Imaging ultrasound field and shear wave propagation using acousto-optic laser speckle contrast analysis (AO-LASCA)

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ABSTRACT

In this paper we present a method to visualize the pressure field of an ultrasound beam in a single shot of the CCD and to image the shear wave propagation based on acousto-optic laser speckle contrast analysis. The contrast images show features in the near field, far field and central region of the ultrasound beam and the pressure profile fits with that measured with a hydrophone. The shear wave propagation was acquired by changing the imaging delay time after the ultrasound burst. This method can be used to study the shear wave properties of common tissue phantoms to guide experiments on tissue.
Key words: Imaging ultrasound field, laser speckle contrast, single shot, shear wave propagation

1. INTRODUCTION

The measurement of the pressure field of an ultrasound beam and the shear wave propagation is important for investigating the ultrasonic properties of the medium, which is highly desirable in disease diagnosis. The measurement of ultrasound beams is also important for understanding and controlling the properties of the ultrasound in real media. Currently hydrophones provide the gold standard method for measuring the ultrasonic field of the transducers, but this method is time consuming due to the requirement to scan the ultrasonic field, and additionally the medium needs to be fluid to allow the free positioning of the hydrophone[1]. The pressure of the ultrasonic changes the refractive index of the material and generates refractive index gratings. Schlieren systems have previously been used to visualise the ultrasound field using the diffraction effect when incident light passes through this grating. Schlieren systems have a high spatial resolution and are able to detect the ultrasound wave period in the media by using pulsed illumination and short camera integration times. However the requirement for a relatively static grating within the acquisition period demands short illumination and therefore low signal levels. Furthermore for imaging the whole ultrasonic field in the media, a series of individual images are acquired with different delay times according to the propagation speed of sound and then these images are stitched together [2] . Previously lock-in detection methods have also been proposed to detect the ultrasound wave in clear media, but this technique requires multiple images to be acquired with different phases between the ultrasound and illumination modulated light[3].

Shear wave propagation in tissue has been investigated for the purpose of diagnosis and disease identification [4-6]. The speed and intensity of shear waves vary depending on the mechanical and acoustic properties of the tissue, such as the tissue elasticity and the absorption coefficient of sound. These properties may be related to pathological changes. The most common method of detecting the shear wave propagation is to measure the time delay of the shear wave generated remotely with a focused ultrasound beam. Some researchers have tried detecting the shear wave propagation optically. by focussing a light beam onto an optically absorbing particle and detecting the light alternatively transmitted and blocked by the particle due to its shear wave-induced displacement[5]. Bossy et al. made use of the temporal decorrelation of the light passing through an ultrasound field to acquire a full field shear wave image and its propagation could be detected by using different delay times between the ultrasound and optical acquisition[7]. However this method requires a fast detector, operating at 2 kHz, and a sequence of images are needed to calculate the decorrelation.

A fast and full-field imaging method for the US pressure field and shear wave propagation can help to identify the location of the ultrasound field in US related experiments, to investigate the tissue elastic properties, which are related to the propagation speed of the shear wave, and may potentially assist the diagnosis for cancer and other diseases.

In this paper we present a method to visualize the pressure field of ultrasound beam and shear wave propagation with pseudo-colour based laser speckle contrast analysis (LASCA). It is a fast and full-field technique and the ultrasound field can be imaged in a single shot and its propagation recorded. The method is applicable not only in water but also solid or gel-like materials, such as agar with intralipid, a common tissue phantom.

2. METHODS

When an ultrasound beam is applied to a medium, the particles in the medium are oscillating at the ultrasound frequency while being gradually displaced due to the acoustic radiation force. Once equilibrium is reached the particles only oscillate about that displaced position at the ultrasound frequency. If we ignore nonlinear effects, there are two waves propagating the media: one is the US beam which travels by the simple harmonic oscillation of the particles at the frequency of the ultrasound and the other is the shear wave that propagates perpendicular to the US beam. The generation and propagation of the shear wave depends on the US absorption of the media. When a laser beam passes through an optically scattering material, a speckle pattern is generated at the image plane due to the random interference of the arriving photons that have travelled through different path lengths. The ultrasound field influences this interference speckle pattern because the phase of the light passing through the ultrasound is modulated due to the acoustic radiance force and the ultrasound induced particle oscillation. The contrast found within the speckle pattern reflects the modulation depth and the speed of the motion, and can be used to detect properties of the ultrasound field[8, 9]. Since the average particle speed depends on the applied pressure, the contrast distribution indicates the pressure field of the ultrasound beam. If an optical image of the ultrasound field can be formed then the effects and spatial location of the ultrasound oscillation and shear wave can be distinguished, as described below.

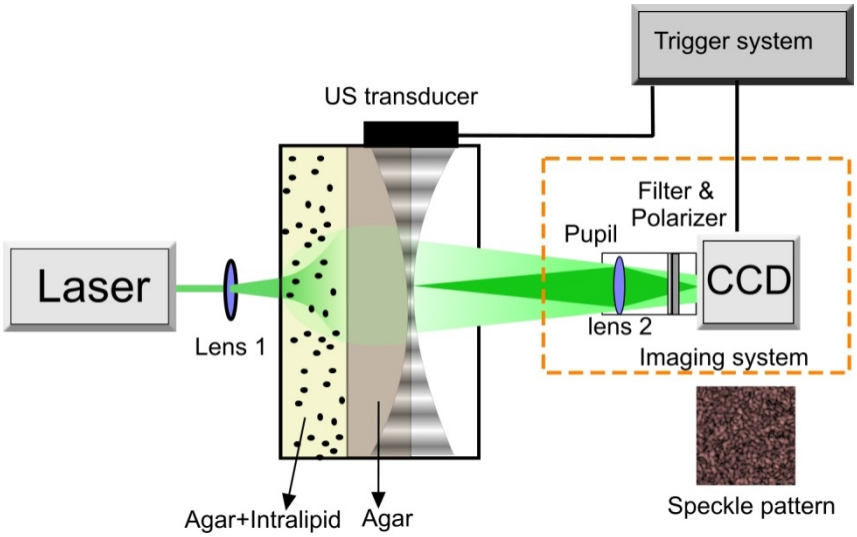


Figure 1. Experiment setup

Two experiments were preformed: one to image the US field and the other to capture the propagation of the shear wave. The experimental setup is shown in Fig 1. A laser beam (Excelsior 532, Newport, Incorporated, U.S., 532 nm, 100 mW) was expanded using a lens and was incident on the phantom. The focused ultrasound beam (5 MHz, 1 mm and 10 mm lateral focal width and focal length respectively at 50 mm working distance) was aligned to pass through the output surface of the phantom and the output surface was imaged onto a CCD (QImaging, Fast Exi, cooled) using a lens (f=30 mm, Thorlabs). The phantom consisted of two layers: one was 2% Agar in water (the transparent layer to US) and the other had the same concentration of agar but was mixed with 10 % intralipid. For the first experiment the US field was applied on the layer with pure agar. This is because Agar lightly scatters the light, so it can generate a clear US beam shape. In the second experiment the phantom was reversed to locate the layer with agar and intralipid in the US field. This time the intralipid played the role of a US absorber to generate the shear wave[10]. A bandpass filter and a polarizer (B in Fig. 1) were added after the lens to eliminate the stray light and maintain the linear polarization

respectively. The speckle size was controlled to be equal to two CCD pixels by an aperture (A in Fig. 1) in front of the lens, thereby satisfying the Nyquist criterion. The FOV was 20 mm x 30 mm to record a large region of the ultrasound beam and the exposure time was set to 2 ms with a trigger system [8] used to control the delay time at which the CCD was exposed. A 7 by 7 moving window was used to calculate the contrast map of the speckle images and then the contrast difference map was derived by subtracting the contrast value of the speckle images captured at the different delay times from that of the initial contrast map when the US was off. The higher the contrast difference, the higher the pressure of the ultrasound.

In the first experiment to image the US beam, the output surface contained only agar. 20 images were recorded both before and after ultrasound was applied. A delay time of 1 ms was used after the ultrasound was turned on so that the modulation reached a stable state before capturing the image. The contrast difference of the ultrasound pressure was averaged over 20 images to reduce the noise and a colour map was applied to illustrate the contrast difference.

In the second experiment a US burst which lasted 2 ms was applied to the phantom. A series of speckle images were recorded after the ultrasound signal was turned on with a step size of 0.5 ms. One image was captured before and after the ultrasound was turned on for each delay time for calculating the contrast difference.

3. RESULTS

The contrast difference image of the ultrasound field is shown in Fig 2 where the ultrasound propagation direction is from top to bottom. The shape of the focused ultrasound beam is clearly evident in Fig. 2 (a), and the focus, which was located in the middle of the image, can be identified not only by the shape of the beam but also by the higher contrast difference in this area. This implies that the particles have a higher average speed and displacement at the focus. The near field structure of the ultrasound can also be observed, especially when imaging at higher magnification as shown in Fig 2 (b).

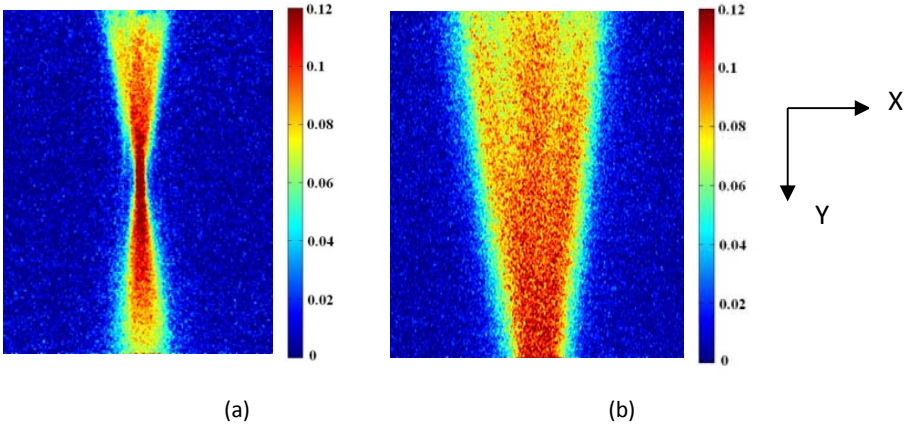
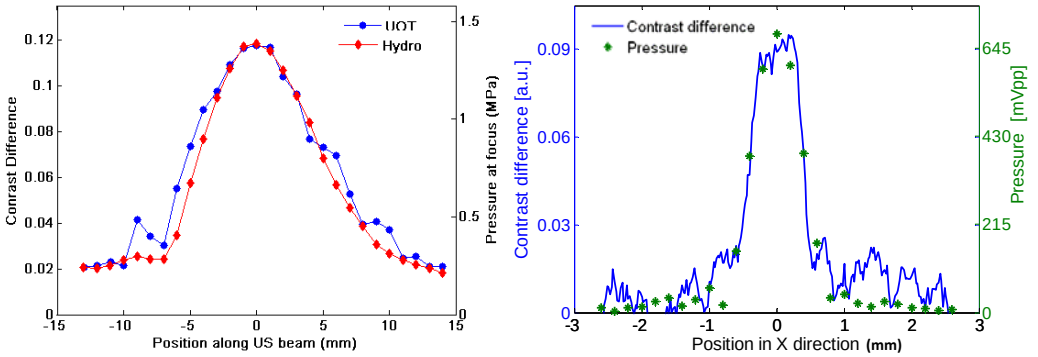


Figure 2: Contrast difference map. (a) the ultrasound beam and (b) the near field area.

Spatial profiles of the contrast were calculated along the ultrasound axis by averaging the three central pixels in x direction at each y position. The result is shown in Fig 3 (a) alongside comparative data acquired with the hydrophone in water. The data sets are scaled to compare the profile shape only, and show good agreement except for some spikes in the experimental result. This same calculation was repeated for the x-direction in the range of -3 to +3 mm corresponding to the central point of the US focus and the result is shown in Fig 3 (b). Again there is a close match to the hydrophone data and the FWHM diameter of the ultrasound was calculated to be around 0.8 mm using both methods. Therefore there appears to be a relationship between the contrast difference and the ultrasound pressure, which could enable the retrieval of the pressure field simply by recording the contrast distribution.

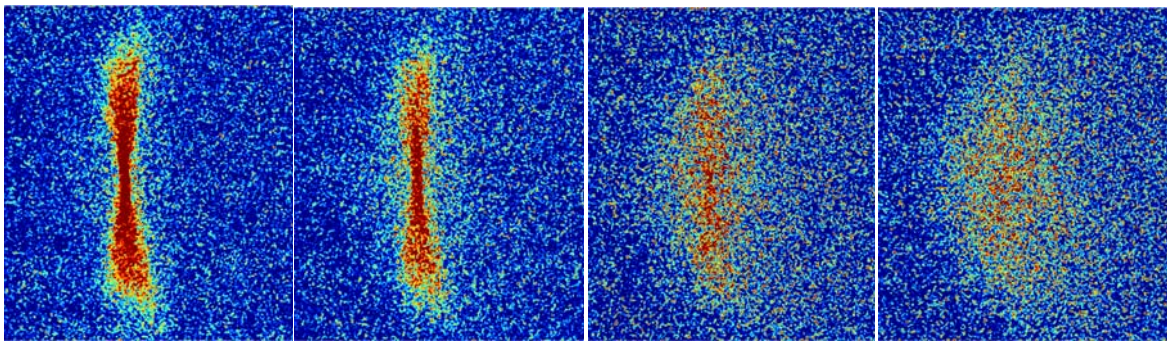
Fig. 4 demonstrates the propagation of the shear wave. Fig. 4(a) was acquired when the ultrasound had been on for 1 ms. Fig. 4(b) was captured 1 ms after the ultrasound was turned off. The ultrasound shape was still perceivable but less

clear than in (a). Fig. 4(c) shows the contrast difference map after 2 ms delay. The shear wave propagated mainly in the x direction. And (d) shows more expanded shear wave field after 3 ms delay. The spread of the shear wave in the X direction was around 6 mm suggesting that the shear wave velocity was 2 mm/ms.



(a) (b)

Figure 3. the profile of the ultrasound field in (a) Y direction and (b) X direction.



(a) (b) (c) (d)

Figure 4. Propagation of the shear wave.
(a) the ultrasound is on; (b) to (d): 1ms, 2ms and 3ms delay after the ultrasound was turned off

4. DISCUSSION

Acousto-optic laser speckle contrast analysis is a fast imaging method to measure the pressure field of the ultrasound. The pressure field is shown in a pseudo-colour image. The CCD exposure time needs to be adjusted to achieve the best image contrast. Otherwise the contrast value in the ultrasound area may be too close to the surrounding area and unperceivable. Here we chose 2 ms after some testing using shorter and longer exposure times. The experimental results showed that LASCA can capture the ultrasonic beam in a single shot, but loses the spatial resolution and the ultrasound wave period is not resolvable. This is because the ultrasound propagates more than one period during the CCD exposure time and the light field collected by the CCD is therefore an averaged modulation of multiple periods. The ultrasound beam has to be located at the output surface of the phantom otherwise the laser modulated by the shear wave will be scattered randomly and the spatial resolution reduced.

5. CONCLUSION

Based on the light modulation induced by the ultrasound, LASCA can capture both the pressure field of the focused ultrasound signal in a single shot and the propagation of the shear wave generated by the radiation force in a time-lapse sequence of images. The contrast profile from the image fits well with the hydrophone data. By changing the delay time of the CCD exposure after turning off the ultrasound modulation, we can capture the propagation of the shear wave. The image noise can be deduced by the average over multiple contrast images acquired at the same delay time.

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