Measuring Spatial Cross Sections of Ultrasound Pressure Fields by Fast Optical Means

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Introduction

Recently, major improvements in transducer technology for producing and detecting ultrasound were made. To achieve acousto-electrical receivers with reasonable two-dimensional array sizes and small pixels, a huge number of electronic elements is necessary. Optical methods offer alternative concepts with small spot sizes for high spatial resolution as well as high bandwidth and parallel data processing facilities like CCD chips. An optical multilayer hydrophone is presented that allows the two-dimensional determination of ultrasound pressure fields by measuring the sound-induced change of reflectivity of a thin-film Fabry-Perot interferometer coating on a glass substrate. The extension of recently established point measurements to the automated two-dimensional acquisition of ultrasound pressure fields is shown. For serial two-dimensional acquisition, a laser beam is scanned across the sensor probe by a micro-mechanically engineered scanning mirror and the pressure waveforms are acquired point by point. In an alternative approach incorporating a commercial CCD camera, the probe is strobe illuminated by a large-diameter collimated beam of a pulsed laser diode and the two-dimensional pressure distribution at a particular moment is derived from the captured reflectivity distribution. Measurement results on ultrasound fields from plain and focussing transducers obtained by these two different approaches are presented and individual advantages and drawbacks and discussed.

Sensor Design

The sensing element of the optical multilayer hydrophone [1, 2] consists of several dielectric $\lambda/4$ coating layers of alternating high and low refractive indices deposited on a flat glass substrate. With a central low refractive index spacer layer with a thickness equal to a multiple of $\lambda/2$, the multilayer system acts as a micro Fabry-Perot interferometer with an overall thickness of about 2.5 μm. An incident pressure wave alters the optical thickness of each layer and thereby leads to a detectable change in optical reflectance R of $\Delta R \approx 3 \cdot 10^{-3}$ MPa^{-1} for the system currently in use. Pointwise measurements are readily available by focussing a laser beam with suitable wavelength and incidence angle on the probe and detecting the variation of the reflected intensity, which is directly proportional to the ultrasound pressure [2]. Previous measurements [3] obtained linescans of ultrasound pressure fields by manual translation of the focusing optics, moving the laser spot on a line over the sensor probe and sequentially aquiring ultrasound pressure time waveforms. This method requires several moving parts and is therefore considered to be slow and of low precision.

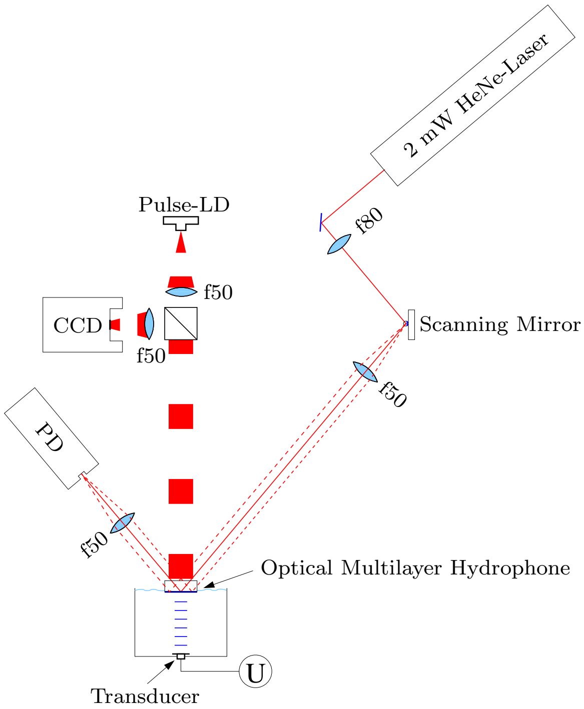

Figure 1: Setup for simultaneous acquisition of pointwise ultrasound pressure time waveforms (serial scheme with HeNe-laser, scanning mirror and photodiode PD) and instantaneous pressure distributions (parallel scheme incorporating the pulsed laser diode LD and a CCD camera)

Serial Scan

A micro-mechanically engineered scanning mirror [4] is used to scan the laser beam focus across the probe. It is capable of deflecting a laser beam independently in two perpendicular directions by incorporating a gimbal-mounted elliptical mirror plate with an area of about 1 mm^2 that oscillates near its resonance frequency of about 400 Hz. Optical deflection angles well exceeding 20 degrees can be achieved. In the measurement setup depicted in Fig. 1, both axes of the scanning mirror are excited with rectangular voltage waveforms of equal frequency and an adjustable phase shift between both. The deflected HeNe-laser beam forms a distorted Lissajous pattern on the probe surface that can be altered by moving the phase shift between the excitation voltage signals. It can be shown that a rectangular area on the probe can be covered if phase shifts ranging over at least 90 degrees are set. A time-resolved calibration measurement of the mirror movement assigns every x, y sensing point of the covered area to a time-phase combination with respect to the excitation waveforms applied to the mirror. With a special triggering and readout scheme a defined sensing point on the probe can be set which is determined purely electronically and can be switched almost instantly to

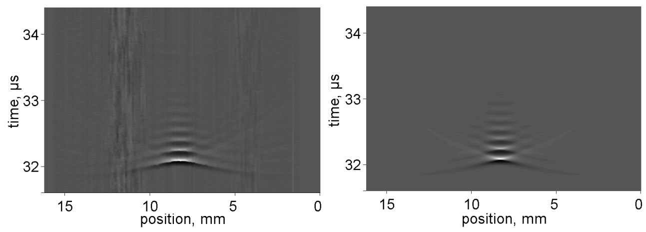

Figure 2: Comparison of a measured ultrasound pressure cross section (left) with a simulation (right) of the focal region of a focussing transducer type Deutsch TS 12 PB 3-12 P50

every location inside the scanning range of the mirror. The movement of the laser focus across the probe is slow compared to the duration of a common ultrasound pulse, so the sensing point can be considered fixed on the probe for a few μs. This serial detection scheme allows the measurement of repeating ultrasound signals at several hundred spatial points on the probe within a few seconds with a good signal-to-noise ratio. Fig. 2 shows the pulse pressure distribution in the focal region of a focussing broadband ultrasound transducer with peak pressures of about 5 MPa. The linescan on the left-hand side of Fig. 2 was extracted from a complete 2-D scan over 16 x 6 mm^2 and shows the variation of the reflected light intensity, i.e. the ultrasound pressure waveform with a resolution of 100 μm and a bandwidth of 80 MHz at 160 equidistant points on the probe. The accompanying simulated linescan on the right-hand side of Fig. 2 was derived using the common *Field II* package in MATLAB [5] and shows good agreement with the measurement results.

Parallel Scan

The need for laser beam steering can be completely avoided by incorporating strobe illumination of the whole sensor with large-diameter collimated laser pulses (see Fig. 1). The reflected intensity is captured by a conventional CCD camera and digitized by a framegrabber card, providing a 10bit grayscale image. The ultrasound-induced change of reflectivity of the coating, hence the ultrasound pressure is then derived by subtracting a reference image of the reflected intensity without the influence of pressure from the captured image with sound and additional normalization. Applying laser pulses with a peak power of 70 mW and a width of 15 ns at 680 nm that illuminate about a quarter of the CCD chip, at least 20 pulses have to be accumulated to saturate the CCD pixels, hence to take advantage of the full digitalization range. Synchronization is required between the acoustic pulse and the laser pulse to ensure that subsequent laser pulses illuminate the probe at a defined delay time with respect to the acoustic pulse. By subsequently tuning this delay time between laser pulse and ultrasound trigger the complete 2-D pressure waveform can be sampled with high spatial resolution. Measured cross-sectional snapshots of the same focussed pulse wavefield as in Fig. 2 are shown in Fig. 3 for three different points in time, clearly displaying structure and evolution of the ultrasound pressure pulse.

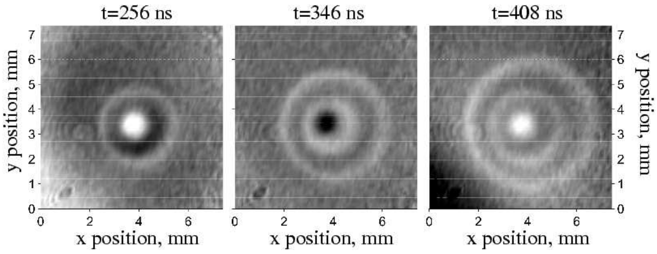

Figure 3: Snapshots of two-dimensional pressure distributions in the focal region of the transducer used in Fig. 2 at three different points in time with respect to the pulse start time, measured with the parallel strobe/CCD setup

Conclusion

An optical setup for the measurement of ultrasound pressure cross sections combining serial and parallel data acquisition from an optical multilayer hydrophone was presented that provides means for the fully-automated high-speed determination of ultrasound fields with high spatial and temporal resolution. Repeating ultrasound pressure waveforms like pulses from focussing and plain transducers were measured over a sensor area of at least 10 x 10 mm^2 with a spatial resolution below 100 μm, capturing the full 2-D pulse wavefields within a matter of minutes. The serial acquisition scheme provides a good signal-to-noise ratio even at bandwidths well exceeding 50 MHz and offers electronical beam steering with no moving parts involved except for the scanning micro mirror. Although it suffers from a lower signal-to-noise ratio and a bandwidth of below 20 MHz, the parallel strobe/CCD acquisition scheme is particulary useful for alignment purposes as it provides snapshots of instantaneous pressure distributions at frame rates exceeding one frame per second. By merging these two approaches into the presented combined serial/parallel setup, a milestone on the way towards constructing an optical ultrasound measuring camera was reached.

References

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