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Displacement and Deflection Sensitivity of Gas-coupled Laser Acoustic Detection

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Abstract
Ultrasound radiated from a surface can change the path of an optical beam, directed through the acoustic field and parallel to the surface, through acousto-optic interaction. Sensing of the beam motion with a position-sensitive detector produces a simple but effective non-contact ultrasound detector, designated Gas-coupled Laser Acoustic Detection, or GCLAD. Recent research has shown that the received signal is a combination of the deflection and displacement of beam. The technique proved capable of detecting displacements of the beam, created by a transducer-generated airborne ultrasound wave, of less than a micrometer. Deflections were recorded that measured less than a microradian. The presented work estimates the sensitivity of GCLAD to an ultrasonic surface displacement. The results are compared to the sensitivities of more standard ultrasound detection methods.

Keywords: Laser ultrasound, ultrasound detection, non-contact inspection, optical beam deflection, ultrasound transducer.

1. Introduction

Airborne ultrasound can be sensed by directing a laser beam through the acoustic disturbance. The disturbance causes a change in the optical path of the beam that can be detected with a position-sensitive photodetector; a technique designated gas-coupled laser acoustic detection (GCLAD). [1-3] One such disturbance is the radiation of an ultrasound wave from the surface of a sample, generated with either a pulsed laser or ultrasound transducer. As shown in Figure 1, the probe beam passes parallel to the surface with a standoff distance that has ranged between 1 mm and 3 cm. This enables laser-based ultrasound sensing that is not dependent upon the optical qualities of the sample surface. The method provides wideband sensing up to 8 MHz and consists of comparatively simple optics and electronics.

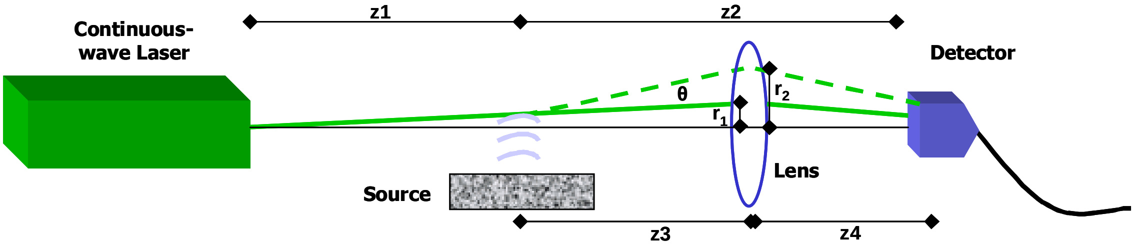

Figure 1. Arrangement for observation of laser-generated ultrasonic waveforms with GCLAD. Ultrasonic waveforms, upon transmission through the material, radiate an airborne wave, which modulates the index of refraction transverse to the probe beam and alters the path of the laser beam. The movement is detected by a position-sensitive photodetector.

Two important achievements were produced from reference [4]. The first achievement was the verification that an airborne ultrasound wave produces a displacement as well as a deflection of the laser beam, as illustrated in Figure 2. To first order, signal sensitivity to the deflection of the beam is proportional to the distance between the interaction point and the detector. Thus higher sensitivity comes at the expense of a larger system. In previous work, [5] the sensitivity of the deflection component has been compared to the sensitivity of other NDE methods. In contrast, the displacement component enables the system to be independent on the length of the optical path, producing a much smaller system.

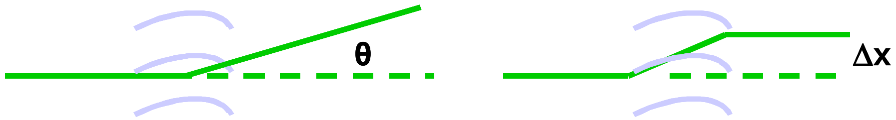

Figure 2. The received signal was found to be a combination of a deflection (left), or a combination of deflections that give rise to a displacement (right).

The second achievement was the development of a quantitative measure of the angle of deflection and the displacement amount could be calculated. In this work, these results are discussed and compared to the theoretical sensitivity of the system.

2. Theory

The derivation of the detection of the deflection and displacement components was presented in reference [4], but is summarized here.

A split-cell, or bi-cell, photodetector is used to sense the position of the laser beam. The received signal at the detector is

$$V_{tot}(\Delta x) \approx \frac{-8GR\kappa P_0}{\sqrt{\pi^3}} erf(\frac{d_c}{2\omega_D})\frac{\Delta x}{\omega_D}\left[e^{-d_c^2/4\omega_D^2} - e^{-t_c^2/4\omega_D^2}\right] \quad (1)$$

where G is the gain of the amplifier, R is the resistance value that converts the current to a voltage, κ is the sensitivity of the photocell, P_0 is the average power of the laser, d_c is the width of the photocell, ω_D is the beam width at the detector and t_c is the separation distance between the two photocells. This relationship shows that for small deviations, the received signal is proportional to the beam displacement on the photodetector.

The beam width at the detector, with no lens in the optical path, is calculated from

$$\omega_D(z) = \omega_o\sqrt{1+(\frac{\lambda z}{\pi\omega_o^2 n})^2} \quad (2)$$

where ω_o is the original waist of the beam, z is the distance along the optical path, λ is the wavelength of light, and n is the index of refraction.

The beam width ω_D at the detector, with a single convex lens of focal length f in the optical path, is

$$\omega_D(z) = \omega_o \sqrt{\frac{A_T{}^2 + B_T{}^2 / s^2}{A_T D_T - B_T C_T}} \tag{3}$$

where $s \equiv \lambda / \pi \omega_o^2 n$ and

$$\begin{pmatrix} A_T & B_T \\ C_T & D_T \end{pmatrix} = \begin{pmatrix} 1 - z_4 / f & z_1 + z_3 + z_4 - z4(z_1 + z_3)/f \\ -1/f & 1 - (z_1 + z3)/f \end{pmatrix} \tag{4}$$

where $z_1 + z_3$ is the distance from the minimum beam waist (the laser) to the lens.

With no lens in the set-up, the relationship between a deflection of angle θ at the interaction point and the beam displacement on the detector is $\Delta \mathrm{x} = \mathrm{z}_2 \theta$.

The displacement component is recorded with a convex lens inserted in to the optical path. The displacement at the interaction point $\Delta \mathrm{x}_o$ produces a displacement at the detector of

$$\Delta \mathrm{x(z)} \approx \Delta \mathrm{x}_o (1 - \mathrm{z}_4/\mathrm{f}) . \tag{5}$$

The received signal *V(z,t)* from the photodetector was shown to be a combination of the two waveforms

$$V(z,t) = A(z)\Delta x(t) + B(z)\theta(t) \tag{6}$$

where *A(z)* describes how the amplitude of the displaced waveform changes with distance, and *B(z)* describes how the deflected waveform changes.

To estimate $\Delta x(t)$, we assume that close to the interaction, as close as the detector can be placed, $V_\theta(0,t) << V_{\Delta x}(0,t)$ such that $\Delta x \approx V_{\Delta x}(0,t) / A(0)$. The beam deflection $\theta(t)$ can be calculated from

$$\theta(t) \approx \frac{V(z,t) - A(z)\Delta x(t)}{B(z)} . \tag{7}$$

3. Experiment

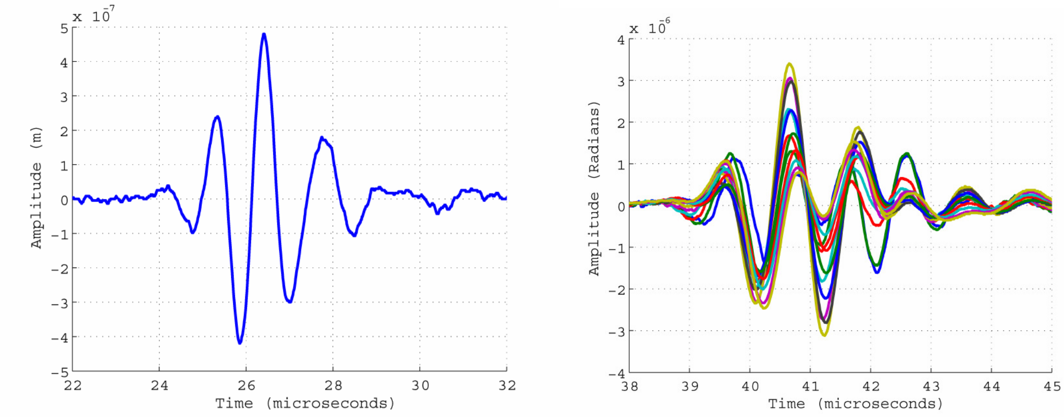

Figure 3. (Left) A displacement waveform measured very close to the interaction point and scaled using $\Delta x \approx V_{\Delta x}(0,t) / A(0)$. (Right) A series of deflection waveforms calculated from equation (7) for various values of z.

Figure 3 (left) shows a displacement waveform created by a 1 MHz contact transducer placed about 1.3 cm from the laser beam. This waveform shows that the laser beam was displaced by total amplitude of 1 μm.

Waveforms were captured as z_4 was increased from 2.9 cm to 97 cm. Inserting the captured waveforms into Equation (7) produced the family of curves in Figure 3 (right). Since $\theta(t)$ is independent of z, these curves having similar amplitudes. The angle of deflection has values that range from –3 to 3 microradians.

4. Analysis

We can use the results above to estimate the minimum detection values for a frequency of 1 MHz. The detection limit occurs when the signal-to-noise ratio is unity. The noise level from the displacement waveform that has been averaged over 64 shots is 0.019 μm. Thus, for a single shot, the noise level is 0.15 μm. From the analysis in reference [5], the signal can be improved 8% by inserting a lens into the system. (This has the added benefit of moving the detector a comfortable distance from the interaction point.) Thus, the minimal detectable beam displacement is about 0.14 μm.

For an average of 64 shots, the noise level for beam deflection where z_4 = 1 meter is 0.054 microradians, producing a single shot value of 0.44 μrad. According to reference [5], a system with z_4 = 5.5 meters would increase sensitivity by 78%, producing a minimum detectable beam deflection of 0.25 μrad.

According to reference [5], the minimal detectable surface displacement (MDSD) [6,7] for the deflection component of GCLAD can be expressed as

$$\delta_{\min} = \frac{n_o u_g^{\,2} e^{\alpha' \nu^2 d} \theta_{\min}}{4\pi^2 b(n_o - 1)\nu^2}$$

where n_0 is the ambient index of refraction, ν is the frequency of surface oscillations, u_g is the speed of sound in air, $2b$ is the width of the interaction, d is the distance from the source to the optical beam, and α' is the attenuation coefficient in air for frequencies above 200 kHz. [8] This relationship assumes the ultrasonic source produces a plane wave with insignificant transverse spreading of the wave front. Although this simplifies the calculation, we note that actual acoustic environment is more complicated.

Using $\theta_{\min}$ = 0.25 μrad, n_0 = 1.00029, u_g = 343 m/s, b = 0.8 cm, ν = 1 MHz, α' = 2 × $10^{-11}\mathrm{m}^{-1}\mathrm{Hz}^{-2}$, and d = 1.3 cm, the MDSD is 0.42 nanometers. For $\Delta\nu$=1 MHz, the MDSD is 4.2× $10^{-13}\mathrm{m\,Hz}^{-1/2}$.

To see how this compares to theoretical predictions, Figure 4 shows a graph with the MSDS plotted as a function of frequency for GCLAD (d = 1.3 cm and d = 0.4 cm) and a confocal Fabry-Perot (CFP) in transmission and reflection mode. [9] The lower the line on the graph, the higher the sensitivity to a surface displacement.

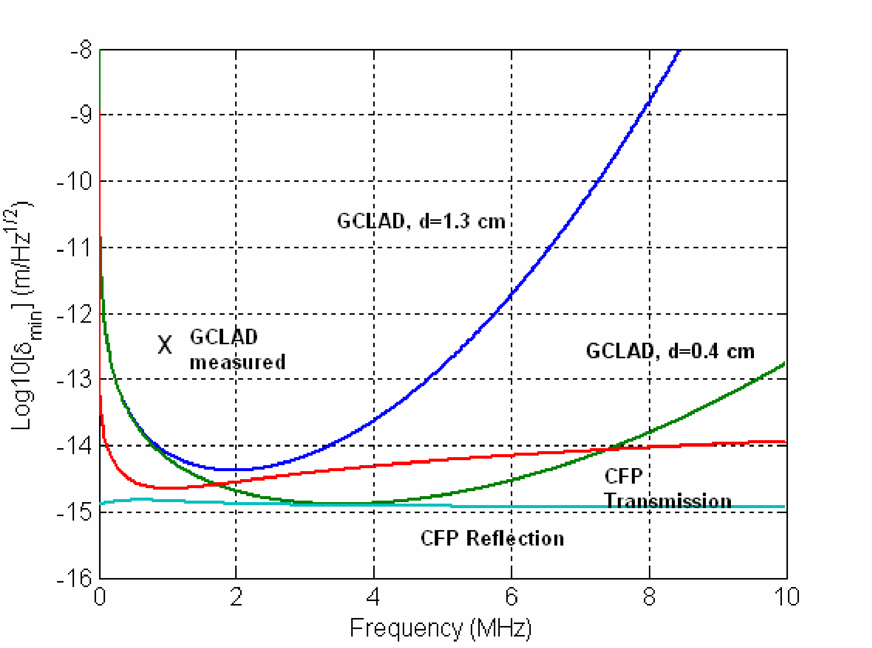

Figure 4. Minimum detectable surface displacements for GCLAD and Confocal Fabry-Perot Interferometers. The 'X' shows the measured value for a GCLAD system with d = 1.3 cm.

The sensitivities were calculated with an average laser power of 0.13 Watts. The sensitivity of GCLAD compares well with a CFP interferometer in the range of 1-3 MHz. This assumes that the surface under test has ideal optical properties. If the surface is less-than-ideal, the CFP sensitivity will decrease whereas the GCLAD curve remains constant.

The ‘X’ on the graph shows the measured value from the analysis above. The value occurs more than an order of magnitude above the theoretical MDSD. We suspect the disagreement is partly due to the assumption that the radiated waveform was modelled as a plane wave. A more complicated waveform would reduce the overall deflection of the laser beam through multiple interior deflections.

In addition, the wavelength of the radiated ultrasound is 0.34 mm, which is comparable to the original width of the probe laser beam. As the waveform passes through the beam, portions of the beam can deflect by different and opposite angles. This would also reduce the amplitude of the received signal. Ideally, the laser probe beam width should be significantly smaller than the ultrasound wavelength.

The plane wave model also does not give rise to a displacement waveform. A spherical waveform radiating from the surface would result in a displacement component. However, the additional dimension complicates the calculation. Since the beam traverses the near-field of the acoustic source, even a spherical waveform may not accurately describe the situation. Thus, future work will develop an improved model of the radiated waveform in hope of improving the accuracy for the deflection component, and adequately describing the frequency dependence of the displacement component.

5. Comments

This work discussed the sensitivity of GCLAD for the detection of radiated ultrasound resulting from a surface vibration. The received GCLAD signal results from the combination of a deflection and a displacement of the optical beam resulting from an acoustic disturbance in the beam path. The amount of deflection and displacement was measured and minimum detection levels were estimated. This produced a value for the minimal detectable surface displacement that can be acquired using the deflection component of GCLAD. The MDSD value was more than an order of magnitude higher than the theoretical value. However, we feel that narrowing the laser beam width, and using a more sophisticated model can mitigate the difference between theory and experiment.

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