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Original

FEM based design of experiment for train wheelset diagnostics by laser ultrasonics / Cavuto, A.; Martarelli, M.; Pandarese, G.; Revel, G. M.; Tomasini, E. P.. - In: ULTRASONICS. - ISSN 0041-624X. - 113:(2021). [10.1016/j.ultras.2021.106368]

Availability:

This version is available at: 11566/300466 since: 2024-12-29T16:59:54Z

Publisher:

Published

DOI:10.1016/j.ultras.2021.106368

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(Article begins on next page)

1 **FEM BASED DESIGN OF EXPERIMENT FOR**
2 **TRAIN WHEELSET DIAGNOSTICS BY LASER**
3 **ULTRASONICS**

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24 **Abstract.**

25 Laser-Ultrasonics Testing (LUT) is a Non-Destructive Technique (NDT) with good potential for
26 application in the railway sector, nevertheless this technique is not yet used in practice because there
27 are some practical difficulties to overcome. The possibility of measuring on a complete wheelset by
28 bypassing the keying of the wheel will allow drastically reducing the inspection time but it has not yet
29 been demonstrated. In fact, the attenuation of the signal in the path makes complex the interpretation
30 of the generated waves. This paper aims at illustrating how the combination of simulated and
31 experimental data allows to optimize the test setup for having output data of unambiguous
32 interpretation. The main innovations presented in this paper are: (i) the possibility to work with low
33 energy waves in the thermoelastic-ablative limit while maintaining satisfactory contrast levels for the
34 purpose of defect detection and (ii) the implementation of a complete Finite Element Model (FEM)
35 including the generation and propagation of waves in the solid domain and the propagation in air. This
36 last step has not considered before in previous papers. The model allows to define the optimal
37 experimental conditions to have a measured signal with an adequate signal-to-noise ratio ($SNR > 6$ dB)
38 and to define an experimental procedure for defect detection reliable and comparable with current
39 standards. This study lays the foundations for an innovative approach for train axle diagnostics which
40 can be used during train extraordinary maintenance interventions. The laser ultrasonics system
41 presented in this paper can be likely integrated in the pit lathe and exploited to monitor the railway
42 wheels during their re-profiling phase, without having to remove them from the vehicle.

43 **Keywords:** Laser-ultrasonics, NDT, air-coupled ultrasound, train wheelset, FE modelling

44

45 **1. Introduction**

46 The development of Non-Destructive Testing (NDT) procedures is a topic of great impact,
47 especially in the train sector, whose aim is the early identification of cracks whose propagation can
48 cause faults and accidents. Those procedures are commonly applied for the identification of damages

49 and defects on train wheelset during extraordinary maintenance. Defects can occur on the wheels
50 because they are exposed to high loads caused by wheel-rail contact, leading to the generation and
51 propagation of defects. Axles are constantly exposed to cyclic rotating bending superposed with
52 torsion, occurring during regular maneuvers like cornering of trains or deceleration and acceleration.
53 These mixed-mode loading conditions cause fatigue processes inducing crack nucleation and
54 propagation, as studied in [1]. Furthermore, axle bending and vibration induce common fatigue cracks
55 along geometrical transitions (like the axle fillet radii) and repetitive micro sliding between wheel and
56 axle itself on the press-fit seat also called fretting fatigue, as described in [2] and [3]. That mechanism
57 is one of the main sources of crack nucleation in the wheel-axle press-fit that is an inaccessible region
58 for inspection unless the wheelset is disassembled.

59 The procedures based on non-destructive tests are constantly evolving to meet the European
60 standards EN 15313, [4], and the directives of the National Agency for Safety of Railways (ANSF),
61 guiding the regulation on the safety of railway traffic.

62 The current standard methods for the detection of radial defects are based on ultrasound phased array.
63 An automated procedure for the inspection of hollow axles has been presented in [5]; a semi-automated
64 rotating probe mounting differently angled transducers has been described in [6] with its application
65 to solid axles. The exploitation of phased array techniques for wheel tread damage detection has been
66 illustrated in [7]. Automated systems equipped with phased arrays tailored for the specific application
67 are available in the market even though they are currently unattractive, given the high costs associated
68 to the acquisition of instrumentation and the adaptation of test benches to these systems. The main
69 disadvantages of phased arrays are the difficulty on the adaptation to different wheel profiles and the
70 complexity of the measurement set-up, e.g. of the system for the accumulation, injection and recovery
71 of the coupling mean, necessary in the application of contact probes.

72 Air-coupled ultrasound probes can solve the above-mentioned problems, but, while their application
73 as receiving transducers is feasible, the use of non-contact ultrasound exciters is almost prohibitive.

74 In fact, the high difference of impedance between air and solid will cause more than 99% of the incident
75 wave to be reflected into the air.

76 Laser-Ultrasonics Testing (LUT) systems instead are non-contact techniques, based on high power
77 laser sources exploited as ultrasonic waves exciters. Some LUT configurations [8], [9] make use of
78 laser interferometers as receiving probes to detect the elastic waves propagating into the solid material.
79 Notwithstanding, the application of laser interferometers is highly influenced by the surface condition
80 of the object under test. The measurement surface must be diffusive, but this is not the case with axles
81 under test during maintenance operations. Their surface is often dirty, i.e. covered with dust, oil or
82 grease and those substances absorb laser light. On the other way around, if the axle is clean the steel
83 surface is highly reflective and the setting of a correct laser angular position is crucial, especially for
84 curved surfaces, for having a good backscattering of the laser light into the receiving photodiode. For
85 that reason, the best compromise is to use a LUT configuration based on high power lasers for
86 ultrasound generation and air-coupled receiving probes, exhibiting flexibility in installation and
87 operation.

88 At present LUT methods have been only applied to disassembled wheelset, i.e. to dismantled axles,
89 like in [10] and [8], and wheels, as presented in [9], [11], [12]. This is due to the fact that the energy
90 of the ultrasound waves is strongly attenuated when travelling through discontinuities like the wheel-
91 axle press-fit region. Additionally, discontinuities produce scattering of ultrasound waves that
92 generates false positives or buries the scattering induced by real defects located in the axle fillet radii
93 regions in which there is the greatest probability of presence of defects caused by common fatigue.

94 In this paper, the authors have demonstrated the applicability of a LUT method for the detection of
95 cracks located in the geometric transition regions close to the wheel seats on a complete wheelset.
96 Experimental data have been presented by the same authors in [13]. In that work it has been evidenced
97 how it is difficult to measure in those prohibitive regions where the ultrasound waves propagation is
98 extremely complex. In this paper a method making use of the inputs derived from a numerical FE

99 model is presented. Specifically, the modeled ultrasound propagation on the tested object allowed to
100 identify the optimal working conditions to achieve an adequate contrast between sound and damaged
101 regions and make the procedure for fault detection reliable and comparable with current standards.

102 The FE model has been developed to simulate the mechanisms that governs the generation of elastic
103 waves in solids in both the thermo-elastic and ablative regimes, the interaction of the laser wave with
104 the material it impacts on, the propagation of ultrasound waves in the material and their interaction
105 with typical defects. This kind of models have been applied in the railway sector and in particular for
106 the simulation of ultrasound waves propagation in axles, as presented in [10], in wheels [12] and
107 wheelset sections [14]. The latter is the most complete model because it considers the whole wheelset,
108 but it is limited to the simulation of the elastic waves' propagation within the solid material. It is
109 therefore very useful for the simulation of ultrasound waves received by contact probes but no
110 enforceable for air-coupled ultrasonic inspections. In this paper, the FE model has been exploited to
111 replicate a non-contact laser-ultrasonics experiment, where the receiving probe is air-coupled and
112 therefore the propagation of the elastic waves in the air domain between the axle surface and the
113 receiving probe has been considered in the simulation. This is one of the main innovations of the paper,
114 since the numerical models presented in the state of the art considered only the generation and
115 propagation of waves in the solid domain and neglected the propagation in air.

116 Finally, the FE model developed has been exploited as a Design of Experiment instrument that
117 allows to identify the optimal experimental parameters. This made it possible to limit the ultrasound
118 wave energy in the thermoelastic-ablative limit while maintaining satisfactory contrast levels for the purpose of
119 defect detection and making the procedure for the detection of defects reliable and comparable with
120 current standards.

121 **2. Laser-Ultrasonics test numerical simulation**

122 To evaluate the efficiency of the air-coupled laser-ultrasonics technique in terms of its ability to
123 detect defects in the wheelset, a numerical model for the design of experiment (DOE) was developed
124 in order to:

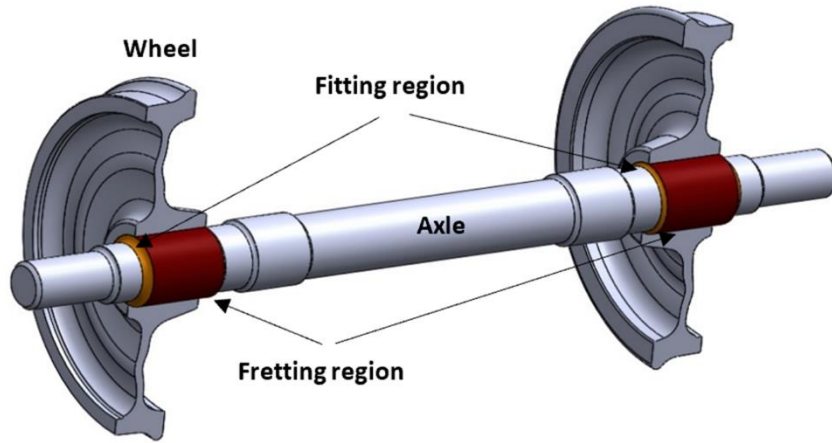
- 125 - identify the optimal position of the air coupled transducer in terms of its angular orientation
126 along the lateral surface of the train axle;
- 127 - determine the elastic wave propagation within the axle material and in the air between the axle
128 surface and the receiving probe in order to recognize which type of propagation mode (longitudinal,
129 shear, surface) is more sensitive to the presence of a defect;
- 130 - define the time window to analyze within the time history acquired depending on the
131 propagation mode to be selected, in relation to the previous point.

132 The model must simulate a typical LUT experiment applied to a wheelset, see Fig. 1(a), with the
133 ultrasonic excitation and receiving probe located at different sides of the wheel and working in
134 transmission mode. This configuration has several advantages with respect to a standard configuration
135 where the exciter and receiver are side-by-side at the same side of the wheel and work in reflection
136 mode. First, the configuration in transmission mode is a sort of blind experiment that works with any
137 defect position regardless its location in the propagation path. In addition, when working in reflection
138 mode, the waves reflected by the section variation could be greater than the wave reflected by the
139 defect, making them difficult to be sensitive to the defect occurrence. By working in transmission
140 mode, the reflected waves will be systematically excluded. Finally, the laser impact on the surface in
141 the presence of oil or grease will generate a detonation of dirt particles that can damage the ultrasound
142 transducer, when positioned next to the exciter. Additionally, the laser impact onto the solid material
143 will induce a strong reflection into the surrounding air, which causes a saturation of the receiving
144 piezoelectric transducer thus degrading the received ultrasonic signal. The numerical model will be
145 exploited to simulate the propagation of the ultrasonic waves generated by a high-power laser source

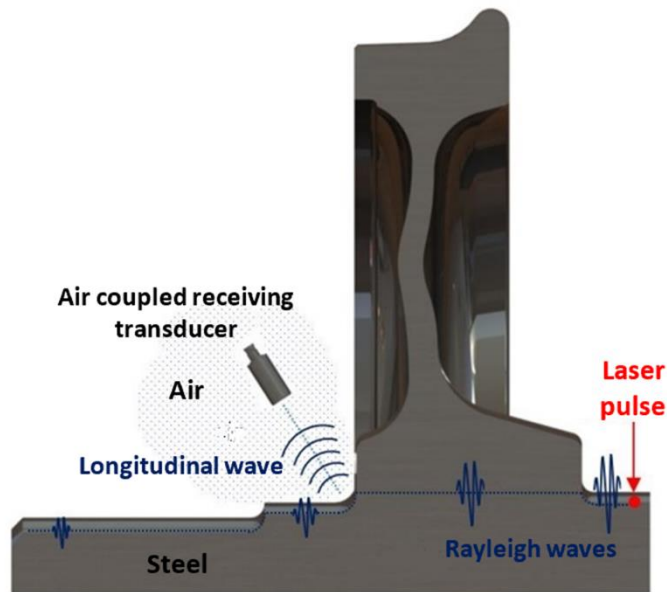
146 and travelling within the axle material, passing through the axle-wheel interface and propagating
147 through the air before reaching the receiving probe. The propagation path is illustrated in Fig. 1(b).
148 The Rayleigh wave undergoes a strong attenuation along the path that goes from the laser source to
149 the non-contact receiving probe. In fact, part of the attenuation occurs when the Rayleigh wave passes
150 through the various filling regions and the wheel fitting seat on the axle, the so-called fretting region
151 (see Fig. 1(a)).

152 The wheel is fitted on the axle with a force fit that has negative allowance [15]; the wheel hub being
153 smaller than the axle means that the contact pressure ensures the transfer of the load between the two.
154 As described in [14], it can be expected that a fraction of the Rayleigh wave will be converted from
155 surface to bulk modes, but a fraction of it will propagate along the interface between the axle and the
156 wheel. In the propagation path, the Rayleigh wave will experience, then, a strong attenuation that will
157 be increased when the propagation passes from solid to air to reach the non-contact receiving probe.
158 In fact, in the solid-air transition zone, the propagation of the Rayleigh wave leads to the generation of
159 longitudinal bulk waves (see Fig. 1(b)) in the air whose energy contents are very low due to the high
160 difference in acoustic impedance between the two media (steel and air).

161 For this reason, the development of a validated FE model able to simulate the propagation of high-
162 frequency ultrasonic waves both in the wheelset section and air domain makes it possible to have an
163 effective tool to guide the design of the experimental procedure based on non-contact LUT aiming at
164 maximizing the SNR of the output signal from the non-contact receiving transducer while minimising
165 the laser pulse energy below the threshold of surface damage.



(a)



(b)

Fig. 1. Wheelset geometry (a) and visualisation of the propagation of the elastic waves (b).

166
167

168 2.1. Numerical FE model

169 COMSOL Multiphysics software was used to carry out the numerical simulation. The FE model
170 developed was validated both on a simplified test item [16] and on a portion of a train axle [10].

171 Two physics, thermal stress and acoustic-structure interaction were exploited to simulate the
172 generation and propagation of elastic waves both in the wheelset section and the air gap between the
173 axle surface and the receiving probe.

174 The generation of the elastic waves in the laser incident location was modelled following the
175 thermal diffusion and thermo-elastic displacement equations [17]:

176 The absorption of the laser pulse on the surface of the axle was assumed to occur without phase
177 change, considering a thermo-elastic model with a heat flux of 16.9 MW/cm^2 that is lower than the
178 limit between the thermo-elastic and the ablative regimes of generation [18].

179 The steel physical parameters used in the equations implemented in the numerical model are
180 presented in the Table 1.

181 Table 1 Physical parameters of steel used in the model.

ρ	Density	7900 kg/m ³
E	Young Modulus (@ 273.15 K)	200 GPa
C	Specific heat capacity	480 J/(kg K)
ν	Poisson's ratio	0.291
k	Thermal conductivity	50 W/(m K)
α	Coefficient of thermal expansion	10.7 e-6 K-1
R	Reflection coefficient	0.3
Ac	Absorption coefficient	3.87 e9 m-1

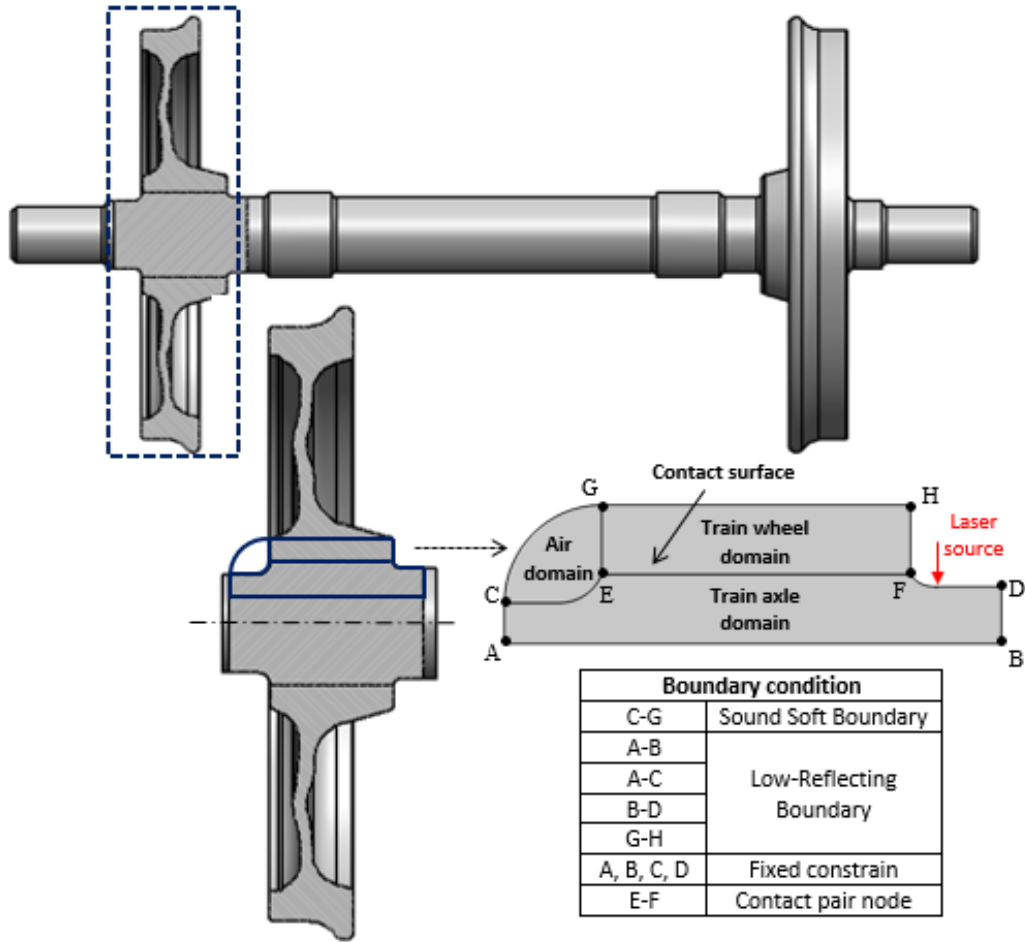
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183 The propagation of the elastic wave within the wheelset was modelled with the wave equation obtained
184 from Newton's second law while the propagation in the air domain was modelled with the wave
185 equation identifying the pressure distribution [19].

186 The boundary condition between the train axle and the wheel domains was set as contact condition to
187 model the fittings between wheel and axle. The contact has been simulated by using contact pair nodes.
188 The augmented Lagrangian algorithm was applied to compute the contact in the normal direction. The
189 contact in the tangential direction has been simulated by using the classical Coulomb approach
190 considering a static frictional coefficient μ_{stat} with a value of 0.6 [15]. Automatic contact controls were
191 adopted to improve the convergence. For a reliable simulation of surface wave propagation, the wheel
192 was considered to be mounted on the axle with suitable contact pressures in accordance with UIC 813
193 and the EN 13260 standards.

194 Fig. 2 shows the modelled geometry and domains in relation to the real wheelset; the boundary
195 conditions are also reported. The boundaries corresponding to the model truncation have been set as

196 low-reflecting boundary and sound soft boundary in the case of solid and air domain, respectively, to
 197 avoid reflections.



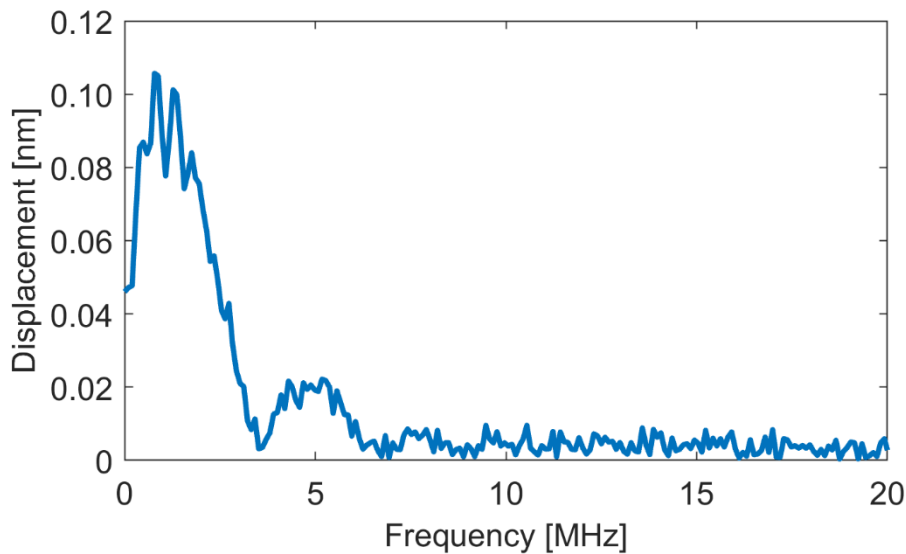
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 199 Fig. 2. 2D numerical model of the axle and wheel.

200 Key parameters for the convergence of the numerical algorithm and for the simulation accuracy are
 201 the time and spatial resolution. Concerning the time resolution or integration time step it has been
 202 established in [19] that it can be calculated using the following expression:

$$\Delta t = \frac{1}{180f_{max}} \quad (1)$$

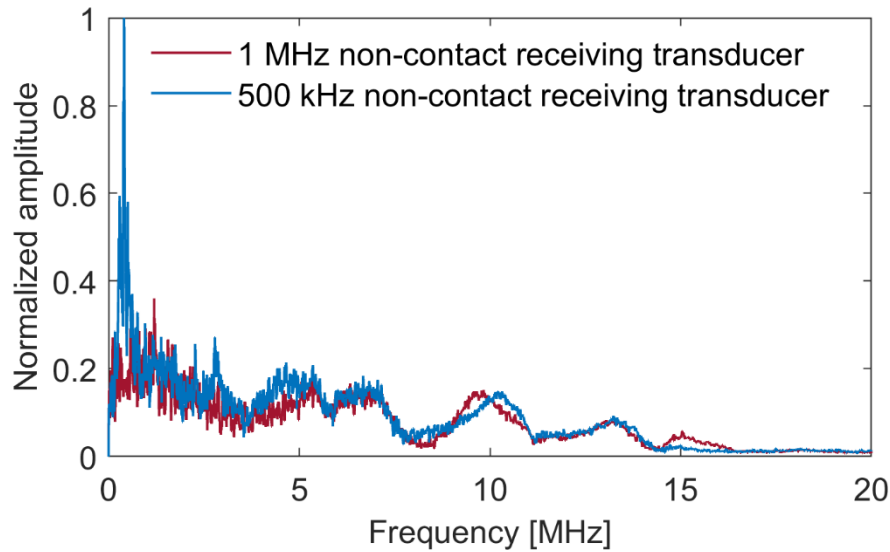
203
 204 where f_{max} is the highest frequency of interest, 500 kHz in our case. The selection of f_{max} is related
 205 to the frequency content of ultrasonic wave generated by the laser and propagating into the solid
 206 material and in the air and to the sensitivity of air coupled ultrasonic probes. In order to determine the
 207 frequency content of the ultrasonic wave in the proximity of the generation area, a measurement of the

208 axle surface displacement has been performed by means of a laser Doppler interferometer (Polytec
209 OFV5000- DD300) with a frequency bandwidth of 20 MHz. The measurement position was set in an
210 undamaged region at a distance of 37 mm from the laser source, which is the minimum distance to
211 avoid interference of the laser source to the receiving one [20]. The frequency spectrum of the surface
212 displacement is shown in Fig. 3 and it evidences that the ultrasound wave frequency content is limited
213 below 2 MHz.



214 Fig. 3. Frequency spectrum of the axle surface displacement related to the ultrasound wave propagation into the material.
215

216 The second driver for the selection of the operating frequency of the ultrasound probe employed is
217 its sensitivity, which is inversely proportional to the frequency for air-coupled transducers [21]. As an
218 example, for Ultran Group 500 kHz (NCG500-D19) and 1 MHz (NCT1-D13) probes the sensitivity is
219 -50 dB and -56 dB respectively. Since the scope of this work is to demonstrate the applicability of the
220 measurement technique at large distances from the laser source, where the SNR is extremely limited,
221 a probe with 500 kHz operating frequency was selected. To demonstrate that the 1 MHz probe has
222 lower sensitivity with respect to the 500 kHz one, the frequency spectra of the signals acquired with
223 the two probes beyond the wheel on the same position on the axle in an undamaged region are reported
224 in Fig. 4.



225

226 Fig. 4. Frequency spectra of the ultrasonic wave acquired by air-coupled ultrasound probes: Ultran Group NCG500-D19,
 227 500 kHz probe and NCT1-D13, 1 MHz probe.

228 The time resolution was also related to laser pulse duration which was of the order of nanoseconds
 229 (≈ 12 ns), because the time step must be suitable to accurately sample the laser pulse time history.

230 The simulations were therefore carried out with an integration time step of 3 ns. Concerning the
 231 spatial resolution, it depends to the FE mesh and specifically on the size of the finite elements. The
 232 model illustrated in Fig. 2 has been discretized with a triangular mesh and the element size has been
 233 set to 1/10 of the shortest wavelength to be analysed, according to [22] and [23], where it is
 234 recommended to have at least 10 nodes per wavelength. The mesh was refined in the proximity of the
 235 solid/air transition regions and in correspondence with the heat source generated by the laser pulse.

236 An implicit analysis with a generalised- α (alpha) time dependent-solver was implemented.

237 *2.2. The tested wheelset*

238 The 2D numerical model, described in Section 2.2, was developed to drive the testing of the
 239 experimental LUT on the train wheelset provided by Trenitalia (see Fig. 5) in whose axle two standard
 240 fatigue cracks, [4], were simulated:

- 241 - Defect A located on the axle surface at 16 mm from the fretting region between the axle and the
 242 wheel,
- 243 - Defect B located on the fitting region.

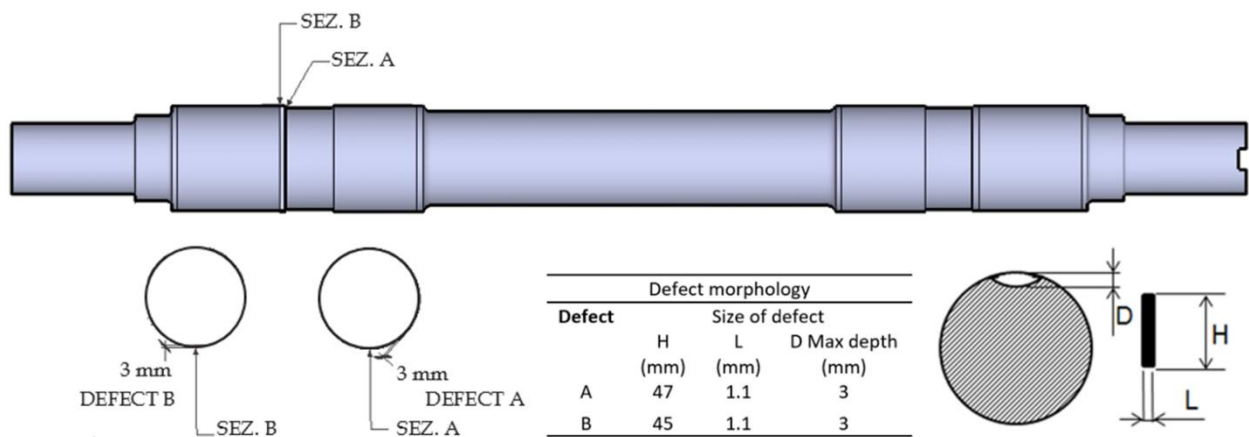
244 Defects geometrical characteristics are reported in Fig. 6. Those defects were simulated in the 2D
 245 numerical model in order to determine their effect on the ultrasound signal received by the LUT air-
 246 coupled probe.



247

248

Fig. 5. Trenitalia train wheelset - zoom of the defected area (a) and wheelset (b).



249

250

Fig. 6. Defects simulated in the wheelset.

251 3. Numerical results

252 The propagation of the elastic waves within the undamaged 2D wheelset section and in the air
 253 domain at different time intervals is shown in Fig. 7. The red dashed arrow indicates the laser source
 254 position, from which the elastic waves are generated. Observing the propagation pattern at 15 μ s (Fig.
 255 7 (b)), the different modes of propagation can be evidenced:

- 256 - the longitudinal (L) and shear (S) waves that propagate towards the inside of the train axle,

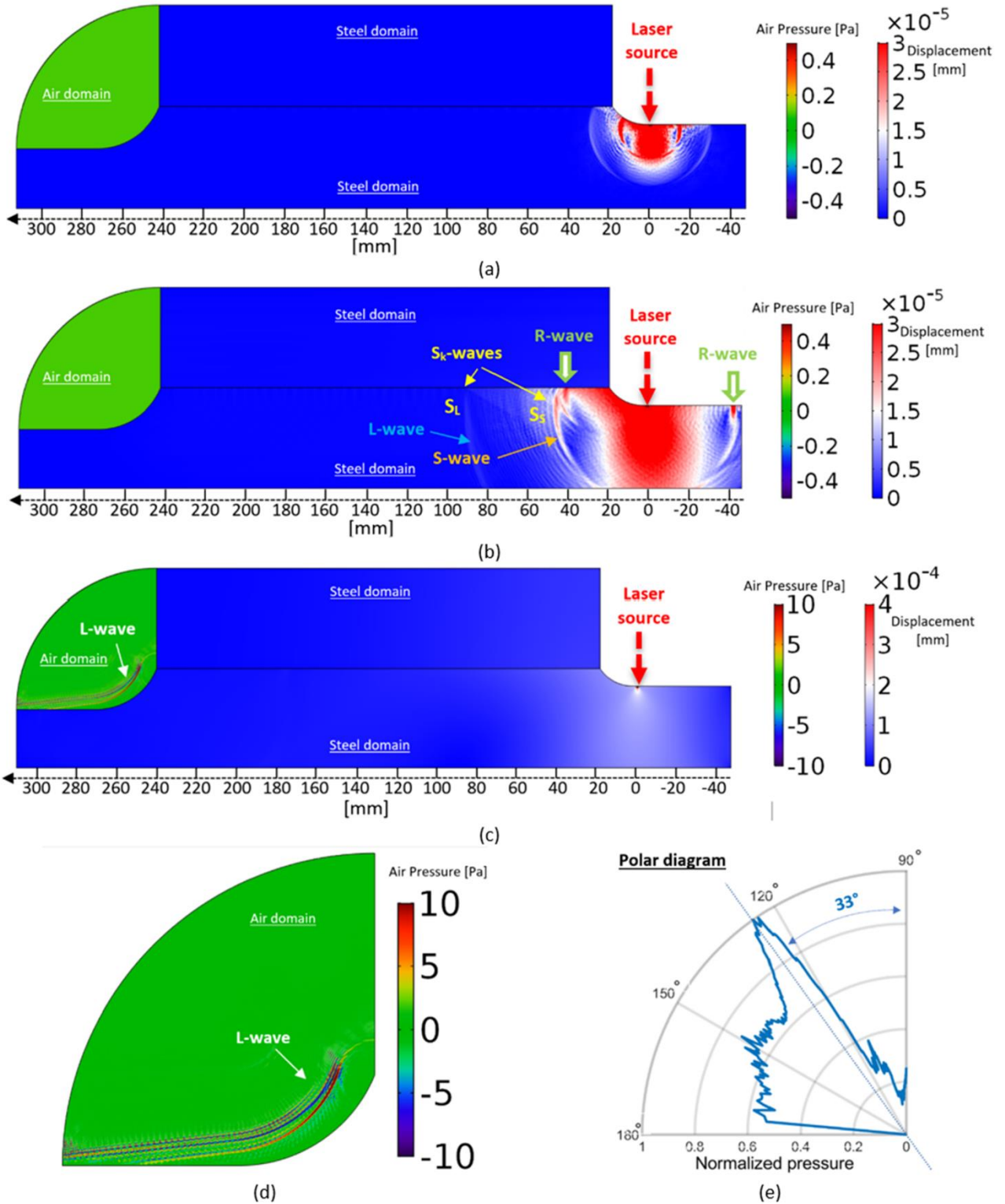
257 - the superficial waves, that can be distinguished into Rayleigh waves (R) and surface skimming
258 bulk waves (S_k) (longitudinal S_L – shear S_S). The S_L and S_S waves mark the intersection with
259 the surface of the longitudinal and shear wave fronts, respectively, which originate from the
260 bulk source [17].

261 The bulk and Rayleigh waves can be distinguished by considering their propagation velocity in the
262 solid material (i.e. steel) which are 5650m/s (for the S_L wave), 3100m/s (for the S_S wave) and 2905m/s
263 (for the R wave), [19]. Those values are in good agreement with the measured ones in the axle material
264 as reported in [10]. At the time instant of 15 μ s the S_L wave front will be at 85 mm from the laser
265 source, the S_S one at 47 mm and the R one at 44 mm. Those data allow to position the different waves
266 in the plot of Fig. 7(b). In order to better evidence the propagation direction of the different modes Fig.
267 8 reports arrow plots filtered at the spatial position of the R, S_S and S_L waves.

268 The directivity pattern of the longitudinal wave that propagate in the air domain originated from the
269 elastic waves travelling along the wheelset section can be plotted in polar coordinates, as in Fig. 7(e).
270 This plot is useful to identify the optimal orientation of the receiver probe in order to catch the
271 maximum level of the signal. The plot indicates that the maximum efficiency in the propagation will
272 occur at an angle of 33 deg with respect to the axle surface normal.

273 Fig. 9 and Fig. 10 reports the same propagation pattern and directivity plot but for the case of damaged
274 axle and specifically with the defect A and B respectively. It is noticeable that when the Rayleigh wave
275 encounters the defect it is reflected: the reflected wave is marked as R_R in Fig. 9(b) and Fig. 10(b). The
276 directivity plots evidences that it occurs an attenuation of about 80% for the defect A and 70% for the
277 defect B of the propagating waves associated to the defect presence either in the solid either in the air
278 domain.

279

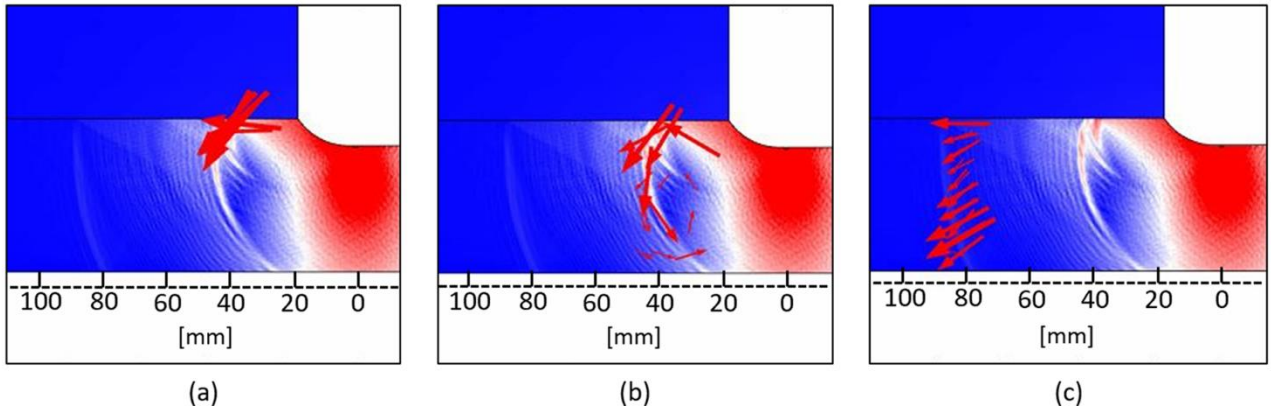


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281 Fig. 7. Propagation of the elastic waves in the undamaged 2D wheelset section at different time instants: 5 μ s (a), 15 μ s (b),
 282 110 μ s (c); propagation of the elastic waves in the air domain (d); directivity plot in the air domain (e).

283

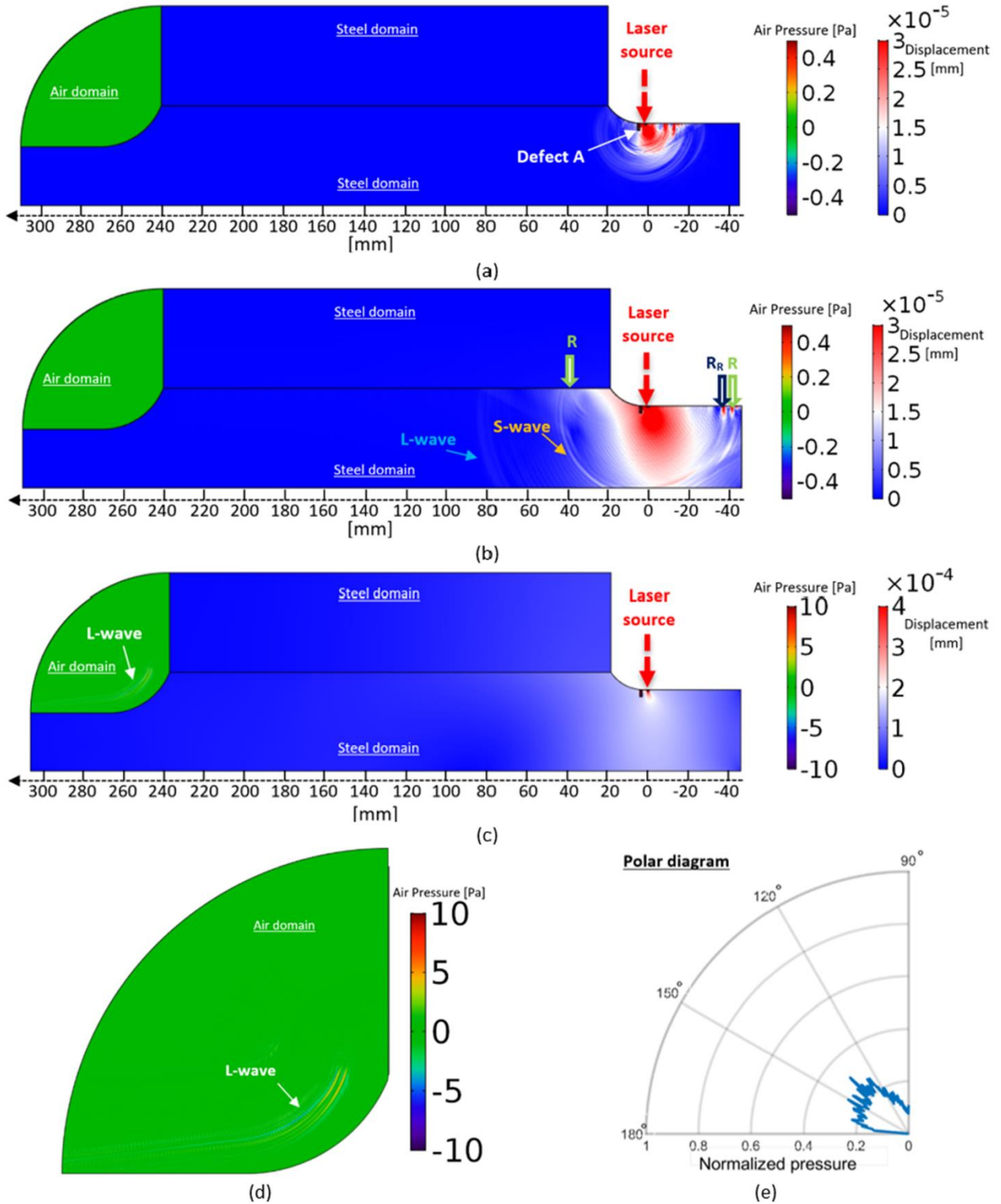
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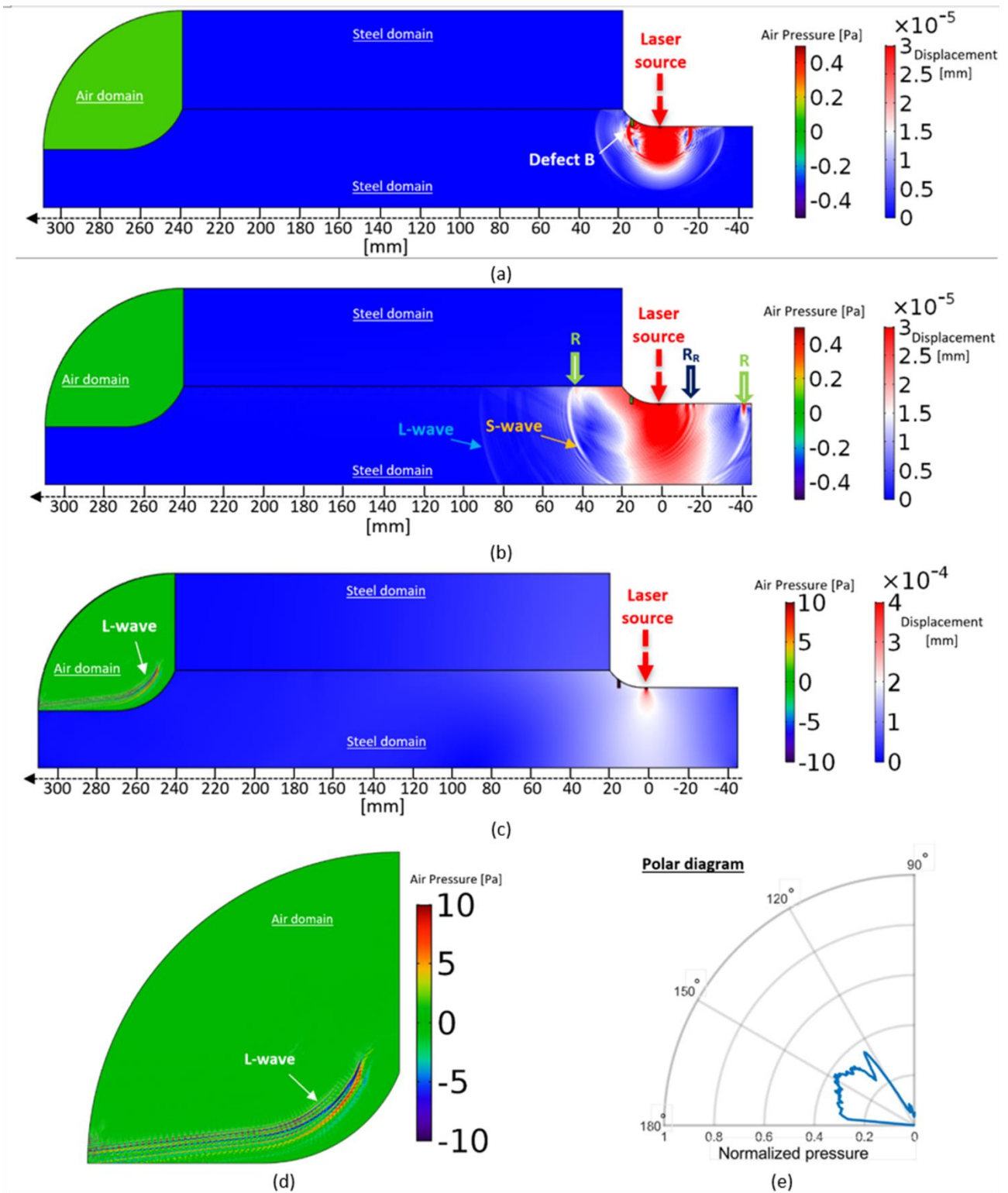
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Fig. 8. Propagation direction of the elastic waves R (a), SS (b), SL (c) at the time instant of 15 μ s.



287

288 Fig. 9. Propagation of the elastic waves in the 2D wheelset section with defect A at different time instants: $5 \mu\text{s}$ (a), $15 \mu\text{s}$
 289 (b), $110 \mu\text{s}$ (c); propagation of the elastic waves in the air domain (d); directivity plot in the air domain (e).



290

291 Fig. 10. Propagation of the elastic waves in the 2D wheelset section with the defect B at different time instants: $5 \mu\text{s}$ (a),
 292 $15 \mu\text{s}$ (b), $110 \mu\text{s}$ (c); propagation of the elastic waves in the air domain (d), directivity plot in the air domain (e).

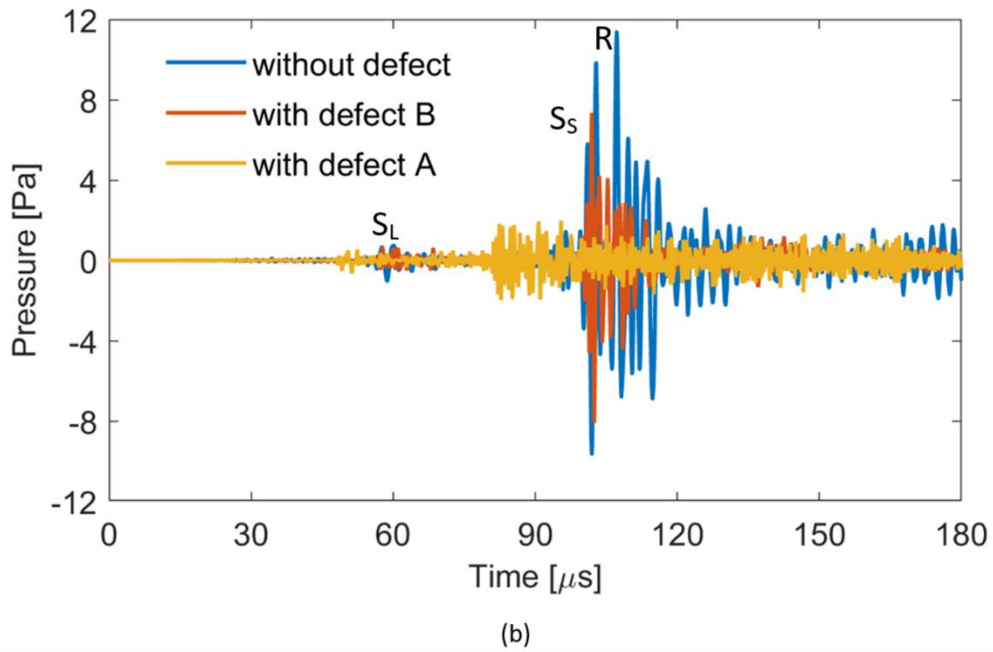
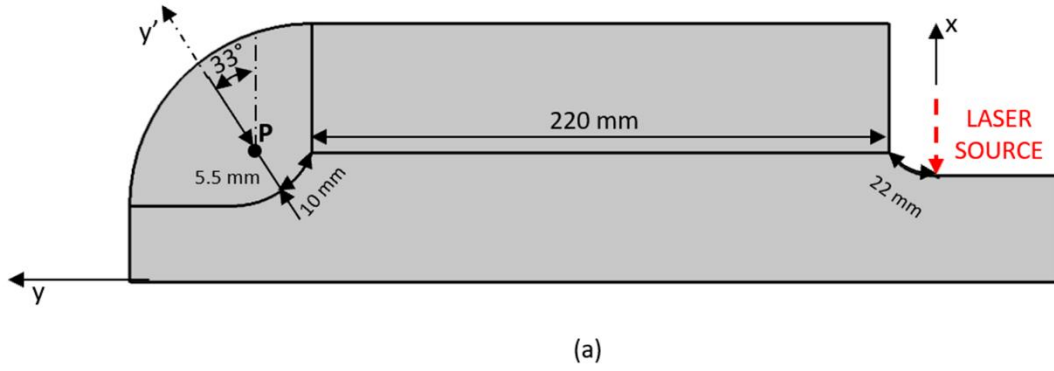
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294 The 2D numerical model in the Fig. 11(a), allows to analyse the ultrasound signals (Fig. 11(b)) that
 295 will be acquired during the experimental tests by a non-contact receiving transducer placed on the

296 opposite side of the press fitting area (point P in Fig. 11(a)) with respect to the pulsed laser impinging
297 point (red dashed arrow in Fig. 11(a)).

298 The distance between the laser impinging position and the detection one was set to 257.5 mm that
299 corresponds to a distance of about 252 mm along the axle profile and 5.5 mm in the air along the y'
300 axis which corresponds to the direction of maximum efficiency. 5.5 mm is the minimum distance in
301 air required considering the encumbrance of the receiving probe (active diameter of 19 mm, probe
302 diameter of 33 mm and inclination of 33 deg) used in the experimental tests.

303 The three waveforms calculated at point P in Fig. 11b were obtained by running the model with and
304 without defects and the waveforms were filtered in the frequency range of the ultrasound probe used
305 in the experiments ($500 \text{ kHz} \pm 100 \text{ kHz}$), to evidence only the frequency content that will be measured
306 in the actual test. The waveforms have been plotted with normalized amplitude. By observing the
307 waveforms, it is clear that the bulk elastic waves (L and S) do not propagate up to the probe position.
308 Their efficiency in the air domain is weak and therefore they are not sensed by the probe [18]. Only
309 the surface waves (R, and SL, SS) propagates through the air domain and are visible in the time
310 histories of Fig. 11(b). Their occurrence in time has been identified by knowing their propagation
311 velocity as explained in the description of Fig. 7.



312

313 Fig. 11. Position of the probe where the pressure waveform signals have been exported, point P (a) and plot of those
 314 pressure waves in the case of undamaged axle and axle presenting a defect type A or a defect type B (b).

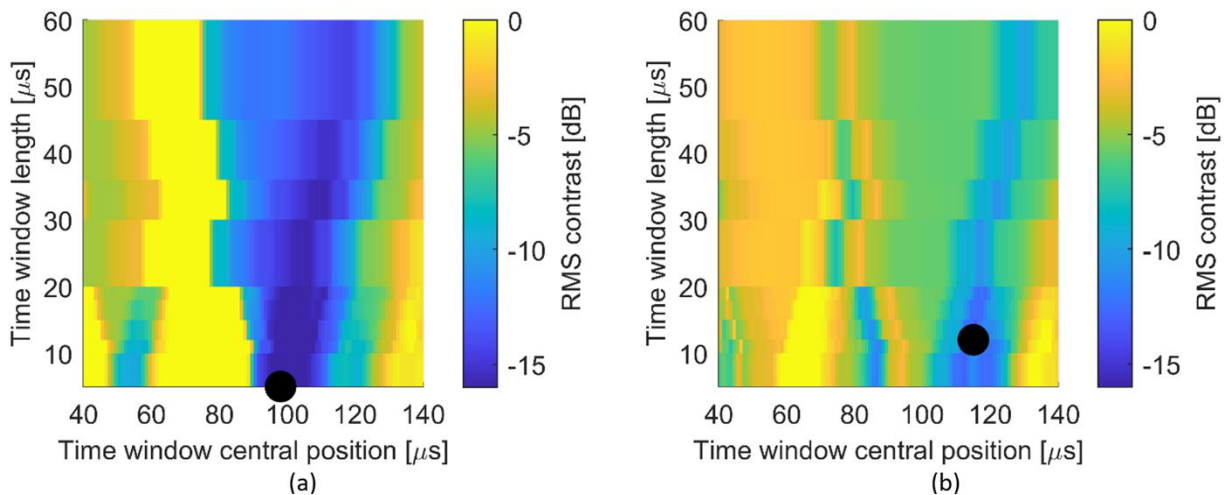
315 The time histories plotted in Fig. 11(b) are coherent with that deduced from the directivity plots, i.e.
 316 the presence of the defect strongly attenuates the elastic waves propagation.

317 In order to identify the presence of the defect from the time histories acquired, a damage indicator has
 318 been assumed and specifically the RMS (Root Mean Square) contrast defined as the ratio between the
 319 RMS calculated from the time history measured on a damaged area and the one measured on a sound
 320 region:

321

$$RMS_{contrast} = 20 \log \frac{RMS_{damaged\ area}}{RMS_{undamaged\ area}} \quad (2)$$

322 By observing the time histories, it can be evidenced that the defect A attenuates all the surface waves,
 323 both the skimmed and the Rayleigh, while the defect B attenuates only the Rayleigh wave. With the
 324 aim to identify the defect type it is possible to select the time window within the signal to consider
 325 only the portion which is effectively sensitive to the presence of the defect. For instance, for the defect
 326 A, the time window can be centred around the time of arrival of both the SS and Rayleigh wave, while
 327 for the defect B, it must be centered only around the time of arrival of the wave R. To evaluate the
 328 centre of the window and its length, the RMS contrast has been calculated by analysing the time history
 329 with sliding windows centred at time steps from 40 μs to 140 μs with an increment of 1 μs and length
 330 from 5 to 60 μs . The plot of the RMS contrast for the different time windows is reported in Fig. 12 for
 331 both defect A and B. In these plots, it is evidenced the position of the RMS contrast minimum (black
 332 dot) which indicates that for the defect A the time window containing the most sensitive signal to the
 333 presence of the defect is centred at 98 μs and has a length of 5 μs . For the defect B the time window is
 334 centred at 115 μs and has a length of 12 μs . Those data will be used to analyse the time histories
 335 acquired in the experimental campaign.



336

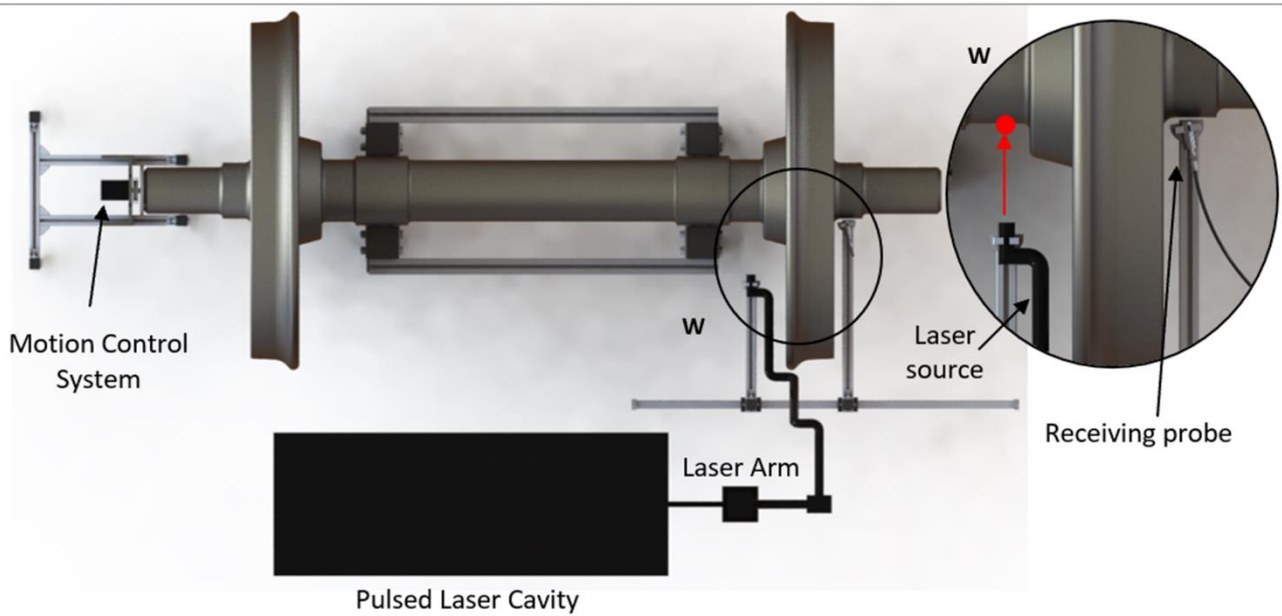
337 Fig. 12. Surface wave sensitivity analysis in the presence of defects A (a) and B (b); RMS contrast at several time
 338 windows.

339 4. Experimental set-up

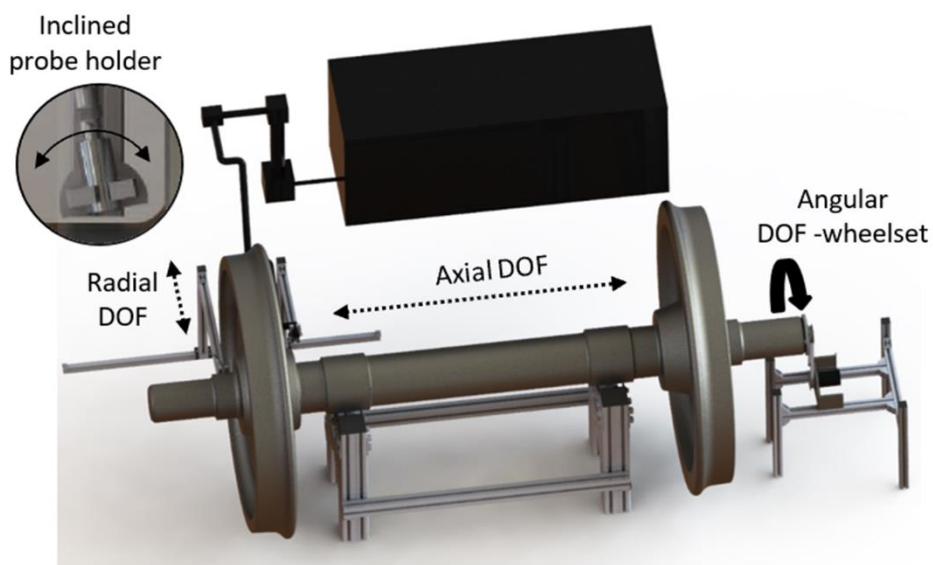
340 The wheelset was mounted on a support that made it possible to control its rotation, so as to be able to
 341 scan the axle surface along a circumference. The probes were installed on a frame where they could

342 move along the tangential direction. Therefore, the complete tangential surface of the axle could be
343 inspected by the laser-ultrasonic system, see Fig. 13.

344 The laser-ultrasonic system was made up of a pulsed laser source and an air-coupled ultrasound
345 piezoelectric probe. The laser source was a Nd:YAG IR laser (1064 nm) with 82 mJ energy able to
346 generate laser pulses of 12 ns duration. The laser wavelength was chosen as a compromise between
347 the energy, the pulse duration [25] and the penetration depth [18]. The ultrasound probe was an Ultran
348 Group NCG 500 with 19 mm diameter of active area and 500 kHz of operating frequency. The probe
349 orientation was set according to the FE model results (see Fig. 11), i.e. it was inclined with respect to
350 the normal to the axle surface of 33 deg. The ultrasound probe conditioning system was a JSR
351 Ultrasonics DPR 300 Pulser/Receiver. The ultrasound signals were amplified with a gain level of 69
352 dB and acquired with a high-speed digitizer board NI PXI-5122 (100 MHz bandwidth). The laser beam
353 was guided towards the axle under test by means of an arm connected to the pulsed laser cavity as
354 shown in Fig. 13.



(a)



(b)

355

356 Fig. 13. Configuration of the laser-ultrasonic scanning system-test bench setup (a) and the DOF scanning system (b).

357 The close-up reported in Fig. 13 and named section W shows the laser source and the receiving probe

358 installed on opposite sides of the wheel. This configuration allowed to detect defects occurring between

359 the source and the receiving probe even if they were located in the shrinking region. A collimated laser

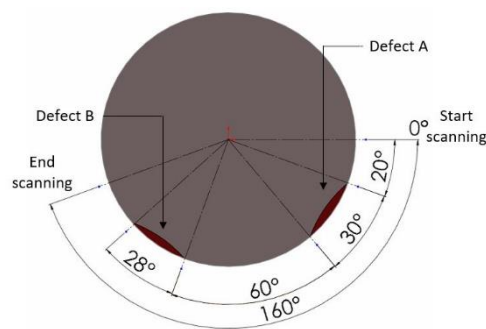
360 beam with a diameter of 6 mm was used to keep the generation of ultrasonic waves within a thermo-

361 elastic regime [24]. The probe was handled by a positioning system that allowed to move the probe in

362 radial and axial direction with respect to the axle, as shown in Fig. 10 by the radial and axial DOF

363 (Degree Of Freedom). The angular DOF was controlled by an electric motor that let the axle to rotate
364 about its axis. The rotation angle was measured by an integrated encoder. The angular position of the
365 defects A and B with respect to the laser source/receiving probe is illustrated in Fig. 14. At reference
366 position (0 degree rotation of the axle), defect A is located between angle 20 deg and angle 50 deg
367 while defect B is located between angle 110 deg and 138 deg. The angular position considered in Fig.
368 16 refers to the configuration reported in Fig. 14. The axle sector considered in the discussion of results
369 is of 160 deg as sketched in Fig. 14.

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375 Fig. 14. Angular position of the defect A and B with respect to the reference angle of 0 deg.

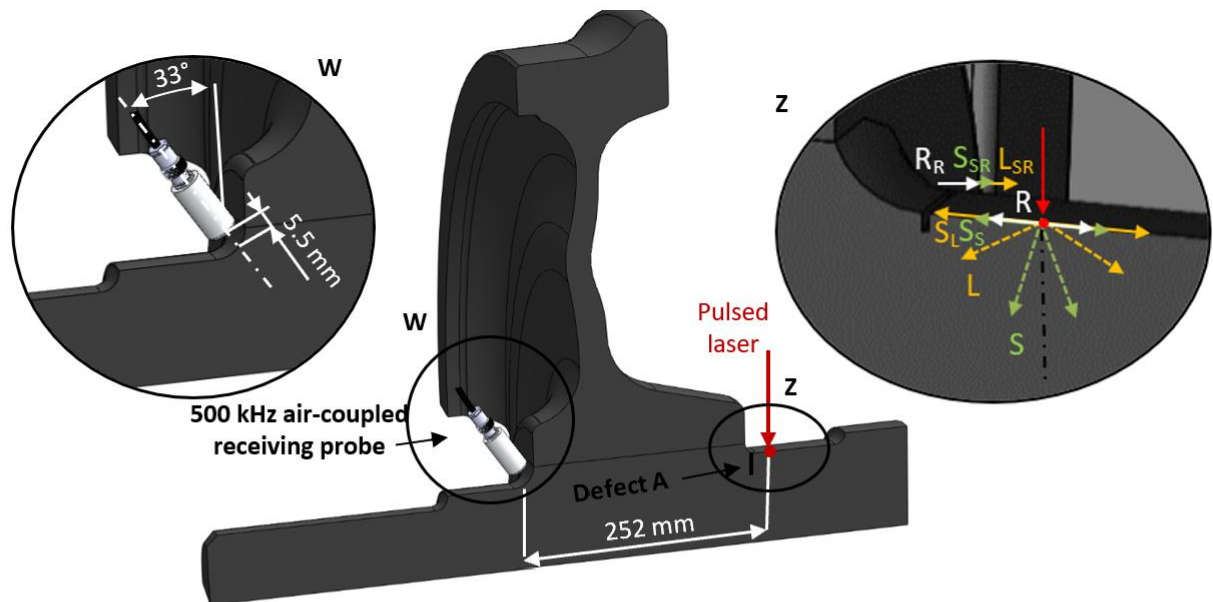
376 5. Experimental results and correlation with numerical data

377 The experimental set-up (i.e. laser and probe positions), the axle section tested and the defect location
378 are shown in the subplot (a) of Fig. 15 and Fig. 16 for defect A and B respectively. The angular position
379 of the receiving probe and its distance from the axle is described in section W. The laser source and
380 the generation path of the ultrasound waves produced by the impact of the laser pulse onto the axle
381 surface are sketched in section Z.

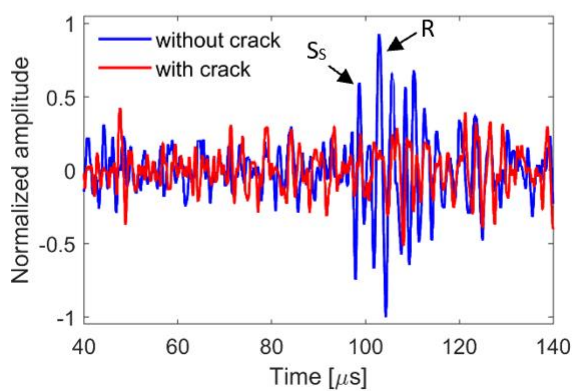
382 For each configuration, a series of ultrasound time histories with a duration of 100 μs starting from 40
383 μs with respect to the trigger associated to the laser pulse were acquired at every scanning position
384 along the arc considered. A comparison between the time histories measured and simulated at two
385 angular positions located within and outside the damaged region is reported in Fig. 15 (b) and Fig. 15
386 (c), respectively, for the defect A, and in Fig. 16(b) and Fig. 16(c), for the defect B. Obviously, also
387 in the experimental case, the attenuation due to the presence of the defect is evident as it arose for the
388 numerical data. That attenuation is clear also from the conventional B-scan plots reported in Fig. 17(a)

389 and (b) for the two defects. It should be pointed out, that if the defect is sub superficial or located on
 390 the back of the sample, bulk waves will be sensitive to the presence of the defect rather than the
 391 Rayleigh ones. In this case the effect on the received signal will be an increase in the amplitude of the
 392 signal due to the received echo.

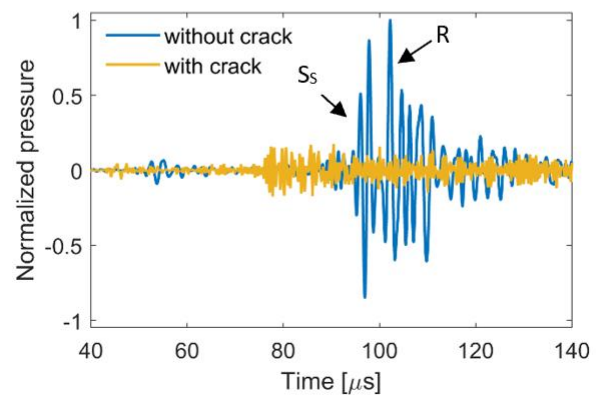
393 If the attenuation is calculated using the damage indicator described in Section 3, equation (2), i.e. the
 394 RMS contrast, by applying the procedure explained in the same section for the numerical data, the
 395 plots reported in Fig. 16(c) and (d) are attained. Spherically, those plots have been obtained by using
 396 a time window of 5 μs and 12 μs for defect A and B respectively. For the binarization of those plots a
 397 threshold of 6 dB has been applied, according to [26].



(a)



(b)

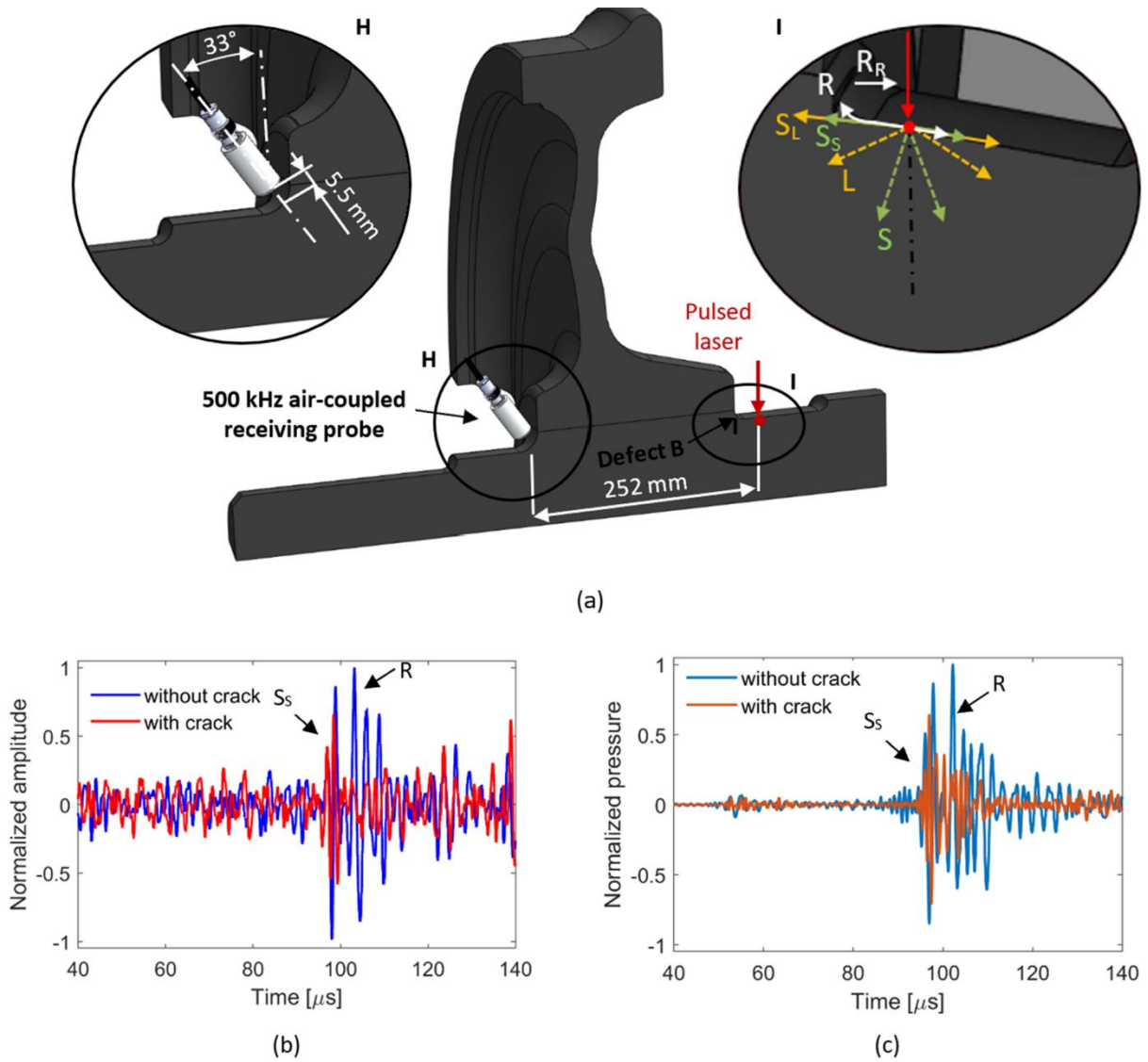


(c)

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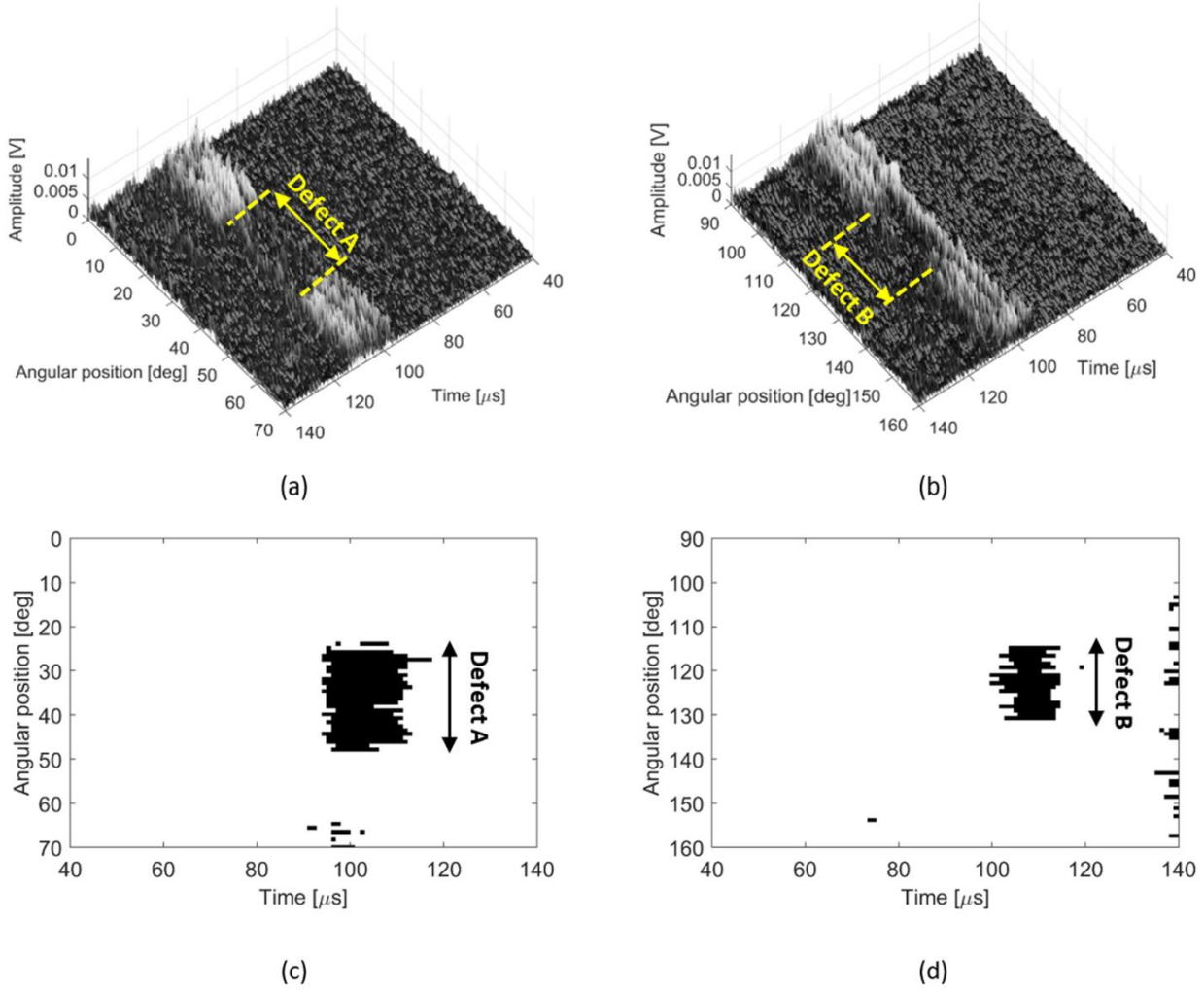
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Fig. 15. Numerical-experimental data comparison for axle presenting a type A defect, experimental set-up (a), experimental data: close up of the time histories around the superficial waves - case of damaged and undamaged axle (b) and numerical data: close up of the time histories around the superficial waves - case of damaged and undamaged axle (c).



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Fig. 16. Numerical-experimental data comparison for axle presenting a type B defect, experimental set-up (a), experimental data: close up of the time histories around the superficial waves - case of damaged and undamaged axle (b) and numerical data: close up of the time histories around the superficial waves - case of damaged and undamaged axle (c).



408

409 Fig. 17. B-scan plots for defect A (a) and defect B (b) and binary RMS contrast plots for defect A (c) and defect B (d)

410 6. Conclusions

411 The paper has shown a dedicated FE numerical model to optimize the experimental non-contact LUT
 412 measurement procedure. This is the first main innovation of the paper since for the first time a complete
 413 FE model has been implemented considering the propagation of ultrasound waves into both solid and
 414 air domain.

415 The results of the FE model were fundamental as a guide for the experiment since they allowed to
 416 determine a priori the energy of the laser source which allows to limit the generation of the ultrasound
 417 wave within the thermoelastic-ablative limit. This is the second main innovation of the paper which
 418 demonstrated the possibility of working in the thermoelastic regime maintaining an adequate level of
 419 accuracy for defect diagnostics. The FE model results have been used also to estimate the angular

420 position of the receiving probe, the propagation mode of the ultrasonic wave most sensitive to the
421 presence of the defect and therefore the time window to observe within the acquired time history. It
422 has been evidenced by the numerical model and demonstrated by the experiments that a defect close
423 to the fretting area (as the defect B) attenuates only the Rayleigh wave and not the skimmed ones while
424 a defect located on the fillet attenuates both the propagation modes (as the defect A). The time windows
425 to be analyzed are therefore different and the numerical model indicated that the best window lengths
426 is 5 μs for the defect A and 12 μs for the defect B.

427 It is clear that the combination of numerical and experimental results with respect to the traditional
428 purely experimental approach has allowed for greater flexibility and gave the opportunity to optimize
429 the control procedure using the LUT technique with significant savings in terms of time spent for
430 experimental design and test realization.

431

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