Immersion laser-induced ultrasound imaging of solids with complex macroscopic geometry of surface

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Abstract. In this paper a real-time experimental system and algorithms for immersion two-dimensional laser ultrasonic imaging of solids with complex geometry of surface are presented. Wideband probe ultrasonic pulse is generated photoacoustically in an opaque plate, which absorbs pulsed laser radiation. The back-scattered acoustic field is recorded by a multi-element piezoelectric array. The signals are used to reconstruct refraction-corrected ultrasonic images, which are post-processed to determine positions of the external and internal boundaries of the object. The numerical simulations are carried out to verify the developed algorithms. The proposed approach allowed measuring the positions of the boundaries of the polymethyl methacrylate (PMMA) sample with accuracy of ~0.1 mm in the direction of the probe beam propagation, and ~0.2-0.3 mm in the perpendicular direction.

1. Introduction
The common approach to ultrasonic imaging of solids is to use contact phased arrays [1]. In this case synthetic aperture focusing techniques based on the ray tracing are used. However, contact ultrasonic imaging can encounter difficulties when non-flat surfaces are inspected. Flexible phased arrays [2] are widely used in practice to inspect such surfaces, but they need a tight contact with surface, and cannot be used for inspection of non-smooth surfaces.

Another approach is immersing both the phased array and the object in a body of liquid. However, accurate determination of the position and the shape of the object’s external boundary is important for correct reconstruction of the scatterers inside the object. The accuracy of the surface measurement accuracy strongly affects the accuracy of localization of internal scatterers. Malkin et. al. [3] studied resolution achieved by phased arrays in the immersion imaging of objects with strongly curved surfaces. The results show, that surface imaging provides rather poor resolution due to complex waveform, side-lobes of the probe pulse and surface curvature.
Figure 1. Numerically simulated propagation and scattering of the probe laser ultrasonic beam through the immersion liquid and the PMMA sample on a steel rod. Time elapsed since the laser pulse absorption at $z = z_0 = -20$ mm: (a) 22 μs, (b) 25.7 μs, (c) 27.5 μs, (d) 38 μs. Black lines outline the boundaries of the specimen (figure 3 (a)): the PMMA sample, the steel rod, and a liquid between them.

In this study we develop the laser ultrasonic imaging approach to accurate inspection of solids which decouples excitation and detection of ultrasound, allowing their separate optimization. The advantages of laser excitation of probe ultrasonic pulse include short duration, aperiodic bipolar waveform, and smooth directivity pattern devoid of side-lobes [4]. All this significantly improves the accuracy and quality of the reconstructed ultrasonic images in comparison with the traditional approach. The presented system and algorithms are suitable for samples with piecewise-linear internal and external profile cross-sections, but could be generalized for more complex objects.

2. Method
The experimental setup used for imaging of solid bodies is based on the combined photoacoustic and laser ultrasonic real-time imaging system [5]. A short laser pulse for excitation of the ultrasonic beam is provided by a Nd:YAG laser (pulse duration – 8 ns, pulse energy – 1 mJ, pulse repetition rate – 20 Hz). The probe ultrasonic pulse has a duration of ~100 ns, and frequency band of ~0.1-12 MHz. The beam is focused by a cylindrical PMMA acoustic lens. The sample is immersed in water. The external surface of the sample and the internal inhomogeneities reflect and scatter the probe pulse backwards, and the scattered waves are recorded by an array of 16 wideband polyvinylidene fluoride sensors. The signals are digitized and averaged on a FPGA, filtered and used for image reconstruction with its further post-processing. The acoustic lens allows focusing the probe beam and reconstructing the cross-section of the object by the image plane. The array and the sample are mounted in a 4-axis positioning system (3 translational axes and rotational axis), which is used to align the sample and image plane. The image reconstruction algorithms are accelerated using NVIDIA CUDA on a graphical processors to provide real-time operation (frame rate – 10 Hz).

Numerical simulations of the 2D probe pulse propagation through the immersion liquid and the sample (modelled as a liquid to speed up the simulations) were carried out using k-Wave Toolbox [6].
Figure 2. The schematic of the proposed algorithm and variable notation.

A CAD model of the sample (PMMA cylinder with complex internal and external generatrices fixed on a steel rod) used for simulations and experiments is shown in Figure 3 (a). Figure 1 shows the normalized acoustic pressure field $p(x, z, t)$ at different time instants. Red and blue colors correspond to positive and negative pressures respectively. Figure 1 (a) shows the positive probe pulse before it is refracted at the external boundary. In figure 1 (b), the pulse is reflected from an acoustically hard sample surface, remains positive and propagates backwards. Inside the sample, the pulse widens due to the difference between the speed of sound in water and PMMA. In figure 1(c) and (d), the pulses reflected from the acoustically hard wall of the steel rod are positive, and the pulses reflected from the water-PMMA boundary are negative.

The signals are recorded by 16 point-like sensors located at $z = z_0 = -20$ mm, where the Gaussian probe pulse is generated.

The image reconstruction algorithm is based on geometrical acoustic ray tracing (figure 2). First, the imaging region is assumed to be filled entirely with acoustically homogeneous immersion liquid (water), and a filtered back-projection algorithm is used to reconstruct the primary laser-ultrasonic image [7]. The image is a distribution of scatterers’ strength $\varepsilon(r)$ calculated using [8]:

$$\varepsilon(r) = \sum_{k=1}^{N} p(d_k, t_k(r)) \cdot |d_k - r| \cdot D(d_k, r),$$

where $t_k^ol(r) = |d_k - r|/c_0$ is time of flight of the acoustic pulse from the optical absorber to the scatterer at $r = (x_i, z_j)$ and from the scatterer to the $k$-th sensor at $d_k = (x_k, z_k)$, $N$ – number of sensors, $c_0$ – speed of sound in water, $p(d_k, t)$ – pressure waveform, recorded by the $k$-th sensor, and $D(d_k, r)$ is its directivity pattern. The primary distribution of scatterers $\varepsilon(r)$ can be processed to segment the external boundary as the set of local maxima closest to the sensor array [8].

Second, the image pixels located inside the object are re-calculated accounting for refraction at the calculated external boundary. The distribution $\varepsilon'(r)$ within the sample is calculated similarly to (1):

$$\varepsilon'(r_{ij}) = \sum_{k=1}^{N} p(d_k, t_k(r)) \cdot D(d_k, r) \cdot W_{ijm}^{el} W_{ijm}^{ol},$$

where $W_{ijm}^{el}$ is coefficient of transformation of the longitudinal wave in water to the longitudinal wave in the sample on the forward path, and $W_{ijm}^{ol}$ is the corresponding coefficient on the backward path. However, the travel time of probe pulse from the absorber to the scatterer and to the $k$-th sensor $t_k(r)$ is the sum of forward and backward travel times, which are calculated from the Snell’s law and the
Fermat’s principle [4] using the known positions of the sample boundaries. The internal boundaries are determined as local maxima or minima of $\varepsilon'(\mathbf{r})$ depending on the sign of the reflected pulse.

3. Results
Figure 3 shows the images reconstructed using the numerically simulated data. Figure 3 (b) is a primary image used to segment the external profile (lines 1-2). The piecewise linear profile segmented from primary image is shown in figure 3 (c) and used to recalculate the pixels inside the sample. Figure 3 (d) is a refraction-corrected image calculated with equation (2). Figure 3 (b) appears to be a ~2 times “squeezed” version of figure 3 (d) due to speed of sound mismatch. The dimensions of the sample calculated using this image are in agreement with the model within 5 $\mu$m due to the finite grid step. This result confirms the correctness of the proposed approach and developed algorithms.

![Diagram](image)

Figure 3. (a) The cross-section of the sample model used for numerical simulation and for experiments. (b) The primary laser ultrasonic image reconstructed under the assumption of a homogeneous medium. (c) The sample profile segmented from figure 3 (b). (d) The final image reconstructed accounting for refraction of waves at the sample boundary. Black and white stripes show positions of the boundaries and sign of the reflected pulse. 1, 2 – external boundary of the sample; 3, 4, 5, 6 – internal boundaries; 7, 5, 8 – the wall of the steel rod. The unnumbered stripes are all artifacts corresponding to the reverberations or the spurious signals.

Figure 4 shows the refraction-corrected images reconstructed from experimental data (sensors are located at $z \approx 40$ mm). Although the images are in a good agreement with figure 3, the lines in figure 4 are wider and the number of artifacts is increased due to the finite detection bandwidth, finite size of the piezoelectric transducers and reverberations within the acoustic lens. The dimensions of the sample measured by the laser ultrasonic imaging and standard gauge instrument are in agreement within 0.1 mm along z-axis, and 0.2-0.3 mm along x-axis. The sample internal surface was then damaged by a file. Lines 3 and 4 in figure 4 (b) are inclined and widened compared to those in figure 4 (a). The results suggest that laser ultrasonic imaging allows quantitative assessment of wear of solid parts.
4. Conclusions
The paper describes the results of application of the immersion laser ultrasonic imaging for measurement of dimensions of solid parts with complex geometry of internal and external surfaces. The refraction-corrected algorithm for reconstruction of 2D images of internal structure and measurement of their dimensions is presented. The algorithms were tested using the numerical simulations carried out in k-Wave Toolbox. The approach and the experimental system were tested on the PMMA sample in damaged and intact states, which suggests the possibility of assessing the wear of parts. The experimental accuracy is ~0.1 mm in the direction of the probe pulse propagation, and ~0.2-0.3 mm in the perpendicular direction. The proposed technique is promising for fast industrial control of the dimensions of solid objects, underwater and immersion non-destructive inspection.

Acknowledgements
This work was supported by the Ministry of Education and Science of the Russian Federation grant No. K2-2019-004 (algorithms, simulation) and as part of the work on the State order of the Research Centre “Crystallography and Photonics” of Russian Academy of Sciences (experimental array).

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