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Schlieren metrology for high frequency medical ultrasound

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Abstract

The increased use of medical ultrasound above 40 MHz poses the challenge of measuring beam features that may be less than 40 μm. We have successfully used the optical Schlieren technique for transducers operating as high as 110 MHz. After a brief discussion of the technique, results are presented, including comparisons to state-of-the-art hydrophones and wire targets.

Keywords: Schlieren; Metrology; Acousto-optic; Beamwidth

1. Introduction

Developing an ultrasonic system for medical imaging necessitates measurement of focal beam characteristics. Such data are important for verification of an acoustic design – for example, to verify focal location, beam symmetry, and characterize sidelobes. Additionally, measurement of the beamwidth provides an objective measure of resolution. It is also worth noting that a measurement of the focal beamwidth is important safety information required by regulatory bodies, because it allows an estimate of maximal intensity when the total output power is divided by the focal area [1].

The increased use of medical ultrasound above 40 MHz poses the challenge of measuring beam features that may be smaller than 40 μm, even smaller than the effective aperture of all available hydrophones. Alternatively, pulse echo measurements can be made with a wire target [2], but the small diameter of the wires used can result in small signal-to-noise ratios, and alignment is time consuming.

Schlieren imaging offers a fast, high-resolution alternative to both hydrophone and wire target measurements. Fig. 1 shows a sketch of the apparatus, which, as described in detail elsewhere [3], optimizes the optics of classical Schlieren imaging, and combines this with a digital frame grabber. Digital image analysis techniques can then be applied to quantitatively determine the focal point, width, and sidelobe levels of the beam [3,4]. The embodiment discussed here uses a 904 nm solid state laser pulsed at 6.0 kHz with a pulse width of 25 ns, triggered to the excitation of the transducer as shown in Fig. 1. The resolution is 16 μm. We will restrict our discussion to examining quasi-continuous excitation of the transducer, because it allows one to see an entire beam at once, and because "jitter" in the pulsing synchronization is not low enough to allow visualizing individual wavelets at these frequencies. In principle, however, this apparatus could be used to capture short bursts down to one cycle of transducer excitation, provided that pulsing electronics with correspondingly high stability are used.

2. An example

As an example, we present data obtained with a focused Lithium–Niobate transducer operating at 50 MHz. This transducer has an active diameter of 3 mm and geometric focus of 6 mm. It was driven by a tone burst of 20 Vpp and 50 cycles long, with a pulse repetition frequency of 2 kHz. The beam pattern was estimated theoretically by numerical evaluation of the Rayleigh–Sommerfeld integral [5], leading to the theoretical result shown in Fig. 2, which shows a −3 dB beamwidth of approximately 60 μm.

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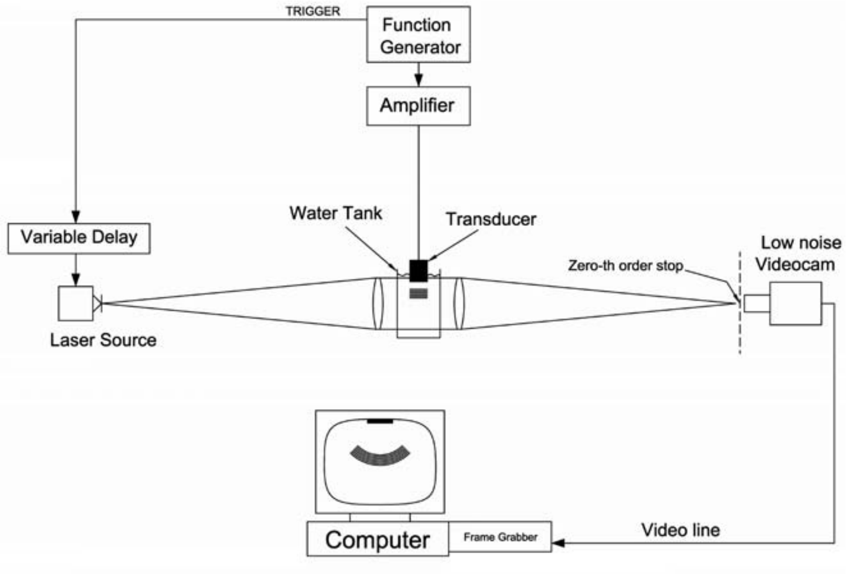

Fig. 1. Schematic of Schlieren system.

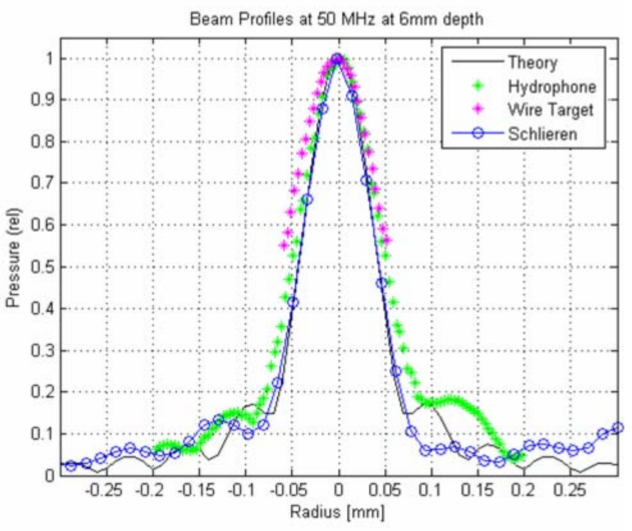

Fig. 2. Beam profiles at 50 MHz at 6 mm depth.

The transducer beam was next measured by carefully aligning it to an 85-μm diameter hydrophone (HGL-0085, manufactured by Onda Corporation), and scanning the transducer across the hydrophone. This hydrophone design has a flat frequency response out to at least 50 MHz [6] so we extrapolated the available 20 MHz calibration out to 50 MHz in order to estimate the size of the signal. From the 220 mVpp measured by the hydrophone, we estimate that the size of the pressure signal was 8.5 MPa, peak-to-peak.

The transducer was then aligned to a 25-μm thick Tungsten wire, and scanned transversally. The return signal was obtained by tapping the transducer-pulser junction with a high impedance scope probe in order to detect the return echo so as to produce a two-way beamplot. The one-way beamplot may be estimated by taking the square root of this signal. The noise level was approximately half the value of the peak signal in this measurement, so data is shown down to a level of 50% of the peak.

Fig. 3 shows a Schlieren image of the beam. The optical background when the beam was off has been subtracted from the image to maximize the signal-to-noise ratio, and the intensity has been mapped to a color scale, with the peak spot in the field mapped to red. A beam profile at 6 mm was then extracted from this image and is shown in Fig. 2, along with the theoretical prediction, as well as the hydrophone and wire target data (the square root of the wire target data is plotted). The theory, hydrophone, and Schlieren data all agree well at least down to 20%

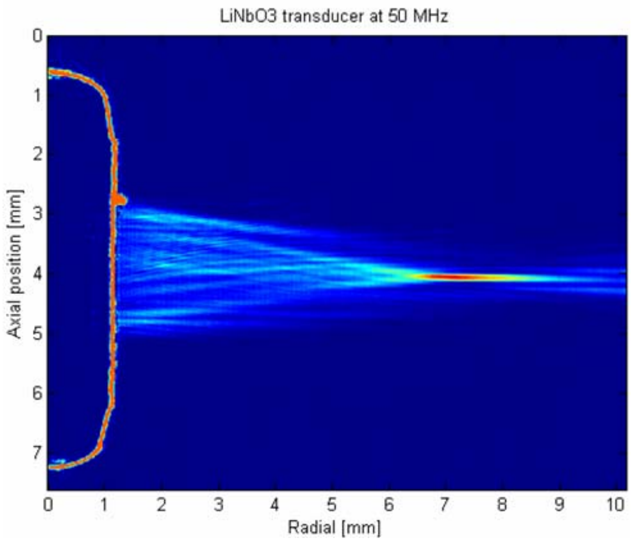

Fig. 3. Schlieren image of beam at 50 MHz.

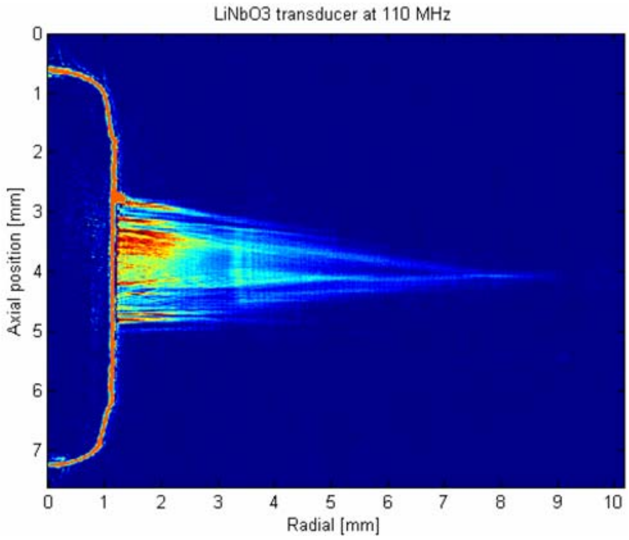

Fig. 4. Schlieren image of a beam at 110 MHz.

below the peak value, and the wire target data agrees until it is corrupted by noise at about 50% of the peak level.

It is worth comparing these three methods in terms of the complexity of their setup as well. Both the hydrophone and wire target measurements required careful alignment to make sure the beam axis was normal to the surface of the hydrophone or target, and orthogonal to the axis of transverse scanning. This requires an iterative process of angular adjustments and scans at different depths [1] and can take a long time. In contrast, once the optical setup is complete for Schlieren, the alignment is far simpler: one only needs to adjust the angular position of the transducer until the brightness of the beam is maximized, which usually is accomplished in seconds.

This same system has been used to make images as high as 110 MHz. Fig. 4 shows an example, using a transducer of the same design as the one imaged in Fig. 3. Note that water attenuation, which is more than 2.5 dB/mm at these frequencies, greatly diminishes the penetration of the beam, so that the peak spot in the field, mapped to red, is in the near field. The bright bands in the image from 3 to 4 mm are due to optical reflections between the lenses; which become noticeable at small signal levels.

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