Application of the Gas-Coupled Laser Acoustic Detection technique to non-destructive monitoring of mechanical components

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Abstract. Non-contact ultrasonic techniques are fundamental to devise online monitoring systems for moving or difficult to access structures. Gas-Coupled Laser Acoustic Detection (GCLAD) is an unestablished, non-contact detection technology which relies on measuring the deviation affecting a laser beam when travelling across an ultrasonic wavefront propagating in a fluid. The aim of the work is to provide in-depth highlights on the principles on which the technique leverages, with a view towards how several laser beam and ultrasonic wave features reflects on the signal acquired by the GCLAD device. By numerical and experimental approaches, parameters needing to be specifically addressed and suitably set during the investigation phase are highlighted, which enable amplitude maximization of the acquired signal. Specifically, effect of the probe laser beam spot size is thoroughly analyzed, as well as the mutual orientation between the beam and the ultrasonic propagation directions. Three test configurations are lastly proposed, providing different results in terms of GCLAD sensitivity to the acoustic waves; such differences are highlighted by applying the technique to a railway axle on which an artificial crack has been machined, providing a first assessment of the GCLAD capabilities in the non-destructive testing field.

1. Introduction  
Non-contact, ultrasonic non-destructive testing (NDT) techniques enable excitation and detection of ultrasonic waves propagating inside a component without direct contact with its surface. This is fundamental to enable the monitoring of mechanical components which rotate, translate [1] or are immersed in aggressive environments (corrosive or subjected to high temperatures [2]). Since no coupling medium is required between the source/receiver and the
solid, evaluation errors regarding time of flight or speed can also be minimized as well as the risk of contamination during inspection on composite materials [3].

The most typical devices for non-contact ultrasonic excitation are air-coupled probes, while Electro-Magnetic Acoustic Transducer (EMATs) and lasers are considered as non-conventional ultrasonic sources. While piezoelectric probes and EMATs are inefficient transducers because the ultrasound needs to travel in air before reaching the component’s surface [4, 5, 6], optical techniques relying on high power laser sources are extremely performing (photoacoustic effect [7]). Regarding detection, the operating principle of EMATs or piezoelectric probes can be inverted to also acquire ultrasonic waves; the most well-established optical technology for non-contact ultrasonic detection is represented by laser interferometers [7, 8]. Laser interferometers feature high resolution, enabling identification of surface oscillations of the order of hundreds of pm. Nevertheless, since their proper functioning depends on the reflectance characteristics of the inspected surface, interferometers exhibit limitations during the inspection on rough and coated pieces.

A recent addition to the wide range of optical ultrasonic detection technologies is represented by the Gas-Coupled Laser Acoustic Detection (GCLAD) technique [9, 10]. This technique is currently unestablished in the NDT field, even if its sensitivity proved to be at least equal (if not superior) to a Fabry-Pérot confocal interferometer in the investigation of low reflectance tissues or composite specimens [11]. A GCLAD device is constituted of a probe laser beam which travels through a fluid in which a pressure field (ultrasound) is present; as the beam intersects such pressure field, consequent differences in the refractive index of the air modify the laser beam travelling direction. Deviation from the unperturbed path is sensed employing a position-sensitive photodetector [10]. The optical properties (reflectance) of the component under interrogation negligibly affects the GCLAD response, because no interaction occurs between its surface and the probe beam; the system is also compact, and characterized by a cost which is down to two orders of magnitudes below that of an interferometer. Still, the device currently has no practical industrial application, so that additional studies are required to enable its proper functioning in the NDT field.

The present study aims at analyzing the GCLAD features that could result in an optimized employment for NDT purposes. In particular, the effect of parameters like the probe laser beam spot and the mutual inclination between probe beam and ultrasound propagation direction are analyzed in detail. Based on such results, different solutions for a GCLAD implementation in NDT procedures are proposed, regarding detection of both longitudinal and surface waves. Finally, a case study of GCLAD application to an NDT investigation of practical use is analyzed [12], in which monitoring is performed on a railway axle on which an artificial crack has been machined.

2. Physical principle

The GCLAD technique [9, 11, 13] detects waves at different frequency contributions which propagate in the air, including ultrasonic waves refracted into the air from a solid surface: these waves correspond to a pressure gradient inside the fluid, so that perturbations in its refractive index are triggered. The probe laser beam (the sensor of the GCLAD technique) translates along a direction perpendicular to the wave propagation direction based on the refractive index gradient. A position-sensitive photodetector transduces such translation of the beam in a proportional current [11, 13].

Variations in the fluid refractive index $n(r, t)$ and pressure $p(r, t)$ (time and space dependence) are tied by the following condition [14]:

$$n(r, t) \approx \frac{(n_0 - 1) (p(r, t) - p_0)}{\rho_0 \gamma^2} + n_0$$  \hspace{1cm} (1)
where \( \mathbf{r}(t) = [x(t), y(t), z(t)] \) is the vector defining the coordinates of the point for evaluation at time \( t \), \( \rho_0 \) is the unperturbed fluid density, \( \gamma \) the speed of the ultrasound in the fluid and \( n_0 \) the refractive index of the fluid. When the probe beam intersects a wave propagating in the fluid, the eikonal equation rules over the refraction phenomenon \cite{15}:

\[
\frac{d}{dm} \left( n \frac{dx}{dm} \right) = \nabla n \tag{2}
\]

\( m \) in Equation (2) is the length of the path travelled by the probe laser beam. If the beam travels along \( x \) (hence coherent with Figure 1), \( dm \approx dx \). Additionally, if a planar ultrasonic field travels along the \( z \) direction perpendicularly to the probe beam, Equation (1) gains the following form considering that \( \frac{dn}{dx} = 0 \):

\[
\left( \frac{(n_0 - 1)(p(r,t) - \rho_0)}{\rho_0 \gamma^2} + n_0 \right) \frac{d^2z}{dx^2} = \frac{(n_0 - 1)}{\rho_0 \gamma^2} \frac{\partial}{\partial z} p(z,t) \tag{3}
\]

Referring to air, \( n_0 \approx 1 \) and Equation (3) simplifies in the following form:

\[
\frac{d^2z}{dx^2} = \left( \frac{n_0 - 1}{n_0 \rho_0 \gamma^2} \right) \frac{\partial}{\partial z} p(z,t) \tag{4}
\]

Double integration subsequently allows evaluation of the displacement along \( z \) of the probe beam in correspondence of the point with \( x \) coordinate \( (z(x)) \). Indicating with \( z_0 \) the initial \( z \) coordinate of the probe beam as it exits from the laser source, deflection along the path affected by the ultrasound is negligible, as well as displacement because of the limited pressure gradient encountered along \( z \). This results in a constant value of \( \frac{\partial}{\partial z} p(z_0, t) \) and, based on Equation (4) in the following relation:

\[
z(x) = \frac{(n_0 - 1)}{2n_0 \rho_0 \gamma^2} x^2 \frac{\partial}{\partial z} p(z_0, t) \tag{5}
\]

At the exit of the intersection region between the ultrasound and the probe beam, the total deviation \( z(x_s) \) is provided by the following:

\[
\Delta z = z(x_s) + \vartheta x_1 \tag{6}
\]

The deflection angle \( \theta \) is sufficiently small to assume \( \theta \approx \tan(\theta) \), hence equalling \( z(x_s)/x_s \).

\[\text{Figure 1.} \quad \text{Deflection} \ \theta \ \text{of a light beam propagating in the} \ x \ \text{direction, orthogonal to the propagation direction} \ z \ \text{of the acoustic plane wavefront} \ p(z,t).\]
Figure 2. Variations in the refractive index along the $x_s$ long path modify the $z$ coordinate of the probe beam; the beam travels in the remaining $x_1$ long segment with an inclination compatible with the deflection angle $\theta$, until it reaches the photodetector.

3. Analysis of the GCLAD characteristics

The characteristics of the GCLAD device are analysed in detail regarding response and sensitivity, to make it suitable for NDT purposes. Based on Equations 1-6 and Figures 12, high response for the GCLAD is obtained employing high values of $x_1$ and $x_s$; still, these could contrast the compactness of the device and could be unfeasible when access to the surfaces is complicated (e.g., in case of braking disks close to the wheels in a railway axle [12]). To evaluate the response based on the value of $\theta$, a monofrequency pressure wave with central frequency $f$ can be preliminarily assumed:

$$p(z,t) = k\rho_0 \gamma^2 \delta \sin(\omega t)$$

(7)

In Equation 7, $\delta$ is the surface displacement, $z$ the distance from the component’s surface, $\omega$ is the acoustic wave angular frequency, $k$ the wavenumber $\omega/\gamma$. To facilitate calculation, the following condition can be imposed:

$$\frac{(n_0 - 1)}{n_0} \delta k^2 = A$$

(8)

and Equations 7,8 can be then substituted inside Equation 5:

$$\frac{d^2 z}{dx^2} - A \cos(kz_0 - k\gamma t) = 0$$

(9)

Solution of Equation 9 with boundary conditions $z(0)=z_0$ and $dz/dx|_{x=0}=0$, is:

$$z(x) = \frac{A}{2} \cos(kz_0 - k\gamma t) x^2 + z_0$$

(10)

The deflection of the optical beam is subsequently obtained:

$$\Delta z(x_s) = \frac{2\pi^2 (n_0 - 1)}{\gamma^2 n_0} \delta f^2 x_s^2 \cos(kz_0 - k\gamma t)$$

(11)

$z/\delta$ represents the sensitivity of the device, i.e., the ratio between the $z$ displacement of the probe beam and the oscillation of the component’s surface; the total deviation of the beam hence depends proportionally on $x_s$ and $f$.

Equation 11 does not consider the photodetector response to several features of the probe laser beam. The objective is hence to analyze the effect of three different elements on the GCLAD performances, also based on the physical assumptions expressed by Equation 11:

- beam spot;
Figure 3. Example of test configuration for the detection of surface waves: the ultrasound is excited by a probe, propagates on the component’s surface and is refracted in air with a specific angle; it subsequently intersects the probe laser beam of the GCLAD device, from which the signal of the photodetector is amplified in a driver box and evidenced on an oscilloscope.

- frequency components of the ultrasound;
- mutual inclination between probe beam and propagation direction of ultrasound.

To verify the results of analytic calculations and simulations obtained in the present Section, the experimental layout provided in Figure 3 has been introduced to receive surface ultrasonic waves propagating from solid pieces. In such a configuration, the probe beam is inclined to be perpendicular to the wave propagation direction.

3.1. Influence of probe beam spot

The probe beam of the GCLAD device can be divided in a series of infinitely small rays, occupying each a different \( z \) coordinate. As a consequence, a different displacement is experienced by the single infinitesimal ray based on the rule in Equation 10, being subjected to a different pressure gradient. Figure 4 depicts the GCLAD device sensitivity as the ratio between beam spot \( w_0 \) and ultrasonic wavelength \( \lambda \), in a simulation considering \( x_s=10 \text{ mm}, \gamma=345 \text{ m/s}, \text{ and } n_0=1.00029 \). In some points, even cancellation of the signal can be evidenced, because each combination of two infinitesimal rays belongs to regions with opposite pressure gradients. Sensitivity diminishes starting from \( w_0/\lambda \) up to values of 1.3, slightly increase for values up to 1.7 and then decreases once again. A similar trend is observed for values higher than 2.4. To validate the obtained simulated results, signals from a 500 kHz contact piezoelectric probe have been acquired using two laser sources with different spot as a probe beam, with \( w_0/\lambda \) of 1.47 and 1.60: a TOPTICA BeamSmart (1 mm spot) and a Cameo laser (1.2 mm); the annular and cross-shaped indicators in the figure represent the points associated with the two lasers, which match the expected behaviour.

3.2. Frequency response

Though nominally narrowband and centred on a specific frequency, even signals excited by a traditional contact probe are associated with a relatively broad band. In case several frequency contents compose the ultrasonic wave, Equation 11 does not fully describe the response of the GCLAD device. For instance, let us refer to a narrowband ultrasound from a 300 kHz piezoelectric probe as that in Figure 4. Introducing such function in Equation 5 the trend in Figure 6 is highlighted regarding the frequency centroid of the simulated acquired signals, as a function
Figure 4. GCLAD sensitivity $z(x_s)/\delta$ as $w_0/\lambda$ varies; the cross-shaped and annular indicators represent experimental points associated with two optical sources with different spot (a 1 mm spot TOPTICA lasers and a 1.2 mm spot Cameo laser, respectively).

of the beam spot $w$ and considering the total deviation as the weighted average of those for the infinitely small rays. A similar trend to that of Figure 4 is derived, namely the lower the wavelength (i.e., higher frequency) the higher the attenuation, $w$ being the same. The beam spot size hence intervenes like a low pass filter, as demonstrated by a comparison with a moving average filter in the same figure in which the order of the filter corresponds to an increasing number of points of the ultrasound intersected by the beam.

Figure 5. Reference ultrasound excited by a 300 kHz piezoelectric probe.
Figure 6. Frequency centroid of the simulated $z$ displacement as a function of the laser spot.

To validate such simulation results, the laser beam has been focused by a lens with focal length of 90 mm so that the beam waist is interposed between the lens and the photodetector. An air-coupled transducer is moved between the lens and the photodetector varying its distance $x_p$ from the photodetector; by this solution, the ultrasound intersects a region in which the beam spot varies continuously. Figure 6 reports the signal Power Spectrum Density (PSD) as $x_p$ varies, demonstrating that contents at increasing frequency are highlighted as the distance $x_p$ tends towards the focal length (i.e., approaching the beam waist).

3.3. Selectivity

Let us consider a laser beam whose propagation direction is not orthogonal to the ultrasonic path, being the mutual inclination defined as the $\alpha$ angle in Figure 8. In this case, the following relation is derived from Equation 1 and Equation 3:

$$\frac{d^2 z}{dx^2} + \frac{(n_0 - 1)}{n_0\rho_0\gamma^2} \frac{\partial}{\partial x} p(z, t) \frac{dz}{dx} = \frac{(n_0 - 1)}{n_0\rho_0\gamma^2} \frac{\partial}{\partial z} p(z, t)$$

(12)

If the pressure field can be expressed by Equation 7, Equation 13 is consequently obtained:

$$\frac{d^2 z}{dx^2} + A \sin(\alpha) \cos(kx \sin(\alpha) - k\gamma t) \frac{dz}{dx} - A \cos \alpha \cos(kx \sin \alpha - k\gamma t) = 0$$

(13)

Starting from Equation 13 and introducing the critical angle $\alpha_{cr}$ for which $\tan(\alpha_{cr}) = \lambda/x_s$, integration by the Runge-Kutta approach leads to the curve in Figure 9 as a function of $\alpha/\alpha_{cr}$. Simulations evidence that the GCLAD is extremely selective to mutual inclination between the probe beam and ultrasonic path, mainly because $\alpha_{cr}$ is typically lower than 0.1°.

The trend reported in the figure has been subsequently sought by experimental means. Starting from the configuration in Figure 2 a $x_s$ length equal to 350 mm of the probe beam has been exposed to acquire the signals from a 500 kHz contact probe; following Snell’s law, inclination of the ultrasonic path with respect to the specimen surface is 6.3°. As evidenced by
Figure 7. Power Spectrum Density (PSD) for four signals from the GCLAD as the probe beam spot is diminished (by decreasing $x_p$).

Figure 8. Definition of propagation directions for mutually non-orthogonal probe beam (radiating along $x'$) and ultrasound (travelling along $z$); the relative inclination is given by the $\alpha$ angle.
Figure 9. Normalized amplitude for the $z$ displacement from simulations as a function of $\alpha$, normalized to $\alpha_{cr}$.

Figure 10, the experimental results overall match the trend highlighted in Figure 9 with the GCLAD system being extremely selective towards the inclination angle between probe beam and propagation direction of the wave in air.
4. GCLAD configurations for NDT

The main inspection methods for typical ultrasonic interrogations are pitch-catch and pulse-echo modes, which can be both employed in a monitoring with the GCLAD device. Figure 11 reports alternatives for using the GCLAD to identify bulk or surface waves propagating in a specimen mainly extending in 1D, differing because of the mutual inclination between the probe beam and the ultrasonic path. Configuration A considers that the probe beam propagation direction ($y$) is perpendicular to the refracted wavefront propagation direction ($x$), so that the ultrasound only partially intersects the probe beam \[11\]. Configuration B leverages on parallelism between the probe beam and the wavefront propagation direction (analogous to Figure 3). In configuration C (similar to that reported by Caron \[16\]), a non-negligible difference exists between the probe beam and the ultrasonic wave propagation directions; since the GCLAD device is extremely selective, the response is almost null. When the ultrasound encounters the defect flank, the ultrasound wave is diffracted intersecting the probe beam in the air. The phenomenon mimics the Time of Flight Diffraction technique \[17\]. The solid rectangular windows in Figure 11 highlights configurations in which in-depth studies are already available.

**Figure 10.** Experimental trend of the normalized amplitude as $\alpha/\alpha_{cr}$ varies.
Figure 11. Configuration schemes of the GCLAD system for inspections by surface and bulk waves; the solid rectangular windows represent configurations whose characteristics have been highlighted by previous researches.

5. Discussion
In the NDT field, the GCLAD can be employed as an alternative to other well-established ultrasonic detection technologies. Differently from interferometric devices, the GCLAD optical technique can be in fact employed independently of the optical properties of the surface from which the waves are refracted.

Ultrasonic interrogation requires a highly sensitive detection system, to maximize the signal-to-noise ratio. The response and the bandwidth of the device can be increased by limiting the probe laser beam size (see Section 3.1). Typically, configuration A in Figure 11 enables a point-like detection of the ultrasound while contextually simplifying the experimental layout. Still, intersection between the probe beam and the ultrasound occurs in a limited portion of space, resulting in low sensitivity. The phenomenon becomes particularly relevant when curved surfaces are interrogated [9]. In contrast, configuration B lends itself to higher sensitivity, since the intersection region between the probe beam and the ultrasound is wide.

Differences among the highlighted configurations can be evidenced by referring to the monitoring of a railway axle body by surface waves. In Figure 12, comparison is made between configuration A and B, in which the ultrasound is excited by a 500 kHz piezoelectric contact probe fixed on an inclined plexiglass wedge; the resulting signals are presented in Figure 12: the amplitude in configuration A is obviously dependent on the dimensions of the emitting probe’s active area, which determines the length of intersection $x_s$, between the probe beam and the ultrasound refracted in the air. As a consequence, the amplitude in configuration B is significantly higher.

For what regards configuration C, a 10 mm deep artificial defect has also been triggered on the axle body. Figure 13 depicts the experimental layout and the signal thus obtained, in which an ultrasonic wave is evidenced in correspondence of 250 $\mu$s. In this case, the signal-to-noise
Figure 12. Scheme of the experiment for the detection of surface waves propagating in a railway axle body (above) and two signals from the GCLAD acquired in configurations A and B of Figure 11 (below).

ratio is lower than in the case of configuration B. However, this solution enables using the probe beam to detect whichever defect on a point belonging to a line at once, precisely locating the defect without moving the GCLAD apparatus.
Figure 13. Scheme of the experiment for the detection of surface waves propagating in a cracked railway axle body (above) and signal from the GCLAD in configuration C of Figure 11 (below). The crack perturbs the wavefront in correspondence of 250 µs.

6. Conclusions
The Gas-Coupled Laser Acoustic Detection (GCLAD) optical technique features interesting elements which could increase its application scenarios in non-destructive testing contexts. As demonstrated in previous works, for instance, its response is negligibly affected by the optical status of the surface, such as in case of coatings and oxidization. In the present work, additional highlights are reported demonstrating that diverse experimental configurations can be devised based on the specific NDT application. Three possible configurations have been proposed, based on the mutual orientation between the GCLAD probe laser beam and the specimen to be interrogated. All solutions provide different sensitivity to the propagating ultrasound, making them more or less apt to a specific type of monitoring process.

Theoretical and experimental discussion has been performed on the elements allowing for the highest performance regarding signal amplitude and bandwidth, mainly based on the probe laser beam spot size and the inclination between the ultrasonic path and the beam itself. The system is extremely sensitive to mutual positioning between the ultrasonic wavefront and the probe laser beam; the highest signal amplitude is obtained when the laser beam is perpendicular to the ultrasonic propagation direction. This relevant effect of mutual orientation between the probe beam and the ultrasound translates towards high selectivity, i.e., detection of specific ultrasonic waves only. Exemplarily, if inspection is performed by a surface ultrasound, the GCLAD automatically neglects bulk waves deriving from mode conversions and reflections inside...
the structure. These phenomena have been demonstrated by applying the GCLAD technique to detection of ultrasonic waves propagating on a railway axle, by which advantages and disadvantages of the proposed inspection configurations have been thoroughly highlighted.

The GCLAD system is constructively simple and economic, especially if compared to other optical devices like interferometers; the GCLAD device proved to be a suitable technology which, once industrialized, will effectively contribute to NDT inspections and interrogation of mechanical organs while in service.

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