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Feasibility study of complex wavefield retrieval in off-axis acoustic holography employing an acousto-optic sensor

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Abstract

We propose and experimentally demonstrate a new method for complex-valued wavefield retrieval in off-axis acoustic holography. The method involves use of an intensity-sensitive acousto-optic (AO) sensor, optimized for use at 3.3 MHz, to record the acoustic hologram and a computational method for reconstruction of the object wavefield. The proposed method may circumvent limitations of conventional implementations of acoustic holography and may facilitate the development of acoustic-holography-based biomedical imaging methods.

Keywords

Acoustic holography; wavefield retrieval

1. Introduction

Acoustic holography^{1,2} is a method of ultrasound imaging that seeks to determine a complex-valued object wavefield from knowledge of a real-valued acoustic hologram recorded by use of an intensity-sensitive area detector. The acoustic hologram represents an interference pattern formed by recording the intensity of the coherent summation of reference wavefield and an object wavefield that has propagated through the sample of interest. The hologram formed in this way contains information regarding the amplitude and phase of the object wavefield, which is the sought-after quantity in imaging applications. In order to determine the object wavefield from knowledge of the hologram, a reconstruction step must be performed. This can be accomplished by use of optical³ or computational methods^{4,5}. In optical methods, the acoustic hologram itself, or an optical transparency of it, is illuminated with coherent light. An optical camera placed at a certain distance behind the illuminated hologram can then record a real image of the object wavefield. Alternatively, an

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estimate of the object wavefield can be reconstructed computationally by use of phase-retrieval algorithm^{4,5}. Numerous imaging systems based on the principles of transmission acoustic holography have been developed and investigated over the past half-century^{6–11}.

There has been continued effort to develop medical imaging systems for breast cancer detection and management based on off-axis acoustic holography.^{10–13} Acoustic holography may permit near real-time volumetric imaging¹⁰. Previous studies of breast imaging using this method have suggested that it can produce informative images of highly dense breast tissue and can be used to detect and characterize breast lesions that are mammographically occult^{13,14}. Because it uses a fixed imaging geometry that does not involve scanning, acoustic holography methods can also circumvent the operator-dependence of conventional ultrasound imaging methods.

Despite promising preliminary results and years of development effort, acoustic holography has not become a viable medical imaging method, nor has it found widespread use in non-destructive testing applications. This can be attributed to, in large part, to the lack of a suitable large area ultrasound detector. The majority of implementations have utilized the principle of liquid surface deformation to form the hologram² on the surface of a liquid bath. The liquid surface detection method is very vibration prone and can require dedicated mechanical equipment to maintain the liquid surface leveled and vibration free⁶. Moreover, when optical methods are employed to reconstruct the object wavefield, the systems can be relatively bulky. For example, an acoustic holography imager developed for breast imaging¹¹ possessed a length of over 80 inches and a weight of over 1200 lbs.

In this work, we propose and experimentally demonstrate a new method for wavefield retrieval in off-axis acoustic holography. The method involves two steps. First, an acousto-optic (AO) sensor is employed to record the acoustic hologram. The AO sensor has been used successfully in previous non-holographic imaging studies^{15,16} based on a shadow-casting technique. Subsequently, from knowledge of the recorded acoustic hologram, a phase-retrieval algorithm coupled with a numerical model of the reference wavefield's phase are employed to computationally reconstruct the object wavefield on the detector plane.

The article is organized as follows. In Section 2, a description of the AO sensor and the computational method for wavefield retrieval is provided. The details of our experimental studies are described in Section 3 and the results of these studies are given in Section 4. The article concludes with a summary of the work in Section 5.

2. Background

Let the complex-valued quantities $O(x, y) \equiv A_o(x, y) \exp(j\theta_o(x, y))$ and $R(x, y) \equiv A_r(x, y) \exp(j\theta_r(x, y))$ denote the time-harmonic object and reference wavefields evaluated on the detector plane. As depicted in Fig. 1-(a), the off-axis acoustic hologram recorded by the intensity-sensitive AO sensor is formed as $I(x, y) = |R(x, y) + O(x, y)|^2$. The goal of wavefield retrieval is to determine an estimate of the complex-valued object wavefield $O(x, y)$ from knowledge of the hologram $I(x, y)$ and reference wavefield $R(x, y)$. Below, the AO sensor and computational method we employ to achieve this goal are described.

A. Description of AO sensor

The operating principles of the AO sensor have been described in detail elsewhere^{15,16} but are summarized here. The AO sensor is an intensity-sensitive ultrasound detector that converts acoustic energy directly into a visible image via the AO effect of a liquid crystal (LC) layer. In the absence of acoustic energy, the tilt angle of the LC molecules is zero and the AO sensor exhibits a uniform dark field of view. However, when an area of the AO

sensor is exposed to acoustic energy, the LC molecules experience a torque that tilts the LC molecules in the acoustically exposed region of the AO sensor. As a result, the acoustically exposed area of the AO sensor appears bright. The acoustically-induced brightness change in the LC material is referred to the acousto-optic effect¹⁵. The AO sensor brightness change is related to acoustic intensity through a characteristic curve. The substrates that confine the liquid crystal layer are both acoustically transparent, and the rear substrate is also optically transparent. This permits the use of a video camera to record a digital optical image of the liquid crystal layer. In this way, the intensity distribution of the acoustic image is converted into an optical image by the AO sensor. The AO sensor has been successfully employed to record ultrasound projection images in non-destructive testing applications¹⁷ and recently of ultrasound projection images of a breast phantom¹⁶. Those studies differ from the present one in that they did not utilize acoustic holography principles for image formation.

The AO sensor possess characteristics that are desirable for acoustic holography applications. Because it permits direct conversion of the intensity distribution of an off-axis hologram into a digital optical image, it is convenient to employ computational methods to reconstruct the phase and amplitude of the object wavefield. The spatial resolution of the image recorded by the AO sensor is limited by the spatial resolution of the optical camera. Cameras with micron-scale pixel sizes are commercially available. The AO sensor also eliminates the need for analog-to-digital conversion/multiplexing circuitry, high conversion rates, electronic cross-talk, etc., which are some limiting factors for two-dimensional (2D) ultrasonic arrays.

B. Computational wavefield reconstruction

We investigated the use of a computational wavefield reconstruction method that was originally developed for off-axis optical holography by Liebling *et al.*⁵. The salient features of the model and its limitations are summarized below. This method possesses at least two characteristics that are well-suited for use with acoustic holography but, to the best of our knowledge, has not been investigated for this application. Such features include the ability to accommodate non-planar reference wavefields and a robust solution strategy that can determine the object wavefield on a pixel by pixel basis without the use of Fourier-based methods.

Because a digital camera is employed to record an optical image of the acoustic hologram as it appears on the AO sensor's exit surface, the measured digital hologram is described as an ordered collection of numbers rather than a function of a continuous variable. We will denote the discrete acoustic hologram as

$$I[m, n] \equiv I(x, y)|_{x=m\Delta, y=n\Delta}, \quad (1)$$

where m and n are integer-valued pixel indices and Δ denotes the pixel pitch of the digital camera. Similarly, $R[m, n] \equiv A_r[m, n] \exp(j\theta_r[m, n])$ and $O[m, n] \equiv A_o[m, n] \exp(j\theta_o[m, n])$ will denote sampled versions of the reference and object wavefields respectively. Although not indicated in Eq. (1), the measured discrete data will also be degraded by the averaging effects of the sampling aperture.

The wavefield retrieval method we investigate⁵ is based on the assumption that the measured hologram $I[m, n]$ and the reference phase $\theta_r[m, n]$ vary much more rapidly with pixel location $[m, n]$ than do the object wavefield $O[m, n]$ and reference amplitude $A_r[m, n]$.⁵ In this case, $O[m, n]$ and $A_r[m, n]$ can be regarded as being approximately constant within a sufficiently small neighborhood. The set $\mathcal{N}[m, n]$ contains the M pixel locations $[k, l]$ within

this neighborhood centered at pixel $[m, n]$. In terms of these quantities, the object wavefield and reference amplitude in a neighborhood of a given pixel location $[m, n]$ are assumed to satisfy $O[k, l] = O[m, n]$ and $A_r[k, l] = A_r[m, n]$ for all $[k, l] \in \mathcal{N}[m, n]$. If these assumptions are not satisfied, an alternative wavefield reconstruction method to the one described below would need to be developed and employed to avoid image artifacts.

Under the assumptions stated above, one can seek to determine $O[m, n]$ by solving the following system of M nonlinear equations at each pixel location $[m, n]$:

$$I[k, l] = |O[m, n] + A_r[m, n] \exp(j\theta_r[k, l])|^2, \quad \forall [k, l] \in \mathcal{N}[m, n]. \quad (2)$$

Note that this equation describes a discrete version of the hologram formation process. In the method proposed by Liebling *et al.*⁵, $A_r[m, n]$ is not required to be known and is estimated concurrently with $O[m, n]$ as a by-product. A weighted least-squares estimate of $O[m, n]$, denoted by $\hat{O}[m, n]$, can be obtained by solving the optimization problem:

$$\hat{O}[m, n] = \underset{O[m, n], A_r[m, n]}{\operatorname{argmin}} \sum_{[k, l] \in \mathcal{N}[m, n]} w[k, l] |I[k, l] - [O[m, n]^2 + A_r^2[m, n] - 2\operatorname{Re}\{R^*[k, l]O[m, n]\}]|^2, \quad (3)$$

where $*$ denotes complex conjugation and $\operatorname{Re}\{\cdot\}$ denotes the real-valued component of a complex-valued quantity. The weights $w[k, l] \geq 0$ satisfy $\sum_{[k, l] \in \mathcal{N}[m, n]} w[k, l] = 1$ and should be chosen to ensure that the measured intensities that are away from location $[m, n]$ influence $\hat{O}[m, n]$ less than those corresponding to nearby locations.

The wavefield reconstruction method is described below and summarized in Fig. 2. Specifically, Eqn. (3) can be solved to determine an estimate $\hat{O}[m, n]$ of the object wavefield in three steps:⁵

1. Define:

$$V[m, n] \equiv \exp(j\theta_r[m, n]) \quad (4a)$$

$$\alpha[m, n] \equiv \sum_{[k, l] \in \mathcal{N}[m, n]} w[k, l] V[k, l] \quad (4b)$$

$$\beta[m, n] \equiv \sum_{[k, l] \in \mathcal{N}[m, n]} w[k, l] V^2[k, l] \quad (4c)$$

Note that since the reference phase $\theta_r[m, n]$ and weights $w[m, n]$ are assumed to be known, $V[m, n]$, $\alpha[m, n]$ and $\beta[m, n]$ are fully determined.

2. Determine the intermediate variables U , Z and Z^* by inverting the 3×3 system:

$$\begin{pmatrix} \sum_{[k, l] \in \mathcal{N}[m, n]} w[k, l] I[k, l] \\ \sum_{[k, l] \in \mathcal{N}[m, n]} w[k, l] V[k, l] I[k, l] \\ \sum_{[k, l] \in \mathcal{N}[m, n]} w[k, l] V^*[k, l] I[k, l] \end{pmatrix} = \begin{bmatrix} 1 & \alpha[m, n] & \alpha^*[m, n] \\ \alpha[m, n] & \beta[m, n] & 1 \\ \alpha^*[m, n] & 1 & \beta^*[m, n] \end{bmatrix} \begin{pmatrix} U[m, n] \\ Z[m, n] \\ Z^*[m, n] \end{pmatrix} \quad (5)$$

3. Determine the estimate of the object wave as

$$\hat{O}[m, n] = \frac{Z[m, n]}{\hat{A}_r[m, n]}, \quad (6)$$

where

$$\hat{A}_r[m, n] = \left(\frac{U[m, n] + \sqrt{U^2[m, n] - 4Z[m, n]Z^*[m, n]}}{2} \right)^{\frac{1}{2}}, \quad (7)$$

is the estimated reference wavefield amplitude that is assumed to satisfy $\hat{A}_r[m, n] > |\hat{O}[m, n]|$. If the reference wavefield amplitude is available from measurements it can be employed in Eq. (6) in place of $\hat{A}_r[m, n]$.

3. Experimental methods

In order to facilitate quantitative evaluation of the method, a simple experiment was considered in which no object was present. In this case, the object wavefield $O(x, y)$ corresponds to the wavefield produced by a circular transducer, evaluated on the AO sensor surface.

A. Data acquisition using the AO sensor

Figure 1-(b) shows a “Top view” schematic of the experimental system. The system consisted of a water-immersion tank that was 36”(L)×36”(W)×12”(D). Two transducers (i.e. ultrasound sources) were suspended in the water tank. One transducer emitted the reference wavefield directed at the AO sensor while the second transducer emitted the object wavefield. The two wavefields interfered with each other to create the ultrasound hologram, which was recorded by use the AO sensor and a digital video camera (Basler A311, not shown) housed in the Optics Box. The camera has an effective pixel size of 0.01 inch, including the effects of the optics employed.

The active area of the AO sensor (obtained from Santec Systems, Inc.) was 2" × 2". Initially, transducers with 2.5"×2.5" radiating surface were used for the experiments. The frequency of the transducers was selected to be 3.3 MHz because the the AO Sensor we employed was designed to operate at that frequency. Transducers were driven with a signal from a single source (PCI Dual Channel, Pickering Interfaces, Inc.) at a fixed frequency of 3.3 MHz. The source signal was split two ways to ensure constant phase of the two sound sources. Radio frequency (RF) Amplifiers (AS-100 model, Santec Systems, Inc.) were used to boost each split signal before it was applied to the respective transducers. The RF Amplifiers were assumed to have no effect on the phase of the original source signal.

As mentioned above, we first experimented with transducers emitting sound beams with cross-sectional areas of 2.5"×2.5". However, the theoretically-simulated field intensities corresponding to a 2.5"×2.5" radiating area transducer could not be observed experimentally. Moreover, the holographic data generated on the AO sensor did not seem to conform to what was expected theoretically. These effects were also difficult to distinguish from the Fresnel diffraction field patterns of the square transducers. Since the transducer area was larger than the 2" × 2" AO sensor detection area, we suspected the possibility of diffraction at the AO sensor edges as a source of error. Therefore, an additional set of identical transducers with radiating area less than the 2"×2" AO sensor area was fabricated. These transducers were disc-type with 1" diameter and 3.3 MHz frequency. Fresnel patterns

of the disc-type transducer could easily be distinguished from the edge effects. Reverberations between the transducer faces and the AO sensors were minimized by increasing the AO sensor-to-transducer distances. At a distance of about 45 cm, artifacts due to reverberations were virtually eliminated.

Experimental data capture was performed as follows. The angle between the central axes of the transducers was set at $\alpha = 20^\circ$. The radiation axes of both transducer were aligned to meet at the same point on the AO sensor. Power was provided to both transducers with the AO sensor held in a steady erased state. The erased state was then release and the camera captured the AO sensor response; after 20 seconds of capture time the data were written to disk for post processing.

B. Implementation of wavefield reconstruction method

In addition to the measured hologram $I[m, n]$, we require knowledge of the phase $\theta_r[m, n]$ of the reference beam, as described in Section 2.B, in order to determine $\hat{O}[m, n]$. Based on knowledge of the transducer diameter, form of the excitation voltage, and imaging geometry, an estimate of $\theta_r[m, n]$ was determined by numerically computing the associated Rayleigh integral for a circular rigid baffle (e.g., see Chapter 3 in the monograph by Cobbold¹⁸.) In this computation a monochromatic excitation waveform of 3.3 MHz was assumed, which corresponded to the center frequency of the narrow-band excitation employed in the experiments. The weights $w[k, l]$ were formed as samples of 2D truncated Gaussian function having a standard deviation of 1.25 evaluated an 11×11 pixel grid.

From knowledge of $\theta_r[m, n]$ and $w[k, l]$, the quantities $V[m, n]$, $\alpha[m, n]$, and $\beta[m, n]$ were computed according to Eq. (4). Subsequently, $Z[m, n]$ was determined by inversion of Eq. (5). Finally, the complex-valued object wavefield estimate $\hat{O}[m, n]$ was determined at each pixel location $[m, n]$ via Eq. (6), where the measured amplitude of the reference wavefield was used in place of $\hat{A}_r[m, n]$.

4. Results

The measured hologram is shown in Fig. 3-(a), and a horizontal profile through the center of the image is displayed in Fig. 3-(b). The hologram displays the expected pattern of fringes, whose spacing is determined by the wavelength employed and angle between the object and reference wavefields. Note that because of the relatively compact imaging geometry employed, the object and reference wavefields are non-planar. As a consequence of this, the intensity of the hologram and the contrast of the interference fringes decreases as one moves away from the center of the hologram. To avoid erroneous results due to very low signal-to-noise ratio in the hologram, we sought to determine the object wavefield only within the 100×100 pixel region bounded by the red box in Fig. 3-(a). In this initial study, the extent of this region was determined in an ad hoc way so as to only include the region of the measured hologram that contained interference fringes whose appearance matched what was expected based on our simulation studies. The noise propagation characteristics of the proposed wavefield reconstruction method remain an important topic for future studies.

The real- and imaginary-valued components of the reconstructed object wavefield estimate $\hat{O}[m, n]$ are displayed in Figs. 4-(a) and (b), respectively. The corresponding true values of $O[m, n]$, which were determined by numerically evaluating the pressure wavefield on the AO sensor surface produced by the object transducer, are displayed in Figs. 4-(c) and (d), respectively. Horizontal profiles through the centers of the images depicting the real- and imaginary components are displayed in Figs. 5-(a) and (b), respectively, in arbitrary units. The profiles depicting the reconstructed (blue, dashed) and true (solid green) values are found to have a high degree of overlap. The mean squared error (MSE), defined as

$\frac{1}{N} \sum_{m,n} (\hat{O}[m, n] - O[m, n])^2$ where N is the total number of pixels in the image and the summation is over all pixels, was used to quantify the difference between the real- and imaginary components of reconstructed image $\hat{O}[m, n]$ and true image $O[m, n]$. The MSE between the real- and imaginary-valued components of the images was computed to be 6.07 and 5.74, respectively.

5. Summary

We have demonstrated a new implementation of acoustic holography. An intensity-sensitive AO sensor was employed instead of the liquid surface detection, and a computational method for reconstructing the object wave was employed instead of optical reconstruction. When coupled with a three-dimensional reconstruction algorithm, we believe the proposed hologram acquisition and wavefield reconstruction method can form the basis for an innovative and effective biomedical imaging modality. The investigation of this remains an important topic for future research.

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- We experimentally demonstrate a method for wavefield retrieval in off-axis acoustic holography.
- An intensity-sensitive, acousto-optic (AO) sensor is employed to record the acoustic hologram.
- A phase-retrieval method is employed to reconstruct the object wavefield.
- The proposed method circumvents limitations of conventional implementations of acoustic holography.

Fig. 1. (a) A schematic depicting an off-axis holography experiment. (b) A schematic of the imaging setup employed in the experimental studies.

Fig. 2.
A flowchart of the wavefield reconstruction algorithm.

Fig. 3.

(a) The measured hologram. The region bounded by the red box was utilized as the input to the wavefield retrieval algorithm. (b) A horizontal profile through the center of the hologram.

Fig. 4. Surface plots of the (a) real-valued and (b) imaginary-valued components of the reconstructed object wavefield. The corresponding plots of the true object wavefield are displayed in (c) and (d).

(a)

(b)

Fig. 5. Horizontal profiles through the centers of the (a) real-valued and (b) imaginary-valued components of the reconstructed object wavefield. In each case, the blue-dashed curve denotes the reconstructed wavefield and the solid-green curve denotes the true value.