Amplification of laser diode-induced photoacoustic signals for non-destructive testing of mechanical components

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Abstract. The present work highlights that the laser diode, acting as an ultrasonic source by photoacoustic effect, can be successfully employed for defect detection in mechanical components; the performed investigation specifically involves a railway axle with cracks on the body and fillets, respectively 13 mm-deep and 2 mm-deep. To ease the inspection process, a methodology for amplification of the ultrasound is introduced which is based on the appropriate choice of the TTL signal modulating the diode; amplification is achieved by constructive interference between two ultrasonic signals: the first is induced by the dilation resulting from the laser ignition, the second conversely derives from the contraction obtained when the laser is powered off. The proposed amplification methodology allows ultrasonic energy to be focused in a narrow range of frequencies, promoting the use of traditional detection devices like narrowband probes. The developed inspection system, which takes advantage of a 20 W source, enables the identification of the ultrasonic pattern and defect detection regardless of the application of post-processing techniques on the acquired signals: allowing for excitation of high-amplitude ultrasound without directly contacting the component, the laser diode represents a suitable source for the non-destructive inspection of the axle while it rotates (i.e., during operation). Thanks to the cost reduction achieved in comparison with the use of more traditional pulsed lasers, the diode lends itself to large-scale application in the field of non-destructive testing on mechanical structures.

1. Introduction
Laser excitation of ultrasound (US) allows for the non-destructive component control even in those cases where traditional contact generation technologies exhibit limitations. For instance, laser excitation is particularly suitable for the inspection of structures in high-temperature, corrosive or highly aggressive environments [1, 2]. These conditions are typically found in nuclear applications [3]; another example pertains to the induction of elastic waves on moving or rotating organs, opening the field to non-destructive monitoring while the component is in service [4, 5].

US induction is based on the photoacoustic effect [6], in which a light radiation pulse causes a sudden localized heating of the material and an equally rapid cooling, with the triggering of stress states and elastic deformations propagating inside the component. The photoacoustic effect is typically obtained by pulsed lasers (e.g., Q-switched), employed in several applications, for the inspection of specimens and components in composite and metallic materials [7, 8, 9] and the Non-Destructive Testing (NDT) of massive mechanical organs [10, 11]. Pulsed lasers
Laser beam focusing in a narrow region of the component allows obtaining a power density close to the ablation threshold of the material (between 10 and 20 MW/cm$^2$ for metals employed in typical engineering applications). The resulting power density is associated with ultrasonic oscillations of the material higher than 10 nm [6], compatible with the resolution of instruments as interferometers: this allows, in addition to the excitement, for the non-contact detection of US propagating inside the component.

Limitations of high-power, pulsed sources relate to complexity in managing the apparatus and the high cost (tens of thousands of euros), which can preclude their application to certain fields. Alternatively, modulable laser diodes can be used to excite the US: diodes are characterized by compactness and low cost, with a price which is often two orders of magnitude lower than that of pulsed lasers. Conceived to operate mainly as a continuous wave (CW) source, diodes can emit light pulses if properly modulated by a feeding TTL; in such conditions, the functioning regime of diodes is similar to the one of pulsed lasers, opening up the possibility of exciting US by the photoacoustic effect.

Laser diodes are widely employed in the biomedical field for the analysis of organic tissues but are rarely used as an ultrasonic source of US. Some preliminary investigations regarding NDT on metal and composite materials are available, in which longitudinal and Lamb waves are excited by modulated low-power diodes [12, 13, 14]. Nevertheless, the amplitude of the generated waves is about 1 pm [15] for a 1 W diode; these waves are thus difficult to detect even by high-sensitivity devices. The joint use of pseudo-noise (PN) codes and cross-correlation is a well-established technique for enhancing the signal-to-noise ratio ($S/N$) of laser diode-induced US: the diode is digitally modulated by a highly-random feeding TTL, with variable duration for both the high levels (pulse) and the low levels. By such a process, the US which is induced and consequently acquired is not characterised by higher amplitude per se; still, when cross-correlation is applied between the PN input and the acquired output, the ultrasonic contribution becomes more evident thanks to the high randomness of the PN codes. PN codes are primarily applied in the field of telecommunications [16]; the PN codes typically employed to feed the diode are the maximum length sequence (MLS) [12] and the Golay Code [15]: it has also been demonstrated that the use of the Golay Code in place of the MLS entails higher capabilities in highlighting the US because of the higher randomness, duration of the sequence being the same.

A recent article [17] highlights that, despite the high randomness of PN codes, using a TTL sequence with the same duration for each high level is beneficial in terms of $S/N$; in case of acquisition by piezoelectric probes, typically resonant in a limited band, such a TTL allows exciting ultrasonic waves with the same features at each pulse: this results in frequency content narrowing inside the band of the receiving probe, thence increasing $S/N$. PN codes, conversely, contribute in broadening the band, scattering the ultrasonic energy in a wide range of frequencies [16]. By employing low power lasers (0.15 W) and processing the signal by cross-correlation, identification of the US on specimens is highlighted only if the source-receiver distance is limited to a few centimetres [18]. The actual applicability of laser diodes to non-destructive monitoring of mechanical components is therefore not fully demonstrated to date.

The present work shows that, by appropriate techniques, the laser diode technology is suitable for NDT purposes on components of engineering relevance. A methodology is proposed to increase the amplitude of the induced US based on constructive interference between elastic waves. The manuscript provides both a theoretical justification of the methodology and its experimental validation. This solution involves important benefits in the detection by narrowband piezoelectric probes, thanks to a significant narrowing of the spectrum.

Specifically, an experimental campaign has been performed on railway axles, for which non-contact excitation of US by laser represents an element of fundamental interest, as evidenced by numerical and experimental studies in the literature [10, 11, 19]. In this type of components,
Rayleigh surface waves play a crucial role in the inspection: cracks are more likely to propagate on the surface, because of the rotating bending moment affecting the component during operation. Through the presented methodology, crack detection both on the axle body (subject to maximum bending moment) and on the fillets (geometric stress concentration) is eased, allowing for a more efficient NDT process.

2. Materials
The devices constituting the experimental apparatus are shown in Figure 1 and are represented by:

- an Opt Lasers 20W-445nm laser diode, featuring a power of 20 W, a wavelength equal to 445 nm and a spot diameter of 7 mm – the diode can be digitally modulated up to 2 MHz, with a minimum pulse duration equal to 250 ns;
- a spherical lens with a focal length equal to 35 mm – the lens has a reflectance of 0.2% and allows focalizing the spot to a 30 µm beam waist;
- a Panametrics narrowband, contact probe – the probe resonates at 1 MHz;
- a railway axle – the axle is positioned on a support allowing for its rotation; the axle rotation, required to detect the US propagating on the surface at various angular coordinates, is obtained by a belt transmission.

![Figure 1. Elements constituting the experimental layout.](image)

Artificial cracks have been tooled on the axle as in the 3D CAD visualization of Figure 2: the crack on the axle body (A) and the fillets between the axle body and the wheel seat (B), the wheel seat and the collar (C), the collar and the bearing journal (D) are highlighted. The geometrical centre of crack A corresponds to the origin of the angular coordinate. Cracks B,
C, and D are centred in an angular position equal to 30°, 120° and 180° respectively; crack A has a maximum depth of 13 mm, while the B, C and D cracks have a maximum depth of 2 mm and a semi-elliptical shape. Positions 1, 2 and 3 indicate the area in which the laser beam irradiates the axle (1,2) and where the detection probes are applied (2,3). The signals acquired by the piezoelectric probe are conditioned by applying a 30 dB amplification and an analogue band-pass filter between 40 kHz and 2 MHz. The number of ensemble averages for acquisition is 64.

Figure 2. CAD visualization of the axle in which the coordinates of artificial cracks (A-D) and the positioning points for the source and the receivers (1-3) are highlighted.

To ensure a fully non-destructive test, the maximum value of pulse duration (δ) which can be applied without entering the ablative regime and compromising integrity of the steel has been evaluated. Temperature change ΔT sustained by the material during heating can be expressed as a function of δ by the following relationship [6]:

\[ \Delta T = \frac{PR}{C_\rho A_\Phi} \cdot \delta \]  

The terms reported in Equation 1 represent the source power \( P \), the irradiated area \( A \), the thermal capacity of the material \( C \), its reflectance \( R \) at the specific radiation wavelength and its density \( \rho \); the \( \Phi \) term represents the skin depth which is equal to \( \sqrt{2K/\rho CF_m} \) for modulated sources, with \( K \) thermal conductivity of the material and \( F_m \) the source modulation frequency. Table 1 reports, for the specific case, the characteristics of the material under analysis and of the employed source: \( F_m \) has been set as the centre frequency of the piezoelectric probe, while a 1 mm spot diameter has been considered. The value of \( R \) at the specific wavelength of 445 nm has been retrieved from literature for standard steels [20]. Allowing for a maximum temperature change equal to 750 K (phase transition), an upper limit of 1.2 ms is derived for \( \delta \).

3. Amplification methodology for ultrasonic signals

Freedom in setting the working parameters is one of the main advantages of laser diodes over pulsed lasers: the duration of diode ignitions and shutdowns at specific time intervals can be adjusted, as well as their number in the time unit. The choice regarding these parameters plays a key role in the amplification of the signal’s peak-to-peak (\( PtP \)) and \( S/N \) [17, 18]). The following section distinctly analyses the influence of three parameters on ultrasonic induction: the pulse duration (\( \delta \)), the relative distance between pulses (\( d_p \)) and the number of pulses (\( N_p \)), to achieve maximum amplification of the output ultrasonic signal.
Table 1. Parameters associated with radiation and steel for the determination of the maximum allowable pulse duration.

| Parameter | Value     |
|-----------|-----------|
| C (J/(kg·K)) | 480       |
| ρ (kg/m³)   | 7.9·10³   |
| K (W/(m·K)) | 50        |
| P (W)       | 20        |
| A (m²)      | 0.79·10⁻⁶ |
| R           | 0.5       |
| fₘ (Hz)     | 1·10⁶     |

3.1. Laser pulse duration δ

A recent publication in the biomedical field [21] evidences that, by feeding the laser diode with a TTL constituted of a single square wave of duration δ, two distinct ultrasonic contributions can be induced: the first is excited during heating when the power of the laser suddenly rises from 0 W to the nominal value; the second US is excited as a result of the cooling when the laser power changes from the nominal value to 0 W. The study highlights that the amplitude of the second US overcomes the amplitude associated with the first US in case δ is lower than the thermal relaxation time, which corresponds to the speed at which the heat provided by the radiation is dissipated by thermal conduction [22, 23]. Indicating with $v_w$ the speed of surface waves (3100 m/s on steel), the concept can be formulated as follows:

$$\delta \leq \tau_{th} = \frac{3K}{\rho C v_w^2} (2)$$

If Eq. 2 is satisfied, heat confinement in the volume of irradiated material occurs and the wholly available thermal energy is converted into ultrasonic oscillation. The study does not provide further information on the expected waveform, but only on the ultrasonic amplitude. Figure 3a shows an experimentally observed waveform detected on the body of the axle in a 170 mm source-receiver path, lacking in geometric discontinuities (fittings) and defects (cracks). Two portions of the signal characterized by high amplitude can be highlighted, with mutual distance δ=12.5 µs starting from the Time of Flight (ToF) equal to 54 µs; their respective close-ups are visible in Figure 3b-c. It is clear that the two ultrasonic contributions have the same waveform but are in counter-phase; the amplitude of the second US is not maximized, because the condition in Eq. 2 is not fulfilled ($\tau_{th}$ is equal to 1 ps referring to Table 1 while it commonly reaches tens of nanoseconds for biological tissues). Interestingly, differently from what can be inferred from a state of the art analysis, applying post-processing techniques to the signal such as cross-correlation is not required to highlight the ultrasonic contribution ($S/N$ equal to 16.8): this is because of the high power of the diode (20 W against typical values of 1 W), which allows a proportional increase in the amplitude of ultrasonic oscillations.

Considering such experimental evidence, an ultrasonic signal amplification technique can be proposed which is based on the interaction between the two ultrasonic contributions excited by the single laser pulse. Let us refer to Figure 4 which depicts numerically simulated acquisitions to illustrate the proposed amplification methodology. Among the three simulated acquisitions, the difference is represented by the value of δ for the pulse; an ultrasonic ToF equal to 5 µs and an $f_0$ oscillation frequency of 50 kHz are set, while complete damping is imposed in six periods – after six periods the amplitude drops to 10% of the $PtP$. In the case of a pulse with δ=170 µs, a weak interference between the two waves is observed, which strengthens as δ decreases (δ=110 µs and δ=30 µs); in case δ is equal to 10 µs, completely constructive interference between the two ultrasonic waves occurs, as the US excited by the contraction adds to the oscillation associated
Figure 3. Input constituted of a single 12.5 µs laser pulse and corresponding output, (b) close-up of the ultrasonic signal associated with the thermal dilation and (c) close-up of the ultrasonic signal consequent to thermal contraction.

with the dilation. This result in a 50% amplification in $PtP$ (3.5 dB), from 1.7 V imposed at 2.5 V. Amplification is, therefore, possible if the following condition is satisfied:

$$\delta = \frac{1}{2f_0}$$  \hspace{1cm} (3)

The latter formulation has an additional and important implication, linked to the frequency content of the induced US: only the centre frequency which is compatible with Equation 3 is amplified by the process, allowing to narrow the band in a small range of frequencies.
Figure 4. Simulation of interaction between the two ultrasonic waves induced by a single laser pulse, as a function of laser pulse duration $\delta$.

Applying to an isolated pulse, amplification is achieved without considering the whole set of possible working parameters of the diode. The amplification and band narrowing effects can be further emphasized by using a laser input consisting of multiple pulses. Some studies [17, 18, 24] have investigated the influence of $\delta$ on $S/N$ for bulk waves and Rayleigh waves while employing multiple pulses: the use of an equal $\delta$ for all pulses allows inducing ultrasonic waves with equal characteristics, concentrating the energy in a narrow range of frequencies and consequently increasing $S/N$ in case of acquisition by narrowband probes [24]. Such a fact highlights that TTL sequences for which $\delta$ is the same for all pulses are functional for the PtP increase.

3.2. Mutual distance between pulses $d_p$

Figure 5 shows a series of numerical simulations with the same settings of Figure 3, in which four pulses with duration $\delta=10 \ \mu s$ (compatible with Equation 3) interact as their mutual time distance $d_p$ is changed; specifically, given two consecutive pulses, $d_p$ represents the time gap between the moments in which the high value of the TTL is reached. As can be derived from Figure 5, ultrasonic interference occurs for $d_p$ values of 110 $\mu s$ or less, resulting in a fully
constructive interaction for $d_p=20 \, \mu s$. In this situation, when the first oscillation of a US ends, the first oscillation of the subsequent US overlaps, with a consequent increase in the $PtP$: this corresponds to amplification of 110% (6.5 dB) compared to the case in which the single pulse fulfils Equation [3] and 210% (9.9 dB) compared to the case in which Equation [3] is not fulfilled. Specifically, the maximum amplification can be achieved if Equation [3] and the following condition are simultaneously met:

$$d_p = 2\delta$$

Figure 5. Simulation of interaction between ultrasonic waves induced by four laser pulses, as a function of the mutual distance between pulses $d_p$.

3.3. Number of pulses $N_p$
As previously introduced, the use of multiple pulses with appropriate duration and mutual distance is crucial for the amplification of the ultrasonic signal. However, the number of pulses
$N_p$ only partially influences the degree of amplification that can be achieved. Let us refer to Figure 5 where $N_p$ is set to 10 and the simulation settings are the same as in Figure 4. As can be highlighted, the amplification effect involves the first six oscillation periods: after six periods, the US associated with the first laser pulse is almost exhausted and cannot constructively interfere with the rest of the excited oscillations. Regardless of the number of pulses to be used in a simulation, when $N_p \geq 6$ the resulting amplification is 235% in terms of $PtP$ (10.5 dB) compared to a single pulse not fulfilling Equation 3.

Figure 6. Simulated interaction between ultrasonic waves induced by ten laser pulses ($d_p=10 \mu s, d_p=20 \mu s$).

4. Validation of the methodology by experimental evidence
The proposed methodology for ultrasonic amplification, highlighted only by numerical means, requires experimental feedback; for this purpose, ultrasonic oscillations are detected on the axle (path free of defects and fillets). Let us refer to Figure 7, which evidences the change in $S/N$ and $PtP$ of the output signal as $N_p$ is varied. In this study, $S/N$ is defined as the ratio of the ultrasonic $PtP$ and the $PtP$ of the signal portion affected by noise only. $\delta$ and $d_p$ values of 0.5 $\mu s$ e 1 $\mu s$ respectively have been used, compatible with the amplification of ultrasonic content with a central frequency of 1 MHz (Equations 2-3). As can be seen, $S/N$ increases until a plateau is reached for $N_p \geq 4$; the justification is to be found in the waveform reported in Figures 3b-c: after four periods, the US is completely dampened and no additional constructive effect occurs. This is why the use of a high value of $N_p$ is unbenefficial in terms of US amplification; nevertheless, the use of a large number of pulses eases in identifying the portion of signal affected by the ultrasonic wave. For this reason, a TTL input consisting of 10 pulses is considered.

Despite a different context, the results obtained in terms of $N_p$ can be compared to further literature studies: in case a low power diode is employed, for which application of cross-correlation as a post-processing tool is required to highlight the ultrasonic contribution hidden by the noise, the increase in $N_p$ is equivalent to applying a higher number of ensemble averages before the acquisition [15]; still, the as-is signal is unsubjected to amplification until cross-correlation is applied.

As for the excited frequencies, ultrasonic signals excited by the laser beam incident to point “1” of Figure 2 have been acquired as $\delta$ varied, with the probe positioned in point “2”. Figure 8 depicts the resulting power spectrum density (PSD), obtained through the fast Fourier transform (FFT); PSDs are normalized to the maximum value for the individual acquisition. As can be highlighted, the frequencies correspond with an excellent approximation to the ideal hyperbolic law of Equation 3 although the resonance frequency of the probe is 1 MHz, its response band
Figure 7. $S/N$ of the signal as a function of $N_p$, in which the set of laser pulses fulfils Equations 3-4.

ranges between 0.4 and 1.4 MHz. For a more in-depth discussion regarding the frequency response based on the performed optimization steps, refer to a previous research by the authors [25].

Figure 8. PSDs of the various excited frequencies as a function of $\delta$. 
5. Application to NDT of a railway axle

Once the correspondence between the theoretical basis of the methodology and experimental evidence has been established, the settings summarized in Equations 3-4 for emission optimization have been applied to the diode for the detection of cracks on the axle body and the fillets; considering the higher sensitivity of the probe for a 1 MHz oscillation, $\delta=0.5 \mu s$ and $d_p=1 \mu s$ have been selected. The axle is rotated at a specific angular coordinate and then stopped to apply ensemble averages and acquire the time history; the process is then repeated with a step of 5° in angular position to obtain a B-scan of the axle. Considering a single artificial crack, the sensitivity of the developed methodology can be established in terms of detection of surface defects. Let us refer to the crack on the axle body, whose profile is represented in Figure 9 on an $x,y$ plane which is orthogonal to the symmetry axis of the axle. The crack is characterized by a depth $p$ that varies as the $x$ coordinate changes; therefore, it is possible to investigate the attenuation associated with different depths by a single crack.

![Figure 9](image)

**Figure 9.** Section view of the artificial crack on the axle body, whose depth $p$ is a function of the $x$ coordinate.

Figure 10a shows the B-scan obtained by making the laser beam incident to position “1” and placing the probe in position “2” (Figure 2), for the different angular coordinates; the B-scan highlights the absence of ultrasonic oscillations in the range of angular positions corresponding to the space occupied by the crack (63°). Figure 10b shows in detail, as $p$ varies, the decrease $A_{\text{drop}}$ in $S/N$ if compared to the case of no crack ($S/N_0$), i.e., $A_{\text{drop}} = 1 - \frac{S/N}{S/N_0}$. $S/N$ significantly lowers as $p$ increases: $S/N$ decreases of 25% and 55% for values of $p$ equal to 1 and 3 mm respectively. For $p$ values greater than 3 mm, the decrease in $S/N$ is less evident and reaches a plateau after a depth of 8 mm; the surface US with the main frequency of 1 MHz features an ultrasonic wavelength $\lambda$ of 3 mm ($v_w=3100$ m/s): when $p$ exceeds $\lambda$, the US is totally reflected by the defect and $S/N$ tends toward the unit.

Concerning the detection of the 2 mm-deep cracks on the fillets, the laser beam has been made incident to the axie surface in position “2” (Figure 2), with the receiving probe in position
Figure 10. (a) B-scan obtained by source and receiver located in position “1” and “2” respectively (Figure 2); (b) attenuation of the signal in terms of S/N as a function of crack depth $p$.

“3”. Figure [11] illustrates the B-scans obtained in the range of angular coordinates affected by the B, C, and D cracks: similar to Figure [10b], areas in which the ultrasonic oscillation is almost absent can be highlighted starting from the ToF, equal to 255 $\mu$s. These areas are less distinct if compared to the case depicted in Figure [10a]: a higher attenuation corresponds to a greater source-receiver distance, while the presence of geometric convexities on the ultrasonic path alters the US properties (such as the phase [26]); overall, the signal is characterized by a lower S/N in comparison to the detection on the axle body.

6. Discussion
From a comparison with the literature on NDT of axles by pulsed lasers [11], it is possible to establish that the proposed laser diode-based technique provides similar results in terms of crack detection. Based on Figures [10] [11] in fact, it is deduced that 2 mm-deep surface cracks are detectable regardless of the acquired signal post-processing; although ultrasonic waves with
a frequency of 1 MHz experience high resistance to propagation in the material as a result of the low $\lambda_{26}$, the oscillations are also evident if fillets are present along the ultrasonic path.

The advantages in terms of diode flexibility over pulsed lasers are evident, allowing energy to be concentrated in a specific and narrow frequency band. The concentration of the band is not essential if broadband instruments like interferometers or vibrometers are employed; nevertheless, it becomes desirable for traditional inspections by narrowband probes (contact or air-coupled probes), whose greatest benefit is the low cost of the apparatus. This study represents an important advance to the state-of-the-art, in terms of applicability of NDT performed by modulable laser diodes: studies in the scientific literature aimed at detecting US propagating in specimens, without analyzing the capabilities of the apparatus in terms of crack detection on real components. The detection of defects is possible, it does not require the application of signal post-processing techniques (such as cross-correlation) and can be eased by the use of pulses with suitable features.

Some elements are shared between the proposed methodology for US amplification and the procedure highlighted in previous research [1], in which wave excitation is achieved by modulating a pulsed laser by Bragg fibres (acousto-optic technique); the present work adds a theoretical justification for the choice of the appropriate values of $\delta$ and $N_p$. The use of a diode also allows to overcome some of the limitations related to the acousto-optic technique, including a high latency time: when the Bragg fibres are deactivated, high time is required to bring irradiation to the pre-activation value; using Bragg fibres, the temperature gradient which can be obtained varies for each modulated pulse and does not allow inducing a US characterized by maximum amplitude.

The proposed methodology for the output processing in the time domain exhibits analogies with a manipulation technique in the space domain, based on the use of a spatial light modulator (SLM) [27]. The SLM, on which a laser beam is made incident before reaching the specimen, divides the power into several beams; if the mutual gap between the beams is set as equal to $\lambda$, the ultrasonic band is narrowed around the frequency associated with $\lambda$. The technique is extremely interesting for inspections performed by narrowband probes: with the power being divided into $n$ beams, more powerful lasers can be used without the risk of localised damage to the material. Therefore, the procedure proposed in this work could benefit from the use of an SLM, resulting in an amplification of the signal through manipulations in the domains of both

Figure 11. B-scan obtained with the source and the receiver located in position “2” and “3” respectively (Figure 2).
time and space.

Compared to previous works, no tool has been used in this study to allow non-contact detection of the US: the probe for the detection of surface US slips on the axle as it rotates, through the plexiglass wedge support. To provide for a totally contactless inspection of the axle, it is necessary to employ air-coupled detection devices, like interferometers or vibrometers [9, 28, 29]. However, since the cost associated with such instruments is typically tens of thousands of euros in case of large bandwidth, their use would conflict with the cost-effectiveness of the inspection apparatus. Experimental investigations have been specifically performed to highlight the sensitivity of conventional acoustic air-coupled probes (Sonotec 200) in detecting the US: these instruments are undoubtedly appropriate to sense high-amplitude ultrasonic signals, like the ones triggered by piezoelectric probes or pulsed lasers; nevertheless, sensitivity of air-coupled probes is not sufficient to allow contactless detection of the US induced by CW lasers (with power up to 20 W). To detect the US by non-contact methodologies, it is thence desirable to employ systems which are sensitive as interferometers; still, more cost-efficient alternatives can be additionally considered. For instance, the use of gas-coupled laser acoustic detection (GCLAD) technology appears extremely promising [30, 31]: the technique allows detecting ultrasonic oscillations propagating in air, based on the deflection sustained by a light beam when it intersects the acoustic pressure field. The GCLAD system has a low cost (hundreds of euros); in specific applications, the GCLAD features some advantages if compared with interferometers, as the detectability of the US is independent of the component’s reflectance [28, 32]. Further analyses should be devoted to non-contact detection through the GCLAD technique; alternatively, given the ample margin that separates from the ablative regime for the material, it is possible to increase the power of the diode to amplify the ultrasonic signal constituting the output.

At the component level, NDT has been performed on an axle and not a complete wheelset. This can have substantial consequences from the US detectability point of view: the mounting of the wheels introduces additional compression states on the wheel seat, which can modify the amplitude of the US. This implies that a high-frequency US dissipates more energy when it travels along such area, as illustrated by a previous numerical study [10]. Experimental analyses will be a key element for extending inspection by laser diode to axles subject to typical working conditions.

7. Conclusions

The study highlighted the performance of a system for non-destructive testing of mechanical components, based on ultrasonic induction through photoacoustic effect by a modulable laser diode. The core objective was to prove suitability of this non-contact, generation technology for industrial applications and on-field studies: the lower cost compared to a pulsed source makes laser diodes suitable for employment on a large scale, i.e., replicating the instrumentation layout on a vast amount of components. The performed investigation specifically involved contact detection of artificial cracks on a railway axle, machined in sections subjected to high stress concentration as the body (maximum bending moment) and the fillets (geometrical stress concentration).

In the process, an amplification methodology for ultrasonic waves has been provided which is based on appropriate modulation of the diode: the use of pulses with equal duration and suitable distance in time enables the concentration of the energy in a narrow and specific range of frequencies, that the operator can directly control; the methodology allows easing crack detection using narrowband devices, such as traditional piezoelectric probes, for the development of a low-cost inspection system.

Demonstrating the applicability of laser diodes to non-destructive testing of mechanical components is in itself a significant advance to the state-of-the-art: previous studies focused on
the propagation of waves on specimens, and no evidence of defect detectability on mechanical organs was available. By allowing the detection of 1 mm-deep cracks, the resulting system exhibited comparable performances to an apparatus making advantage of pulsed lasers. The work has also highlighted techniques which seem promising for additional amplification of the excited ultrasound; the resulting increase in sensitivity would be crucial for the development of a low-cost, fully non-contact system applicable on a large scale. In the railway field, this would result in the possibility of inspecting not only the individual component but extending the inspection to the whole set of axles which make up the vehicle, during its operation.

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