Quantitative Analysis of Pulsed Ultrasonic Beam Patterns Using a Schlieren System

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***Abstract*—The acoustic output from pulsed ultrasonic transducers has traditionally been analyzed with a hydrophone. Recently, a new faster technique has been developed using the principles of optical diffraction. This schlieren method allows the direct two-dimensional visualization of the ultrasonic beam as a pulse train. In order to obtain quantitative information in the form of temporal-average acoustic intensity, however, tomographic reconstruction has to be performed. In this study, tomographic reconstruction was achieved by acquiring 250 images over a 180° angle. Automation of the measurement was obtained by using a frame grabber, a stepper motor, and digital delays all controlled by an IBM-compatible computer. Comparisons of the schlieren results to those obtained by a hydrophone are made in terms of both the -3 dB beamwidths and axial profiles. The results demonstrate that the schlieren method may be a more time efficient alternative for the characterization of ultrasonic transducers.**

I. INTRODUCTION

SINCE Raman and Nath first reported in 1935 that ultrasonic waves behave like a phase grating to a propagating light wave [1], optical diffraction methods for analyzing ultrasonic beam patterns have been studied by many investigators [2]–[15]. Recently, a new Optison$^{\text{TM}}$ schlieren system (Intec Research Company, Sunnyvale, CA) capable of detecting transient ultrasonic fields has been developed [16]. This system uses an infrared laser and highly sophisticated optics to create an image of the ultrasonic beam pattern on a charge-coupled device (CCD) camera. To date, it has been used successfully to analyze the continuous wave output of high-intensity focused ultrasonic transducers used for surgery and to measure acoustic pressures in the nonlinear range [17], [18]. Pitts *et al.* [19] used this system along with tomographic reconstruction to qualitatively compare schlieren and shadowgraph results to those of a hydrophone. In this study the system has been utilized to analyze the pulsed output of single-element transducers for the measurement of the beamwidth and axial profile following tomographic reconstruction. Its performance was assessed by comparing these results to those obtained with a hydrophone.

Tomographic reconstruction has to be used to estimate the acoustic beam intensity at a point along the optical path because the gray level of a pixel in an image from this system represents the temporal-average acoustic intensity spatially integrated over the optical path. It was accomplished by collecting 250 of these images over a 180° angle. The gray level intensities in a two-dimensional (2-D) slice, or tomogram, are directly proportional to the average acoustic intensities in this slice from which beamwidth and axial profile data can be extracted.

Currently, the hydrophone method is the gold standard for characterizing ultrasonic transducers, but it has been shown to have many problems [20]. First, the point by point data collection procedure is very time consuming. Therefore, especially in industry where time is a major constraint, this method may be too slow and not cost effective. Although at low frequencies the hydrophone has a desirable flat response, its response at frequencies greater than 15 MHz depends highly on the thickness and construction of its sensing element made of polyvinylidene difluoride (PVDF). Tiny microbubbles can appear on the surface of the hydrophone resulting in inaccurate measurements from the reflection and refraction of sound off the microbubbles. In addition, measurements made off-axis in the lateral direction suffer from an angular response of the hydrophone. This means that the further off-axis a measurement is made, the lower the sensitivity of the hydrophone. Finally, the hydrophone method also depends highly on the performance of both the hydrophone and the measuring equipment.

Some of these problems may be alleviated by using the schlieren method which has the advantage over the hydrophone measurements that it can characterize ultrasonic transducers more quickly. This is because the entire field is visualized at once so that point by point data collection is not necessary. Each image of the field may be acquired in a matter of seconds.

II. THEORETICAL CONSIDERATIONS

The basic theory behind schlieren optical diffraction was first reported by Raman and Nath in which they proposed that high-frequency sound waves behave like a phase grating to a normally incident plane, monochromatic light [1]. This phase grating results from the fact that ultrasonic pressure waves produce a periodic density variation in the transmission medium and thus a change in the index of refraction of the medium. Appropriate optics have been developed to allow the formation of a near-field image of the phase grating onto a film or a video array [6], [7], [16].

Fig. 1 shows the basic configuration of a schlieren system. The laser produces a monochromatic light which is normally incident upon the acoustic output from an ultrasonic trans-

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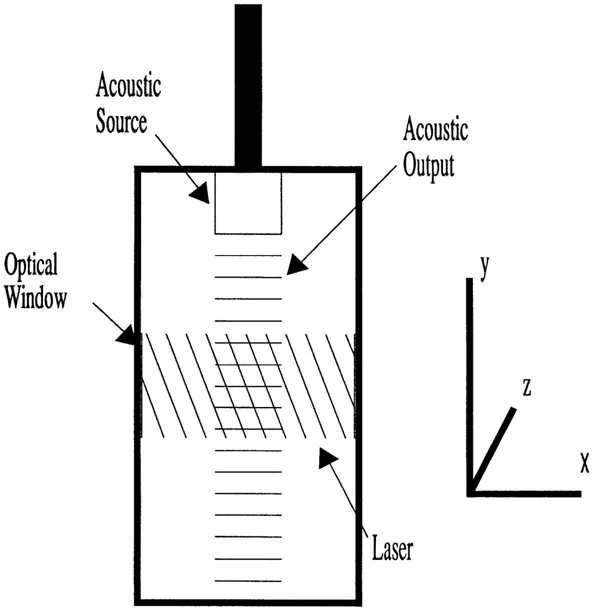


Fig. 1. Basic configuration of a schlieren system.

ducer. Fraunhofer diffraction patterns result from the shifting of the phase of the laser beam which is proportional to the integral of the pressure along the light path [2]. The nth-order resultant normalized intensities of the diffracted light beam are given by

$$I_n = J_n^2(\nu) \tag{1}$$

where J_n is the nth-order Bessel function and ν is the Raman–Nath parameter which represents the maximum optical phase retardation [16]. The maximum local acoustic pressure on a y–z plane is directly proportional to the Raman–Nath parameter given by

$$\nu(y,z) = A\sin(w_a t + k_a y) f_p(z) \tag{2}$$

where A is a constant, w_a is acoustic frequency, k_a is the acoustic wavenumber, and f_p is the line integral of the acoustic peak pressure (p_i) given by

$$f_p(z) = \int p_i(x,z)dx. \tag{3}$$

The video gray level intensity seen in an image is related to the acoustic intensity integrated over the optical path since each image is only a side view of the ultrasonic beam [16]. Using tomographic reconstruction, a 2-D gray level map of any slice at $y = y_0$ may be obtained. This map shows the distribution of gray level in a plane perpendicular to the y axis which is proportional to the acoustic intensity in that plane.

III. MATERIALS AND EXPERIMENTAL METHODS

In order to implement the schlieren method for evaluating ultrasonic transducers, several additional pieces of equipment are necessary; namely, a stepper motor with translator and power supply, a pulser, a function generator, a digital delay circuit, and an IBM-compatible PC equipped with a frame grabber and necessary software. Fig. 2 shows the block diagram of the experimental arrangement.

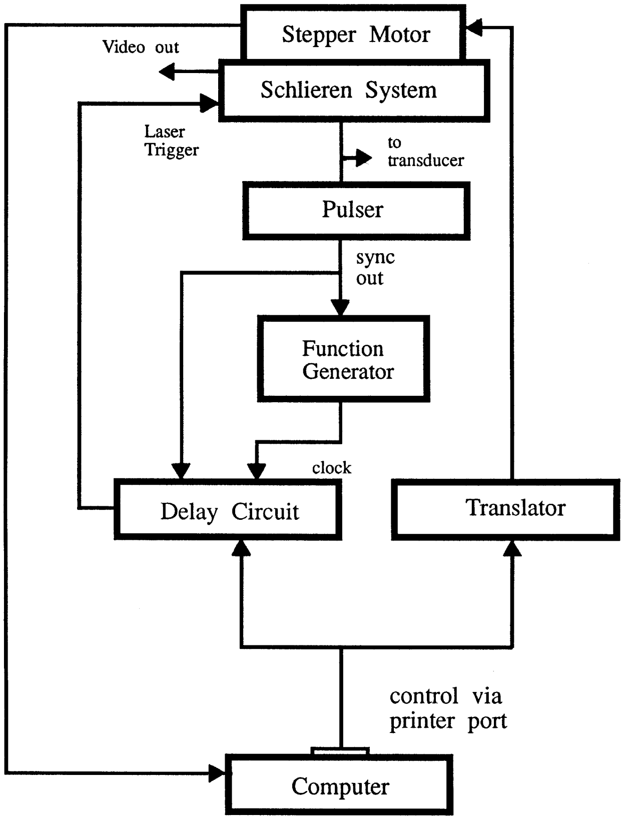


Fig. 2. Block diagram of the experimental arrangement.

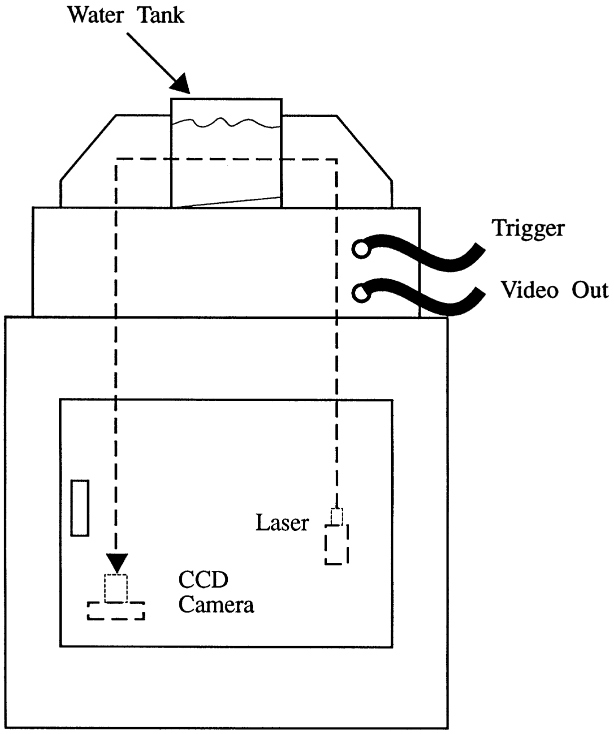


Fig. 3. Configuration of the Optison$^{\text{TM}}$ schlieren system.

The central piece of equipment in the experimental arrangement is the Optison$^{\text{TM}}$ schlieren system shown in Fig. 3. This system consists of a water tank, an infrared laser, a CCD camera for capturing the images, a pump system for water circulation, and sophisticated optical lenses and mirrors located inside the system used for schlieren imaging. The water tank on top of the system is where the experimentation takes place. A transducer is inserted face down into the water for measurements. The bottom of the tank is angled so that reflections will not travel back into the incident acoustic path. One of the limitations of this particular schlieren system is the depth of the tank. Because the tank is only 17.25 cm deep, the measurable distance along the axis of propagation is limited.

For this schlieren system, the light source is an 810-nm infrared laser which fires whenever it is triggered by a TTL pulse. By controlling when the laser fires relative to the transducer and how often the laser fires, one can control where the ultrasonic pulse is imaged along its propagation path and the intensity of the resultant image, respectively. The rate at which the laser fires is also the repetition rate of the transducer. The maximum firing rate of the laser is 7.0 kHz.

A CCD camera is used to capture the image at the focal plane of the optics. The array size is 768 × 493 pixels. This video image is converted to RS-170 format and is available at the output on the front panel. A frame grabber is needed to capture this image and store it for further processing.

The high-resolution optics of the schlieren system make it capable of detecting small particles in the water. These particles will appear on the image, thus affecting results. In order to remove these particles, a water circulation system is needed. A pump is used to circulate the water in the tank through a filter. Also, a temperature gradient will change the index of refraction of the medium. By circulating the water constantly, the heat given off by the transducer will not cause a large enough temperature gradient to affect the resultant image.

The schlieren system has its optical lenses and mirrors enclosed in a dust-free environment for protection. These lenses and mirrors are of very high quality and are used to collimate the laser beam, detect the changes in the index of refraction, and project the schlieren pattern onto the CCD camera. Another limitation of this schlieren system is the size of the optical lenses used. The field of view of each image is only 2.81 cm high and 3.75 cm wide. The field of view can be enlarged by using larger but more expensive lenses. The limited field of view often makes it necessary to move the transducer to find the region of interest. When tomographic reconstruction is performed, it is preferable that the transducer is present in the image in order to find the axis of rotation. Therefore, the total acoustic path with this field of view is limited to about 3.5 cm.

The protocols involved in a typical measurement are as follows. First, the transducer is pulsed. After a predetermined delay, the laser is triggered and fires. The laser beam is normally incident upon the acoustic beam which acts like a phase grating along the optical path. After the interaction, lenses and mirrors are used to obtain and focus the schlieren image on the CCD camera. The image is captured by a frame grabber for postprocessing. It is important to realize that the pulsing of the transducer and firing of the laser occur thousands of times per second so the pulse appears to be stationary in the captured image.

Tomographic reconstruction is necessary to obtain depth information along the optical path. To do so, the transducer was rotated 250 times over a span of 180° achieved by a Superior Electric Slo-Syn® stepper motor (Model M061-FC02) with a Slo-Syn® Translator (Model SS2000MD4). The input to the translator was controlled by the computer. Each step resulted in a 0.1° rotation of the transducer. Therefore, several steps were necessary to rotate the transducer correctly to acquire each of the 250 images over a 180° span.

A Panametrics Pulser (Model 5052UA) was used to excite a transducer and trigger the laser. The synchronous output from the pulser was used to trigger a function generator and was the input to a delay circuit which ultimately caused the laser to fire.

A Wavetek 50-MHz Pulse/Function Generator (Model 81) was used to generate a 3.23-MHz square wave burst lasting 262 cycles with an amplitude of +5 V. This burst was triggered by the synchronous output of the pulser. It was used as a TTL input to a clock in the delay circuit. The high frequency was necessary in order to have an adequate precision for the delay being generated.

The delay circuit was a programmable delay controlled by an IBM-compatible PC. The delay was varied so that the distance that the pulse appeared from the transducer might be varied. Therefore, it determined the axial distance where the pulse output from the transducer would be seen and captured. The delay ranged from 2 to 81 μs depending on the count set by the computer. Since sound waves travel at 1500 m/s in water, this delay corresponds to a possible range of axial distances of 0.3 to 12.2 cm from the face of the transducer.

The IBM-compatible PC controlled the delay circuit and stepper motor through the printer port as well as the frame grabber in order to acquire and store a train of pulses for each of the 250 images needed for tomographic reconstruction. Each pulse from the printer port of the computer decreased the delay by one clock cycle, or 0.31 μs. Another output from the printer port was used to reset the delay to its original value. A TTL pulse input to the Slo-Syn® Translator from the printer port stepped the motor in increments of 0.1°.

The Data Translation Frame Grabber card (DT2867) in the computer was programmed to combine regions from several images to create a pulse train which was then saved as one of the 250 images needed for reconstruction. This was possible because the frame grabber has an on-board buffer where the image can be temporarily stored and added. Each region was 16 × 480 pixels. Therefore, pieces from several images might be fused together to obtain a pulse train image which was 640 × 480 pixels.

A program was written in C to control all of these functions. The basic flow of the program is as follows. First, the motor was stepped to the appropriate position for acquiring the first image. Next, the delay circuit was set to the initial delay for acquiring the farthest pulse of the train. The region containing this pulse was then grabbed and stored in the on-board buffer. After this pulse had been acquired, the delay was decreased and the next pulse in the train was ready to be acquired and added next to the first pulse. This process was repeated until an image of the pulse train was completed. The last region captured was of the transducer itself. This was necessary in order to be able to detect the axis of rotation during the tomographic reconstruction. Now that one of the 250 images was completed, it was stored on the hard drive, the motor was stepped, and the next pulse train was acquired.

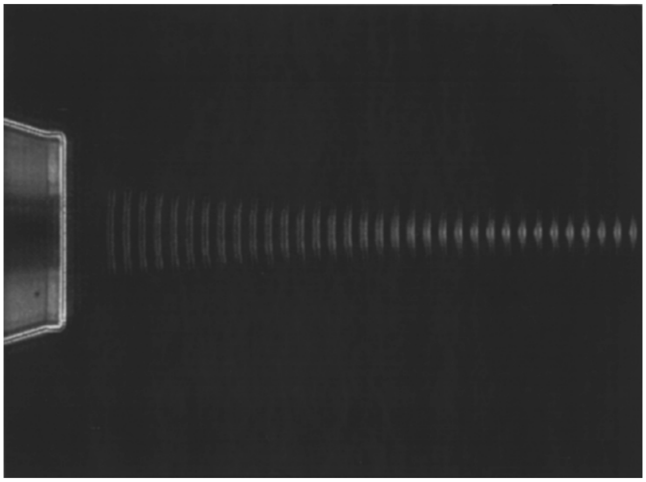


Fig. 4. Pulse train image for 15-MHz focused transducer.

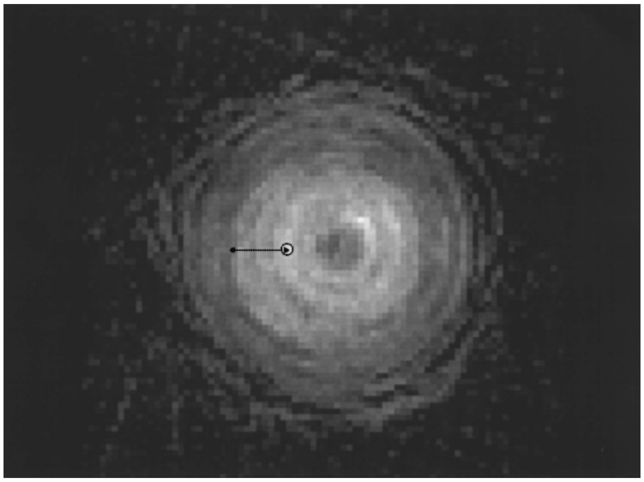
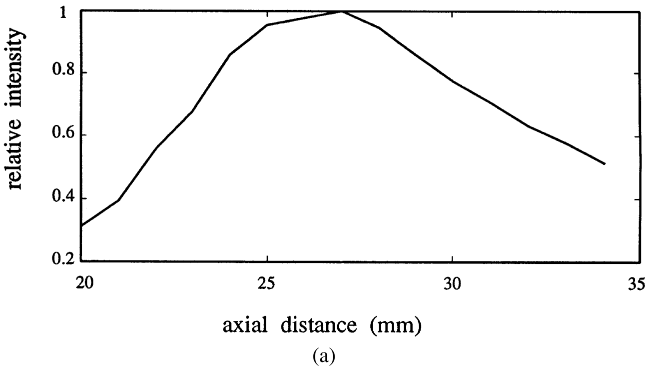


Fig. 5. Tomogram reconstructed from schlieren data showing maximum (circle) and beamwidth (line) in one direction.

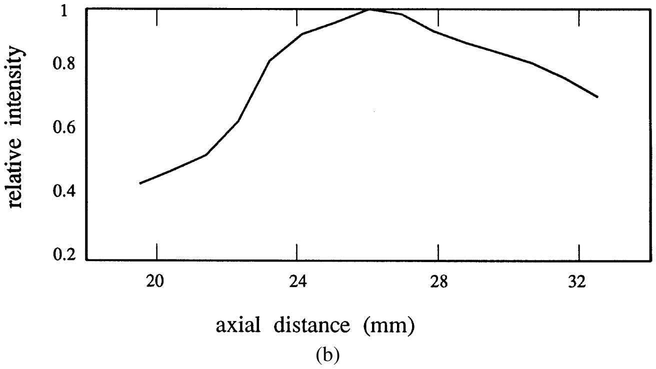
This continued for about 75 min until all 250 images were captured and stored. Using the hydrophone method, collecting a similar amount of data would last several hours.

The next step of the process was to perform the three-dimensional (3-D) reconstruction from the 250 acquired images, which was accomplished by a filtered backprojection tomographic reconstruction algorithm provided by Intec Research Company. This software allowed any vertical slice of the image to be reconstructed. The slice was 1 pixel wide by either 120, 240, or 480 pixels high. Once this slice was selected, a sinogram composed of all slices from the 250 images was composed and used for the tomographic reconstruction. After the reconstruction was completed, a 2-D rendering of the slice was performed. The gray level in this image is proportional to the temporal-average acoustic intensity. Therefore, by calibrating the gray values from this image with those obtained by the hydrophone method, intensity and peak pressure may be obtained.

To ensure that there were no bubbles and impurities in the water, degassed water was used. and the pump was run for about 10 min before acquiring images. If the water was not degassed, bubbles could have been present in the images acquired and also on the face of the transducer.



(a)



(b)

Fig. 6. Axial intensity profiles for 15-MHz focused transducer obtained with (a) hydrophone method and (b) schlieren method.

IV. RESULTS

For this study, a 15-MHz focused transducer of 0.635 cm diameter was used. The focus of this transducer is 2.5 cm. The results obtained were then compared to those obtained with a membrane hydrophone of 0.06-cm diameter spot size (Sonic Technologies, Hatboro, PA). One of the 250 pulse train images is shown in Fig. 4.

In performing measurements with a hydrophone, the exact acoustic beam axis was difficult to locate. In order to minimize this problem, the following procedure was used. The hydrophone was first placed as close to the acoustic axis as possible at a set axial distance and then was moved up, down, right, and left collecting data points. To construct an axial profile, the maxima in these four directions were averaged at each axial distance. To measure the −3 dB beamwidth, first the maximum was found and then the hydrophone continued to move in that direction until the −3 dB point was reached. Again, the beamwidths from the four directions at each axial distance were averaged.

The reconstructed slices from the schlieren method were analyzed in the same way even though the acoustic axis was more evident in these slices. Fig. 5 shows a reconstructed slice taken at 19.5 mm along the acoustic axis. The maximum in one of the four directions is noted by a circle along with the beamwidth. Maxima and beamwidths in all four directions were collected in the slice. These values were averaged to obtain the beamwidth and axial profile at this axial distance. Fifteen slices from the 15-MHz focused transducer were analyzed to construct an axial profile and the profile of −3 dB beamwidths.

Fig. 6 shows the axial intensity profiles obtained with the hydrophone method and the 3-D schlieren method. The

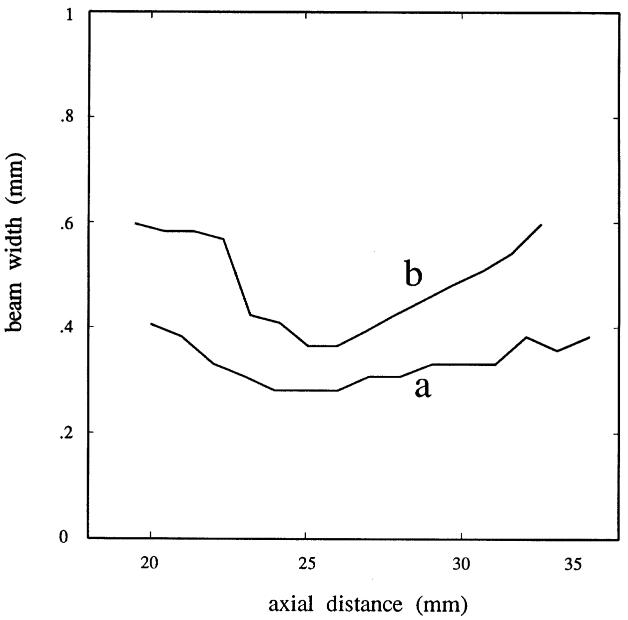
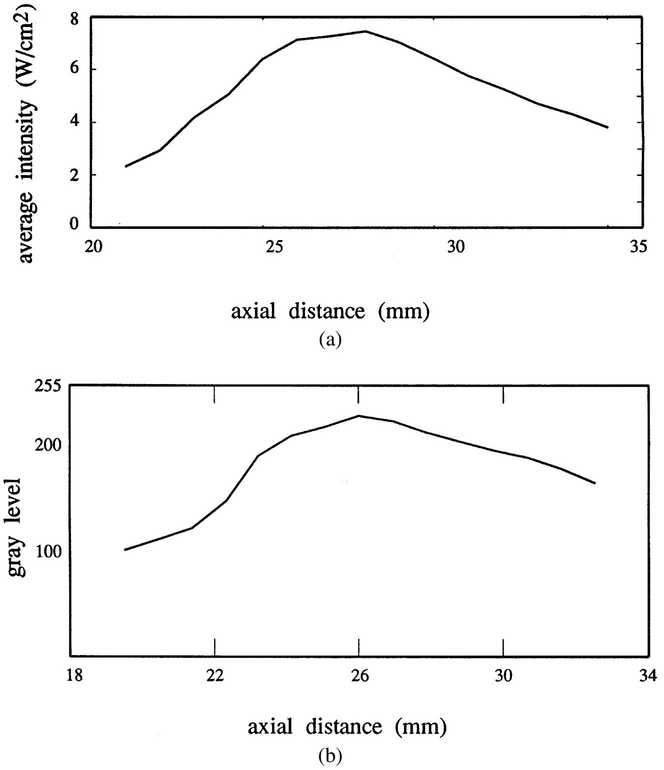


Fig. 7. The -3 dB beamwidths for 15-MHz focused transducer obtained with (a) hydrophone method and (b) schlieren method.



(a)

(b)

Fig. 8. Axial profile expressed as (a) average intensity for hydrophone results and (b) gray level for schlieren results.

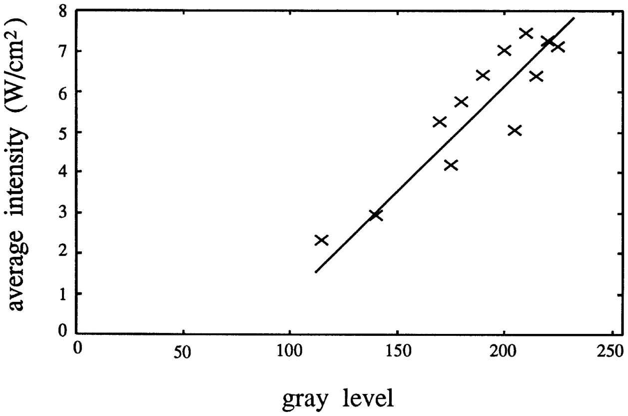


Fig. 9. Calibration curve for laser rate of 500 Hz.

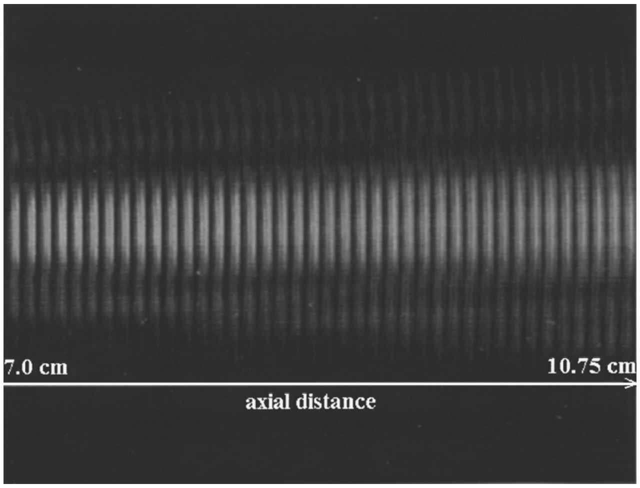


Fig. 10. Schlieren results from 7.5-MHz 128-element linear array showing the main lobe and sidelobes of the beam.

peak intensity is seen to occur at approximately 2.7 cm for both methods. The relative intensity profiles at other axial distances in the far field seem to be in good agreement and do not deviate more than 17%.

It is important to note that the hydrophone measures peak pressures, whereas the gray value measured by the schlieren method is proportional to the average acoustic intensity. The relationship between the light intensity or gray level and the peak pressure in the linear range is given by

$$I = \alpha P^2 \tag{4}$$

where α is a constant and P is the peak pressure [16], [19]. For a valid comparison, the hydrophone data must be squared.

Fig. 7 shows the -3 dB beamwidths obtained with the hydrophone and tomographic schlieren methods. The results agree well near an axial distance of 25 mm where the beam was the narrowest. At this distance, the schlieren and hydrophone results show, respectively, beamwidths of slightly greater than 0.30 mm and slightly less than 0.30 mm. Although both the schlieren and hydrophone results exhibit linear increases of the beamwidths in the far field, a discrepancy in the results is observed. In the near field, the results from both methods show a complicated behavior.

Since the tomographic schlieren data are proportional to the average acoustic intensity, a calibration may be made in order to extract quantitative intensity information from them. Using the axial intensity curves shown in Fig. 8, a calibration of the schlieren results with the hydrophone data is possible. The hydrophone data were acquired in microvolts before amplification and are related to pressure by a calibration curve supplied by the manufacturer.

Fig. 8(a) shows the intensity axial profile measured by a hydrophone method, whereas the schlieren results shown in Fig. 8(b) are expressed as a gray value from 0 to 255. A calibration curve may be obtained from tomographic reconstruction as seen in Fig. 9 relating video gray level to the temporal-average acoustic intensity. Using this curve, the gray level in a schlieren tomogram at a laser firing rate of 500 Hz may be readily converted to an acoustic intensity.

Extending this method to the characterization of linear arrays is also possible. Preliminary results are shown in Fig. 10 for a 7.5-MHz linear array with 128 elements. The transducer was positioned with long axis of the array probe parallel to the optical path so the vertical axis of this image represents the elevational direction of the array or slice thickness of imaging plane whereas the horizontal direction represents axis of the acoustic beam. Sidelobes may be seen to exist above and below the main beam.

V. DISCUSSION AND CONCLUSION

The axial profile obtained by the schlieren system is in good agreement with that obtained by the hydrophone. The results for beamwidth measurements with the hydrophone and schlieren system, although in agreement where the beam width is narrowest, show a slight discrepancy for the results in the far field.

There are three possible reasons for the discrepancy. First, the tomographic reconstruction of the schlieren results is not as accurate as the point by point measurement with a hydrophone. Tomographic reconstruction relies on estimating where the center of the acoustic beam is and assuming a perfect rotation. Another reason for the discrepancy is that the membrane hydrophone has a finite aperture and an angular response due to its effective diameter of 0.6 mm which may cause spatial averaging and error in the measurements. However, these effects are less significant in the far field of the transducer. Finally, the fixture supporting the transducer might not be sufficiently rigid and straight, causing the transducer to wobble slightly as it was rotated over 180°.

One of the main limitations of the schlieren method is the small field of view in the axial direction. Tomographic slices may be reconstructed only at axial positions where the transducer appears in the field of view. Eliminating this limitation will allow for the characterization of a wider range of transducers.

Experimental results obtained in this study demonstrate that the schlieren method is both a fast and accurate method for determining the acoustic field characteristics of an ultrasonic transducer. Although the results obtained with the schlieren system and the hydrophone are in good agreement, further improvements are still necessary to achieve the desired accuracy and range in measurements. Finally, it is shown that by calibrating the results obtained by the schlieren system, a quantitative measurement of the average acoustic intensity from the gray level is possible.

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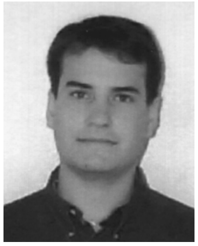

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K. Kirk Shung (S'73–M'75–SM'89–F'93), for a photograph and biography, see p. 481 of the May 1996 issue of this TRANSACTIONS.