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A simple Schlieren system for visualizing a sound field of pulsed ultrasound

N Kudo 1, H Ouchi 1, K Yamamoto 1 and H Sekimizu 2

1Graduate School of Information Science and Technology, Hokkaido University, N14W8, Kita-ku, Sapporo, 060-8628, Japan
2Fukuda Denshi Co., LTD, Hongo, Bunkyo-ku, Tokyo, 113-8420, Japan

E-mail: kudo@bme.eng.hokudai.ac.jp

Abstract. A new Schlieren method for visualizing an acoustic field of pulsed ultrasound was proposed, and a system was developed to evaluate the validity of the proposed method by visualizing an acoustic field of a focused ultrasound field of diagnostic frequency range. A conventional Schlieren optical system is not used in the developed system. The system uses a short-pulsed laser, a CCD camera with a wide dynamic range, and a PC that processes images captured by the CCD camera. In the proposed method, extraction of light diffracted by ultrasound is carried out by subtraction of images captured with and without ultrasound exposure. The usefulness of the developed system was confirmed by an experiment in which acoustic fields of a 5-MHz focused transducer were visualized. Good agreement was found between the visualized and simulated ultrasound fields.

1. Introduction
Measurement of acoustic fields is a basic technique used for not only development and design of diagnostic and therapeutic ultrasound equipment but also quality control of these equipment. In the field of diagnostic ultrasound equipment, a mechanically scanned hydrophone has been used as the golden standard of three-dimensional pressure distribution measurement. Schlieren imaging is another method for evaluating pressure distribution of ultrasound. This method uses an optical technique instead of mechanical scanning of a hydrophone. Although the use of this technique can provide useful information for applications such as quality control, this technique has limitation in accuracy for evaluating a three-dimensional acoustic field of a diagnostic ultrasound probe because a two-dimensional Schlieren image is given by the integral of three-dimensional pressure intensities.

The Schlieren method requires high-quality optical elements because this method is very sensitive
to phase distortion of light. Aberration and scratches in the Schlieren optical elements directly cause poor contrast and fidelity of the Schlieren image. Therefore, a Schlieren system generally becomes large size and expensive. We have developed a simple Schlieren system for visualizing an acoustic field of pulsed ultrasound that does not use a conventional Schlieren optical system, and the usefulness of this system has been confirmed by an experiment to visualize the acoustic field of a 5-MHz focused transducer.

2. Method

A plane wave ultrasound field works as a phase grid, and the light that enters at a right angle will be diffracted by this grid. A typical Schlieren optical system consists of a point light source, two lenses and one optical stop. Extraction of light diffracted by ultrasound is carried out by the optical stop.

Figure 1 shows the principle of the proposed method. In this method, two images are captured for visualization of the ultrasound field: one is an image obtained under the condition of ultrasound exposure (image (a)), and the other is an image obtained without ultrasound exposure (image (b)). In image (a), light diffracted by an ultrasound pulse is superimposed on non-diffracted light, and there are no diffracted components in image (b). Therefore, subtraction of image (b) from image (a) will give an equivalent image with a conventional Schlieren image. Since there is no need to use high-quality optical elements in this method, considerable simplification of the observation system can be achieved.

Figure 2 shows a block diagram of a system developed for validation of the practical usefulness of the proposed method. The Schlieren method was first used to visualize a temporally averaged image of CW ultrasound; however, this method is now applied to visualize a field of pulsed ultrasound by using the stroboscopic imaging technique [1]. This technique is also used in the developed system. A pulsed laser diode of 0.2 ns in pulse duration (Hamamatsu Photonics, SLDH-081C) was used to visualize an instantaneous acoustic field of pulsed ultrasound. Controlled delay between ultrasound and laser pulses allows visualization of time-sliced images of pulse propagation. Since the intensity of non-diffracted light is much greater than that of diffracted light, a low noise CCD camera with a wide dynamic range was used. A focused transducer of 5 MHz in center frequency (Panametrics, M307) was used in the experiments. The peak pressure at the focal point was about 7 MPa.

![Figure 1. Principle of the proposed Schlieren imaging method.](image)
3. Results and discussion

Figure 3 shows visualized acoustic fields of the focused transducer. Images (a1), (b1) and (c1) show acoustic fields near the focal point of the transducer. Difference in focusing effect was visualized in these images. Images (a2), (b2) and (c2) are results of two-dimensional simulation. There is good agreement between the results of the experiment and simulation.

Figure 4 shows a comparison of pixel intensities of Schlieren images and the pressure amplitudes measured by a membrane hydrophone (NTR, MHA500B) at the focal point of the transducer. Since the pixel intensities were not calibrated, both results were normalized by values at maximum driving pressure. As shown in the figure, good agreement was found in driving-voltage dependence of the two values.

The spatial resolution depends on the pixel size of the CCD device and optical magnification of the lens attached to the camera. The temporal resolution depends on duration of the light pulse and also on spatial resolution. Since the light pulse duration is sufficiently short, 0.2 ns, the spatial resolution also dominantly determines the temporal resolution. Since improvement of spatial resolution is easily achieved by using a high-magnification optical system, it is thought that the proposed method is suitable for visualizing an acoustic field of a small-size high-frequency transducer.

Figure 3. Visualized and simulated acoustic fields of a focused transducer.

Figure 4. Comparison of pixel intensities of Schlieren images and pressure amplitudes measured by a membrane hydrophone at the focal point of the transducer.
4. Conclusions
A new method for Schlieren imaging that can be used for visualization of a pulsed ultrasound field of diagnostic ultrasound equipment was proposed. In this method, the high-quality Schlieren optical system was replaced with a CCD camera and simple image subtraction, making the system very simple. An experimental system was constructed, and acoustic fields of a 5-MHz focused transducer were visualized. The results of field imaging and hydrophone measurement showed good agreement.

5. References
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