Parallel detection of amplitude-modulated, ultrasound-modulated optical signals

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Received March 19, 2010; revised June 21, 2010; accepted June 28, 2010;

posted July 13, 2010 (Doc. ID 125696); published July 29, 2010

We investigated the effect of amplitude-modulated (AM) ultrasound (US) on acousto-optic (AO) signals. A phantom was exposed to both AM US and a green laser, and CCD measurements of speckle contrast were made with various exposure times. The results show that the AO signal oscillates at the AM frequency when the CCD exposure time is a fraction of the AM period and stops oscillating when the CCD exposure time is a multiple of the AM period. The AO signal decreases quickly as the AM frequency increases or peak-peak (pk-pk) amplitude decreases. With 4 ms exposure time, 250 Hz AM frequency and 1.27 MPa pk-pk acoustic pressure, there is an ~30% increase in the AO signal compared with that of CW US. The increase in the signal is likely to be due to the particle oscillation and the induced shear wave as a result of the radiation force generated by the AM US. © 2010 Optical Society of America

OCIS codes: 170.1065, 170.7170.

Acousto-optic (AO) imaging (also called ultrasound-modulated/mediated optical tomography, or UOT) is a hybrid technique that combines optical contrast with ultrasound (US) resolution at millimeter-centimeter depths. US waves cause periodic displacement of scatterers and changes to the refractive index in tissue, which modulates the phase of passing photons and can be detected optically. Reviews on this topic can be found in [1,2]. Currently, a key challenge in AO imaging is how to detect the low quantity of light modulated at the US frequency on top of the high unmodulated background. Various optical detection methods were developed, including the use of single detectors [3], parallel multiple speckle detection using CCD to improve the signal-to-noise ratio [4], photorefractive holography and interferometry, and a nonlinear narrowband optical filter achieved by a spectral hole burning crystal [5]. On the other hand, improved acoustic methods have been explored using intense acoustic bursts, which allow much greater acoustic amplitudes compared with CW US [6]. The bursts also generate an acoustic radiation force (ARF), which leads to a displacement of the scattering particles, typically several micrometers [7], on top of the periodic movement at the US frequency, typically several tens of nanometers [8]. In this study, we used an amplitude-modulated (AM) US beam to produce a low-frequency oscillating radiation force in order to theoretically and experimentally study the effect of the ARF on the optical signal.

Radiation force (F) is generated by changes in the spatial energy density of an acoustic field [9]: $F = d_r S \langle E \rangle$, where $\langle E \rangle$ is the time-averaged energy density of the incident wave, S is the projected area of the object, and d_r represents the acoustic attenuation properties of the object. Attenuation of the wave causes changes in the spatial energy density of the wave. This force is steady if the incident acoustic intensity does not change over time. Alternatively, an oscillatory radiation force can be generated by AM US [9].

In this Letter, we generated an oscillatory radiation force by using the modulation of a single US beam driven by an AM US signal. Consider an AM ultrasonic plane pressure field $p(t)$ as

$$p(t) = p_0[1 + \cos(\Delta\omega t)] \times \cos(\omega_0 t), \quad (1)$$

where p_0 , $\Delta\omega$, and ω_0 are the pressure amplitude, modulating frequency, and central frequency, respectively. For a traveling plane wave, the energy density is given by $E = p^2(t)/\rho c^2$, where ρ and c are the density and propagation speed in the medium. In our analysis and experiments, we assume that the condition $\Delta\omega \ll \omega_0$ holds. The oscillatory radiation force on the target can be derived:

$$F = \frac{d_r S p_0^2}{2\rho c^2} (1 + \cos(\Delta\omega t))^2. \quad (2)$$

Simulations were performed to predict the theoretical displacement induced by the oscillating source in Eq. (2) by numerically solving the classical Navier equation [10]. In the 3D simulation, the oscillating point force is at the origin and an observer point A is set close to the focus. We chose AM frequencies of 250 Hz, 500 Hz, 1 kHz, and 8 kHz. The temporal response received at the observer point A for a sinusoidally oscillated force lasting for 20 ms is calculated and shown in Fig. 2. The medium parameters were shear-wave velocity 1 mm/ms, bulk velocity 1500 mm/ms, bulk viscosity 0 Pa.s, and shear viscosity 0.2 Pa.s.

A phantom (93.5 mm × 43 mm × 20 mm) was created with 1% agar (mass concentration) in water, yielding a Young's modulus of approximately 25 kPa, with 0.4% intralipid (volumetric concentration) to simulate the scattering properties of biological tissue with a thickness of 20 mm and a reduced optical scattering coefficient of about 5 cm⁻¹ [11].

The experimental setup is shown in Fig. 1. A focused US transducer generated a 5 MHz constant US wave with a lateral focal width of 1 mm and a length of 10 mm at 50 mm working distance. An rf power amplifier (240L, ENI, Incorporated, U.S.), with a linear gain of 50 dB between 10 kHz and 12 MHz, amplified the signals driving the transducer. The US focus was positioned 20 mm into the phantom. Two function generators (33250A, Agilent

Fig. 1. (Color online) Experimental setup: FG, function generator; NDF, neutral density filter. The inset illustrates the triggers from the delay generator.

Technology, Incorporated) were used to create the AM US signal. The first generated a low-kilohertz sinusoidal burst that modulated the amplitude of the 5 MHz US signal from the second. CW US was also generated with a single function generator for comparison. The peak-peak (pk-pk) amplitude of the AM US was kept the same as the CW US, therefore delivering less energy to the phantom. The acoustic pk-pk pressure varied between 318 kPa to 1.27 MPa for both the AM and CW US.

A diode-pumped CW green laser (Excelsior 532, Newport, Incorporated, U.S., 532 nm, 100 mW) was expanded to 10 mm diameter and was incident on the glass wall of a 60-mm-thick water tank containing the phantom. The scattered light transmitted through the phantom generated speckle patterns, which were detected by a 1392 × 1040 pixel CCD camera (Retiga EXi, QImaging, Canada) with a maximum frame rate of 15 Hz and an iris to ensure that the speckle size was approximately 2 CCD pixels (6.45 μm pixel size).

A computer-controlled delay generator (DG535, Stanford Research, U.S.) was used to synchronize the US and CCD using three triggers, T1, T2, and T3. Trigger T2 controlled the AM US signal, and triggers T1 and T3 started the two CCD exposures (one before and one during the US signal burst). Multiple groups of triggers were used in the experiments where the time delay between the start of the US (T2) and CCD recording (T3) was varied. This delay was set to be the US propagation time to the focus area plus 0, 1, ..., 25 ms so that measurements at different phases of the AM signal cycle could be made, well within the speckle decorrelation time for this phantom.

The CCD exposure time was varied between 0.25 and 4 ms for AM US modulation. For CW US modulation, a 2 ms CCD exposure was used, as the AO signal was independent of CCD exposure time.

The CCD image contrast was calculated by dividing the standard deviation of the speckle image intensity by its mean value $C = \sigma / \langle I \rangle$, where σ and $\langle I \rangle$ stand for standard deviation and mean of speckle intensity. The image contrast difference, ΔC , represents the AO signal and is defined as the difference in C between US on and US off [6]. Increased modulation by US and radiation forces can cause C to decrease when the US is on and, hence, cause ΔC to increase. Error bars were calculated from the standard deviation of four repeated measurements.

The simulation results of the radiation force and particle displacement as a result of AM US are shown in Fig. 2. This shows that particle displacement passes

Fig. 2. (Color online) Normalized particle displacements at different oscillation frequencies.

through a transient state before reaching a steady state approximately 3 ms after the force was applied. The oscillation amplitude decreases quickly as the AM frequency increases and is not visible in Fig. 2 at 8 kHz.

Figure 3(a) shows a comparison of AO signal for different CCD exposure times when applying 250 Hz AM US. The signal was modulated (green dashed-dotted curve) when using a shorter exposure time of 0.25 ms, which was much less than a period of the AM signal, and the peak values were the same as those generated by the CW US of equal amplitude (black solid curve). As the CCD exposure time increased to half the AM period (2 ms), the AO signal still varied periodically but the peak values were significantly larger than with a 0.25 ms CCD exposure time. As the CCD exposure time increased to 4 ms and 8 ms (equal to and twice the AM period), no significant signal variations were observed and the amplitude was similar to the peak value measured at the 2 ms exposure time.

Figure 4(a) shows the variation of the AO signals for different modulation frequencies. The AO signals were averaged over a 5 ms period after reaching a steady state. The averaged AO signal decreased as the modulation frequency increased from 250 Hz to 16 kHz. This corresponds well to the simulation in Fig. 2, which showed that higher frequency signals generate smaller particle displacements. Figure 4(b) shows the AO signal as a function of US amplitude for both AM and CW US. It can be seen that at 250 Hz, AM US at amplitudes higher than ~ 550 kPa can outperform CW US of the same amplitude for the tissue phantom and measurement geometry used in this study.

Fig. 3. (Color online) (a) Contrast difference versus CCD trigger delay time for CW US and 250 Hz AM US with various CCD exposure times, recorded with the same maximum pk-pk amplitudes. (b) AO signal values for different detection area to tank boundary distances.

Fig. 4. (Color online) (a) Average AO signal versus AM US frequency (kilohertz) for US amplitude of 1.13 MPa pk-pk (800 mV) and CCD exposure time of 2 ms. (b) Average AO signal versus US amplitude. AM frequency is 250 Hz, CCD exposure time is 2 ms, and pk-pk acoustic pressures for 225 mV and 900 mV are 318 kPa and 1.27 MPa, respectively.

It can be seen from the results that at shorter CCD exposure times, the maximum AO signal due to AM US is consistent with CW US. At longer exposure times, however, there is a significant increase in the AO signal, indicating that with the shorter exposure time, photons are mainly modulated by pure US and particle displacements due to radiation forces and shear waves are small. With longer CCD exposure times, larger radiation force-induced particle movements can be captured. Such particle movements due to radiation forces can be local or nonlocal. To maintain reasonable spatial resolution, only contributions from local particle movements are desirable and those due to nonlocal shear waves reduce the resolution. According to our calculation based on a Voigt model [12], with shear-wave elasticity of 40 kPa and density of 1000 kg/m³, the calculated shear-wave attenuation coefficient is over 20 dB/cm in the range of most physiological tissue viscosities for frequencies larger than 1 kHz [6] but is only about 3.8 dB/cm at 250 Hz. Therefore, more contribution from shear waves is expected for low AM frequencies.

Because a 250 Hz shear wave can propagate over a significant distance before its amplitude is negligible, we have investigated the effect of shear-wave reflections from the tank boundaries on the optical contrast measurement. The US focus and optical detection area were moved horizontally relative to a boundary, thereby changing the distances between the detection area and the boundary. Figure 3(b) shows that when the US focus was near the boundary, the AO signal had a peak at approximately 20 ms, whereas when the US focus was moved away from the boundary, this peak disappeared. Because the shear-wave propagation speed at this frequency is only a few mm/ms [11], the timing of the peak is in general agreement with the round-trip time between the detection area and the tank boundary (~ 3.6 cm). Further investigation is needed as the relatively large

wavelength (cm) of the shear wave means its relative reflected phase may result in either a peak or a trough in the optical AO signal. Similar results have recently been reported in [13].

It should be noted that in this Letter, comparisons were made between AM and CW US when the maximum pk-pk amplitudes were equal. In this case, substantially more energy is transmitted by the CW US than the AM US. If compared on an energy-equivalent basis, even AM US at 8 kHz would have outperformed CW US.

In this study, the effect of low-frequency AM US on optical signals was investigated using a CCD-based speckle contrast detection system. Large periodic variations in contrast at the modulation frequency were observed using short CCD exposure times, and constant signals were measured for longer CCD exposures. Our experimental results indicate that low-frequency (hundreds of hertz to several kilohertz) AM US was able to increase the modulation signal when longer exposure times were used. The relative contribution of shear waves and their effect on the spatial resolution are the subjects of our further study.

The authors would like to thank the UK Engineering and Physical Sciences Research Council (EPSRC) (grant EP/H02316X/1) and the Royal Society for their financial support.

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