraction tomography applied to the investigation of ultrasonic fields. II. Standing waves," *Acustica*, vol. 63, p. 283, 1987.