Line Scanning with Gas-Coupled Laser Acoustic Detection

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Abstract. The Gas-Coupled Laser Acoustic Detection (GCLAD) is an optical technique for ultrasonic detection based on the deviation that a laser beam sustains when travelling in a fluid that features refractive index fluctuations. If the laser beam is perpendicular to the wave propagation direction, the technique enables simultaneous detection of direct waves in mechanical components and eventual echoes from defects to be achieved.

The technique is applied to the inspection of elements predominantly extending in one/two dimensions as bars and axisymmetric pieces, exploiting a signal enhancement effect occurring in defects’ proximity. The phenomenon, namely constructive interference between wave crests of a direct Rayleigh ultrasound and those associated with reflections on a defect flank, is first illustrated numerically. The effect of parameters like the angle between wave propagation direction and source-receiver distance on the GCLAD sensitivity is then experimentally highlighted. The technique is finally implemented to B-scan a steel plate with 1 mm wide, 20 mm long, and 3 mm deep surface defects.

Since the GCLAD probe laser beam insists on an entire line, defects present on that line can be identified without moving the device along such direction. This reduces the monitoring time compared to techniques leveraging on traditional air-coupled transducers or more sophisticated methods (Scanning Laser Source).

1. Introduction
Continuous ultrasonic monitoring of mechanical components in non-destructive practices involves the development of effective techniques in a wide range of operating conditions. For the online verification of the integrity of some structures, it is for example necessary to consider the
possibility that the piece rotates [1, 2, 3] or translates [4, 5] with respect to the inspection system. In the case of elements subjected to elevated temperatures, the positioning in correspondence of the structure surface involves a relevant risk of deterioration for the instruments and the need to use special couplants [6]. Further problems arise from the need to move the emitter/receiver in multiple spatial directions with respect to the component: at least one direction is represented by the normal to the piece surface, which is necessary for the coupling between structure and sensor. For these reasons, the number of application areas is constantly expanding in which non-contact ultrasonic systems are well-established, like optical technologies, Electro-Magnetic Transducers (EMATs) [7, 8, 9, 10] or more consolidated instruments like air-coupled piezoelectric transducers [11, 12]. In this context, the optical excitation and ultrasonic detection systems are extremely performing, because of the high transduction efficiency compared to other devices [13, 14, 15, 16]. An application example is represented by the SLS (Scanning Laser Source) and SLLS (Scanning Laser Source) techniques, for elements which mainly extend in two dimensions: induction of elastic waves in the component takes place by means of a pulsed laser through photoacoustic effect, while the detection is obtained employing an interferometer [17]; during the inspection, one element between the source or the detector is moved providing different sensitivity to angled defects [18]. Monitoring by these methods does not correspond to a traditional pitch-catch inspection, as the identification of a defect results from an increase in the amplitude of the ultrasonic signal rather than from its decrease. The detector is moved along the line connecting it with the emitter: when the sensing area of the detector reaches the surroundings of the crack, the amplitude of the signal undergoes intense enhancement. The cause of this enhancement is to be found in phenomena of constructive and destructive interference between direct waves and echoes deriving from defects [19].

Compared to classic contact technologies consisting of single probes or probe arrays, SLS, SLLS systems, or the likes dually contribute to the simplification of the inspection process for elements predominantly extending in two dimensions [20]. Foremost, they allow defects with limited dimensions and far from the source and/or receiver to be identified, for which the wavefront tends to almost completely overcome the discontinuities and return to the pristine conditions before its detection [21]. Secondly, if the contact detectors are positioned in mutually close points, both would have to be moved; this involves the design of complex handling and layout strategies for obtaining repeatable results (e.g., separate but rigidly connected probes, movement via two distinct arms). The SLS and SLLS instead highlight the presence of a defect by moving only the detector, leading to the generation of more flexible inspection layouts. The techniques demonstrate high sensitivity to defects: using pulsed lasers with energy per shot equal to 1.5 mJ as an ultrasonic source, with these techniques it is possible to identify surface cracks on plates which are 125 µm long and 60 µm deep [22]; with similar procedures applied, Dhital et al. [23] also demonstrate the possibility of identifying surface braking cracks with an average width of 20 µm triggered on fatigue test specimens. However, the SLS and SLLS techniques are based on the reflection of the detector probe beam by the surface of the component and can be applied with difficulty to elements with reduced reflectance, like composite materials [24].

In the so-called Gas-Coupled Laser Acoustic Detection (GCLAD) optical technique, the probe laser beam propagating in a fluid is deflected in correspondence of points with refractive index values differing from that for the unperturbed fluid [25]. These changes can be associated with a pressure field, directly related to the presence of an ultrasound. The system preferentially detects waves that propagate perpendicularly to the probe beam, so that a suitable inclination of the beam allows technicians to highlight diverse refracted ultrasonic contributions starting from the surface under investigation. As in the case of other optical detection methods, the system is broadband; the band becomes broader as the spot of the probe laser beam gets smaller [26, 27] (up to 8 MHz in air and 20 MHz in water [28]). The fundamental advantage of GCLAD, when compared with the detection part of the SLS and SLLS techniques, lies in an extremely
large sensing area corresponding to the total length of the laser beam. This translates into the possibility of inspecting any point below the beam corresponding to the refraction zone of the wave from the component to the fluid; as a consequence, the detector can be moved along a single direction to inspect the structure along the different directions. This promotes both the speeding up of the interrogation process and the flexibility of the inspection system, resulting in the minimization of the movements necessary for the apparatus to perform a complete and continuous monitoring of the component.

The present work aims to highlight the capabilities of the GCLAD system in case of inspection of mechanical components mainly extending in one or two dimensions, such as elements with axisymmetry or bars and plates. First, a brief overview is provided on how the detector can be employed in this type of inspections, as well as the waveforms typically detected. Numerically, the physical principle of amplification of the ultrasonic signals for acquisition in correspondence of surface cracks is subsequently illustrated, considering that the GCLAD device detects oscillations in the air rather than in the solid as other enhancement-based techniques (SLS, SLLS, etc.). The sensitivity of the system is also highlighted in case the probe laser beam extends along a straight line that does not lie on the plane defined by the flank of the crack (condition of maximum sensitivity). Finally, the developed system is used to B-scan a plate on which four different surface defects have been machined.

2. GCLAD technique and modes of application to inspections
The Gas-Coupled Laser Acoustic Detection (GCLAD) technique [27, 29, 30, 31] depends on the deviation that a probe laser beam sustains when intersecting a fluid domain where the refractive index continuously varies. This variation can be generated by an airborne ultrasound, typically resulting from the refraction of a bulk wave at a solid/fluid interface [32, 33]. Figure 1 exemplifies the functioning principles of the GCLAD technique, respectively in a 3D (a) and in a 2D (b) environment. A Continuous Wave (CW) laser continuously emits laser radiation in the generic direction, which travels along an airborne ultrasound affecting an \( x_s \)-long region and propagating along the \( z \) direction; such probe laser beam sustains a displacement along \( z \) in the process, up to a value of \( \theta \) (deflection angle) at the exit of such region. The beam subsequently travels in the air unperturbed for a length equal to \( x_s \), until it reaches a photodetector with a total deviation equal to \( \Delta z \). The photodetector is divided into at least two photocells, on which the probe laser beam differently insists (in terms of radiated area) based on the oscillations it sustains across the variable pressure field; the photodetector thus senses the displacement from the condition of ultrasound absence and outputs an electric signal proportional to the total deviation [34].

The sinusoidal pressure field triggered by an acoustic wave that propagates along the \( z \) direction can be expressed as follows (coherently with the definitions provided by the authors in previous works [26, 35, 36]):

\[
p(z, t) = k \rho_0 \chi^2 \delta \sin(kz - \omega t) e^{-\alpha d}
\]  

In Equation 1, \( t \) represents the time variable, \( \omega \) the wave angular frequency, \( \chi \) the wave speed in the fluid, \( k \) the wavenumber \( \omega/\chi \), \( \alpha \) the wave attenuation coefficient in air, \( \rho_0 \) the unperturbed fluid density, \( z \) the quote from the surface of the piece \( (z=0) \), \( \delta \) the displacement of the piece surface from which refracted waves in the fluid are triggered, and \( d \) the liftoff distance of the probe laser beam from such surface.

Considering Figure 1 once again and starting from the eikonal equation [37], the total deviation \( \Delta z \) at the photodiode of an infinitesimal optical ray which propagates along \( s \) (normal direction to the pressure wave with analytic expression in Equation 1) is obtained:
Figure 1. (a) 3D visualization of the GCLAD device functioning principle: a CW laser constantly emits a probe laser beam which deflects when intersected perpendicularly by an ultrasound propagating in a fluid (typically, an airborne ultrasound from refraction by a solid surface); such deviation is sensed by a photodetector. (b) Planar visualization of the GCLAD device: the probe laser beam propagates along a generic $s$ direction, displaces for an $x_s$ length in correspondence of the pressure field $p(z,t)$, and subsequently travels unperturbed in the fluid for an $x_1$ length with an inclination $\theta$; the resulting deviation in correspondence of the photodetector is indicated as $\Delta z$.

\[
\Delta z = \frac{2\pi^2 (n_0 - 1)}{\chi^2 n_0} \delta f^2 x_s^2 \cos (k z_0 - k c t) + \theta x_1
\]  

In Equation 2, $n_0$ is the refractive index of the unperturbed fluid, $z_0$ the $z$ position of the unperturbed laser beam, $f$ the main frequency of the acoustic wave and $\theta$ the deflection angle (i.e., $\theta = \frac{d}{dx} (z(x_s))$. Hence, in this classical configuration, sensitivity for an optical beam $\Delta z/\delta$ augments as several parameters are increased, i.e., the free distance from the photodiode $x_1$, the acoustic wave frequency $f$, and the length of the pressure field $x_s$ to which the probe beam is subjected. The expression obtained is valid only if the optical beam is infinitely small. When the probe beam has finite dimensions, the response of the GCLAD device increases for high acoustic wavelengths, the beam spot being the same [27].
Figure 2. GCLAD solution with an interposed lens, to increase repeatability of the measurements by making the signal amplitude independent by the length $x_1$.

Independence of the GCLAD response from these parameters would enhance the retrieval of similar signal amplitudes with different testing layouts and increase repeatability of the measurements; from this standpoint, the introduction of a focusing lens as in the layout of Figure 2 can relevantly reduce the influence of deflection (and thus of the $x_1$-long path) on the acquired signal. With such a solution, the photodetector response results in fact as follows [32]:

$$\Delta z = \theta x_0$$  \hspace{1cm} (3)

$x_0$ in Equation 3 represents the length between the sensor of the photodetector and the geometrical centre of the lens (which is double convex in Figure 2).

To provide preliminary indications on how the GCLAD system can be applied in NDT investigations, the experimental layout scheme of Figure 3 is considered: a piezoelectric probe positioned on a plexiglass wedge excites surface Rayleigh waves in a bar, which predominantly extends in the $x$ direction. By propagating at the interface between the specimen and the air, the surface waves on the specimen are refracted in air and propagate inclined with respect to the normal direction to the solid surface. Numerous additional waves coexist and propagate inside the specimen, such as shear waves or the back wall echo which also originate waves refracted in the air at various inclinations. If the laser beam is oriented in the $y$ direction (s in the diagrams of Figures 1-2), different types of waves at different instants deviate while travelling in the air. If these types of waves are sufficiently resolved in the time domain, the GCLAD system provides a signal in which all the contributions deriving from the various types of waves can be highlighted.

To evidence the real behaviour of the system, the scheme in Figure 3 has been replicated in a laboratory environment. A 1”, 500 kHz nominal frequency Panametrics piezoelectric probe is positioned on a plexiglass wedge support to chiefly excite surface Rayleigh waves in a S355 steel bar. The rectangular section specimen is 60 $\times$ 18 mm$^2$. The high emission angle for the probe collaterally induces shear waves in the piece and the surface waves refracted in the air propagate normally to the probe laser beam axis. Based on Snell’s law, it is derived that the direct surface wavefront is refracted in the air with an inclination of 6.8° relative to the specimen surface. The probe laser beam is positioned at 30 mm of height from the specimen surface, while the lengths $x_s$ and $x_1$ are respectively 90 mm and 250 mm. Figure 4a depicts an exemplary signal acquired by the GCLAD system in the experimental configuration of Figure 3; the signal obtained is pre-processed with a Brul & Kjaer 2638 wideband conditioner. An analogue bandpass filtering is applied to the signal from 0.3 MHz to 2 MHz, while amplification is set to 60 dB. 64 ensemble averages are applied before acquisition. Based on time-of-flight
Figure 3. Scheme of experimental layout in which the GCLAD probe laser beam propagates in the $y$ direction; a piezoelectric probe excites surface Rayleigh waves in the solid specimen, and collaterally also bulk shear waves. In this configuration, all diverse types of refracted ultrasound are sensed by the GCLAD.

evaluations, direct surface waves can be highlighted as well as the echo from the backwall (wavefront propagating in opposite direction compared to the direct surface wave). Being both ultrasonic waves detectable, the GCLAD device can be used for the non-destructive monitoring in pulse-receive or pulse-echo modes. Even if shear waves feature a different refraction angle in the air, they can be additionally identified inside the acquired signal. The spectrum of the signal is represented in Figure 4b, which demonstrates the broad band of the GCLAD device and its capability to identify frequency components in the whole band of the probe, from 0.3 to 0.9 MHz; such capability chiefly depends on the small probe laser beam spot [26], profiled as a $0.7 \times 1.2 \text{ mm}^2$ elliptical beam by a Gentec-EO beam profiler (refer to Section 3).

Let us assume to machine an artificial defect on the surface of the specimen, as schematically represented in Figure 5, and to maintain all other elements of the layout as in Figure 3. Assuming to locate the probe laser beam in a point between the ultrasonic source and the position of the defect (generally unknown), the scheme corresponds to a typical pulse-echo inspection.

Referring once again to the experimental configuration schematically represented by Figure 3, an artificial crack has been machined on the surface of the same bar; the crack is 1 mm-thick and features an elliptical section, with a depth of 3 mm and a length of 20 mm. Similar to the experiment on an intact bar, the ultrasound is generated by a piezoelectric probe at 500 kHz supported by a wedge. The surface wave is refracted at 6.8° from the metal to the fluid; the echo from the defect flank propagates in the opposite direction, at an angle of -6.8°. The height of the probe laser beam from the surface of the component (liftoff) is 30 mm, while $x_s$ is 90 mm and $x_1$ is 250 mm. Figure 6 highlights the signal received from the GCLAD in the laboratory test represented by Figure 5. The direct surface wave (Rayleigh wave) is evident while the echo resulting from the reflection on the defect flank is low in amplitude, even if easily identifiable. The echo from the backwall is attenuated compared to the case of Figure 4a, because part of the ultrasonic energy is reflected by the artificial defect.

3. Materials and methods

Based on the physical principles and from the preliminary investigations reported in Figures 1-6, the GCLAD system has been employed to observe the amplification effect of the signal caused by the interaction between defect and surface wave. The experimental layout for inspection on bars is schematically highlighted in Figure 7. The probe laser beam is moved along the $x$ axis in both directions. Tests have been performed as a function of the $\beta$ angle between the axial direction of the bar (along which the wavefront propagates) and the propagation direction of the probe laser beam (angle on the $x$-$y$ plane): the relative inclination between defect flank and wavefront can significantly modify the monitoring performance of the inspection system [38], in particular for techniques as the SLS or the SLLS [17]. The probe laser beam is parallel to the bar surface,
Figure 4. (a) Example of a signal generated on a steel specimen by a 500 kHz piezoelectric probe and detected in the air by the GCLAD system, in the experimental configuration of Figure 3; (b) corresponding spectrum which confirms the broadband nature of the GCLAD device.

Figure 5. Scheme of a pulse-echo inspection layout for identification of a surface defect in a bar by the GCLAD device.
at a variable liftoff distance $d$. The laser source-photodetector distance is 850 mm and the $y$ distance between the centre of the bar and the laser source is 140 mm. The bar and defect are the same as for the preliminary analysis in the layout of Figure 3 (Section 2). A Panametrics piezoelectric contact probe is placed on a plexiglass wedge (inclination of 24.0° with respect to the $x$ direction) to excite Rayleigh waves in the steel specimen. The probe has a diameter of 1" and 500 kHz central frequency, with a bandwidth of 600 kHz. The wavelength in the steel of the Rayleigh waves is approximately 5.7 mm, greater than the defects’ depth. A 2 mW TOPTICA iBeam Smart 640 laser is employed as the probe laser beam, which has a wavelength of 640 nm and an elliptical spot (minor axis of 0.7 mm along $z$, major axis of 1.2 mm along $x$). The photodetector is represented by a Luna Optoelectronics Red Enhanced Quad Cell Silicon Photodiode (mod. SD 197-23-21-014). The signal acquisition from the photodetector is triggered with the excitation of the probe by a Panametrics computer controlled pulser (mod. 5800). The obtained signals are processed by a Bruel & Kjaer 2638 conditioner before acquisition, which also applies an analogue filtering between 0.1 MHz and 2 MHz.

Subsequently, the GCLAD technique has been applied for a B-scan of a plate on which four different artificial defects have been machined, analogous to those triggered on the bar and visible in Figure 8. The plate is made of S355 structural steel, having a thickness of 12 mm and planar dimensions of 500 x 400 mm$^2$. The machined defects are located in the positions of Figure 8, which also evidences the movement directions for the GCLAD and the piezoelectric probe during the inspection. The defects are similar to that on the bar, being 1 mm-thick, 3 mm-deep and 20 mm-wide (elliptical section). For each position along $y$ of the piezoelectric probe, a scan of the laser beam probe in the $x$ direction has been performed. The distance of the laser beam from the plate is initially considered as 3 mm. The same probe, conditioner and laser source compared to the case of bar interrogation are employed. The GCLAD layout depicted in Figure 1 is always considered in the experiments, if not otherwise specified.

Figure 6. Signal obtained in the setup of Figure 5 with the GCLAD system (layout of Figure 1), in which the defect echo can be highlighted.
4. Results and discussion

In the following, results are reported relating to tests performed to verify the signal amplification effect in close proximity of the defect; as will be discussed, this definitely depends on the interaction between surface Rayleigh waves and the defect itself in the component, translating in the air as a consequence of ultrasonic refraction.

4.1. Signal enhancement effect

Initially, the tests of Figure 7 have been carried out considering $\beta=0$, i.e., with the probe laser beam aligned along the $y$ direction, perpendicular to the surface Rayleigh wave propagating along $x$; the artificial crack length extends along $y$. Both direct Rayleigh waves and the corresponding echo from the defect propagate in the air in a normal direction to the laser beam. Figure 9 depicts a signal acquired in a location far from the defect, for which the first received wave packet corresponds to the direct surface wave generated by the probe while the defect echo arrives at a second time. The defect echo has low amplitude if compared to the direct surface Rayleigh wave, being difficult to observe independently from the distance between the detector and the discontinuity: if the probe laser beam is far from the defect, the echo has low amplitude because of attenuation along the paths in both the solid and the air; if the probe laser beam is close to the defect, the echo mixes with the direct wave packet and becomes unrecognizable. A procedure to increase the detectability of the signal resulting from the discontinuity presence is hence recommended.

The ultrasound from the piezoelectric probe and that caused by the reflection on the defect are refracted in the air, with an angle of $6.8^\circ$ and $-6.8^\circ$ respectively. Such waves constructively and destructively interact in diverse areas. Figure 10 shows a simulation of the interaction of
Figure 8. Plate with indication of the artificial defects to be identified during the B-scan by the GCLAD device.

Figure 9. Signal acquired by the GCLAD when the probe laser beam is far from the defect, in a bar and considering $\beta=0$. 
the surface wave with the defect, in which the area of constructive and destructive interference in the air is visible, generated in close proximity of the defect. The simulation mirrors the layout of Figure 3 for the 2D solution of a linear visco-elastic wave propagation problem. The software Wave2000© for ultrasonic analysis allows initially simulating the path of the longitudinal waves in the plexiglass wedge, surface waves in the solid piece and afterwards of the refracted waves in the air; inclination of the wedge is so that Rayleigh waves are triggered inside the steel specimen, which are subsequently refracted in air from the solid surface along their path. The simulated wave excited by the probe consists of a 500 kHz exponentially damped pulse, whose energy reduces to 10% of its maximum value in five periods. The direct Rayleigh waves propagate in the piece and reach the crack flank; slight ultrasonic oscillations overcome the defect (low amplitude zone) because the crack depth is approximately half the ultrasonic wavelength in the solid. The first oscillations reflected by the defect interfere with the subsequent ones, first constructively (generating a high amplitude zone in the proximity of the defect) and then destructively (low amplitude). The amplitude of the oscillation in the high amplitude region decreases moving away from the surface of the component, because of the attenuation associated with the path in the fluid. Sohn and Krishnaswamy [17] explained such an effect as a complex interaction of bulk wavefronts and the crack tip, caused by wide propagation lobes for the photoacoustically-generated ultrasound in SLLS inspections (the source, rather than the detector, was moved over the defect). It was later demonstrated [19] that the signal enhancement phenomenon only takes place because of constructive interference, by using EMATs for both emission and detection. The presented results are in line with this latter interpretation, and demonstrate the effect translates also in the air determining characteristic geometries in terms of ultrasonic propagation patterns.

Translating the probe laser beam in proximity of the crack, modifications to the signal amplitude are expected to be highlighted. Figure 11 shows the trend of the peak-to-peak amplitude of the signal to the photodetector, in the $x$ coordinate, for various distances $d$ of the laser beam from the surface of the bar. In particular, the analysed portion of the signal is the one relating to the first received wave packet (direct surface Rayleigh wave). The origin of the $x$ coordinate is assumed to be placed in correspondence of the defect. The signal enhancement effect is evident for positive, close to 0 values of $x$ independently of the $d$ distance, proving that the artificial defect can be successfully located by the GCLAD device. Identification of the crack by monitoring eventual increases in the amplitude for the direct surface wave is undoubtedly more convenient than searching for the defect echo, since it can typically mix with the direct wave or have low amplitude (Figure 9).

Approaching the defect (positive and decreasing $x$ coordinates), the signal attenuates slightly: the wave moves away from the source and is therefore attenuated in the metal; this equally applies to the wave refracted in the air that interacts with the probe laser beam. Approaching the defect, the probe beam insists on the areas in which interference between refracted waves occur, so that also an enhancement effect is achieved in its close proximity. After the defect scanning (i.e., the probe beam overcomes the discontinuity), the peak-to-peak amplitude decreases because of the reflection of the surface Rayleigh wave on the defect itself; afterwards, continuing for negative $x$ values, the signal peak-to-peak amplitude gets gradually back to stable values, lower than the initial values obtained for positive $x$ values. The enhancement clearly depends on the liftoff distance $d$, decreasing as $d$ increases.

This phenomenon cannot be evidenced by traditional detection tools, such as contact or air-coupled probes: the effect involves an extremely narrow region near the defect, which is specifically long half the ultrasonic wavelength (the low amplitude is obtained by destructive interference between ultrasonic waves at the same frequency, but in counterphase). For this reason, it is necessary to rely on point detection methods such as interferometric sensors (as

1 Cyberlogic, Wave200, CyberLogic Wave2000 ultrasound simulation software (last access: February 10, 2022)
Figure 10. 2D simulation by the Wave2000© software of the experimental layout in Figure 3: longitudinal waves are induced in the plexiglass by the 500 kHz probe and then convert into surface Rayleigh waves inside the metal. These latter waves reach the defect generating low amplitude zones (destructive interference), high amplitude zones (constructive interference), very low amplitude zones (in correspondence of the crack), and again low amplitude zones (crack overcoming).

Figure 11. Signal peak-to-peak amplitude based on the $x$ coordinate, for liftoff distances of the probe beam from the bar surface equal to 1 mm, 3 mm, and 6.5 mm. The origin of the $x$ is considered to be placed in correspondence of the defect.
Figure 12. Trend of the peak-to-peak amplitude of the signal as a function of the $x$ distance between probe laser beam and defect, as the $\beta$ angle is varied.

in the case of SLS and SLLS) or the GCLAD device; in case elements with dimensions greater than the ultrasonic wavelength as traditional probes or EMATs, the oscillations in the low and high amplitude areas are averaged, with consequent loss of information.

The above-described phenomenon becomes less evident as $\beta$ raises. In Figure 12, the peak-to-peak values are evidenced based on the probe laser beam-defect $x$ distance, as the $\beta$ angle varies; such amplitude is measured by placing the laser beam at a distance of 3 mm from the surface of the piece. The $\beta$ angle has a relevant effect on the signal amplitude; it must in fact be considered that:

a the probe beam insists on the midpoint of the crack when $x = 0$; since the defect is not aligned with the direction of the beam, part of the probe laser beam is in the high amplitude zone and part in the low amplitude zone. Based on Equation (2), the probe laser beam displacement in correspondence of the photodetector is the integral of all the displacements sustained along its path in the air. Hence, an averaging effect is obtained;

b when the defect is angled with respect to the laser beam, the probe laser beam no longer lies on the plane on which the echo pressure wave propagates in the air; the beam can hence intersect several wave crests. The averaging effect caused by the integral of the deviations sustained by the beam in its path reduces the total displacement also in this case: the pressure gradient encountered by the beam varies, also with a possible sign reversal when it completely intersects a wave period, according to Equation (2).

Figure 13 shows the amplitude trend of the peak-to-peak signal obtained with the laser beam located at $d=3$ mm, as a function of the $\beta$ angle and at various $x$ coordinates for the direct and echo waves. For all the types of waves, the ultrasonic contribution has a signal-to-noise ratio close to 1 and is no longer distinguishable from noise above $\beta =45^\circ$. For the direct wave at $x=0$ mm, the attenuation of the signal occurs because of the two mechanisms (a) and (b) outlined above. For the direct wave at $x = 80$ mm, the reduction in the amplitude as the $\beta$ angle increases depends on effect (b) only. At this distance from the defect, the echo of the
Figure 13. Peak-to-peak amplitude trend for the direct wave at $x=0$ mm and $x=80$ mm and for the echo at $x=80$ mm, as a function of the $\beta$ angle.

A defect is also distinguishable. The trend of the echo amplitude is similar to that of the direct signal, except for being scaled.

4.2. B-scan of a steel plate by GCLAD

The effect of signal enhancement can be advantageously employed to identify defects, as it allows practitioners to observe only the first received wavefront as a function of the receiver position (in this case, the $x$ coordinate of the probe laser beam): this solution is more convenient than seeking for echoes caused by the defect, since they often mix with possible spurious echoes linked to other wave paths inside the component. Even with the classical pitch-catch technique, if the distance between source and receiver is large, the received signals tend to assume an amplitude which is comparable to the original signal in case no defect is present, considering the attenuation of the waves in the material. Therefore, small defects are not easily detectable with the transmission technique or with the pulse-echo technique. Conversely, the signal enhancement effect leads to the detection of a defect whose depth is even less than the wavelength of the surface Rayleigh wave.

As an application example, a plate scan was performed by the GCLAD coherently with Figure 8. Figure 14 shows the B-scan of the plate, where the peak-to-peak amplitude of the first wave packet received by the photodetector is reported for each $x$-$y$ coordinate. Amplitude variations in positions for the probe laser beam which are close to a defect clearly evidence its presence. Specifically, in the defects’ proximity, the signal enhancement effect in points between the source and the defect is highlighted, as well as an attenuation in all other coordinates on the same line (same $y$ coordinate).

Although the defects are namely the same, the variation in the amplitude of the signal differs based on the defect location on the plate: since the configuration in Figure 1b is employed for the scanning in Figure 14, a different $x_1$ is obtained if the location of the defect varies; therefore, from Equation (2) a different total deviation $\Delta z$ of the probe beam results. In contrast, $x_s$ does not vary among the different defects because it depends solely on the size of the acoustic wavefront: the portion of the probe laser beam extension affected by the airborne ultrasound
Figure 14. Result from the plate B-scan, in which amplitude fluctuations are observed in close proximity of the four defects.

Figure 15 shows the result of the plate B-scan with focusing lens. From a comparison between the signals of Figures 14 and 15, it is possible to highlight how the exclusion of the displacement contribution through the lens does not significantly change the amplitude of the signal, due to the limited value of $x_s$ (a few cm).

5. Conclusions
The present work aimed at highlighting the modes of application of the Gas-Coupled Laser Acoustic Detection (GCLAD) non-contact, ultrasonic technique to the monitoring of components which predominantly extend in 1D and 2D – e.g., bars, axisymmetric elements and plates. In particular, an enhancement effect for surface Rayleigh waves has been exploited that occurs when the GCLAD detector is positioned in the proximity of surface defects: the discontinuity is identified based on amplitude fluctuations for the signal associated with the direct surface wave, a solution which is definitely more convenient than searching solely for echoes deriving from defects: the echoes are often characterized by low amplitude, incorporated in the direct wave pattern, or mixed with other types of waves propagating within the material and subsequently refracted in the air (where detection by the GCLAD device takes place).

In contrast with the available literature, the work has shown that the enhancement effect is strictly attributable to phenomena of constructive interference between wave crests of direct surface ultrasound and echoes reflected by the defect. Since the interaction among wave crests occurs in a region of the material confined to half a wavelength in the solid medium, the effect can be evidenced by point detectors in air such as interferometers or GCLAD and not by more traditional elements like unfocused air-coupled probes.

Since the GCLAD technique allows to inspect at the same time all the points lying on a line (projection of the probe laser beam on the surface of the component), the developed methodology allows reducing the movements required for the instruments to inspect an $x$-$y$ plane: if the source is moved along the $x$ direction, the GCLAD detector can be moved solely in the $y$ direction and...
Figure 15. Result from the plate B-scan for the layout with lens located before the photodetector, in which amplitude fluctuations are observed in close proximity of the four defects.

vice versa. Compared to a traditional system in which source and receiver must both be moved in two directions, the use of the GCLAD system provides the basis for halving the inspection time; the reduction in monitoring time is relevant even when more refined techniques such as the Scanning Laser Source (SLS) are considered: based on the same physical principle, these latter methods require at least one between the source and the receiver to be moved in both directions, and the remaining one to be translated along a single direction. Regardless of the baseline, the use of the GCLAD technique provides a solid basis for the simplification of layouts and automation of non-destructive inspection processes.

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