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Tomasini

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EXPERIMENTAL INVESTIGATION BY LASER ULTRASONICS FOR HIGH SPEED TRAIN AXLE DIAGNOSTICS

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Abstract

The present paper demonstrates the applicability of a laser-ultrasonic procedure to improve the performances of train axle ultrasonic inspection. The method exploits an air-coupled ultrasonic probe that detects the ultrasonic waves generated by a high-~~power~~~~energy~~ pulsed laser. As a result, the measurement chain is completely non-contact, from generation to detection, this making it possible to considerably speed up inspection time and make the set-up more flexible. The main advantage of the technique developed is that it ~~is working~~~~works~~ in thermo-elastic regime and ~~it~~ therefore can be considered ~~as a~~ non-destructive method.

The laser-ultrasonic procedure ~~investigated~~ has been applied ~~for~~~~to~~ the inspection of a real high speed train axle provided by the Italian railway company (Trenitalia), ~~on which typical~~~~standard~~ fatigue defects have been expressly created according to standard specifications.

A dedicated test bench has been developed so as to rotate the axle with the angle control ~~-and to speed up the inspection of the axle surface~~. The laser-ultrasonic procedure proposed can be automated and is potentially suitable for regular inspection of train axles.

The main achievements of the activity described in this paper are:

- the study of the effective applicability of laser-ultrasonics for the diagnostic of train hollow axles with variable sections by means of a numerical FE model,
- the carrying out of an automated experiment on a real train axle,
- the analysis of the sensitivity to experimental parameters, like laser source – receiving probe distance and receiving probe angular position,
- the demonstration that the technique is suitable for the detection of surface defects purposely created on the train axle.

Keywords: Laser-ultrasonics, NDT, air-coupled ultrasound, train axle, FE model

50 1. Introduction

51 Safety and reliability are two key issues in the railway field. Wheelset components, i.e. axle and
 52 wheels, are often the main responsible for breakdowns and accidents, they being most subjected
 53 either to static stress or fatigue. Although designed for unlimited life, they occasionally collapse
 54 during operation because of the propagation of incipient cracks. Therefore their periodic inspection is
 55 crucial. An open problem is, however, the estimation of the optimal inspection [frequency](#) intervals
 56 (according to the concept of damage tolerance) [1] so as to increase safety without shortening the
 57 periods between controls, this making it possible to reduce maintenance costs [2]. Currently periodic
 58 inspection of axles is carried out by ultrasonic techniques using, for example, a number of rotating
 59 contact probes, phased arrays or bore probes (for hollow axle diagnostics) [3, 4, 5].

60 Ultrasonic techniques, which are ~~a long-established method~~ [well known in the state of the art](#), have
 61 the disadvantage of requiring the probes to be in contact with the object to be investigated, which
 62 lengthens the inspection time necessary to prepare the object and apply the coupling medium.
 63 However, the typical problems of conventional techniques can be overcome by using a hybrid laser-
 64 ultrasonic system based on the detection of ultrasonic waves generated by a high-~~power~~[energy](#)
 65 pulsed laser via air-coupled ultrasonic transducers. Air-coupled ultrasound inspection has already
 66 been successfully used in many industrial applications e.g. NDT on both thick [6] and thin [7]
 67 composites, NDT on light thin historical vaults [8], density measurement of ceramic tiles [9], wood
 68 detection [10], and thin metallic laminated [11, 12].

69 The hybrid system [here](#) proposed is completely non-invasive and it makes it possible to:

- 70 - overcome shape and accessibility problems,
- 71 - avoid the application of the coupling medium,
- 72 - shorten the inspection time for large surfaces.

Laser-ultrasonics has been applied in the aeronautical field for damage detection on thick composite materials [13] and honeycombs [14] and in the railway field for rail [15,16], rail wheels [17] and axle inspection [18]. Gonzales et al. [18] presented a Laser Air-Hybrid Ultrasonic Technique based on air coupled ultrasounds. The limitations of the technique are due to the fact that it ~~is working~~ works in ablative regime and it exploits the Rayleigh waves reflected by the crack. Since that technique works in ablative regime which damages the surface it cannot be considered a non-destructive method. The use of Rayleigh wave reflection makes it extremely difficult to ~~work~~ deal with complex geometries, ~~as~~ like hollow axles with several section variations. In fact, the reflections due to the geometry can overlap with the one induced by the crack and thus the desired signal can be buried into ~~the~~ noise. In a very recent work the suitability of laser-ultrasonics for the inspection of wheelset flaws was proved by means of a numerical study [19]. A numerical simulation with dynamic explicit integration was presented, showing that the perturbation produced by the defect on the ultrasonic propagation, and specifically on the surface or Rayleigh wave, is evident and therefore the technique is suitable for diagnostic purposes.

The present paper shows the experimental application of laser ultrasonics ~~to~~ for the inspection of a real high speed train axle ~~provided~~ supplied by the Italian railway company (Trenitalia), where standard fatigue defects have been expressly created according to standard specifications.

The first aim of this work is to demonstrate that the technique works in ~~the~~ termo-elastic regime. ~~Furthermore it has been shown~~ shows its functionality also that the technique can be applied also for the inspection of complex geometries using direct Rayleigh waves. It ~~has been proved~~ proves that the technique can be applied also when the distance between laser source and ultrasound probe exceeds 200 mm. Consequently it ~~is possible to apply it~~ can be applied for the diagnostics of flaws located in the fretting surface by ~~locating~~ positioning the laser source and the ultrasound probe ~~on~~ at the opposite sides of the wheel press fitted area. That holding, the potentials of such technique for the application to wheelsets are quite evident, as demonstrated by the results of the numerical model

presented in [19]. This would be the next step of the experimental investigation performed by the authors.

The paper is structured in four Sections. Section 2 presents a numerical feasibility study performed with the aim to verify the suitability of the technique proposed for axle flaw diagnostics. Such study has been carried out by means of a numerical FE model simulating the generation of the thermo-elastic displacement by a high-~~power~~~~energy~~ pulsed laser impinging on the material surface and the propagation of the ultrasonic wave produced by the thermo-elastic effect within the material. The numerical simulation has been used by the authors to design the experiments and optimize the diagnostic procedure for flaw identification. The experimental set-up and the sensitivity analysis to experimental parameters are reported in Section 3, and the results obtained in the tests are discussed in Section 4.

2. Feasibility study of the Laser Ultrasonic technique by means of a numerical FE model

In this section the finite element model developed for the design of the experiments based on laser ultrasonics for the detection of flaws in a train axle is described. A coupled thermo-stress analysis was exploited to simulate the generation and the propagation of Rayleigh waves and to drive the experiments, by identifying the optimal testing parameters.

2.1. Simulation of the elastic wave generation

For the generation of the ultrasound wave from the pulsed laser excitation, a 2D axisymmetric model simulating the half cross section of a steel disk with a radius of 20 mm and thickness of 3 mm was developed.

Such undersized model makes it possible to optimize the numerical mesh and the input parameters for an accurate simulation of the Rayleigh waves generation and to put the basis for the complete model of the train axle.

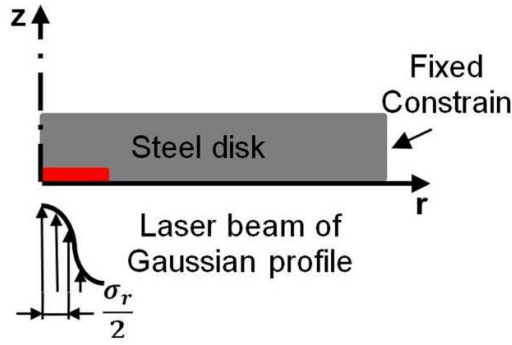


Fig. 1. Schematic view of the numerical model.

Two different physics need to be considered in laser-ultrasonics: thermo-elasticity, for the ultrasonic wave generation due to the thermo-stress induced by the laser impulse [20, 21], and acoustics, for the ultrasonic wave propagation within the material [22]. Comsol Multiphysics software was used to carry out the numerical simulation. An implicit analysis with a generalized- α (alpha) time dependent-solver was implemented.

A convective cooling boundary condition ~~has been~~ was used on the top and bottom surface. Other boundaries were assumed to be thermally insulated. The body heat load within the steel disk is given by the following expression:

$$Q_{in}(r, z, t) = Q(t)(1 - R) \left(\frac{A_c}{\pi \sigma_r^2} \right) e^{-\left(\frac{r^2}{2\sigma_r^2} \right)} e^{-A_c z} \quad (1)$$

where σ_r is the standard deviation of the Gaussian laser beam. The value ~~assumed by~~ σ_r in the model is 1.5 mm (for a laser beam ~~of~~ with a diameter of 6-mm). The steel thermal, mechanical and optical properties appearing in equation (1) and in the following equations (2) and (3) are reported in Table 1. The variation ~~with temperature in~~ of the material properties ~~with temperature~~ was assumed to be low, when considering a thermo-elastic model with a heat flux lower than 16.9 MW/cm².

~~We assume~~ The absorption of the laser pulse ~~on~~ at the surface of the steel sample ~~was assumed to~~ occurs without phase change and therefore the thermal properties of the metal are independent of

temperature [23]. The Young modulus ~~has been~~was considered to be varying linearly with ~~the~~ temperature (about 0.15 GPa/K).

Table 1 Steel mechanical/thermal/optical properties.

ρ	Density	7900 kg/m ³
E	Young Modulus (@ 273.15 K)	200 GPa
C	Specific heat capacity	480 J/(kg K)
k	Thermal conductivity	50 W/(m K)
α	Coefficient of thermal expansion	10.7 e ⁻⁵ K ⁻¹
R	Reflection coefficient	0.3
A_c	Absorption coefficient	3.87 e ⁹ m ⁻¹

The time-dependence of the thermal power $Q(t)$ irradiated by the laser pulse is taken into account in equation (1) using a triangular function [24] with 12 ns of duration and an energy of 82 mJ. An integration time step of 4 ns was considered, thus leading to a sampling frequency of 250 MHz. Equation (4) expresses the power density of the impinging laser beam absorbed by the material, depending on the reflectivity properties of its surface. The reflectivity was calculated analytically [23] according to the following equation:

$$R = \frac{2 - 2\xi + \xi^2}{2 + 2\xi + \xi^2} \quad (2)$$

where $\xi = \mu_0 \sigma c \delta$, and $c = 300\text{m/s}$ is the speed of light in vacuum, $\mu_0 = 4\pi 10^{-7} \text{ Hm}^{-1}$ is the magnetic permeability in vacuum, σ is the steel conductivity and δ is the skin depth. The skin depth can be estimated from the following equation:

$$\delta = (\pi \sigma \mu_r \mu_0 \nu)^{-1/2} \quad (3)$$

with μ_r the relative magnetic permeability and $\nu = 2.82 \times 10^{14} \text{ Hz}$ the radiation frequency at the IR wavelength of 1064 nm.

For the steel given in Table 1 $\mu_r = 1900$ and $\sigma = 7.04 \times 10^6 \text{ (}\Omega\text{m)}^{-1}$, thus $\delta = 0.258 \text{ nm}$, $\xi = 0.68$ and $R = 0.3$.

The heat flux (Q) was estimated by knowing the laser energy (E), the pulse duration (τ) and the area of the laser beam (A) corresponding to a laser beam ~~of~~with a diameter of 6 mm, according to the following equation:

$$Q = \frac{E}{\tau \cdot A} (1 - R) = \frac{0.082}{(12 \cdot 10^{-9}) \left(\frac{\pi}{4} \cdot 0.6^2\right)} 0.7 = 16.9 \frac{\text{MW}}{\text{cm}^2} \quad (4)$$

For a metallic material in the near infrared/visible wavelength region, the transition between the thermo-elastic regime and ablative regime is governed by the laser power density absorbed by the material [23]. For the steel given in Table 1 the transition value was calculated to be about 20 MW/cm². Since the value of the thermal heat flux calculated with equation (4) is lower than 20 MW/cm² it can be stated that the ultrasound waves are generated in the thermal-elastic regime.

In order to investigate the effect of thermo-elastic expansion in terms of ultrasound wave propagation, the solid-acoustic interaction was added. The acoustic model makes it possible to connect the elastic wave propagation with the thermal deformation evaluated in the thermal stress module. A prescribed displacement (in r and z directions, see Fig.1) boundary condition was set in order to impose the thermal displacement, output of the thermal stress module, as the input of the acoustic one.

A structured quadrilateral mesh with variable size was created. The element size varied between a minimum value of 0.1 nm and a maximum of 1 μm . The minimum element size was set with the aim to have some elements within the penetration area of the laser source. The penetration depth was 0.258 nm. The maximum element size was in agreement with the rule of $\lambda_r/10$ [25, 26], e.g. 0.29 mm considering a frequency of 1 MHz and the shortest wavelength corresponding to Rayleigh wave which travels at the speed of 2905 m/s.

An attenuation of ultrasonic waves of 4 neper/m was considered in the numerical model.

The simulation time was 5 μs , to detect all the phenomena implied in the process. The test sample made for the model is shown Fig. 2, where the propagation of the different bulk waves is visible.

On the ~~epicentri~~epicenter surface of the disk, see Fig. 2c, the surface skimming longitudinal (sP) and shear (sS) waves are visible as well as at 1.2 μs . Those waves mark the intersection with the ~~epicentri~~epicenter surface of the disk with the longitudinal and shear wavefront [22].

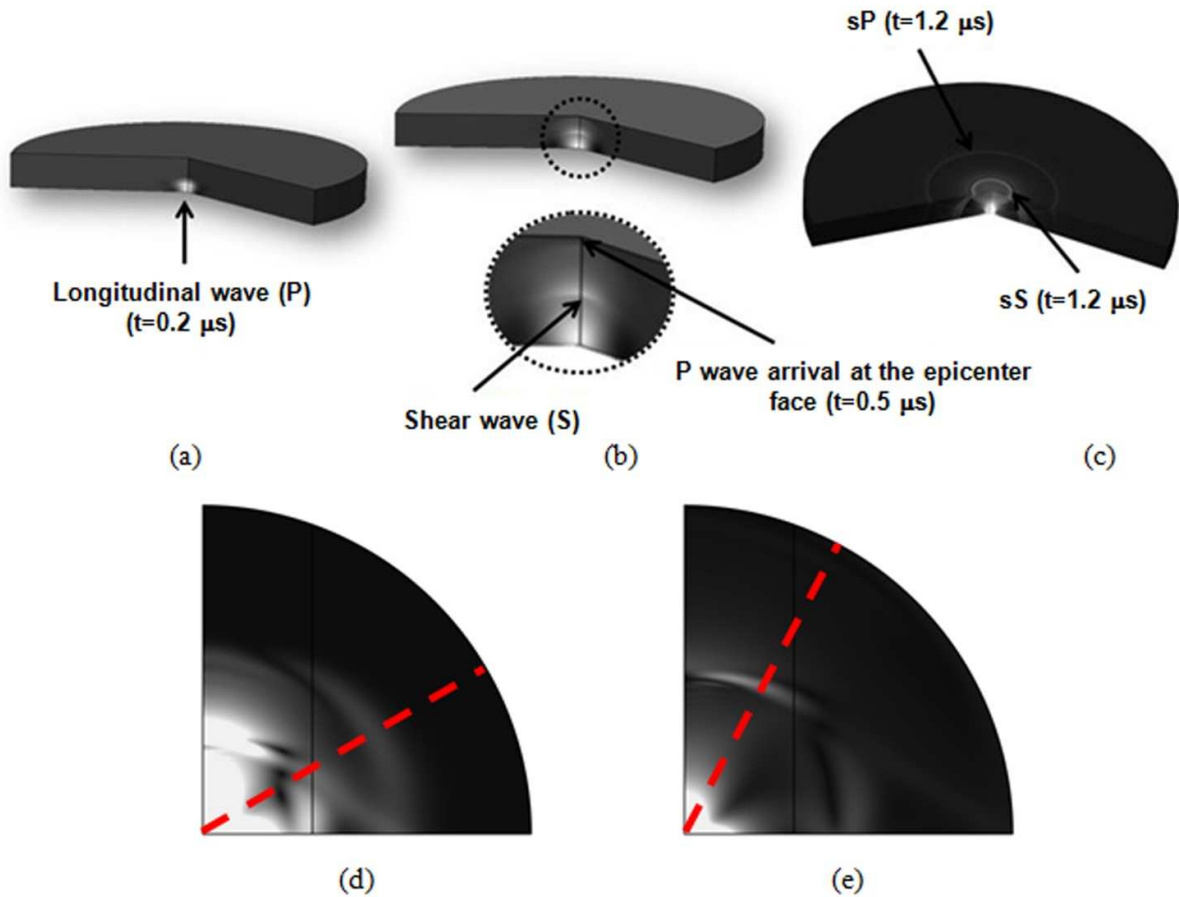
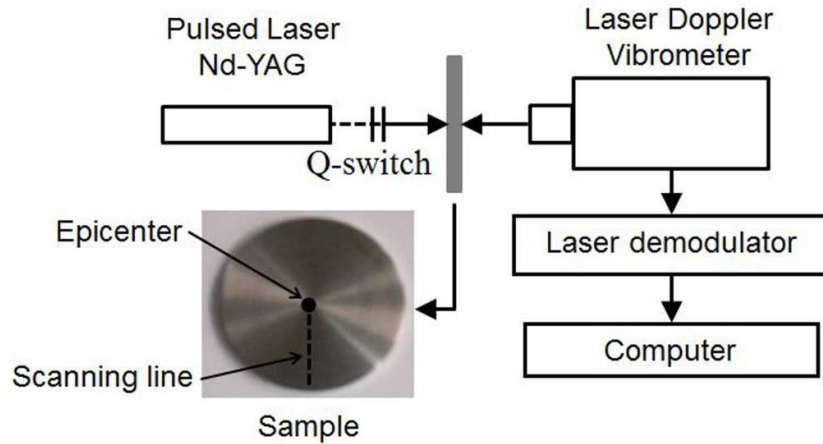


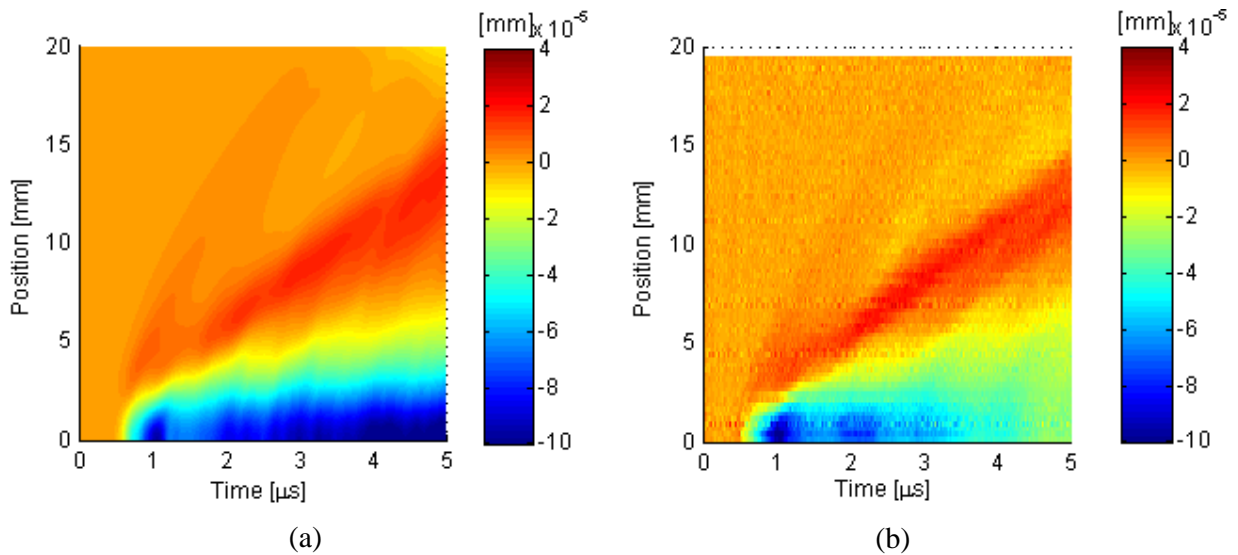
Fig. 2. 3D visualization of the propagation of the elastic waves: (a) Longitudinal (P) wave at $t=0.2 \mu\text{s}$. (b) P wave arrival at the epicenter face ($t=0.5 \mu\text{s}$) together with the arrival of the shear wave (S) at the disk half thickness. (c) Surface skimming longitudinal (sP) and shear (sS) waves ($t=1.2 \mu\text{s}$). (d) ultrasound propagation at $0.3 \mu\text{s}$, the P wave direction is evidenced by the dashed line. (e) ultrasound propagation at $0.5 \mu\text{s}$, the S wave is evidenced by the dashed line.

190 The model was validated with experimental data, showing correspondence in terms of propagation
 191 mechanisms. The wave propagation was measured by a Laser Doppler Interferometer with a
 192 frequency bandwidth of 20 MHz (Fig. 3).



193 *Fig. 3. Experimental set-up.*

194 Fig. 4 shows the numerical and experimental B-scans respectively, i.e. the waterfall plot of the
 195 surface displacement in the z-direction with respect to time (in abscissa) and spatial position along
 196 the scanning line, reported in Fig. 3.



197 *Fig. 4. Waterfall of the numerical (a) and experimental (b) displacement in the z-direction.*

198

2.2. Simulation of the elastic wave propagation on a 2D axle section

The model developed for the Rayleigh wave generation from the pulsed laser source shown in the previous section was exploited on a more complex model, where a 2D axle section was simulated. The propagation of the elastic waves was modeled following the thermal diffusion and thermo-elastic displacement equations [22]:

$$\rho C \frac{\partial T}{\partial t} + \rho C \mathbf{u}_1 \nabla T = \nabla(k \nabla T) + Q \quad (5)$$

$$(\lambda + \mu) \nabla(\nabla \mathbf{u}_1) - \mu \nabla \times \nabla \times \mathbf{u}_1 - \rho \frac{\partial^2 \mathbf{u}_1}{\partial t^2} = \alpha(3\lambda + 2\mu) \nabla T \quad (6)$$

where T is the temperature rise in the metal, k is the thermal conduction coefficient, ρ is the density, C is the constant specific heat, $Q(r, z, t)$ is the power density of the heat source created by laser irradiation expressed in two-dimensional cylindrical coordinates (r, z) , α is the linear thermal expansion coefficient, λ and μ are the Lamé constants and \mathbf{u}_1 is the displacement vector due to the thermo-elastic effect.

The elastic wave equation is obtained from Newton's second law:

$$\rho \frac{\partial^2 \mathbf{u}_2}{\partial t^2} - \nabla \mathbf{s} = \mathbf{F}_v \quad (7)$$

where \mathbf{u}_2 is the displacement vector due to the elastic effect, \mathbf{s} is the stress tensor and \mathbf{F}_v represents the volume force vector. To study the propagation of Rayleigh waves with frequency components up to 1 MHz the shortest wavelength is given by:

$$\lambda_r = \frac{c_r}{f} = \frac{2905 \cdot 10^3}{1 \cdot 10^6} = 2.90 \text{ mm} \quad (8)$$

The Rayleigh velocity was measured experimentally, it resulting in 2905 m/s.

A quadrilateral mesh was used. The size of the finite elements was chosen in order to have a sufficiently suitable spatial resolution of the propagating waves. In [25, 26] it is recommended to have at least 10 nodes per wavelength and therefore the element size must be at least 1/10 of the shortest

wavelength to be analyzed, i.e. smaller than $l_e = \lambda_r/10 = 0.29 \text{ mm}$, where λ_r is the Rayleigh wavelength.

The model made it possible to simulate the propagation of the elastic wave within the axle section and to verify that the Rayleigh wave would not ~~attenuate and~~ bury into the floor noise when traveling long distances, like the press fitting areas where the wheel sits. Besides, the model aimed at proving that the presence of a flaw in the path travelled would produce a perturbation on the Rayleigh wave which could be detected by an ultrasound transducer. In Fig. 5 the propagation of the elastic waves within the 2D axle section and their interference with a flaw are presented. Fig. 6 shows the ultrasound signals that could be acquired by a transducer placed on the opposite side of the press fitting area (red arrow on the left in Fig. 5) with respect to the pulsed laser impinging point (red arrow on the right in Fig. 5). In the model the distance between the laser impinging position and the detection one has been set to 143.5 mm that corresponds to 154 mm distance along the axle profile. The two signals reported in Fig. 6 were obtained by running the model with and without a crack of 1.1 mm length and 1 mm depth located at 11.5 mm with respect to the laser impinging position, as shown in Fig. 5. The waveforms calculated on the undamaged and damaged configurations have been filtered on the frequency range of the ultrasound probe used in the experiments ($1 \text{ MHz} \pm 200 \text{ kHz}$) and they have been plotted with normalized amplitude. The attenuation produced by the flaw is evident and it is of 7.3 dB, which was determined as the ratio of the undamaged signal RMS value and the damaged signal RMS value. The RMS was calculated in a time window centered on the Rayleigh wave time of arrival. That window is represented by the gray box illustrated in Fig. 6. An attenuation of 7.3 dB can be detected by an ultrasound transducer, as it will be demonstrated experimentally in Section 3, where the attenuation produced by the defect is of the same order of magnitude as the one calculated with the model.

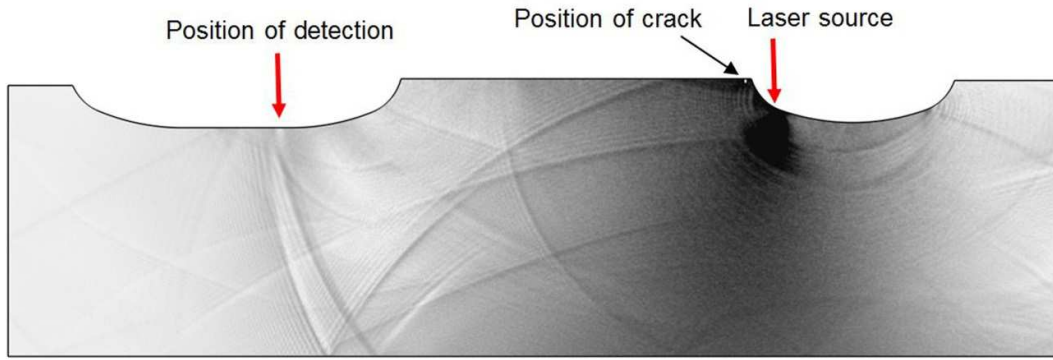


Fig. 5. Propagation of the elastic waves in the 2D axle section and their interference with the flaw.

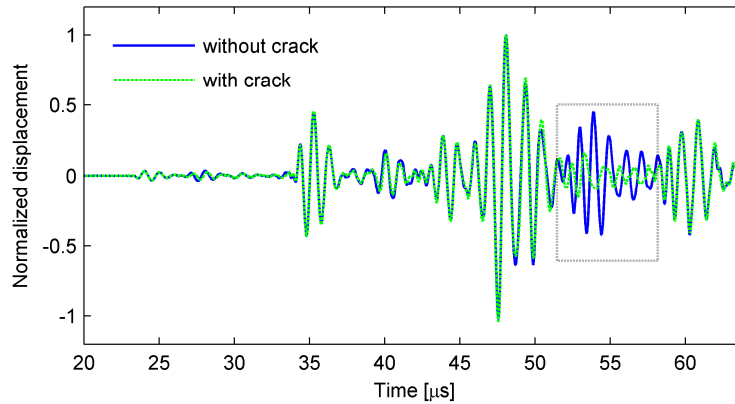


Fig. 6. Displacement waves with crack and without crack at the position of detection.

3. Experimental set-up

3.1. Test item

The test item is a train axle, Fig. 7a, on which typical fatigue defects were created. In practice four convex defects were machined on the external surface, see Fig. 7b, two of them in the wheel fitting area (D1 and D3) and the other two in the section transition (D2 and D4). The defect morphology is reported in Table 2.

Table 2 Defect morphology.

Defects	Size of defect		
	H (mm)	L (mm)	D Max depth (mm)
D1	31	1.1	1
D2	28	1.1	1
D3	28	1.1	1
D4	28	1.1	1

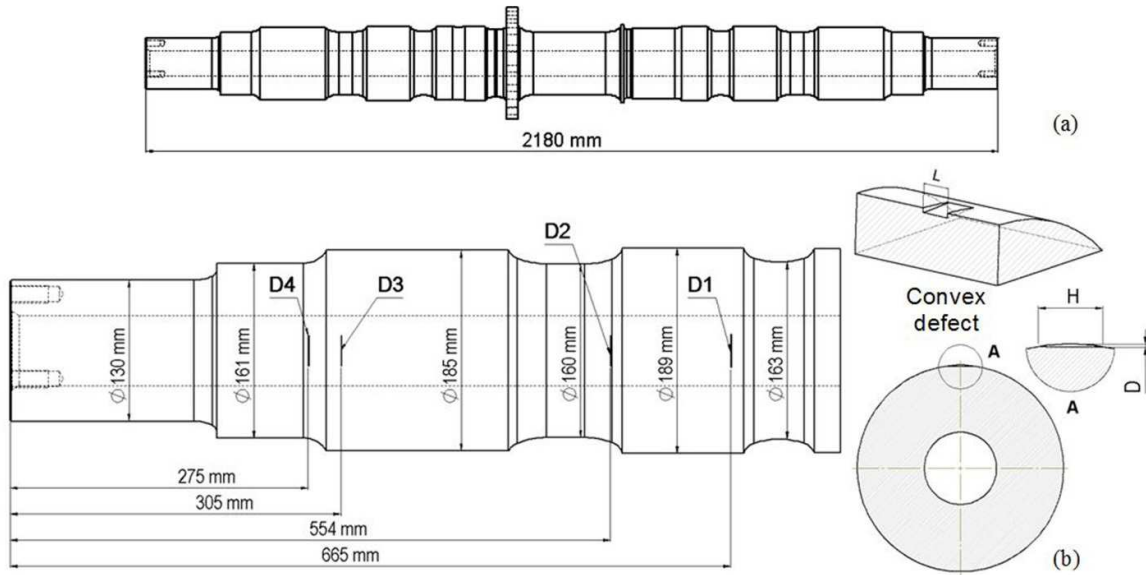


Fig. 7. Test item (a) and defect positions (b).

3.2. Test bench

The train axle was mounted on a support that made it possible to control its rotation, in order to be able to scan the axle surface along a circumference. The probes were installed on a frame where they could move along the axial direction. Therefore the complete lateral surface of the axle could be inspected by the laser ultrasonic system, see Fig. 8.

The laser ultrasonic system was made up of a pulsed laser source, a Nd-Yag IR laser (1064 nm), pulses of 12 ns duration and 82 mJ energy, from Continuum, and a 1 MHz air-coupled ultrasound piezoelectric probe from Ultrat Group (model NCT210, with 8 mm diameter of active area). The ultrasound probe conditioning system was a DPR 300 Pulser/Receiver from JSR Ultrasonics. The ultrasound signals were amplified with a gain level of 69 dB and acquired with a high speed Digitizer board NI PXI-5122 (100 MHz bandwidth). The laser beam was guided towards the axle under test by means of an arm connected to the pulsed laser cavity as shown in Fig. 8.

The axle was made to rotate by an electric motor and the rotation angle was measured by an integrated encoder. A circumferential scan was performed along an angle of 93 deg with an angular resolution of 1.5 deg. The real setup is shown in Fig. 10.

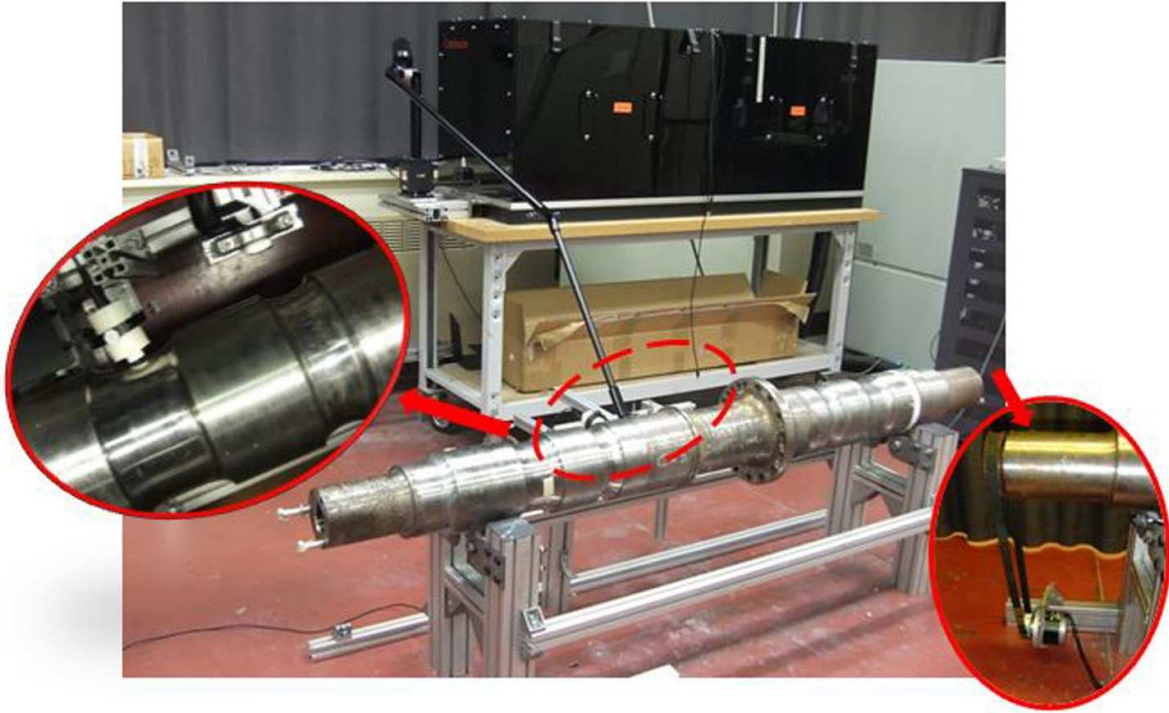


Fig. 10. The laser-ultrasonic scanning system.

3.3. Analysis of the sensitivity to experimental parameters

The aim of the experimental technique proposed in this paper is to be able to acquire a consistent signal even at a long distance from the laser source and therefore to make it possible to perform the measurement by pointing the laser source and the ultrasound probe above and beyond the press fitted zones of the axle, respectively. In order to verify the operation of the laser-ultrasonic technique in dependence of the source-probe distance, a sensitivity analysis to this particular parameter was performed. In practice, the ultrasound probe was moved along the axle surface starting from a distance of 32 mm up to 247 mm, with a spatial resolution of 5 mm, (see Fig. 11a) and the RMS of the signal acquired plotted again the sound-probe distance (see Fig. 12a). The probe angle used in

this analysis was of 6 deg. It is clear that the RMS decreases with the distance but, when comparing the ultrasound time history acquired at 32 mm with the one acquired at 247 mm (see Fig. 13, where the Rayleigh waves are highlighted by the dashed box), the arrival of the Rayleigh wave is still evident: its SNR is 12.5 dB.

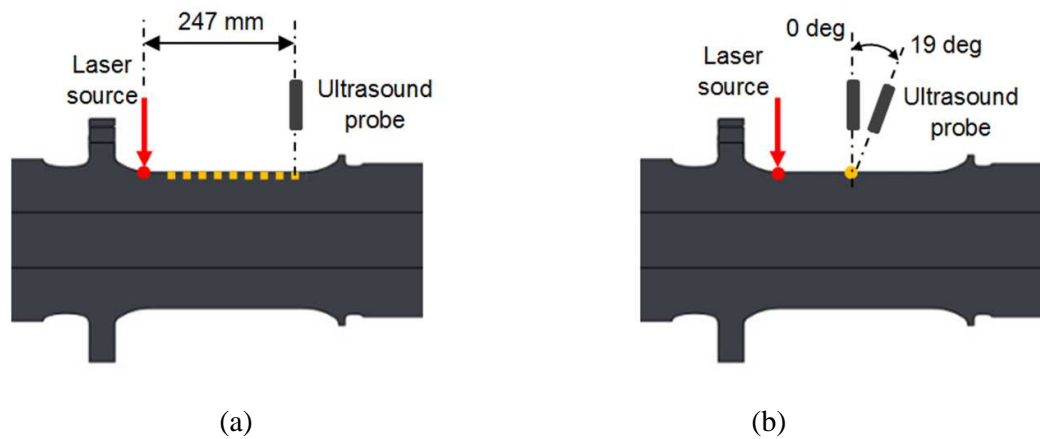


Fig. 11. The laser ultrasonic experimental set-up for the sensitivity analysis to source-probe distance (a) and probe angular position (b).

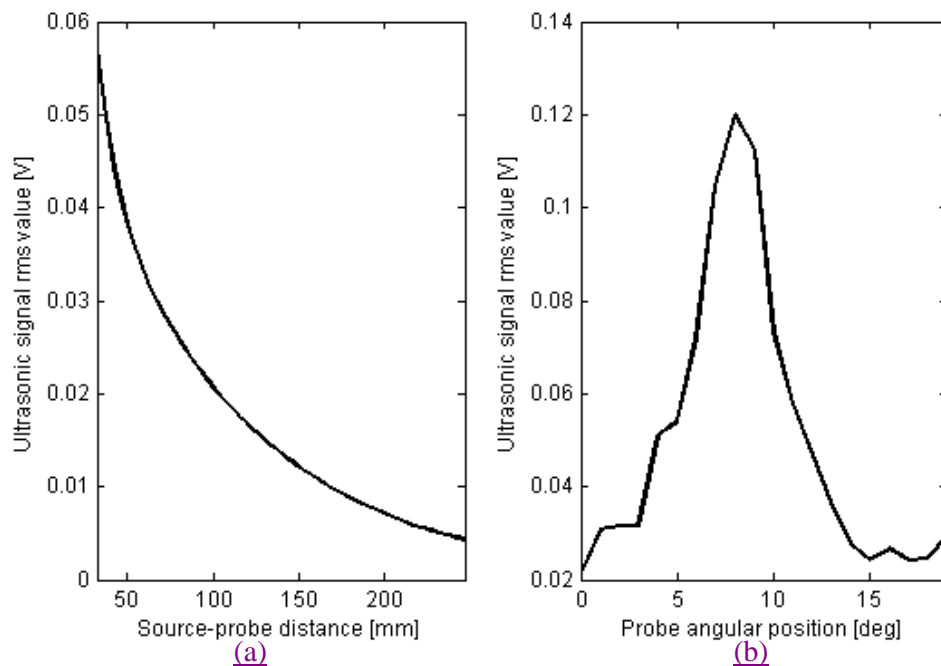


Fig. 12. Ultrasonic signal RMS variation with respect to source-probe distance (a, probe angular position 6 deg) and probe angular position (b, source-probe distance 32 mm).

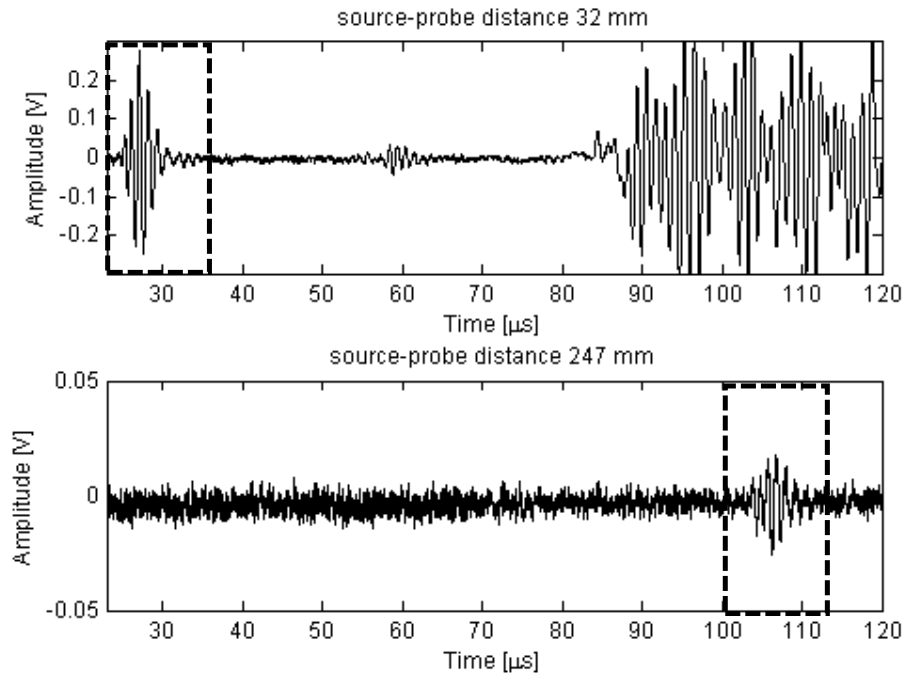


Fig. 13. Ultrasonic time history at the minimum (32 mm, dashed line) and the maximum (247 mm, solid line) source-probe distance.

A sensitivity analysis to the angular position of the ultrasound probe axis with respect to the normal of the axle surface was then performed. The probe was placed at 32 mm from the laser source and, starting from an angle of 0 deg, where the probe axis was normal to the axle surface, it was tilted up to 19 deg with a resolution of 0.5 deg. As it is evident in Fig. 12b, the optimal angular position was at about 8 deg, according to [the](#) Snell's law [27].

4. Analysis of results

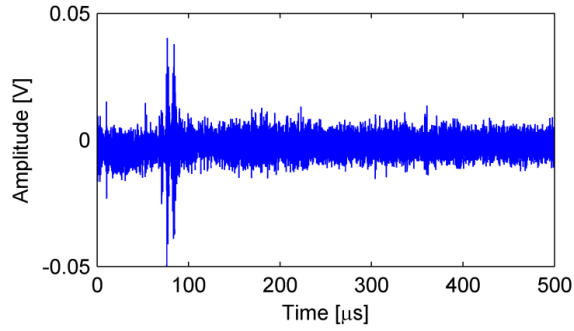
For each configuration, a series of ultrasound time histories with a duration of 500 μs was acquired at every scanning position along the arc considered. The attention was focused on the Rayleigh wave propagation, it being the most sensitive elastic wave to the presence of the defect. Moreover, because

of the geometry complexity and of the generation of elastic waves by the laser-material interaction, the Rayleigh wave is also the most efficient for surface defect identification.

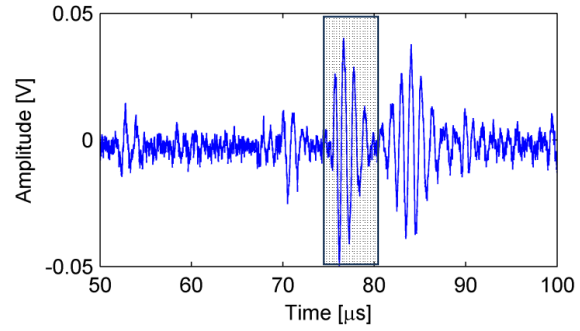
The experimental set-up (i.e. laser and probe positions), the axle section tested and the defect location (D1) are shown in Fig. 14c. The time history acquired in the first scanning position is plotted in Fig. 14a. A close up around the time of arrival of the bulk waves is given in Fig. 14b: that time history evidences the Rayleigh wave arrival time at about 75 μ s. However, other waves are visible in the waveform which are reflections of longitudinal and shear waves due to the geometry complexity (section transitions).

The B-scan close-up around the Rayleigh wave time of arrival, shown in Fig. 15, evidences the presence of the defect, which produces a strong attenuation ~~and delay~~ of the Rayleigh wave itself.

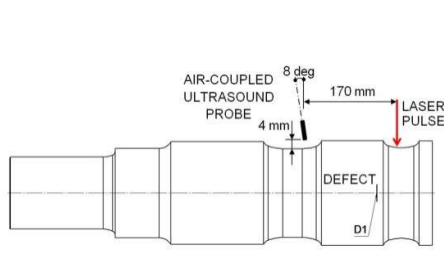
The same plots given for defect D1 are reported for the other defects (D2, D3 and D4 respectively) in Fig. 16. Again, the Rayleigh wave ~~_, highlighted in the time histories and in the B-scans,~~ evidences the presence of the defect. It should be noticed that the experimental set-ups of both defects D1 and D2 are similar: the distance between the pulsed laser and the air-coupled ultrasound probe is the same and therefore the Rayleigh time of arrival is equal, ~~of~~ about 75 μ s. The same occurs for defects D3 and D4, where the distance between the pulsed laser and the air-coupled ultrasound probe is larger and therefore the Rayleigh time of arrival is of about 87 μ s.



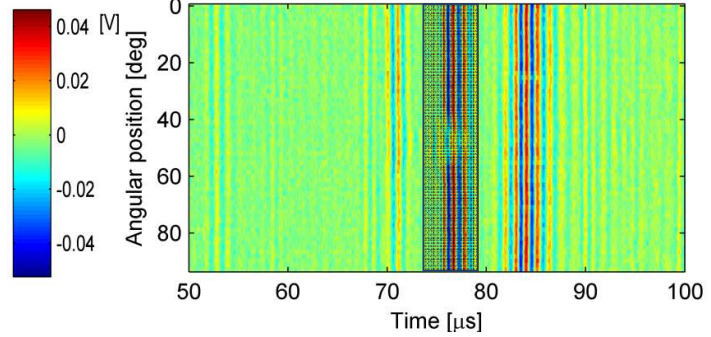
(a) Entire time history



(b) Time history close-up on the bulk waves



(c) Experimental set-up



(d) B-scan

Fig. 14. Time histories (a) and (b), experimental set-up scheme (c) and B-scan (d) – D1.

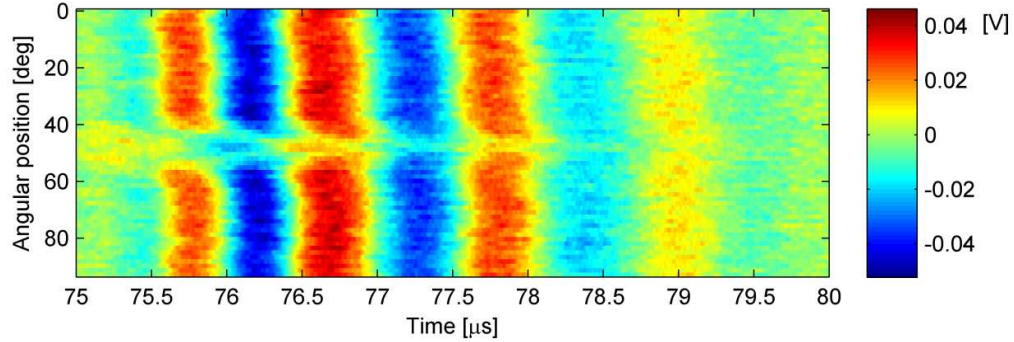
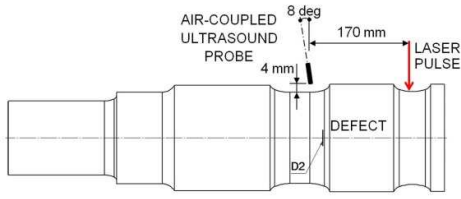
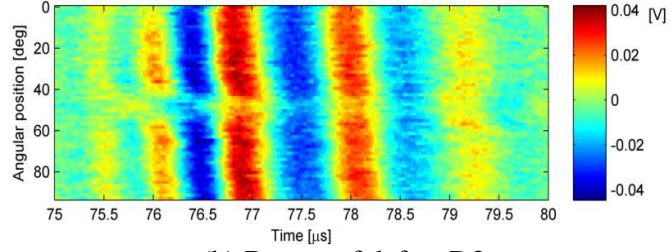


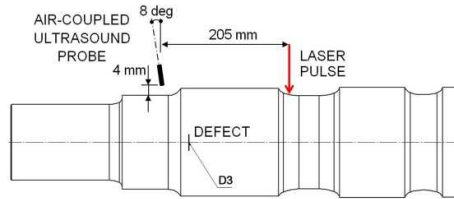
Fig. 15. B-scan close-up around the Rayleigh wave time of arrival – Defect D1.



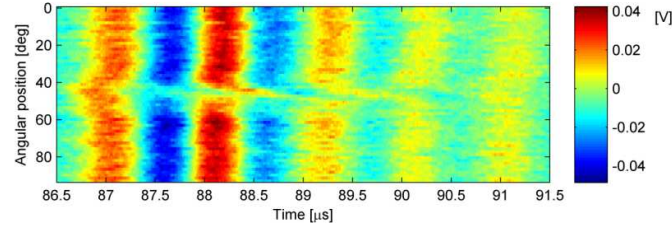
(a) Experimental set-up - defect D2



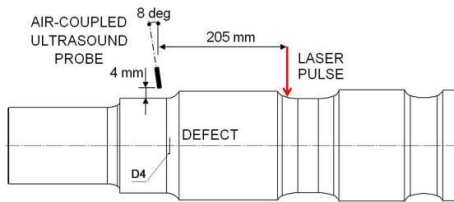
(b) B-scan of defect D2



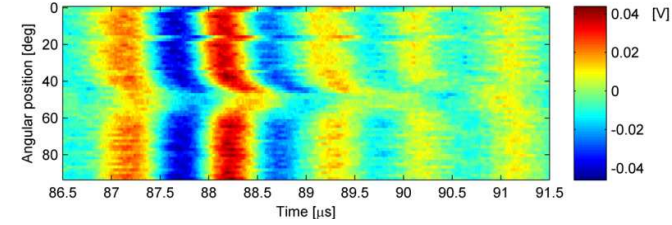
(c) Experimental set-up - defect D3



(d) B-scan of defect D3



(e) Experimental set-up - defect D4



(f) B-scan of defect D4

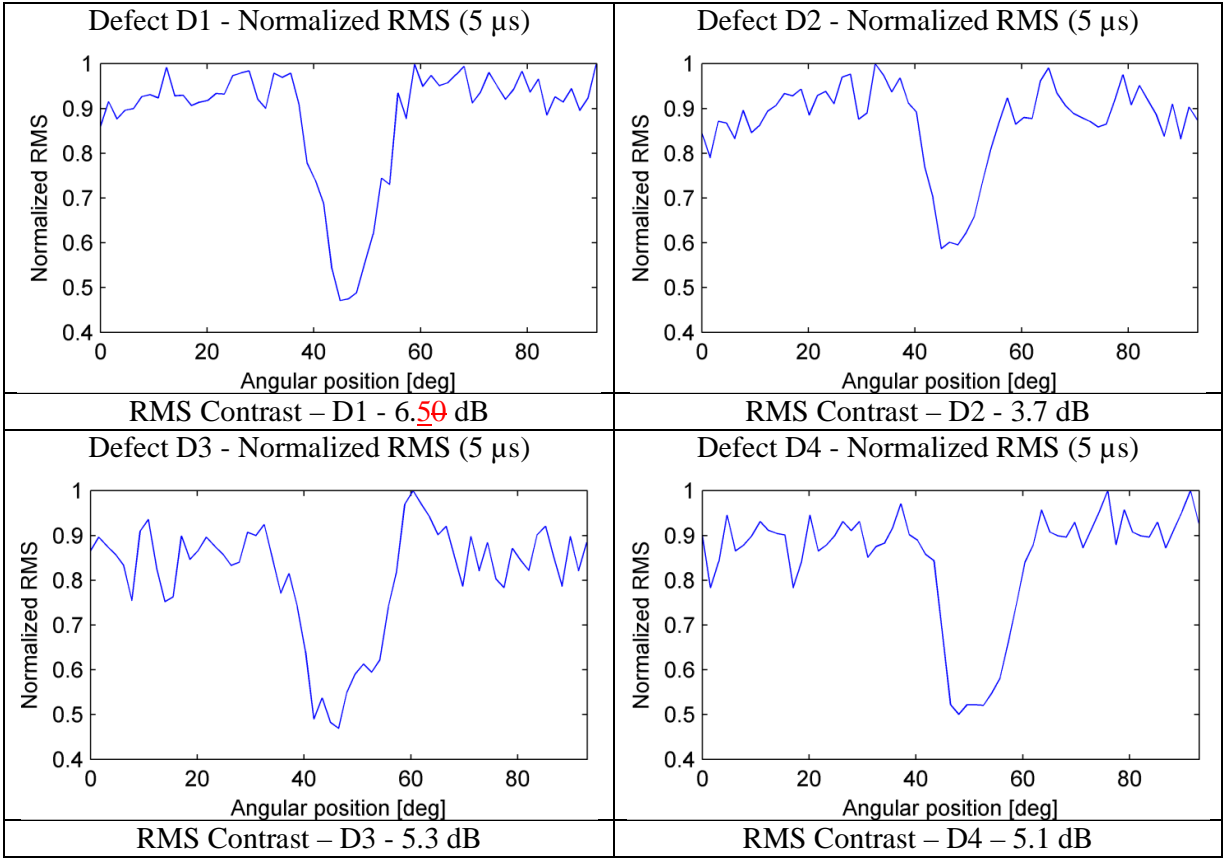
Fig. 16. Experimental set-up scheme (a), (c), (e) and B-scan (b) (d), (f) for defects D2, D3, D4 respectively.

The RMS plots over the time axis (abscissa) of the B-scans obtained for the four defects were calculated and compared in Table 3. Those plots were normalized against the maximum RMS value of each plot. The contrast between the RMS in the damaged and in the undamaged areas is presented also in Table 3, which was calculated considering the minimum values of the RMS (in the damaged area) and the floor values RMS (in the undamaged area). It is clear that the best contrast between the undamaged area and the damaged one occurs for defect D1 (6.5 dB), where the pulsed laser is close to the defect. On the other hand, it is possible to see that the contrast between the undamaged area and the damaged one undergoes a drop when the defect is far from the laser source, which is the case of defects D2, D3 and D4. The worst contrast occurred for defect D2 and it is due to the fact that the receiving probe is located after a very sharp transition, this strongly attenuating the ultrasound wave propagation (e.g. it is evident that the signal minimum is lower than the other ones). Concerning

defects D3 and D4, instead, the receiving probe is located after a smoother transition, this reducing the attenuation of the ultrasound waves.

The attenuation measured experimentally confirms the result achieved with the model exploited in Section 2 for the feasibility study, where a 7.3 dB attenuation was calculated. The order of magnitude of the attenuation is comparable, although despite the differences exist between the numerical and experimental data, e.g. the experimental signals are acquired with air-coupled transducers while the numerical model does not take propagation in air into account propagation in air.

Table 3 Normalized RMS and Damaged/Undamaged RMS Contrast.



5. Conclusions

The paper has shown the applicability of laser-ultrasonics, a non-destructive, non-contact technique, for the inspection of train axles. The main advantage of the proposed technique with respect to the state of the art is that it operates in thermo-elastic regime and therefore it can be considered a non-

destructive method. ~~A further advantage is that the crack produces an attenuation~~ Furthermore, it is
~~based on the fact that the crack produces an attenuation~~ of the direct Rayleigh wave. That wave can
be generally distinguished from the reflections produced by the geometry and therefore it can be used
as defect classification feature also with very complex geometries.

Four convex defects typically generated by fatigue on the external surfaces of an axle have been
investigated. Two of the defects were on a transition section and the other two on a wheel fitting
area. All the defects have been identified by observing the Rayleigh wave propagation, it presenting
an evident attenuation when passing through the damaged area. The contrast between the undamaged
area and the damaged one made it possible to identify the complete set of defects, although it has
been evidenced that the best situation occurs when the defect is close to the laser, i.e. the ultrasound
waves source, where the contrast reaches 6.5 dB.

The good results achieved with the experimental procedure proposed in this paper incentivized the
authors to extend the application to axles mounted on a complete wheelset, with the aim to prove its
suitability for the remote inspection of railway axles in service.

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2009PSJW8Z "Development of a laser-ultrasonic system for non-destructive-testing aiming at
improving railway safety".

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Figure captions

Fig. 1. Schematic view of the numerical model.

Fig. 17. 3D visualization of the propagation of the elastic waves: (a) Longitudinal (P) wave at $t=0.2 \mu\text{s}$. (b) P wave arrival at the epicenter face ($t=0.5 \mu\text{s}$) together with the arrival of the shear wave (S)

471 at the disk half thickness. (c) Surface skimming longitudinal (sP) and shear (sS) waves ($t=1.2\ \mu\text{s}$).

472 (d) ultrasound propagation at $0.3\ \mu\text{s}$, the P wave direction is evidenced by the dashed line. (e)

473 ultrasound propagation at $0.5\ \mu\text{s}$, the S wave is evidenced by the dashed line.

474 Fig. 3. Experimental set-up.

475 Fig. 4. Waterfall of the numerical (a) and experimental (b) displacement in the z-direction.

476 Fig. 5. Propagation of the elastic waves in the 2D axle section and their interference with the flaw.

477 Fig. 6. Displacement waves with crack and without crack at the position of detection

478 Fig. 7. Test item (a) and defect positions (b).

479 Fig. 8. Scheme of the laser-ultrasonic scanning system.

480 Fig. 9. The laser-ultrasonic experimental set-up.

481 Fig. 10. The laser-ultrasonic scanning system.

482 Fig. 11. The laser ultrasonic experimental set-up for the sensitivity analysis to sound-probe distance

483 (a) and probe angular position (b).

484 Fig. 12. Ultrasonic signal RMS variation with respect to source-probe distance (a, probe angular

485 position $6\ \text{deg}$) and probe angular position (b, source-probe distance $32\ \text{mm}$).

486 Fig. 13. Ultrasonic time history at the minimum ($32\ \text{mm}$, dashed line) and the maximum ($247\ \text{mm}$,

487 solid line) source-probe distance.

488 Fig. 14. Time histories (a) and (b), experimental set-up scheme (c) and B-scan (d) – D1.

489 Fig. 15. B-scan close-up around the Rayleigh wave time of arrival – Defect D1.

490 Fig. 16. Experimental set-up scheme (a), (c), (e) and B-scan (b) (d), (f) for defects D2, D3, D4

491 respectively.

Fig. 1. Schematic view
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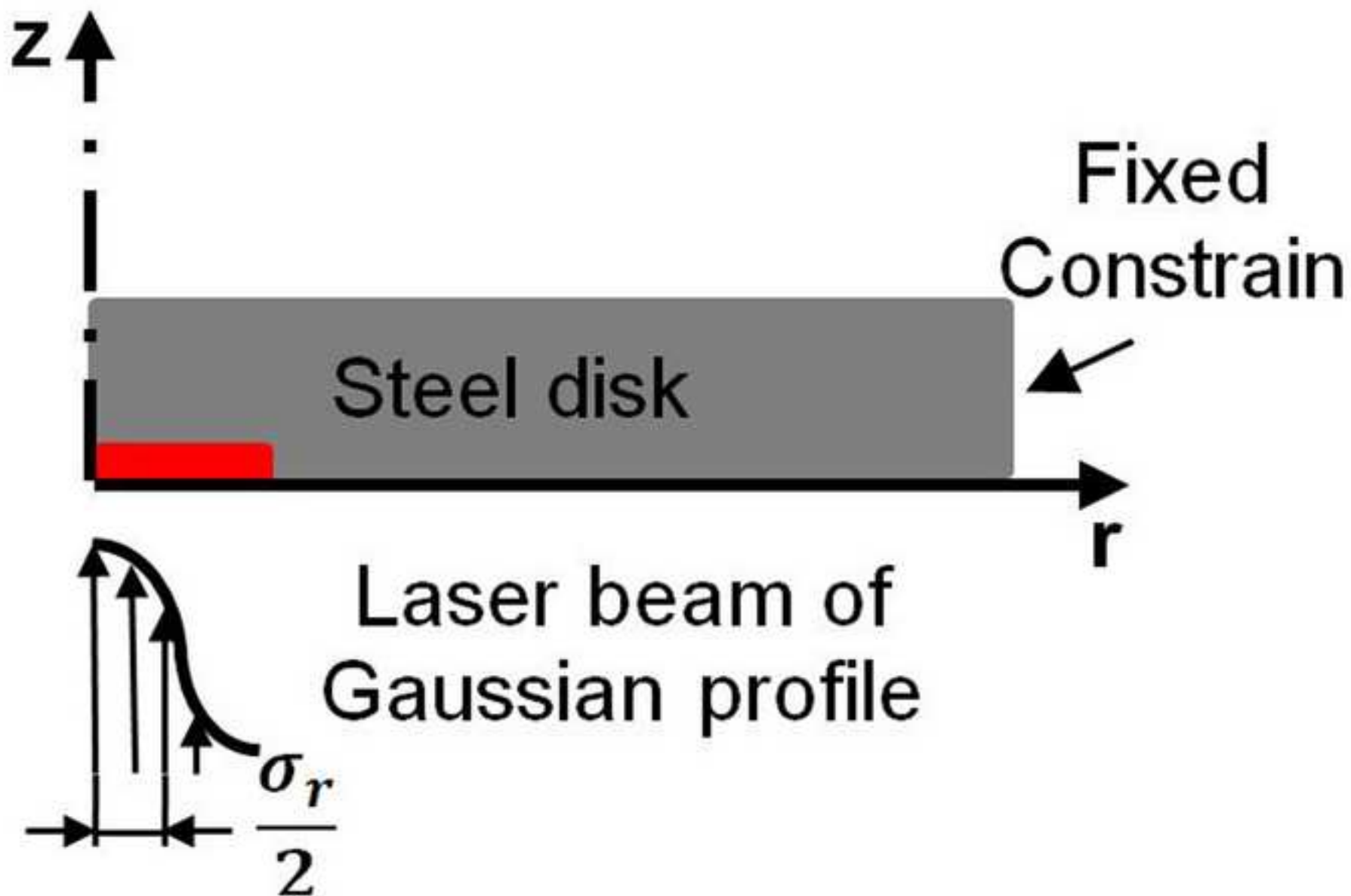


Fig. 2. 3D visualization of the propagation of the elastic waves
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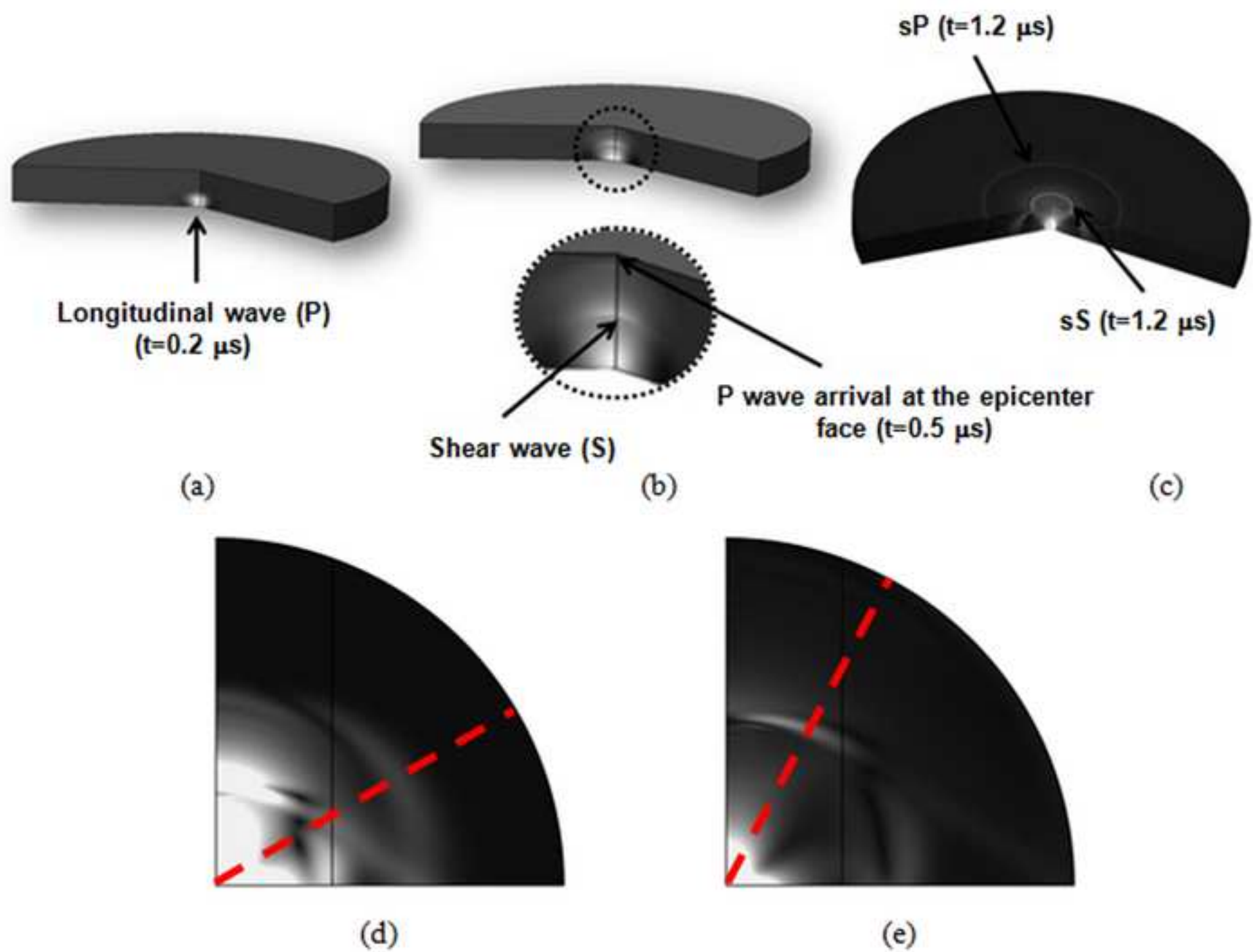


Fig. 3. Experimental set-up

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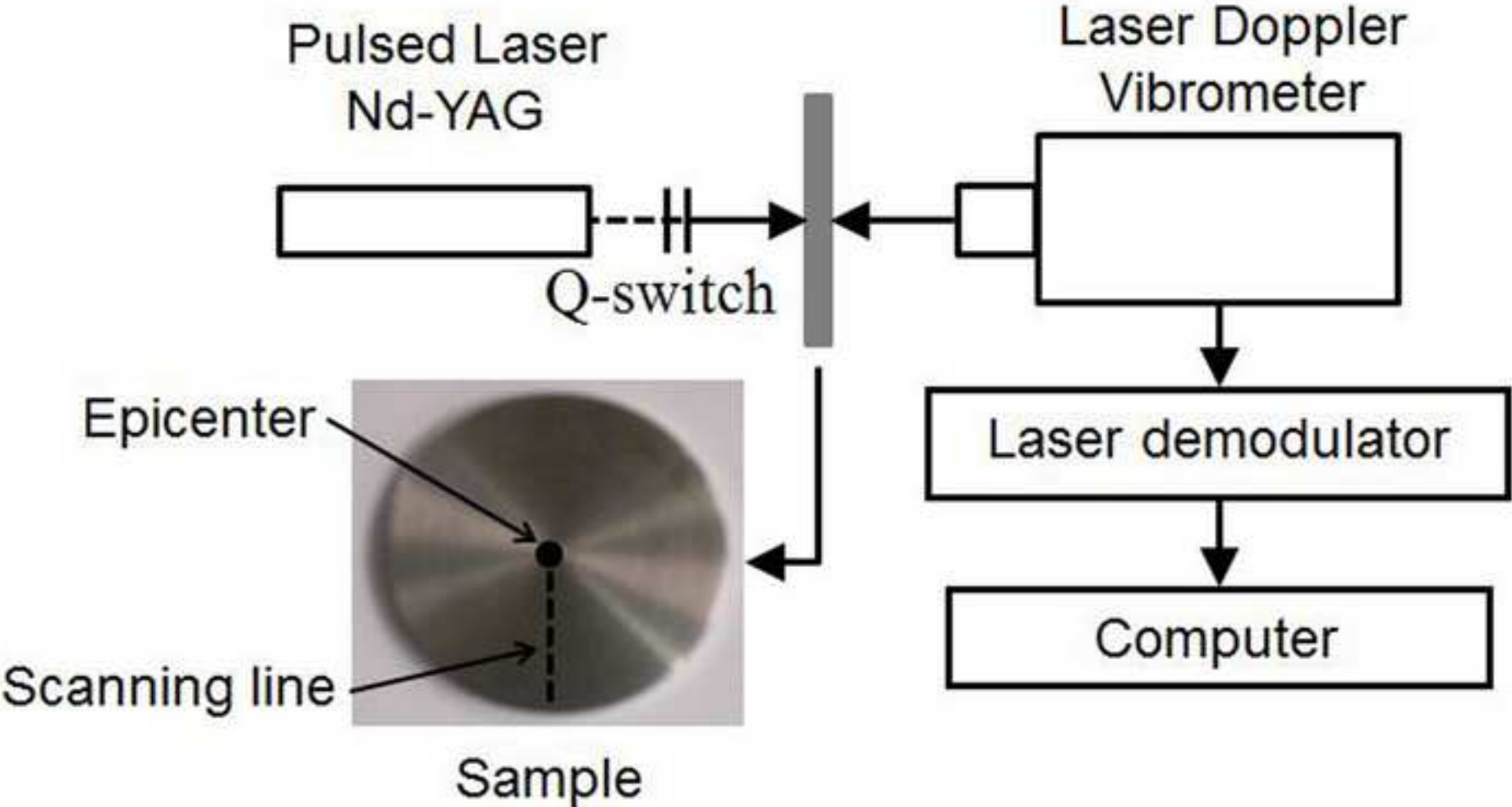


Fig. 4. Waterfall of the numerical (a)
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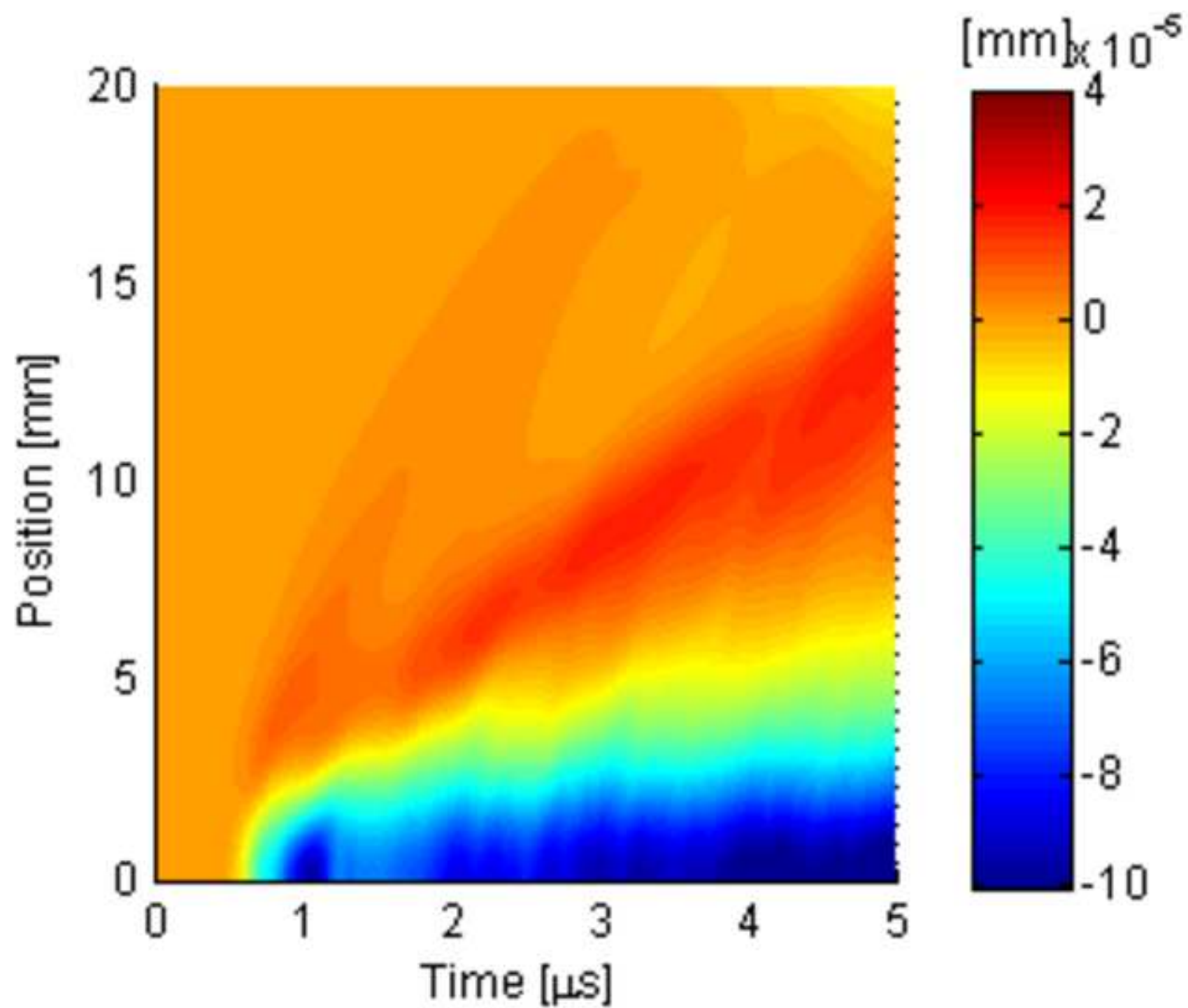


Fig. 4. Waterfall of the numerical (b)
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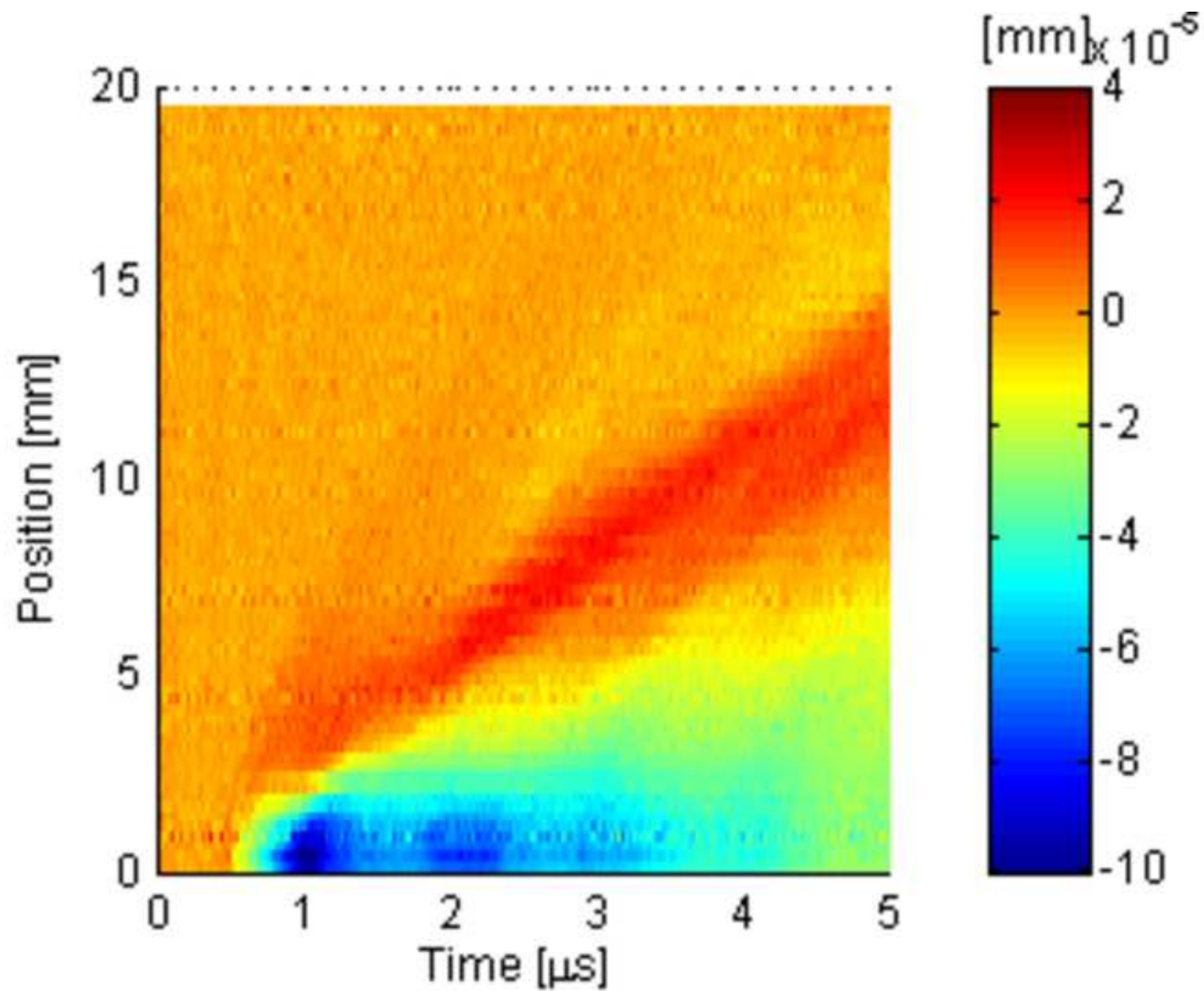


Fig. 5. Propagation of the elastic waves
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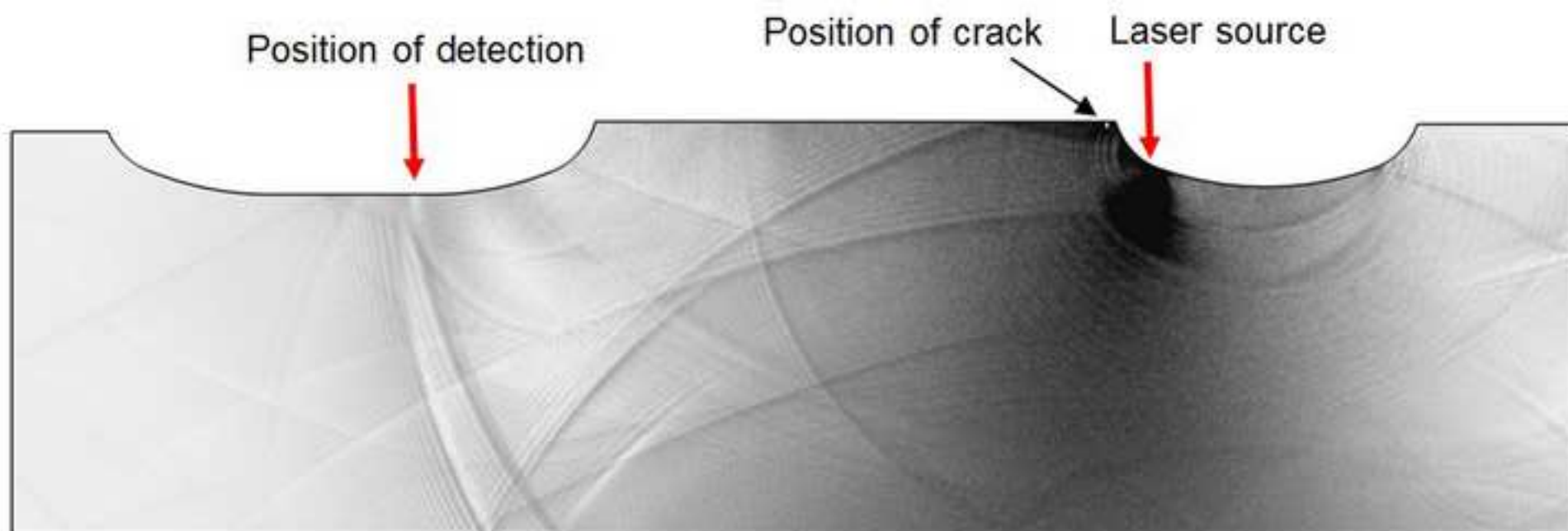


Fig. 6. Displacement waves
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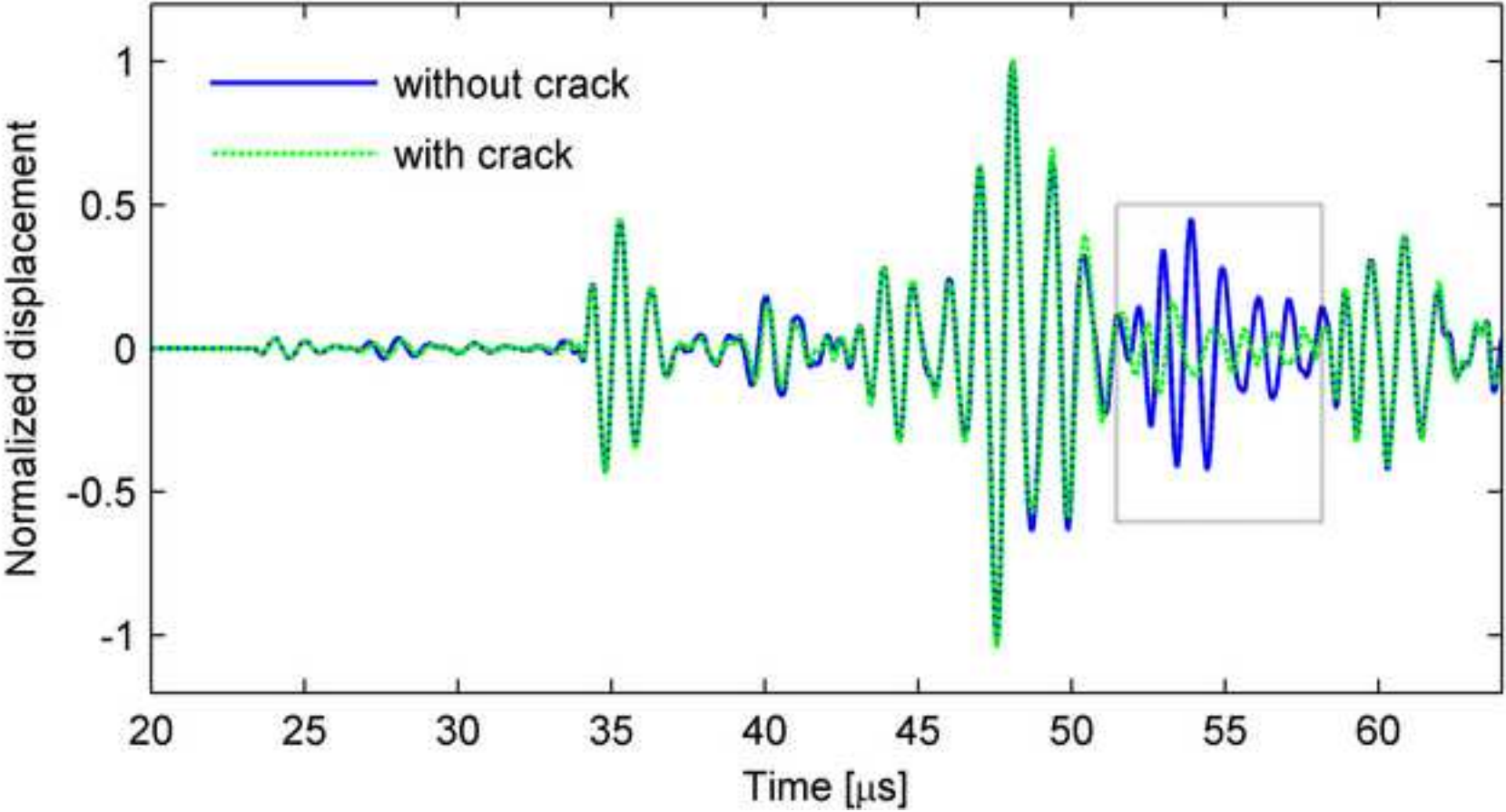


Fig. 7. Test item
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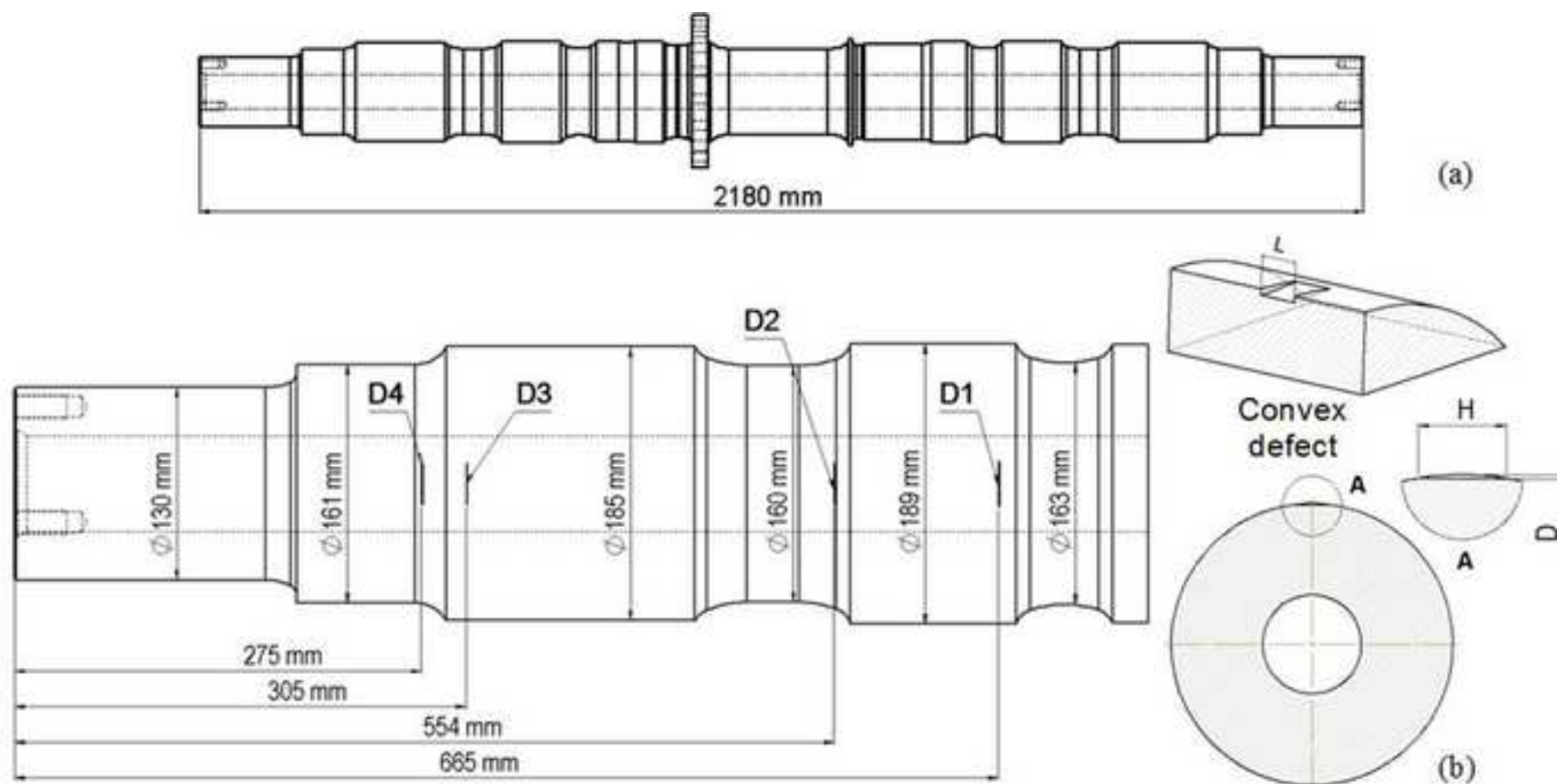


Fig. 8. Scheme of laser-ultrasonics scanning system.
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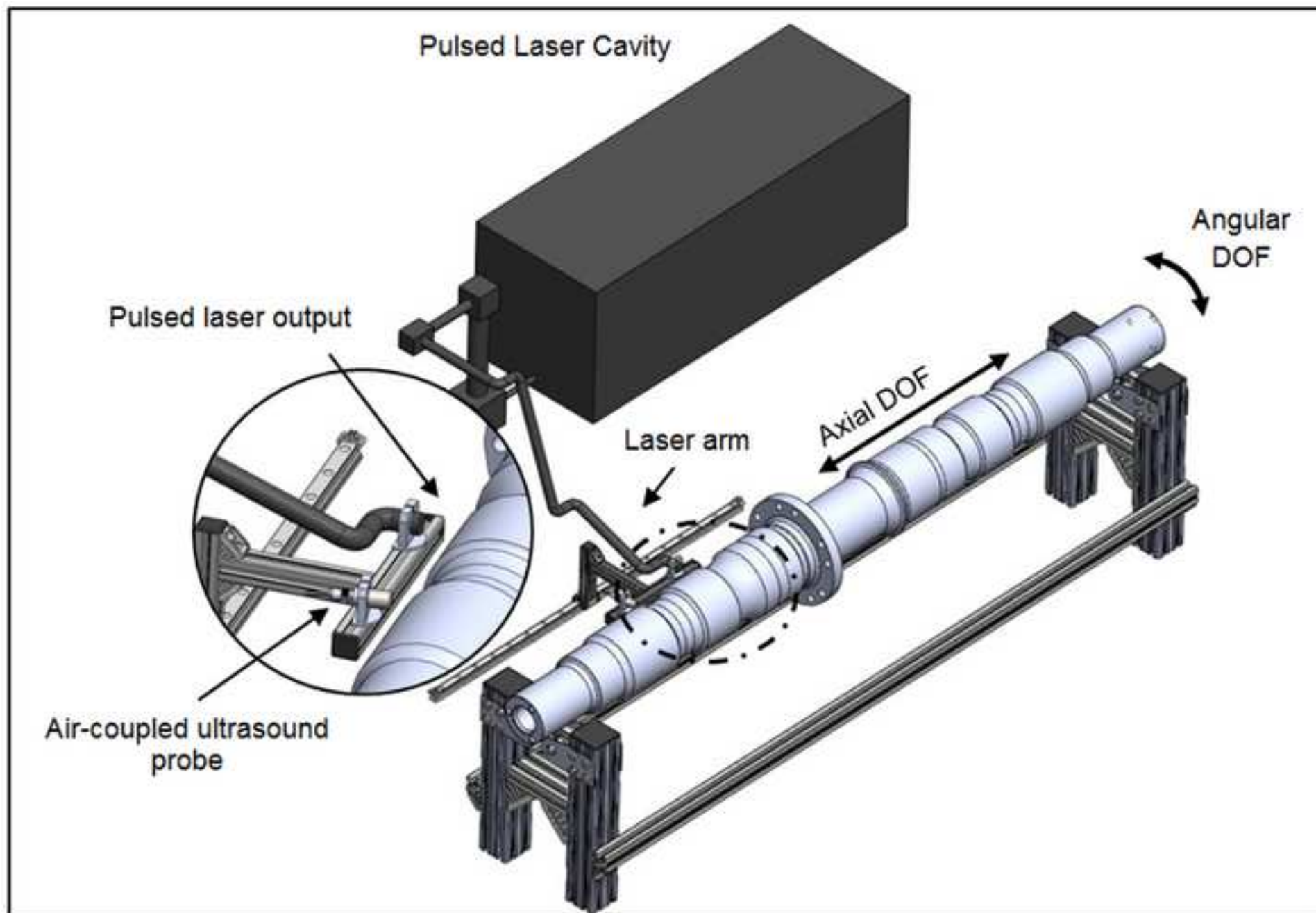


Fig. 9. The laser-ultrasonics experimental set-up.
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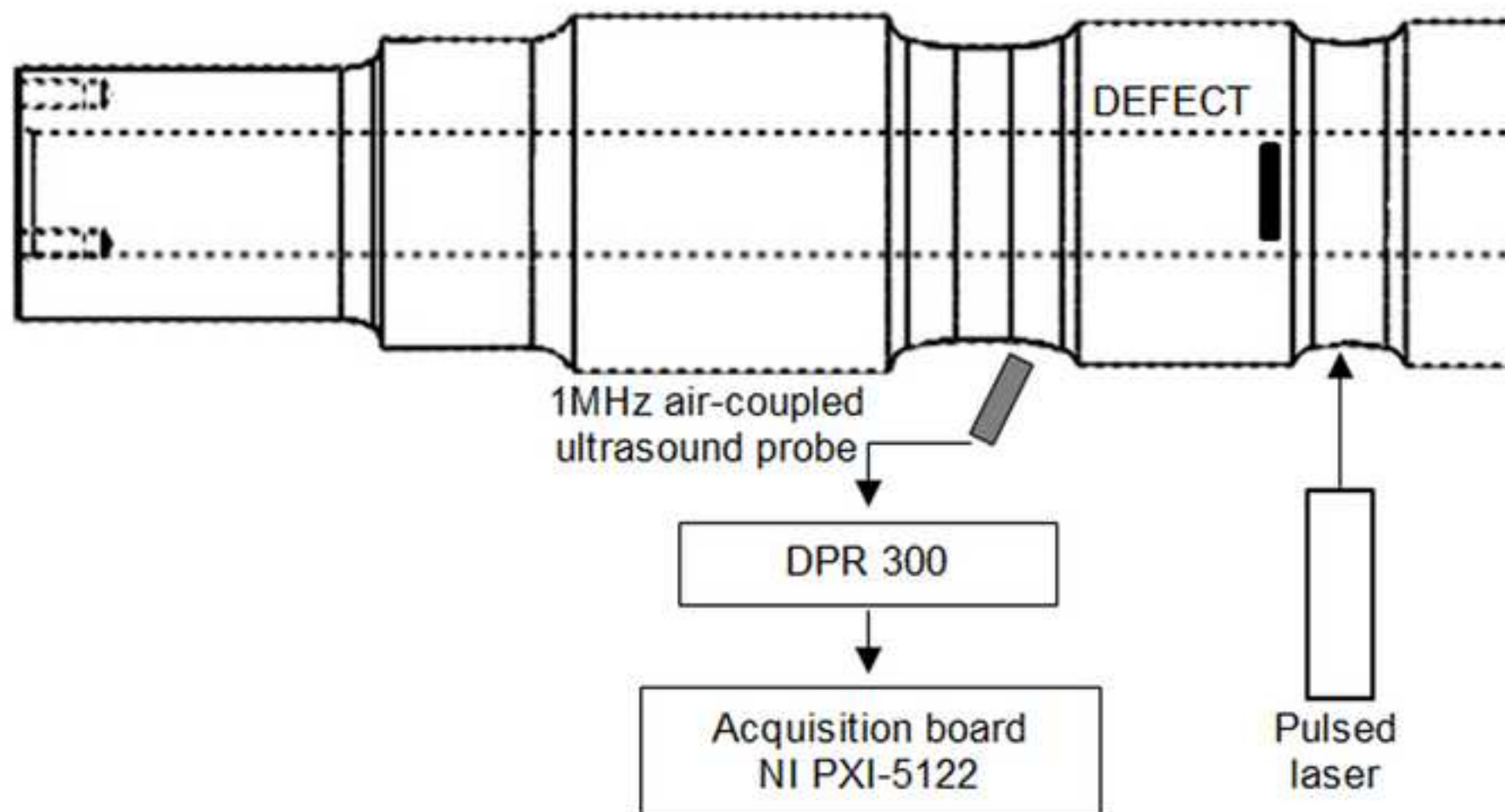


Fig. 10. The laser-ultrasonic
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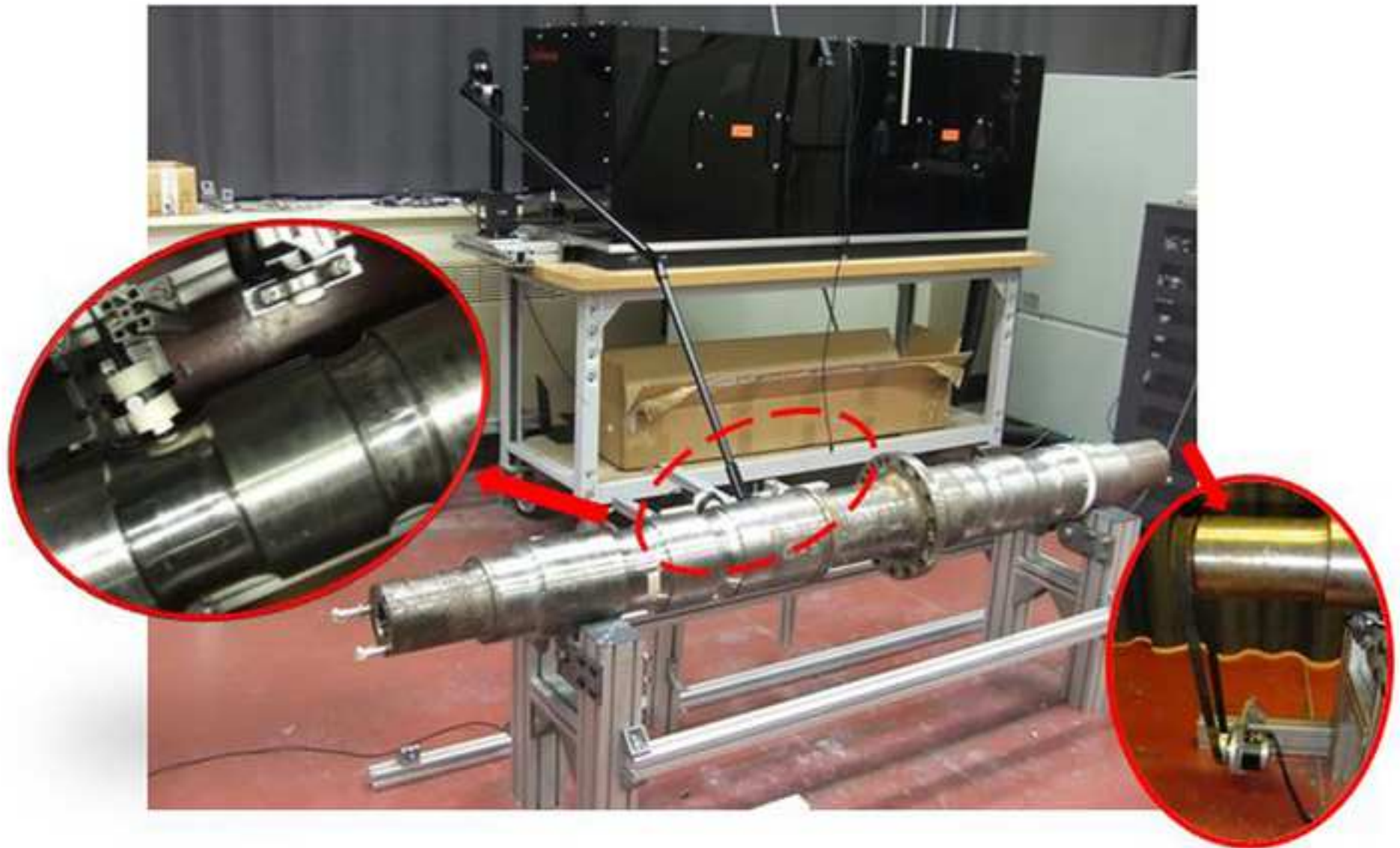


Fig. 11. The laser ultrasonics experimental set-up
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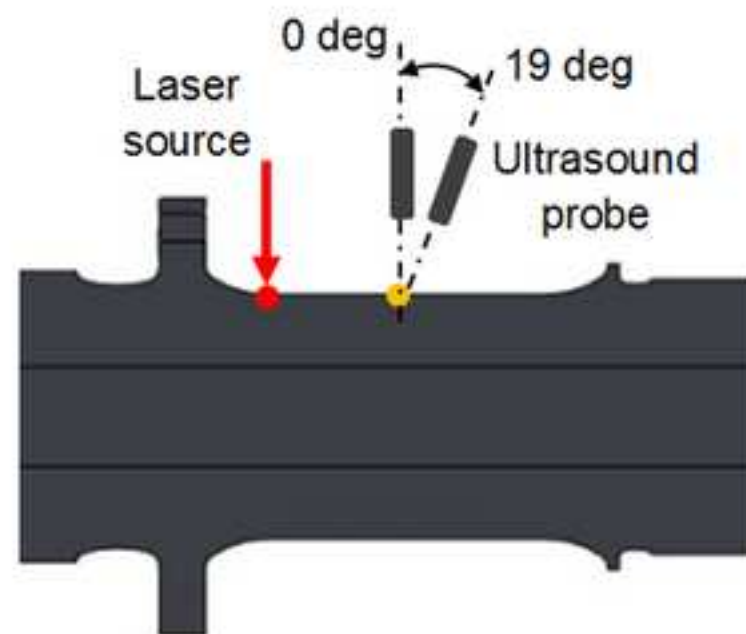
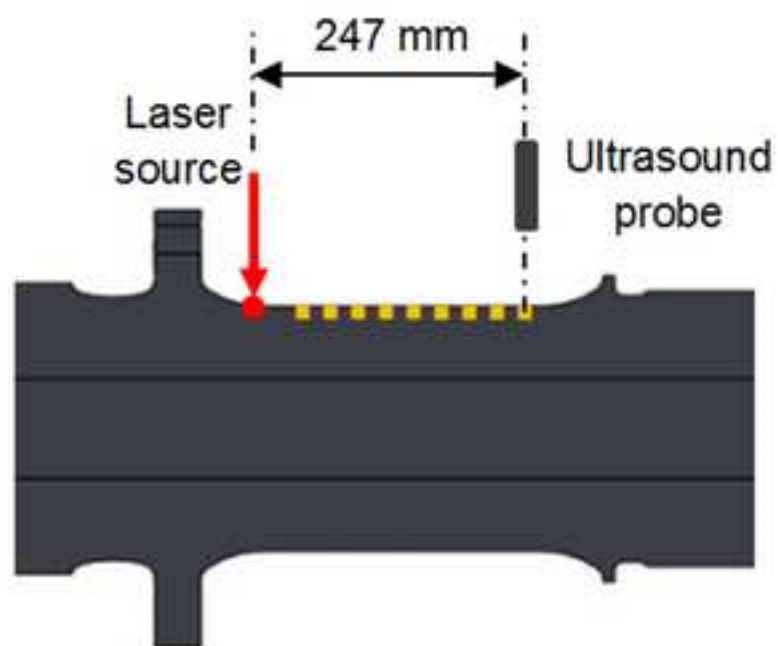


Fig. 12. Ultrasonic signal RMS variation
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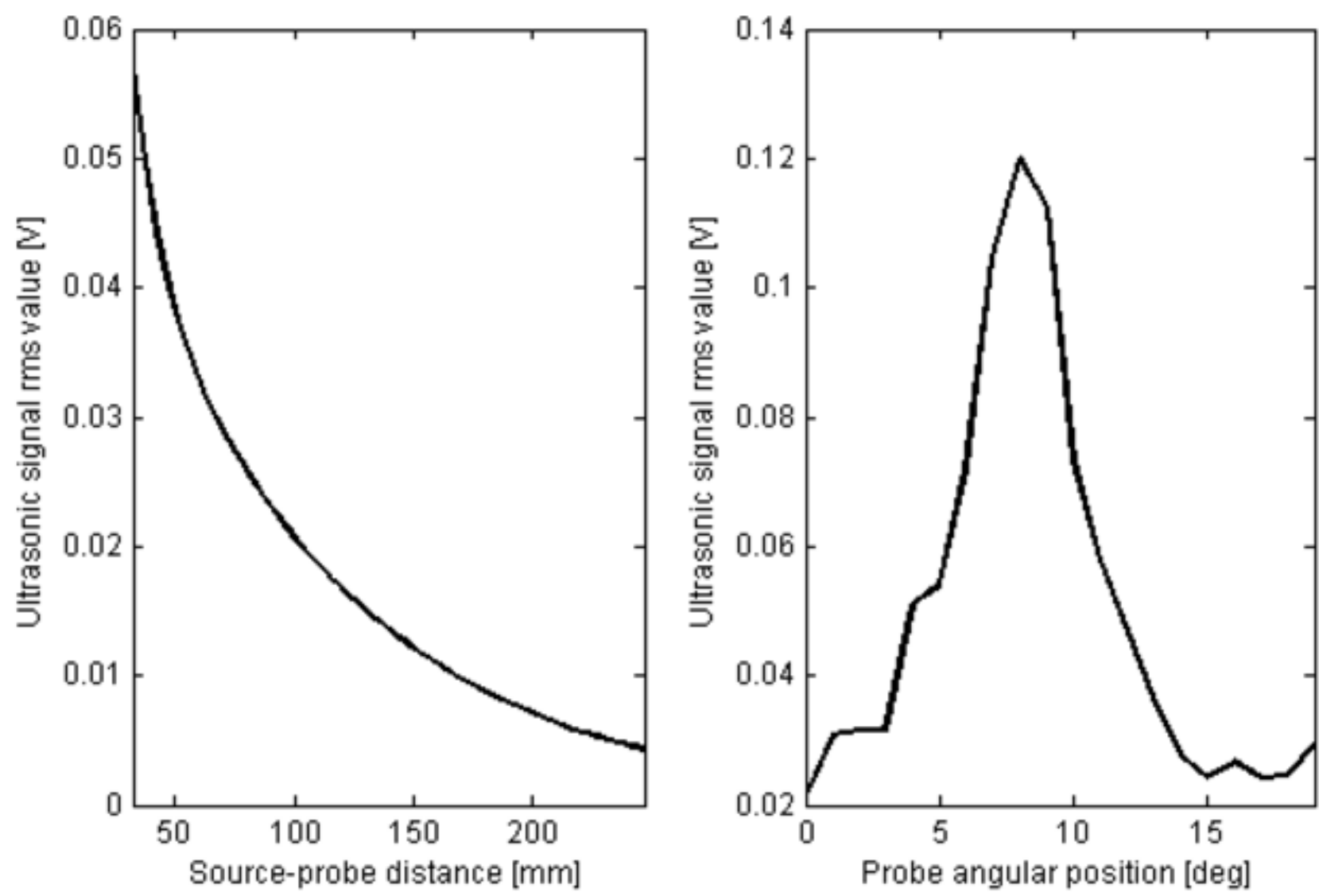


Fig. 13. Ultrasonic time history
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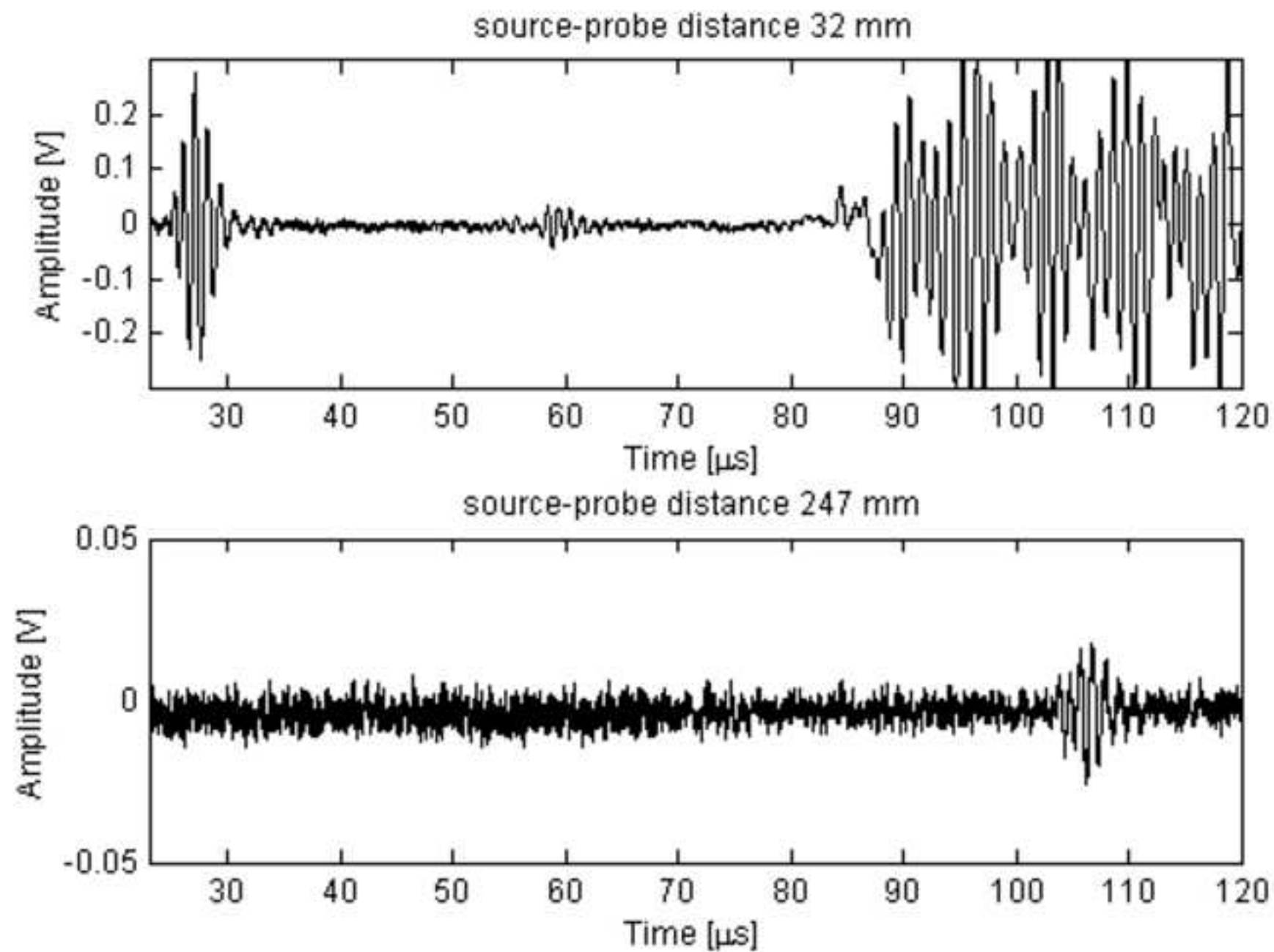
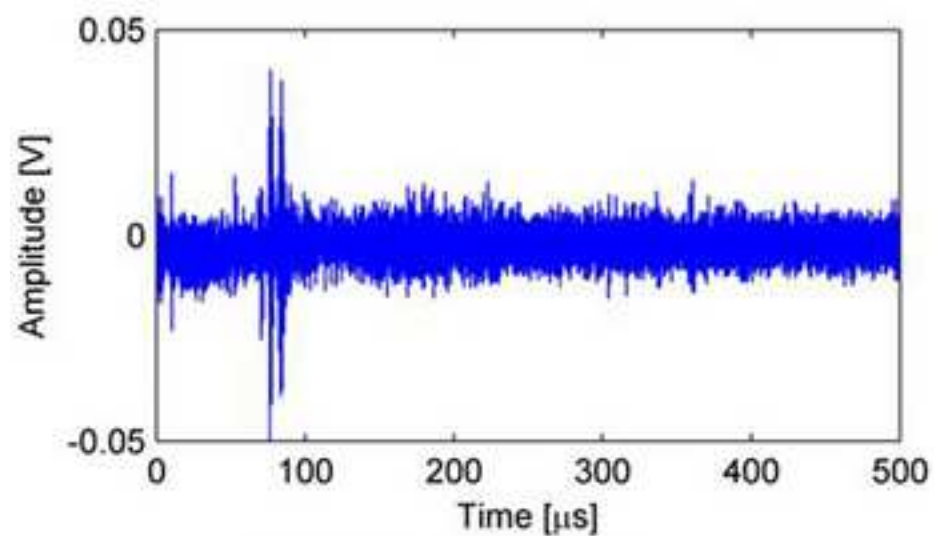
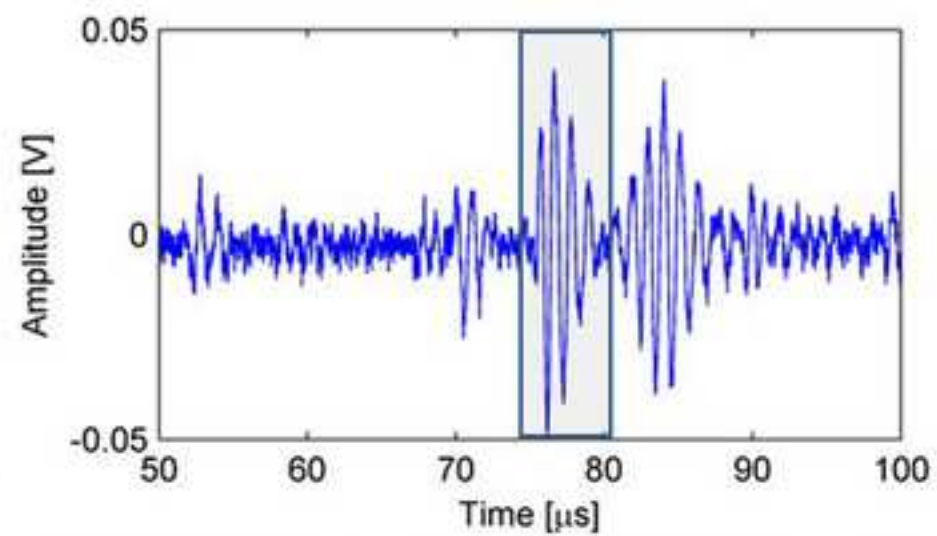


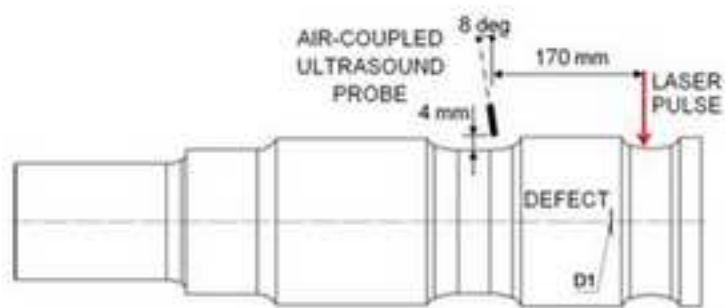
Fig. 14. Time histories
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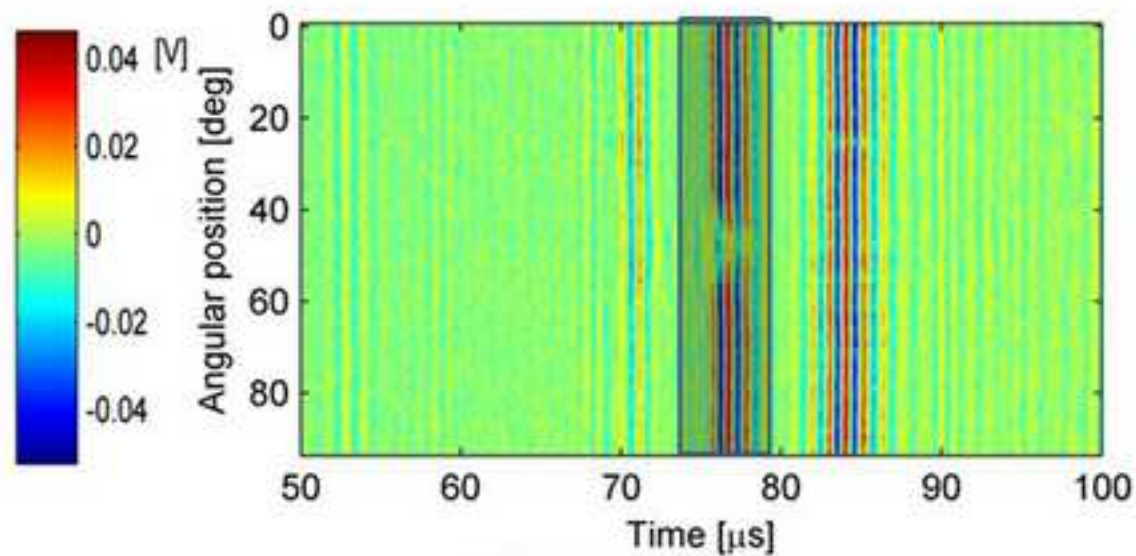
(a) Entire time history



(b) Time history close-up on the bulk waves



(c) Experimental set-up



(d) B-scan

Fig. 15. B-scan close-up around the Rayleigh wave.
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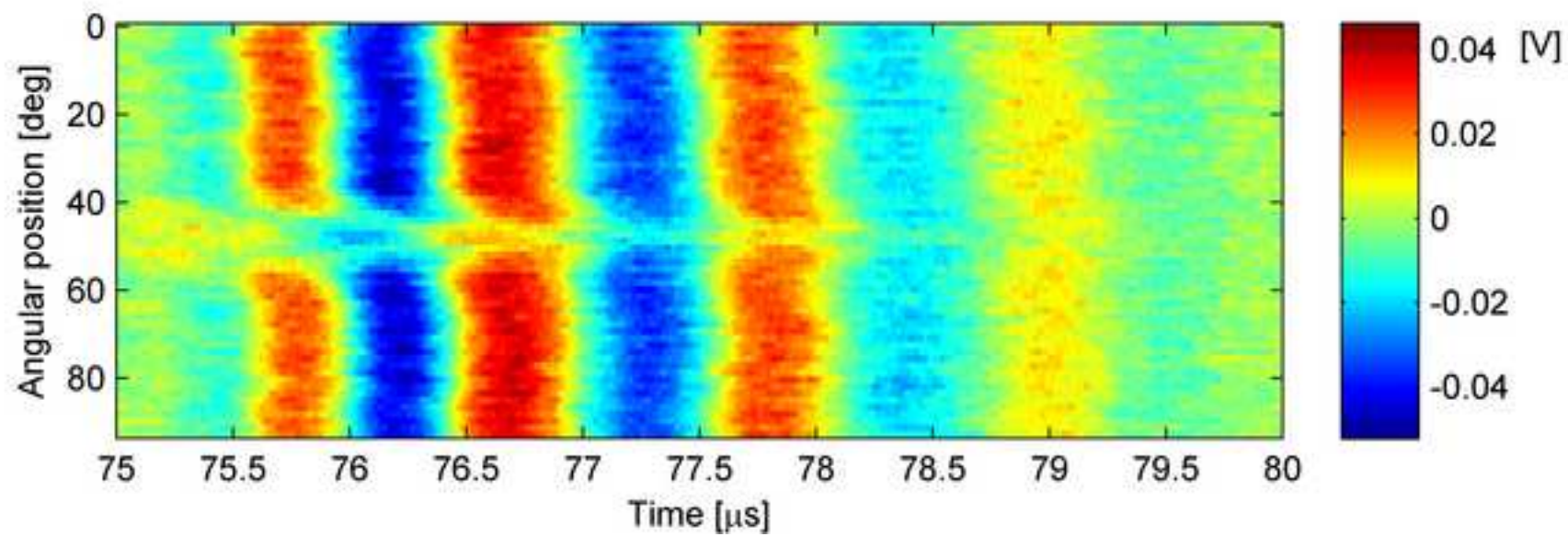
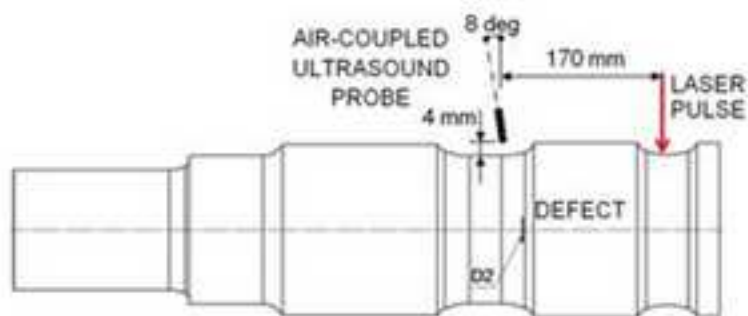
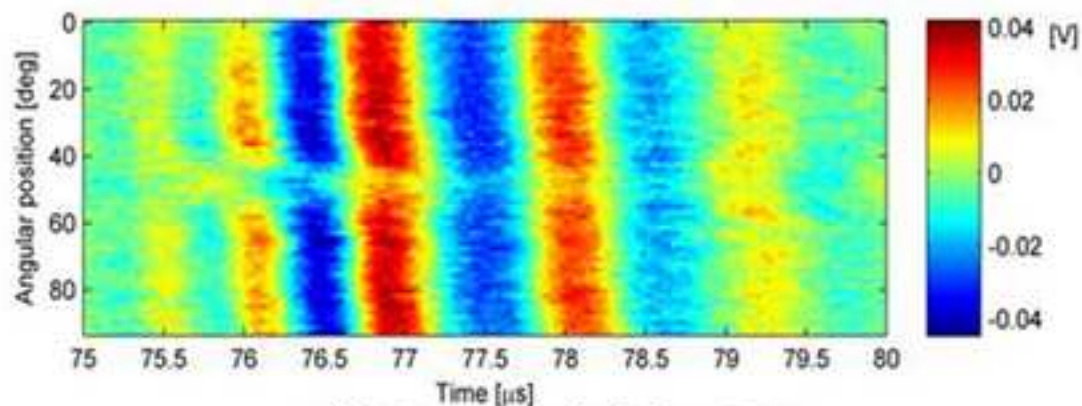


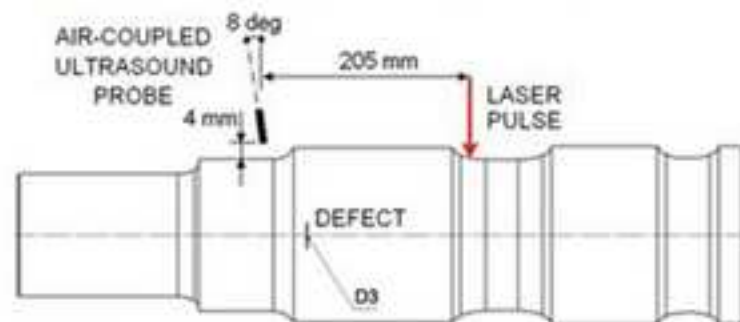
Fig. 16. Experimental set-up scheme
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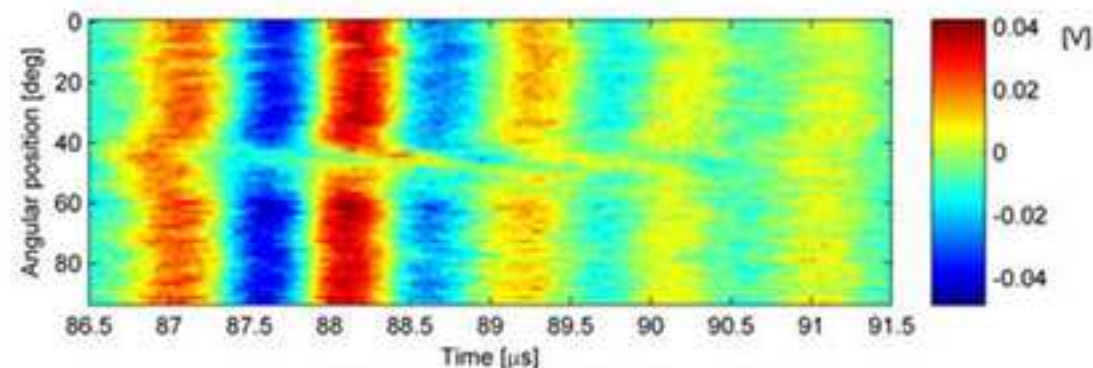
(a) Experimental set-up - defect D2



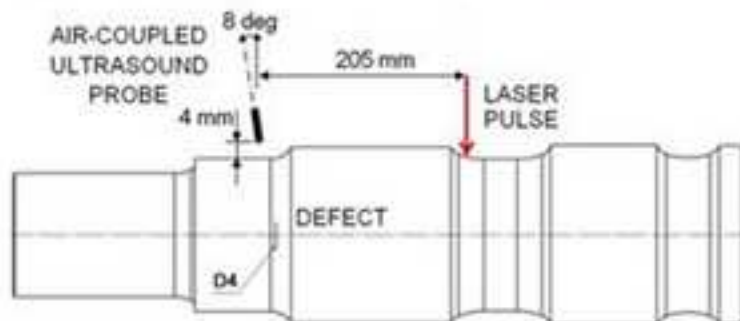
(b) B-scan of defect D2



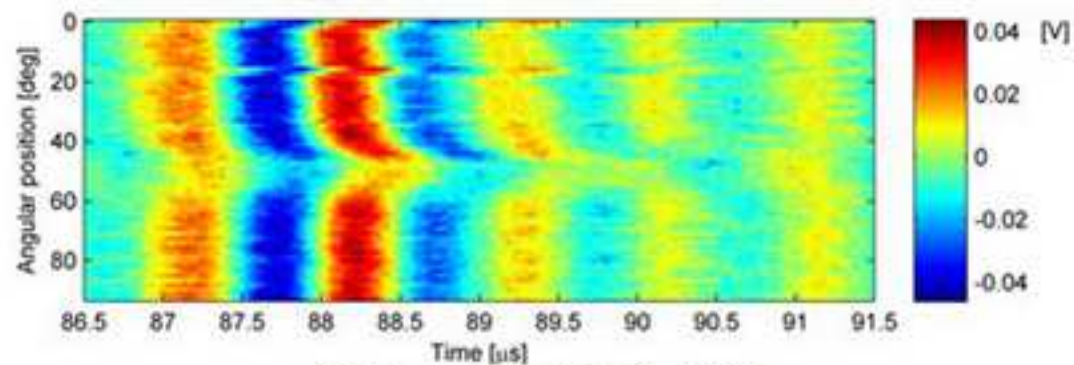
(c) Experimental set-up - defect D3



(d) B-scan of defect D3



(e) Experimental set-up - defect D4



(f) B-scan of defect D4

Table 1

Table 1 Steel mechanical/thermal/optical properties.

ρ	Density	7900 kg/m ³
E	Young Modulus (@ 273.15 K)	200 GPa
C	Specific heat capacity	480 J/(kg K)
k	Thermal conductivity	50 W/(m K)
α	Coefficient of thermal expansion	10.7 e ⁻⁵ K ⁻¹
R	Reflection coefficient	0.3
A_c	Absorption coefficient	3.87 e ⁹ m ⁻¹

Table 1 Defect morphology.

Defects	Size of defect		
	H (mm)	L (mm)	D Max depth (mm)
D1	31	1.1	1
D2	28	1.1	1
D3	28	1.1	1
D4	28	1.1	1

Highlights

- A laser-ultrasonics procedure for train axles ultrasonic inspection is reported.
- A FE model for the design of experiments based on laser-ultrasonics is described.
- A sensitivity analysis to the angular position and distance was performed.
- The experimental tests was able to identify the presence of defects.