Immersion Detection of Ultrasound using a GCLAD system

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Abstract. When an optical beam passes through a medium with acoustic disturbances, fluctuations in the medium's index of refraction divert the beam from the original path. As such, an acoustic wave can be detected by directing a laser beam through the disturbance and sensing the path changes with a position-sensitive photodetector. Depending on the optical components used, the detector can sense the deflection or displacement portion of the diversion. In a gas medium, this technique is designated Gas-coupled Laser Acoustic Detection (GCLAD) and has been used to sense audio-frequency and ultrasonic waves. The method has proven to be a relatively simple and effective method for sensing ultrasound that has been transmitted from materials for applications in materials characterization and nondestructive evaluation.

Here we present research where the GCLAD system is used to detect ultrasonic waves in water. As with noncontact transducers, the advantage of using water as the medium is the comparatively low attenuation of higher ultrasound frequencies. This produces stronger signals at lower frequencies and enables detection of higher frequencies that would be difficult to sense in air. Recent modelling has shown that this approach produces broadband sensitivity, allowing detection from a few hundred Hertz to 20 MHz for a 2.5 cm travel distance.

GCLAD also allows the acoustic wave to be detected undisturbed at different travel distances by repeatedly passing the beam through the medium. The presence of the laser beam does not have any affect on the acoustic wave. This characteristic is used to sense the ultrasound wave both before and after passing through a material. The second waveform can be then be calibrated per shot using the amplitude of the first wave. Frequency changes in wave, beyond the attenuation from travel through water, can be attributed to the material itself, producing additional information about the material characteristics.

INTRODUCTION

Gas-coupled laser acoustic detection (GCLAD) senses both audio-frequency and ultrasonic waves in air. This is accomplished by sending a laser beam through the region where the acoustic disturbance is expected. The compression and rarefaction from the acoustic wave produce similar fluctuations in the air's index of refraction, diverting the beam from the original optical path. A position-sensitive photodetector senses the beam path producing a signal that is dependent on the acoustic wave. GCLAD has been used to sense ultrasound waves in different materials for nondestructive evaluation and as an audio-frequency microphone. [1]

Recently, this approach has been investigated for the detection of acoustic waves in water. [2, 3, 4, 5] By using water as the coupling medium, the practical frequency range is increased. The directional sensitivity, first reported in LU2013, may also be beneficial for maritime sensing or in photo-acoustic sensing. [6] In this paper, we discuss the frequency response of this system and the application of the technique for the ultrasonic C-scans of different materials.

FREQUENCY RESPONSE

The attenuation of ultrasound in air becomes prohibitive for GCLAD and other air-coupled techniques as frequencies increase above several megaHertz. [4] The attenuation in water is several orders of magnitude smaller at these frequencies. In reference [4], we calculated the frequency response of optical beam deflection in water with primarily assumption that the beam width is significantly smaller than the ultrasound wavelength. In summary, the pressure distribution produced by a piston radiator into fresh water can be stated as

$$p(r,t) = \frac{2p_o T}{akz} e^{-\alpha'\nu^2 r} e^{i(kr-\omega t)} J_1(ak\sin\theta). \tag{1}$$

where p_o is the ambient pressure, T is temperature, a is the radius of the piston, k is the wavenumber, $r = \sqrt{x^2+z^2}$ and $\sin\theta = z/r$, ν is the acoustic frequency [10,11] and α' is a frequency-independent attenuation coefficient in fresh water given by [7]

$$\alpha' = \frac{4.34(2\pi)^2}{\rho_F c_F^3}\left(\frac{4\mu_F}{3} + \mu_F'\right) \tag{2}$$

From equations 1 and 2, we can compute the ratio of pressure at a specific distance as compared to the original, with some representative values shown in the Table 1. For a moderate-sized water tank, attenuation is generally inconsequential for frequencies of 1 MHz or below.

The relationship between the pressure change and the index of refraction is expressed as

$$n(\overline{p}) = \sqrt{\frac{1 + 2(a_9 + a_{11}\overline{p} + a_{12}\overline{p}^2 + a_7\overline{p}^3)}{1 - (a_9 + a_{11}\overline{p} + a_{12}\overline{p}^2 + a_7\overline{p}^3)}}. \tag{3}$$

where the constants and derived quantities are described in reference [4] based on a formula from the International Association for the Properties of Water and Steam. [8]

The angle of reflection θ_b, as shown in Figure 1 produced by a variation in the local index of refraction can be approximated by

$$\theta_b \approx \int \frac{1}{n(x,z)} \frac{\partial n(x,z)}{\partial x} dz. \tag{4}$$

when the beam travels in the z direction and the sound travels in the x direction.

Equation 4 was evaluated using quadrature integration for frequencies ranging from 2 kHz to 21 MHz for a water temperature set at 14 C and ultrasound velocity of 1461 m/s. A pressure of p_o = 1000 Pa and transducer radius of a = 0.75 cm were used to simulate our laboratory system while the integration was performed from z= -10 cm to 10 cm.

The results, shown in Figure 2, produced a broadband response for beam positions x =2, 5, and 10 cm. Maximum sensitivity is reached between 1.4 and 1.9 MHz, where beam deflections range from 0.42 and 0.49 $\times 10^{-3}$ degrees. The data is presented as decibels, according to the formula

$$OBD_{dB} = 20\log_{10}\left(\frac{\theta_b}{\theta_{bmin}}\right) \tag{5}$$

where θ_{bmin} is an empirically derived minimal beam deflection angle of 0.3 μm. [4] If the optical lever arm is 0.25 meters from detection point to detector, the minimum detectable beam deflection is 68 μdeg. Comparison of this value to the calculation reveals that one can obtain detectable signals in the range of 15.8 kHz to 13.6 MHz for x = 10 cm, 6.8 kHz to 14.1 MHz for x = 5 cm. An additional calculation at distance x =2.5 cm revealed a detectable range from 100 Hz to 20.0 MHz.

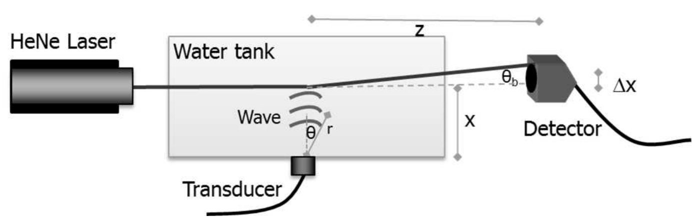

FIGURE 1. Schematic for underwater detection of ultrasound using optical beam deflection. An ultrasound transducer is mounted to the side of the water tank in order to deliver an ultrasonic wave to the sample. The optical beam passed behind the sample to sense the through-transmission ultrasound. A position-sensitive photodetector senses the deflection of the beam.

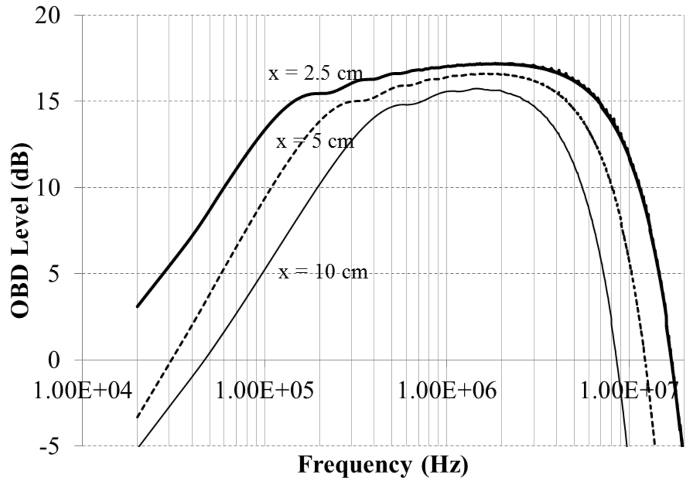

FIGURE 2. Optical beam deflection levels (displayed in decibels in reference to the minimal detectable deflection) as a function of frequency is shown for three distances between the transducer and the detection point. Values above zero reflect frequencies that can be detected with state-of-the-art position-sensitive photodetectors.

ULTRASOUND SCANS

The improved frequency response of the system can be beneficial for the nondestructive evaluation of materials. A through-transmission arrangement for this experiment is shown in Figure 3. A 10 MHz contact transducers was mounted on the outside glass of the water tank to serve as the acoustic source, producing a setup where no electronics are immersed. The laser beam intercepts the waveform before and after it has propagated through the material enabling sensitivity corrections. A convex lens is inserted before the detector to decrease the size of the system without sacrificing sensitivity. [9] We used a 10 mW HeNe laser that was chosen for convenience. Additional signal resolution can be obtained by using a laser of higher power and lower noise, but this laser was sufficient to validate the concept. Figure 4 shows example waveforms after propagation through different materials.

To create C-scan images, the samples were moved using a two-axis scanning system while recording the peak-to-peak amplitudes of the through-transmission and reference waveform at each position. Figure 5 (left) shows the ‘flat field’ derived from the reference waveforms, the through-transmission C-scan (center), and corrected C-scan (right) for a 0.4 mm thick uni-weave carbon fiber fabric. The scan size was 120× 80 pixels for an area of 23 by 15 mm^2 area. Each pixel was taken from the average of 128 shots at that position. The flat field shows mostly line-by-line variations which are compensated for in the corrected image.

The second example, shown in Figure 6, was taken of a 1 mm thick graphite-reinforced composite panel. Scan size was 100× 100 pixels over an area of 25.4 by 12.5 mm^2 area. Both examples exhibit significant horizontal smear. This resolution loss is likely due to the integration of the ultrasound along the length of the laser in this direction. The use of a focused transducer would reduce this artifact.

TABLE 1. The loss of signal amplitude due to attenuation in water expressed as a ratio of the pressure at a specific distance to the original pressure.

Loss at	1 mm	1 cm	10 cm	1 m
1 kHz	1	1	1	1
10 kHz	1	1	1	0.999997
100 kHz	1	0.999997	0.999969	0.999690
1 MHz	0.999969	0.999690	0.996905	0.969482
10 MHz	0.996905	0.969482	0.733492	0.045077

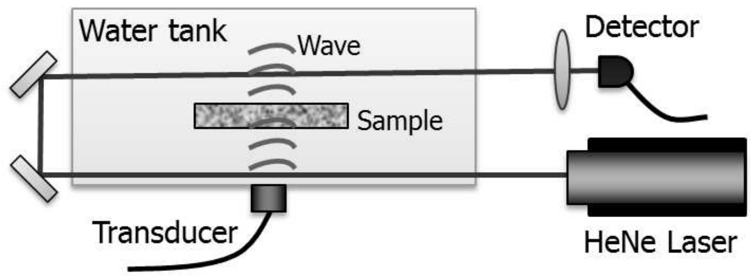

FIGURE 3. Schematic for underwater detection of ultrasound using optical beam deflection. In this configuration, the ultrasound diverts the laser beam twice. The first diversion occurs before passing through the object and is used for shot-by-shot calibration.

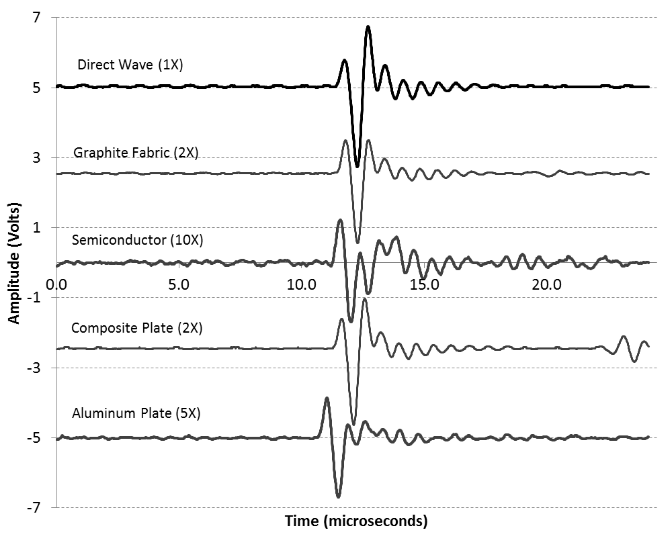

FIGURE 4. Several examples of transducer-generated through-transmission waveforms captured using the configuration in Figure 3. Each waveform is the average of 128 shots. Scale factors, for display purposes, are shown in parentheses. The direct wave was captured without a sample between the source and detection point.

COMMENTS

The application of GCLAD system to the underwater sensing of ultrasound has several advantages for the nondestructive evaluation of materials. The method provides a broadband frequency response without microphone ringing. The method is easily configured, requires no special optics, and precludes the introduction of electronic equipment into the water tank. As demonstrated here, sufficient signal-to-noise can be obtained with basic laboratory equipment. Improved signal-to noise can be achieved using lasers with increased power and lower noise characteristics. The double-pass configuration shown here provides a shot-to-shot reference wave that can be used to correct for drifts in system sensitivity.

In future work, we aim to gauge changes in the shape of the wave as it passes through the material. In this manner, the material acts like a filter. The changes, on a point-by-point basis, may help to locate variations in material density or determine pororsity. In addition, further information can be extracted from the reflected waveform, providing information about the front surface, and the pulse-echo wave, providing information about the back surface.

FIGURE 5. An example of a flat-fielded C-scan taken of a 0.4 mm thick uni-weave carbon fiber fabric. The left image represents reference amplitude levels taken before the waveform traverses the sample. The middle image represents amplitudes taken after the waveform passes through the material. The image on the right is the through-transmission C-scan values divided by the normalized flat-field values.

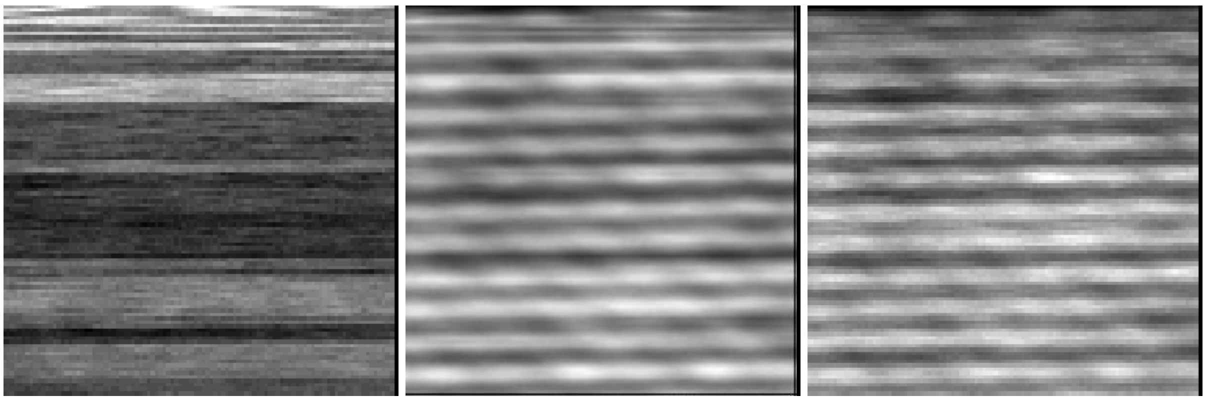

FIGURE 6. A second example of a flat-fielded C-scan taken of a 1 mm thick graphite-reinforced composite panel. The left image represents reference amplitude levels taken before the waveform before traversing the sample. The middle image represents amplitudes taken after the waveform passes through the material. The last C-scan is the through-transmission C-scan values divided by the flat-field values.

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