

Defect reconstruction by non-destructive testing with laser induced ultrasonic detection

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Abstract

This work envisages a detailed study of two-dimensional defect localization and reconstruction, using laser generated ultrasound and its application as a remotely controlled non-destructive testing method. As an alternative to full ultrasonic or full optical approaches, we propose a hybrid configuration where ultrasound is generated by impact of laser pulses, while the detection is done with conventional transducers. We implement this approach for defect reconstruction in metallic elements and show that it combines advantages of both photonic and ultrasonic devices, reducing the drawbacks of both methods. We combine our experimental results with a high-resolution signal processing procedure based on the synthetic aperture focusing technique for the benefit of the final two-dimensional visualization of the defects.

Keywords: laser ultrasonics, defect reconstruction, non-destructive testing, synthetic aperture focusing technique, NDT, SAFT, B-scan

1. Introduction

Non-Destructive Testing (NDT) methods are nowadays implemented in industrial applications for the detection of fractures and defects in different materials [1]. The most extended NDT techniques involve transducers generating ultrasound waves and detecting them after the propagation through the material [2]. Typically, they excite ultrasound using conventional transducers placed in contact with the sample and they analyze the ultrasonic pulse's Time Of Flight (TOF) through the material under test from the transducer to the receiver in order to identify discontinuities in the wave propagation. This approach was extensively discussed in many research papers where defects were localized in space, e.g. the measurement of the crack location, height and width [3][4][5], or of the crack penetration, using ultrasonic guided waves [6]. The detection commonly relies on pulse-echo or

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33 pitch-catch modes. Pulse-echo mode uses the same ultrasonic transducer to generate and
34 detect the signals and for a good detection, the defect should be vertically aligned with the
35 sensor. The pitch-catch mode uses an emitter and a receiver and has more flexibility to
36 work both in transmission and reflection modes. This technique can take measurements at
37 different angles, but it is more expensive as it requires many sensors and more complex data
38 processing [7][8]. Ultrasonic signal frequency, ranging from fractions of MHz up to 20 MHz,
39 affects the sensitivity and resolution of the measurement. At higher frequencies, smaller
40 defects can be detected more accurately, but also surface scattering reduces the penetration
41 depth. These methods have the advantages of low cost, easy implementation and provide
42 satisfactory results in many applications. Among the drawbacks we mention low output
43 power preventing such systems to be used remotely, low frequency bandwidth range that
44 makes necessary the use of transducer arrays, small excitation areas that prevent covering
45 large object areas at once and require ultrasonic scanners, and quite low spatial resolution
46 in the excited volume and in the detection.

47 As an alternative, all-optical methods known as laser-ultrasonics, based on laser gener-
48 ated ultrasound waves and optical detection of the propagated waves, showed up in the NDT
49 field, offering the possibility of remote excitation and detection at a much higher resolution
50 [9][10]. The laser pulse is rapidly absorbed into a shallow volume of the material inducing a
51 stress wave that generates an acoustic pulse [10]. The detection of the transmitted and/or
52 reflected signals can be done as well using optical systems detecting the vibration created
53 by the acoustic wave at the surface, as for example optical interference [11] or techniques of
54 holographic interferometry [9]. All-optical methods have important advantages such as the
55 remote non-contact application and control, the generation of broadband frequency wave
56 spectrum (from KHz to GHz), high output power and the possibility to easily scan a larger
57 object area at once. As a drawback we mention the critical mechanical stability and the need
58 for an anti-vibration setup in order to obtain reliable results, which makes them difficult to
59 apply in certain fields.

60 In this work, we propose a hybrid system that combines the advantages of the optical
61 systems for remotely laser-generated ultrasonic with conventional transducers for detection.
62 The ultrasound will be induced by laser pulses, as in the all-optical methods, allowing inspec-
63 tion from a far distance from the object and enabling a scan of the test specimen remotely,
64 without the need of a direct contact. Laser generated ultrasound also provides a broad
65 frequency bandwidth excitation compared with the limited bandwidth of ultrasonic trans-
66 ducers, covering the whole ultrasonic bandwidth needed for different applications. On the
67 other side, the use of traditional transducers (contact or contactless) for the ultrasound detec-
68 tion removes the interferometric stability problems in the all-optical techniques. The hybrid
69 system allows an improved measurement of the defects location and size by implementing
70 scan measurements over a specific surface area. We combine our experimental results with a
71 signal processing technique based on synthetic aperture focusing technique (SAFT). SAFT
72 technique is based on the principle of superposition of multiple signals captured at differ-
73 ent positions on the surface of the object under test and shifted numerically in time by a
74 delay corresponding to the spatial displacement of the excitors/receivers. This generates a
75 focused image of the defect out of multiple unfocused images. This focused image would

76 have a much higher amplitude at the defect position due to the diffraction of the waves at
77 the defect boundaries compared to healthy positions inside the object of interest. SAFT has
78 the advantage of being able to visualize the whole volume providing 2D or 3D information
79 about the object depending on the resolution and the number of scans performed on the
80 object [12][13][14][15]. Our contribution mainly considers visualizing the defect using SAFT
81 algorithm in volumetric regime instead of two dimensional regimes (depth plane) we found
82 in the literature. This is achieved through a hybrid system using Laser as an exciter and a
83 contact transducer as a receiver. To our knowledge, the articles discussing SAFT algorithm
84 were mainly interested in scanning the receivers across the scan line/area or scanning both
85 transmitter and receivers. However, in our case we are avoiding scanning the receivers and
86 we are interested to scan the exciters with a lot of scan points with high step resolution,
87 thanks to the Laser source that make it much faster, easier and reliable.

88 2. Experimental set-up

89 The set-up designed for our experiments is shown schematically in Figure (1). We use an
90 Nd:YAG laser doubled in frequency, emitting pulses of 8ns at a wavelength of 532 nm, with
91 an energy per pulse of 10mJ. The focused laser beam impacts onto the surface of the object
92 under study where the pulse is rapidly absorbed into a shallow volume of the material and
93 creates a localized thermo-elastic expansion. This expansion induces a stress wave and an
94 acoustic pulse generating broadband ultrasound waves that propagate inside the material.
95 The laser beam can scan a selected area of the object surface by means of a programmable
96 XY galvanometer. For each excitation point, the ultrasonic waves propagate through the
97 object, they are reflected or scattered by different material particles in the volume, and then
98 is detected by the ultrasonic transducer.

99 For the detection we use two conventional ultrasonic sensor transducers (Olympus V133-
100 RM) at 2.2 MHz central frequency, coupled to the surface of the object. The sensors can be
101 placed on the incident surface (measuring reflection/scattering) as well as on the opposite
102 side (measuring transmission). The signal collected by the sensors is sent to a preampli-
103 fier (Olympus 5662), connected to a high-performance Gage A/D card (50 MHz sampling
104 frequency, 16 bit of resolution), linked to a computer for further data processing. For each
105 excitation point the transducer records a voltage/time (A-scan) data set.

106 We analyze two aluminum cuboid samples with identical dimensions of 300 mm x 200
107 mm x 20 mm. One sample is homogeneous, without any holes or defects, referred in the
108 following discussion as “healthy”. The second one, shown in Figure (2), has a cylindrical
109 hole with a diameter of 8 mm and hole depth of 85mm and is referred to from now on as
110 “unhealthy” sample. Two different experiments were performed on this sample: (i) the laser
111 performs a 1D scan (B-scan) and the detection is made with only one transducer; (ii) the
112 laser perform a 2D scan, we use two transducers for detection and we apply SAFT algorithm
113 for the signal processing. The laser scan is performed on the 300 mm x 200 mm face of the
114 cuboid and the receiving transducers are located at the same face of the cuboid where laser
115 excitation is performed, i.e; working in reflection mode. Figure (2) shows the laser scanning
116 line/area and the sensors positions in each experiment.

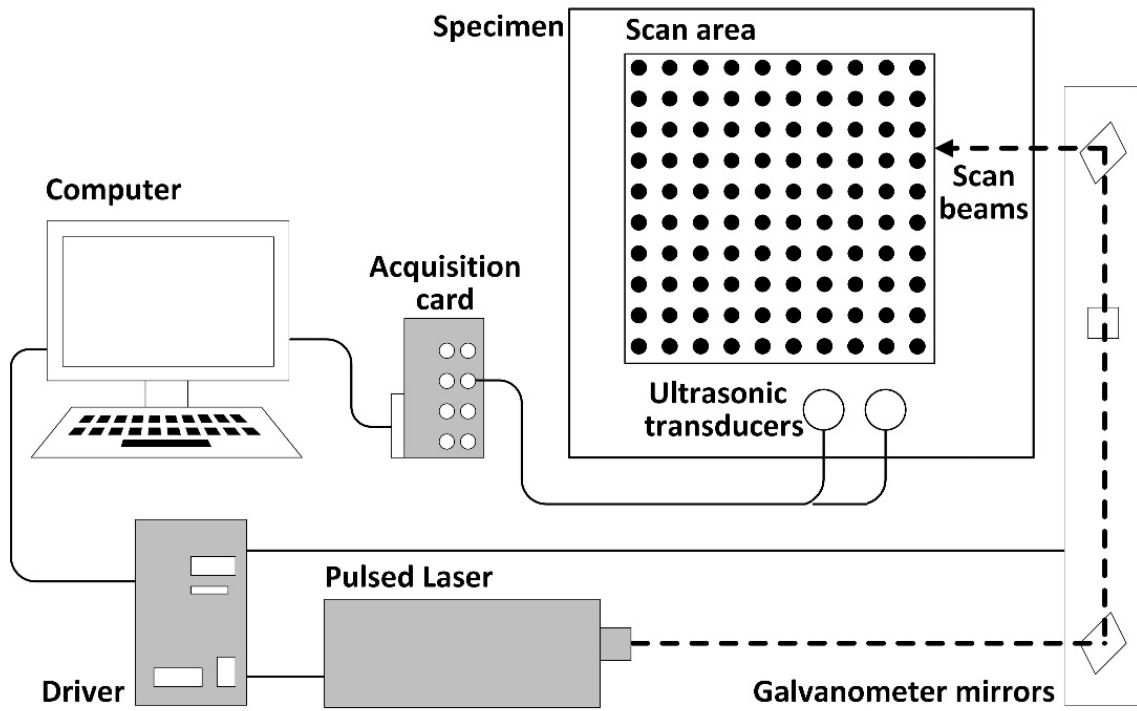


Figure 1: Schematic representation of the experimental set-up

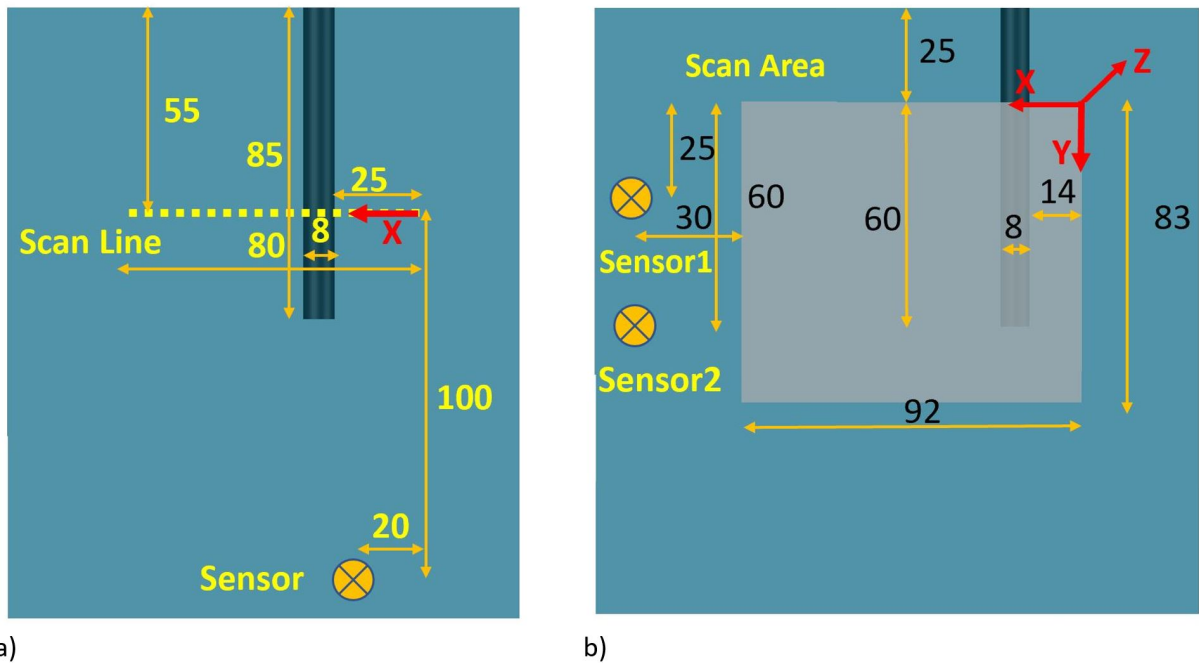


Figure 2: Experimental sample with a) scan line and ultrasonic sensor positions for B-scan experiment and b) scan plane in grey for SAFT experiment and ultrasonic sensors for second experiment.

117 **3. B-scan and signal processing**

118 In the first experiment the galvanometer was programmed to execute a 1D scan (B-
 119 scan) along one line of the object surface in the horizontal (X) direction, crossing on top
 120 of the defect, Figure (2a). We selected 120 scan points covering a distance of 80 mm. For
 121 each excitation point the ultrasound waves detected by the sensor were recorded using our
 122 data acquisition system. For the signal processing we applied a band pass filter of 3 MHz
 123 bandwidth around the 2.25 MHz central frequency and an interpolation algorithm to reduce
 124 the excessive oscillation noise and unnecessary perturbations.

125 The B-scan results for all processed signals are shown in Figure (3). For the healthy
 126 sample in Figure (3a) and for the unhealthy one in Figure (3b). We plot the position of the
 127 scan points as a function of the time of flight (TOF) frames, while the color bar represents
 128 the intensity of the signal. A higher intensity is a sign of a high reflection towards the sensor
 129 coming from a reflecting source that can be a boundary or a defect embedded in the object
 130 under test.

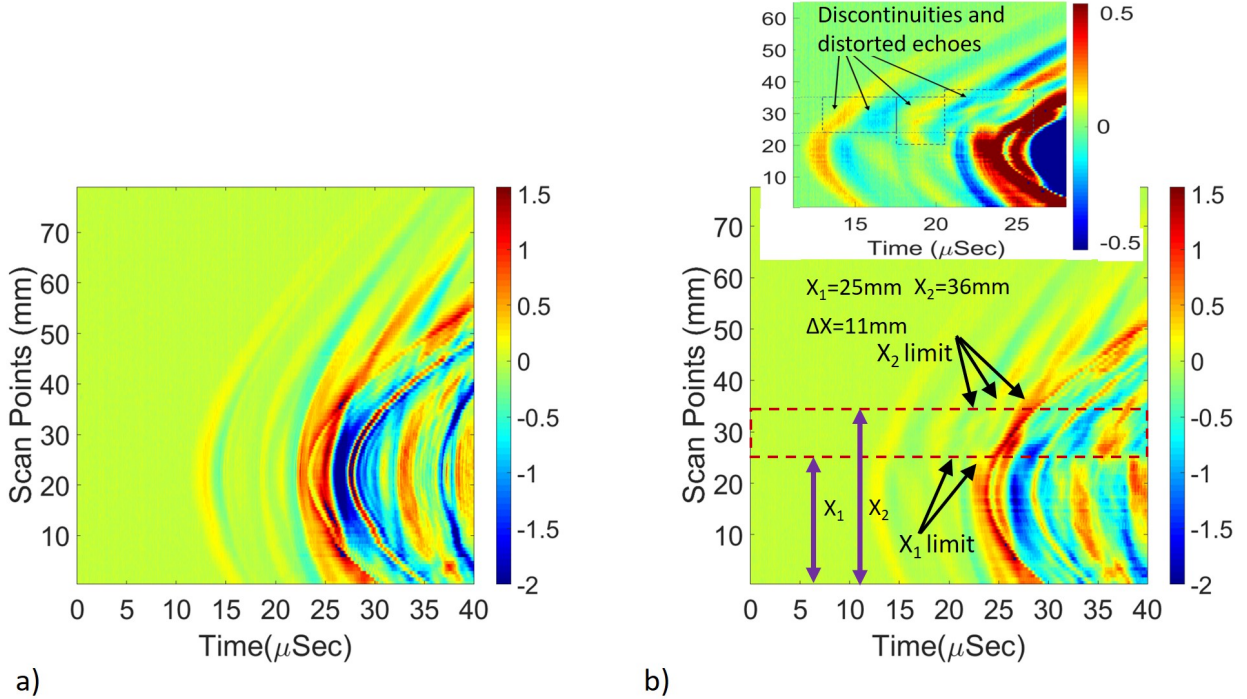


Figure 3: a) B-scan results of the healthy b) B-scan results of the unhealthy sample and an inset with zooming the discontinutites in the result.

131 The TOF of the waves depends on the distance between the laser incidence point and the
 132 acoustic sensor's position. The first wavefront arriving from the laser to the sensor starts to
 133 appear at $t=11\mu\text{s}$ for both samples, since the relative position of the laser scan line and the
 134 sensor was the same. For the healthy sample there is no visible perturbation in the B-scan
 135 map, due to the homogeneity of the sample. All reflections come from the borders. For

136 the unhealthy sample we see the same boundary reflections, overlapped with the reflections
137 coming from the defect. The latter ones alter the B-scan map, showing a major discontinuity
138 and perturbations that correspond to the effect of the hole. As highlighted in Figure (3b), the
139 discontinuity clearly appears in the range between $X_1=25$ mm and $X_2=36$ mm, respectively
140 ($\Delta X=11$ mm), on the vertical axis and it is centered at scan position $X=30.5$ mm.

141 In Figure 3b, we have added an inset inside the figure for better visualization of these
142 discontinuities with reduced limits of the color map to exaggerate the effect of the disconti-
143 nuities and the arrows are indicating the points of discontinuity. We need to emphasize that
144 the echoes from the hole are reflected from both the front and rear surfaces of the cylinder.
145 Front surface is providing higher intensity due to this reflection, while the signal passing to
146 the rear surface is already moving in the air in the hole until it reaches the rear surface and
147 then reflected back to the transducer (passing again by the air in the hole). This attenuates
148 the signal and causing lower amplitude for this reflection. Other echoes appearing later in
149 time axis are multiple reflections from defect and boundaries and include a lot of interfer-
150 ence, so they are not essential in this analysis. These main reflections are highlighted by the
151 arrows in the larger Figure 3b with the full color map range.

152 These values are very close to the actual hole diameter of 8 mm and its position on the
153 sample, with a sizing error of 37% (the defect appears to be bigger than it really is), and a
154 positioning error of 0%.

155 This first experiment shows that B-scan technique, using a remote 1D laser scan and
156 only one sensor, is a very simple and robust technique that provides reliable information
157 about general position of defect location in a fast process. The resolution of the results is
158 comparable with the best commercial NDT full ultrasonic devices but have the advantages
159 of noncontact excitation and remote control of the scan. However, this method does not
160 allow a 2D reconstruction of the defect.

161 4. 2D scan and SAFT analysis

162 When a 2D or 3D reconstruction of the defect is envisaged, a 2D scan configuration,
163 easily achievable with our laser induced excitation system, is required. We programed our
164 experimental setup, shown in Figure (1), to perform a 2D scan over a $M \times N$ matrix points
165 by remotely controlling the position of laser incident point onto the object surface. The
166 scanning area (in grey) as well as the position of the receivers (in yellow) in this second
167 experiment are shown in Figure (2b). For each excitation point, each receiver records a
168 corresponding A-scan signal. The experimental results combined with the SAFT technique
169 are expected to give accurate information about the area of the defect for getting a precise
170 2D visualization of its location and dimensions.

171 SAFT is commonly used for the signal processing in the characterization of embedded
172 defects in the volumetric regime. The technique is based on the delay and sum (DAS)
173 principle, that superimposes the relatively low-resolution A-scan data at every excitation
174 point of the scanned area, creating a higher resolution focused image, with a higher signal to
175 noise ratio (SNR), referred to as the synthetic aperture (SA). Depending on the implemented
176 setup, the analysis can be performed in the time or frequency domain [12][13][14]. SAFT

177 can generate a 2D image of a particular plane of the object, or can be generalized to the
 178 3D mode to cover all planes in a volume. The reconstructed 3D image can project maps of
 179 the defect in any image plane, regardless of the plane used for the scanning of the ultrasonic
 180 signals. In the time domain analysis, the TOF is calculated across all SA points, starting
 181 from the excitation signal source position at a particular scan index to all geometrical target
 182 points in the object's volume and back to the signal receiver, for each particular scan point.
 183 For each geometrical point, an integration of all received signals at a particular value of TOF
 184 is calculated, to produce the final pixel value of this particular scan point in the final image.
 185 This integration results in a higher contrast, resolution and better SNR value[14][15]. Figure
 186 (4) shows a schematic representation of the SAFT technique, assuming a 3D object under
 187 investigation with an arbitrary scatter point (P) and an exciter-receiver set in a pitch-catch
 188 mode, similar to our experimental set-up. We consider an arbitrary excitation point (T)
 189 generating spherical waves and a receiver (R), both placed on the XY plane. The SA top
 190 view is assumed to be on the XY plane.

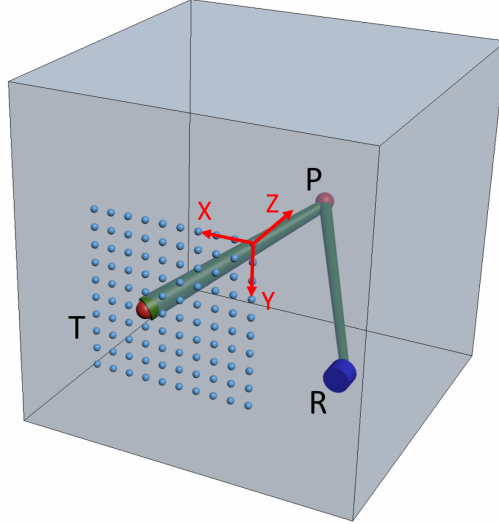


Figure 4: Scheme of the SAFT technique processing used for the object detection. A wave is sent from a point of interest (P) by a transmitter (T). It is reflected/scattered by the defect and measured at the receiver (R). The procedure is repeated with the transmitter in every point of interest.

191 The $TOF_{(i,j,k)P}$ of the ultrasonic signal generated by T and detected by R after it has
 192 been propagated to and reflected by the arbitrary point (P), can be calculated as:

$$TOF_{(i,j,k)P} = \frac{\left| \vec{d}_{(i,j,k)P} - \vec{d}_{(i,j,0)T} \right| + \left| \vec{d}_{(i,j,k)P} - \vec{d}_{(i,j,0)R} \right|}{c} \quad (1)$$

193 where d is the displacement vector at T, R and P positions, i, j, k are the indexes of the
 194 volume image points in the X, Y, Z planes respectively, and c denotes the speed of the
 195 longitudinal waves in the material [12][16][17][18]. This calculation is done for every point in
 196 the A-scan measurements to produce a preliminary unfocused image y_R of this particular

197 point P. The combination of all individual images results into a high resolution focused
 198 image y_f . We assume that the scan is done for MxN points denoting the number of the 2D
 199 excitation steps over the SA, and that only one receiver collects all the transmitted A-scan
 200 data from all scan points at an arbitrary point in the SA. The final signal is given by:

$$y_f(\vec{R}_P) = \sum_{j=1}^N \sum_{i=1}^M y_R(TOF_{(i,j,k)P}, i, j) \quad (2)$$

201 Where y_R is the measured A-scan signal amplitude at the corresponding $TOF_{(i,j,k)P}$ at scan
 202 point i and j and y_f is the focused signal received from all the scan points at this particular
 203 receiver R. This can be regarded as an integration of all received signals from MxN excitation
 204 points at the SA.

205 In equation (2) we need to add a coefficient that represents the effect of the attenuation
 206 and decay in the acquired signal when it passes from the exciter to the scattered point and
 207 back to the receiver. This coefficient is called weighting function or apodization function:
 208 $a(TOF_{(i,j,k)P}, i, j)$ [16].

$$y_f(\vec{R}_P) = \sum_{j=1}^N \sum_{i=1}^M a(TOF_{(i,j,k)P}, i, j) * y_R(TOF_{(i,j,k)P}, i, j) \quad (3)$$

209 In order to account for the diffraction in propagation, the apodization function applies lower
 210 weights to the signals captured at the far ends of SA and filters the unfocused signals in
 211 the SAFT analysis. Equation (3) represents the DAS where summation is applied to the
 212 delayed versions of the signals at the corresponding scan points.

213 The focused signal results from the superposition of the A-scan data from MxN excitation
 214 points captured by one receiver, where each A-scan itself is a superposition of signals coming
 215 from point scatters in the whole volume. If we go further and we assume that we could
 216 implement also a MxN scanning matrix for the receiver position, equation (3) can be modified
 217 to consider the integration of all receivers as well. In this case each image point will be
 218 constructed from $(MxN)^2$ points of integration instead of MxN scan points as for the case
 219 when we use only one receiver. SAFT can, thus, be applied to any image of all planes to
 220 produce an image for the defect from any projection direction.

221 There are several assumptions that we have to make when we apply SAFT to the final
 222 image reconstruction. The exciter is considered to be a point source, which perfectly applies
 223 for the laser generated ultrasound. Receivers are assumed to be point-like transducer: the
 224 smaller the size, the less numerical errors in the algorithm. The laser scanning area and the
 225 receiver locations are assumed to be far enough from the object's boundaries to avoid reflec-
 226 tions that could cause misleading data. The medium is assumed to be homogeneous, with
 227 non-spatial dependent physical parameters. In other scenarios where the wave dispersion
 228 could be significant due to the presence of composite or inhomogeneous materials, the SAFT
 229 algorithm should be modified to account for different wave velocities and wave diffraction.

230 Experimental measurements have been conducted in a pitch-catch mode, using two re-
 231 ceivers placed at the fixed positions indicated in Figure (2b). The laser has been programmed
 232 to scan an area of 92 mm x 83 mm, with 101 x 91 scan points. The signals captured by the
 233 two sensors have been recorded using the amplifier and data acquisition system described

234 in section 3, and were pre-processed using a band pass filter and an interpolation algorithm
235 to remove the background noise and low/high frequency components. Then, an averaging
236 algorithm was applied to remove the DC components from the signal. The SAFT algorithm
237 was finally applied, considering a Gaussian weighting function.

238 The reason we did not add more receivers (e.g: microphone array) is that our main focus
239 is to use the transmitter, not the receiver, as the scanning mechanism with a lot of points
240 with high step resolution. With laser excitation, we can do the scanning of the transmitter
241 with a step size of 0.9mm for more than 9000 scan points. This is very difficult to achieve
242 with conventional arrays. In addition, the scanning with the laser makes the incident pulse
243 on the object surface equivalent to a point source, which is better for the SAFT efficiency.

244 As a result, we obtain the volume reconstruction of the selected scanned area shown
245 in Figure (5a), where the defect corresponds to the yellow shadows. The position and
246 dimensions of the defect can be better visualized and measured if we select projections of
247 different cross-sections in the volume of interest, that can be extracted from Figure (5) for
248 any required coordinates. Figures (5b) and (5c) show two cross-section slices in the XY and
249 XZ planes respectively. From these projections we measure a defect with horizontal (ΔX)
250 size of 8.2 mm and vertical (ΔY) size of 56 mm.

251 The contour map of one of the cross-sections is another representation of the results
252 that can even better visualize the defect. Figure (6) shows the contour map of the XY
253 cross-section, enabling the reconstruction of the X and Y dimensions: the defect is centered
254 at X=20 mm and Y=40 mm with the corresponding size $\Delta X=8.2$ mm and $\Delta Y=56$ mm.
255 Compared with the real size and position of the defect in our sample, the resulting recon-
256 struction has the following errors: a sizing error of 4.6 %, concretely, $\Delta X_{error}=2.5\%$ and
257 $\Delta Y_{error}=6.7\%$ and a positioning error of 12.25%, concretely, $X_{error}=2.5\%$ and $Y_{error}=22\%$.
258 There are several reflections in the resulting images that do not come from the defect, that
259 could be misleading. The contour map helped to identify and ignore them. These reflections
260 can be overcome in further experiments.

261 The reflections appearing in the reconstructed images, as well as the resolution of the re-
262 construction are conditioned by some aspects of our experiment. On one hand, Z-dimension
263 of the object studied here was too small compared with X and Y ones. In other words, the
264 distance between the laser/sensor and defect is larger than the one to the Z boundaries of
265 the object itself. This results in multiple reflections which arrive to the receiver faster than
266 those coming from the defect, leading to misleading wavefronts that produce some errors
267 in the reconstructed results. To solve this problem, Z dimension of the object under test
268 should be large enough to avoid internal reflections from the boundaries. This applies to
269 all object boundaries in all directions. On the other hand, in our experiment we fixed the
270 position of the receiving sensors and only scanned the laser impact points. This change in
271 laser scan point position results in a change in the angle between the excitation point and
272 the ultrasonic receiving sensor. This angle at certain points of scan increases significantly
273 due to object geometry. Large angles reduce the performance of the SAFT technique and
274 can significantly reduce the signal-to-noise ratio. These constraints can be resolved by in-
275 creasing the object's depth and reducing the angle by scanning the receivers along with the
276 laser beam.

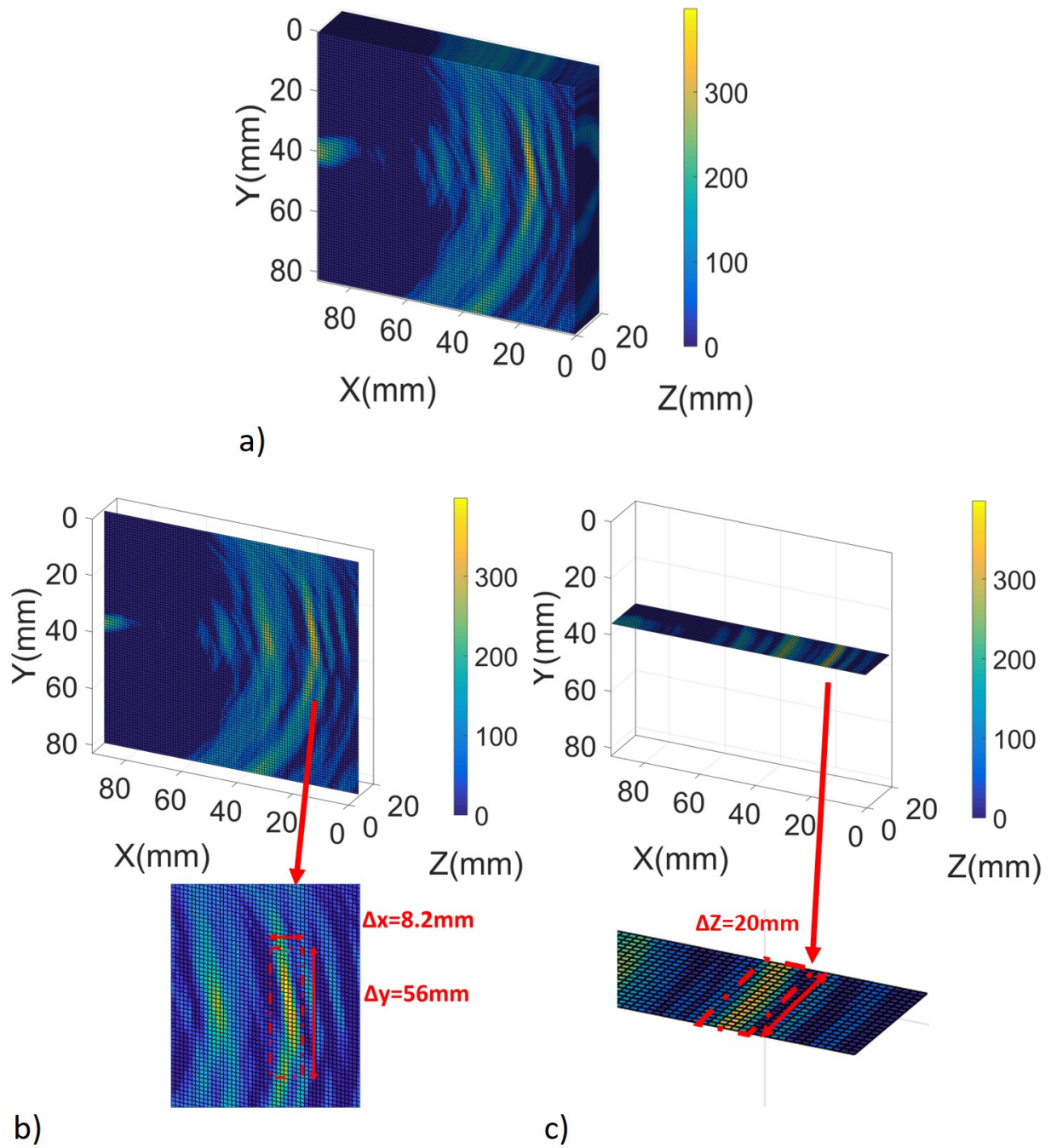


Figure 5: Reconstruction results of SAFT technique for a) 3D volume representation b) 3D slice for XY plane c) 3D slice for XZ plane.

277 Using our actual experimental setup, SAFT algorithm and post-processing, these shad-
 278 dows cannot be directly removed. However, it is important to remove those redundant shad-
 279 dows for better visualization to avoid confusion between main echo and other echoes and to
 280 distinguish which of the shadows is the one we are interested in. We consider the main
 281 shadow is the one with higher amplitude and the redundant shadows are rather faded away
 282 with low amplitudes. We added an image processing filter To remove the redundant shad-
 283 dows. We applied an amplitude threshold filter that removes any point in the reconstructed
 284 image with amplitude less than 65% of the maximum amplitude. This threshold value was
 285 selected after visualizing the unfiltered reconstructed images. We found that the points with
 286 high intensity are starting around color map of 65%. This leaves only the main shadow as
 287 the reconstruction of the defect with minor traces of the other shadows that are negligible.
 288 The results in Figure 6b represent the contour map representation of Figure 6a after adding
 289 the rejection threshold of 65%. A cylinder representing the actual defect shape is superim-
 290 posed on the reconstructed images to represent the correlation between the main shadow
 291 location and the actual defect location. It should be noted that adding this rejection thresh-
 292 old filter is also removing some important data from the main shadow, hence it is important
 293 to calculate the size errors based on the unfiltered reconstructed image of Figure 6a. Fine
 294 tuning was applied to this filter to get optimum results. We can add a more restrictive filter
 295 to remove completely those negligible minor traces of redundant shadows ,but this would
 296 affect the size of the main shadow and would result in losing important data. Thus, there
 297 is a compromise between neglecting the redundant shadows and losing some intensity data
 298 of the main shadow.

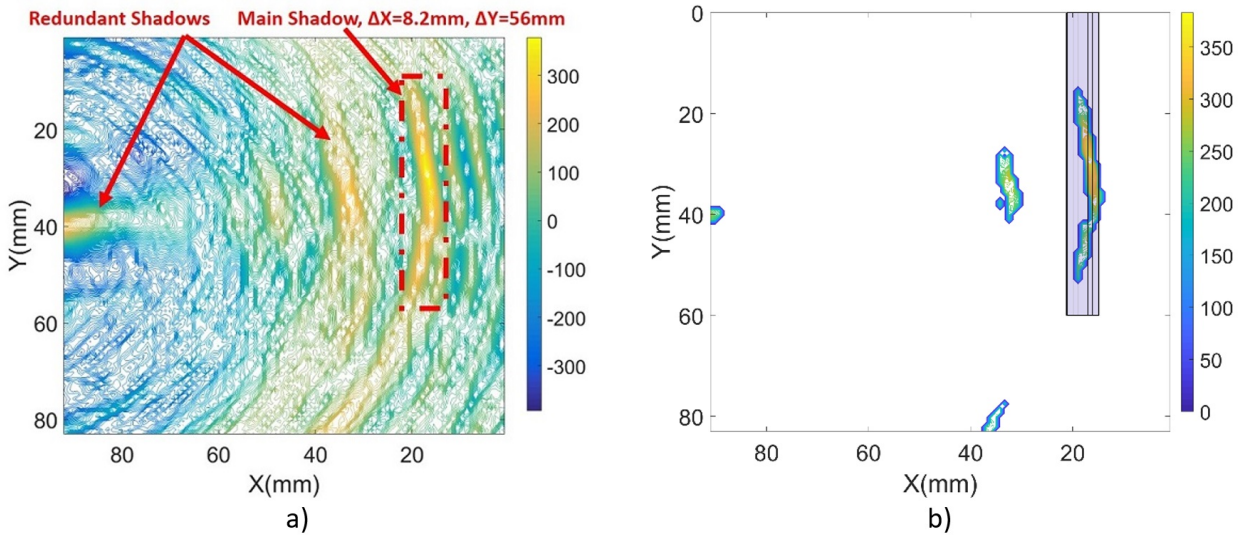


Figure 6: a) Contour map of the defect at XY plane at Z=10 mm using SAFT technique: b) contour map of Figure 6a after applying a reject threshold for data with an intensity below 65% with original geometry of the defect superimposed.

299 Comparing the results presented in this section with the previous B-scan ones, it should
 300 be noted that B-scan measurements allow the defect reconstruction only from one per-

301 spectively, and with a limited resolution. The implementation of the 2D scanning area and
302 the signal processing using the SAFT technique over the object's volume allows the defect
303 visualization from different angles and at different depths, making possible a 3D image re-
304 construction. For this application laser generated ultrasound excitation is much easier to
305 implement than scanning with conventional transducers as it can be applied and scanned
306 remotely and therefore the volume in which the ultrasound is generated is smaller. In the
307 experiment presented here we scanned the laser across $M \times N$ points, and we used only two
308 fixed ultrasonic receivers. This helped make the scan easier and show that by increasing
309 the number of exciters (laser scan points in our case), we can obtain the same good-quality
310 images with a very limited number of receivers fixed at particular points.

311 SAFT technique is sensitive to defects in agreement with the size of the measuring
312 transducers. It is able to detect and reconstruct 3D defects at relatively large angles despite
313 the corresponding errors. The position of the sensor and scan points do not need strict
314 rules as long as the angle is within the allowable limits and the scan points as well as the
315 sensors are at a relatively far distance from the boundaries of the object. The resolution of
316 the reconstruction is in a range between those of the classical ultrasonic and the full optical
317 methods. The algorithm is having a very high signal-to-noise ratio of the defects relative to
318 other techniques.

319 5. Conclusion

320 We applied and compared two different techniques for defect localization and recon-
321 struction, both using a hybrid system composed by laser generated ultrasound and conven-
322 tional transducer receivers. The results obtained with both methods, the B-scan and the
323 SAFT technique, indicate similar position of the defect, confirming the reliability of both
324 algorithms. The SAFT technique offers the advantage of visualizing the defect in 3D and
325 obtaining the projections of the sample planes, making it easier to distinguish the location
326 of the defect in a 3D view, instead of just getting the one dimensional or two-dimensional
327 results commonly used. We used the discussed algorithms to localize the defect position with
328 a good signal-to-noise ratio, taking into consideration the limitations of structural dimen-
329 sions. We believe that this hybrid approach combines different advantages of both photonic
330 and ultrasonic devices, reducing the drawbacks of both methods. The remote control of the
331 broad band excitation, possibility of scanning large areas and reduced number of receivers
332 make it easy to implement for different materials and applications.

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