2D imaging of ultrasound fields using CCD array to map output of Fabry-Perot polymer film sensor

M. Lamont and P.C. Beard

A 2D ultrasound field imaging system that uses a CCD array to map the optical output of a planar Fabry-Perot polymer film sensing interferometer is described. This system enables ultrasound fields to be rapidly mapped over a 6.6 × 4.7 mm aperture with spatial and temporal resolutions of the order of 10 μm and 10 ns, respectively. The concept was successfully demonstrated by imaging the acoustic field at the focus of a pulsed 5 MHz PZT ultrasound transducer. The technique offers an alternative to piezoelectric-based methods for high-resolution biomedical and industrial ultrasonic imaging and field characterisation applications.

Introduction: Mapping broadband ultrasound fields in water, for characterisation or imaging purposes, is most commonly achieved using piezoelectric detectors, either by mechanically scanning a single element or using an array of elements. Limitations associated with piezoelectric detectors include difficulty in achieving the necessary acoustically small element sizes (<100 μm) at MHz frequencies to avoid spatial averaging while retaining adequate detection sensitivity. Additionally, in the case of systems based upon the use of a mechanically scanned element, acquisition speed can be unacceptably low, while the use of a 2D array of detectors to overcome this can be prohibitively expensive on account of the high channel counts required to spatially sample usefully large ($\sim$cm^2) acoustic apertures with adequate resolution.

A promising optical method with potential to overcome these limitations is based upon the detection of acoustically-induced changes in the optical thickness of a planar Fabry-Perot sensing interferometer (FPI) [1–4]. The use of a polymer film FPI in particular has been shown to provide a highly versatile and practical approach to ultrasound detection, capable of providing high sensitivity and a broadband response in the tens of MHz range [1, 2]. By optically addressing different points on the sensor, the lateral spatial distribution of an incident acoustic field can be spatially sampled with a significantly higher resolution than can be achieved with piezoelectric receivers, in principle down to the optical diffraction limit of a few micron. Several methods of mapping the output of this type of sensor have now been demonstrated. These include optically scanning a focused laser beam over the surface of the sensor and detecting the reflected light with a stationary photodiode [5] or illuminating with a large diameter beam and mechanically scanning a photodiode over the reflected sensor output [6]. In both cases, the lateral spatial distribution of the acoustic field incident on the sensor is sequentially mapped as a continuous function of time. In this Letter we describe an approach whereby the incident acoustic field distribution is mapped in parallel at discrete time intervals using a 2D CCD array, the concept being notionally similar to that of an acoustic camera taking snapshots of acoustic field distributions as used to map the output of other optical ultrasound sensors [3, 7]. As well as the benefit of rapid data acquisition afforded by parallel detection, the high element density (typically $>10^3$ elements/mm^2) of even a standard 2D CCD array enables the optical output of the sensor to be spatially resolved over centimetre sized apertures with a resolution of the order of 10 μm – a level of spatial discretisation that would be prohibitively expensive, even if technically feasible, using discrete piezoelectric receivers.

Principles of operation: The underlying principle is one in which a Fabry-Perot (FP) polymer film sensing interferometer is illuminated with a large diameter laser beam and the reflected light imaged on to a 2D CCD array. An incident pulsed acoustic wave modulates the optical thickness of the FP sensor and therefore its reflectivity. The lateral spatial distribution of the incident acoustic field is thus mapped on to the optical beam reflected from the sensor and spatially resolved using the CCD array. Since the exposure time of a standard CCD is of the order of tens of milliseconds, the necessary temporal resolution (<100 ns) to sample an acoustic field at MHz frequencies is achieved by interrogating the sensor with a short laser pulse. By timing the emission of the laser pulse to coincide with the arrival of the acoustic pulse at the sensor, a discrete snapshot of the incident acoustic field distribution at a single time can be acquired. By advancing the timing of the laser pulse in discrete steps over the time course of the acoustic pulse and recording the CCD output at each step, a complete spatial-temporal record of the incident acoustic field can, in principle, be acquired.

Experiment: The practical implementation of the scheme is shown in Fig. 1. The FP sensing head is mounted in the vertical wall of a water tank opposite a focused 5 MHz PZT transducer of diameter 29 mm and focal length 63.5 mm driven by an electrical pulser unit operating at a repetition rate of several kHz. To provide a spatially localised plane-wave field at the sensor, the latter was situated near the focus of the transducer.

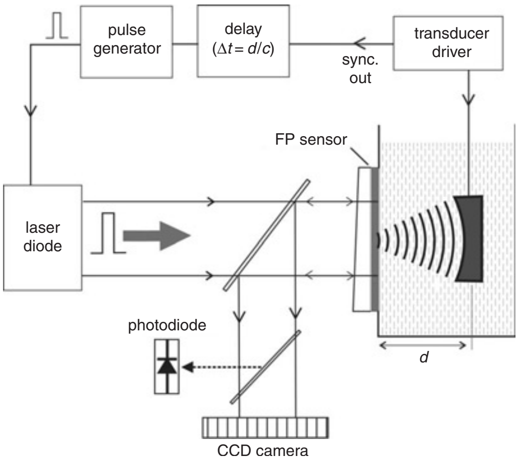

Fig. 1 *2D optical ultrasound field mapping system*

The FP sensor was fabricated by thermally evaporating a semi-reflective aluminium coating on to a 4 mm-thick wedged glass backing to form the first FPI mirror. This was followed by the vacuum deposition of a 40 μm-thick Parylene C-polymer film spacer and on top of this, the second FPI mirror, a fully opaque aluminium coating, was deposited. Finally, a protective, 2 μm-thick Parylene C-barrier coating was deposited over the entire structure. This sensing configuration provides a predicted -3 dB acoustic bandwidth of 17.4 MHz, defined by the thickness of the polymer film spacer and the acoustic impedance of the glass backing.

The sensor is illuminated with the collimated elliptical output beam (of dimensions 16 × 12 mm) of a 70 mW, 850 nm thermally tunable DBR laser diode. This is driven either by a standard laser diode driver operating in constant current mode to provide a CW output, or a pulse generator to provide 50 ns optical pulses. In the latter case, the pulse generator was triggered by the output of the transducer driver and a time delay $\Delta t = d/c$ (where d is the transducer-sensor separation and c is the sound speed in water) introduced in order to synchronise the emission of the optical pulse with the arrival of the acoustic pulse at the sensor. The beam reflected from the FP sensor head is imaged on to a 6.6 × 4.7 mm CCD array composed of 768 × 576 rectangular elements each of dimensions 8.6 × 8.3 μm. A fraction of the reflected sensor output is also incident, via a beamsplitter, on a single 25 MHz AC-coupled silicon photodiode/transimpedance amplifier configuration. A frame grabber was used to acquire the output of the CCD and a digitising oscilloscope (DSO) to record that of the photodiode, the data for both being downloaded to a PC.

To operate the sensor, it is necessary to adjust the laser wavelength so that it corresponds to the point of maximum slope on the FPI transfer function; at this point the sensor is optimally biased and at its most sensitive to acoustically-induced phase shifts. To achieve this, the laser was operated in CW mode and the acoustic signal produced by the ultrasound transducer observed by monitoring the photodiode output on the DSO. The laser diode wavelength was then thermally tuned until the detected signal amplitude was at a maximum. At this wavelength, and for the area of the sensor that is addressed by the photodiode, the sensor provides maximum sensitivity. Although the sensitivity is not strictly uniform across the sensor head owing to variations in the optical thickness of the polymer film, this was found to be insignificant over the relatively small area of the sensor (6.6 × 4.7 mm) addressed by the CCD.

Results: To obtain 2D images of the incident acoustic field distribution using the CCD array, the following procedure was undertaken. To set the time delay Δt between the emission of the acoustic and optical pulses, the laser diode was first operated in CW mode and the temporal output of the sensor monitored using the photodiode. This is shown in Fig. 2, the characteristic tripolar shape of the ultrasound pulse emitted by the transducer being clearly evident. The laser diode driver system was then operated in pulsed mode such that 50 ns pulses were emitted 44.92 µs after the excitation of the ultrasound transducer. As Fig. 2 shows, for this time delay, the sensor is only illuminated or 'on' when the initial positive part of the acoustic pulse arrives at the sensor. The CCD output was recorded for this time delay and, as shown in Fig. 2, appears as a circular region of uniform amplitude, the latter being characteristic of the planar nature of the wavefront at the focus of the acoustic field. The diameter of this region is approximately 1 mm and in agreement with that measured previously. The sensor was operated in a similar fashion for two additional time delays of $\Delta t = 45.0$ µs and $\Delta t = 45.08$ µs, which correspond to the negative peak and second positive peak, respectively, of the acoustic waveform. These appear as circular regions of opposite polarity in the CCD images, as shown in Fig. 2. In this way the 2D acoustic field distribution is discretely sampled at three different times.

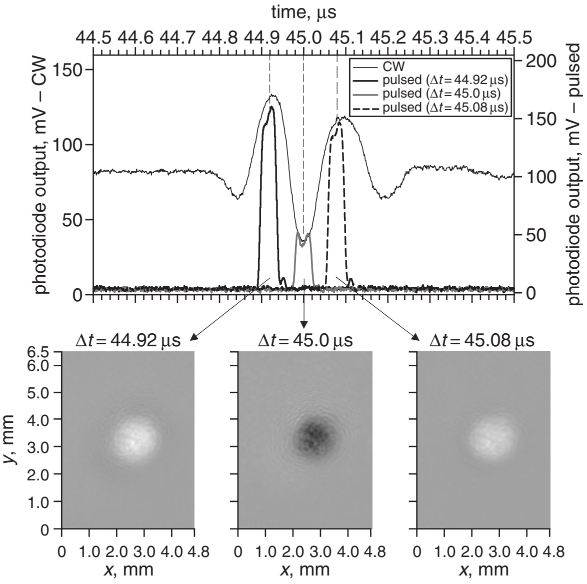

Fig. 2 *(Top) Photodiode output for CW and pulsed sensor illumination owing to acoustic pulse emitted by focused 5 MHz PZT transducer. When operating in pulsed mode, sensor was illuminated with 50 ns optical pulses at three different time delays $\Delta t = 44.92$ µs, $\Delta t = 45.0$ µs, $\Delta t = 45.08$ µs as indicated. (Bottom) Corresponding 2D images captured by CCD array at these times*

Conclusions: It has been shown that the output of an optical ultrasound sensor can be mapped with high spatial resolution using a time gated illumination approach and a 2D CCD array. This approach offers a practical and inexpensive method of rapidly imaging ultrasound field distributions with a spatial resolution of the order of 10 µm. Applications include the characterisation of ultrasound fields produced by transducers and arrays used in diagnostic and therapeutic medical ultrasound and industrial ultrasonic NDT or for medical and industrial imaging applications that require a high density passive receive array such as photoacoustic or transmission ultrasound imaging.

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