Numerical and Experimental Studies towards Improvements in Laser-Acoustic Microscopy by Optical-Based Sound Beam Shaping

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Abstract. Incorporating Laser-Ultrasound systems for excitation and acquisition of ultrasonic waves into NDT&E systems establishes the benefits of contact free methods to high-frequency ultrasonic measurements. Techniques using this huge potential were investigated for a long time but in most cases with focus to surface waves. To study the material bulk properties strong surface damaging laser pulses were mostly used. However, by shortening the pulse length down to some nano-seconds at moderate intensities one can excite ultrasonic waves in the bulk of the material without any damage.

The work presented deals with the prediction of the acoustic fields shape based on arbitrary energy distribution across the excitation laser spot and its use in ultrasonic inspection. An algorithm is discussed which uses the laser beam profile, measured surface normal displacements and bulk wave speeds as input. Comparing simulated an measured data reveals basic agreements but also still some discrepancies caused by additional thermal diffusion in the excitation region. Using this algorithm already offers to analyse the presumed location and shape of longitudinal and transversal wave foci. Further, its capability for optimizing laser-acoustic systems is demonstrated.

1. Introduction
Laser-acoustic techniques offering both, excitation and detection of ultrasonic waves, are still progressing according to the massive improvements of laser sources and systems. Especially in nondestructive testing and materials characterization (NDT&E) laser-acoustic methods receive high attention because of their wide range of application. One major benefit is the ability to handle high frequency ultrasonic waves without the need of any contact or couplant.

Further advantages are found in the wide spectral nature of laser-acoustic sources which build a short pulse-like signal in the time domain. This increases the ability of detecting flaws within the bulk material that are close to other boundaries. Concerning material characterization applications the wide spectrum distribution offers to evaluate frequency dependent parameters within one single measurement.

Beginning in the late 1950s, researchers started to study laser-acoustic sources theoretically and experimentally, wherein ablative and thermoelastic regimes were described [1]. Due to its much stronger acoustic waves high power lasers ablation sources were studied first, although they come with a small dislocation of surfacial matter. In contrast, the thermoelastic regime solely
introduces a temporal-spatial temperature gradient which is preferred by NDT&E. Because of its much weaker acoustic amplitudes, it was hardly possible to detect them by contact methods even less optically, which titled them as non-applicable. Nowadays, compact laser systems offer several thousand pulses per second and to measure displacements in the pico-meter range which dramatically pushed the interest towards thermoelastic sources. In this article, a method is proposed to calculate thermoelastically generated sound fields in isotropic media excited by different laser beam shapes. It combines an analytic formulation of the source mechanism with spatial and temporal measurements across excitation area. Especially for laser-acoustic microscopy or material characterization it is essential to know, how the waves are radiated, where they superimpose and from which region reflection can be expected. As a result of a better knowledge concerning the sound field, laser-acoustic measurements are dramatically increased in their informative value.

2. Sound fields of arbitrary shaped sources

In order to tailor the sound field to its specific application one need to know the spatial and temporal development of the acoustic waves inside the material. Due to the fact, that it is hardly possible to probe the particles elastic motion in solids, one approach is to sample all necessary information outside of the solid and calculate the sound field as a representation of the real waves. To do so, several mathematical techniques are well known but most of them are limited by assumptions which reduce their applicability to real sources. For example, requirements like source diameters significantly smaller than the acoustic wavelength or the ability to describe the shape in an analytical manner is rarely the case. As shown in figure 1 the intensity distribution across the focal area distinctly differs from mostly point-like assumed shapes. Shown are three intensity distributions across the focal region. The figure on the left represents the so called beam profile of a higher quality cw-laser but not able to excite acoustic waves. In the middle and the right two examples of laser for acoustic excitation having arbitrary shapes. As a consequence, these sources can’t be calculated by symmetry-based methods without having significant errors.

2.1. Theoretical Background of thermoelastic sources

While applying a single laser pulse to a free metal surface, part of the radiation is reflected while the remainder is absorbed by the lattice which causes heating. By keeping a power density below $10^6 \text{W/cm}^2$ at a pulse length in the lower nanosecond range, melting or vaporization of matter is prevented. In time scales of the laser pulse the resulting thermal expansion is limited to a

![Figure 1. Beam profile measurements representing an almost gaussian laser beam (left) and two intensity distributions of sources for laser-acoustic excitation at large (center) and small focus sizes (right). Bright represents high intensity.](image-url)
disk-like volume at the surface resulting in a horizontal force dipole \([6]\). Its thickness equals the thermal skin depth of some \(\mu m\) \([2]\) while the diameter equals the laser spot size. According to the slow thermal diffusion compared to the short pulse duration the temporal characteristic is well approximated by the Heaviside function \(H(t)\) as the integral over time of the Dirac pulse \(\delta(t)\) \([3]\). The lattice displacement is directly connected to the surface guided Rayleigh wave as well as the longitudinal and transversal waves propagating into the volume. A diversified discussion concerning the mechanism behind thermoelastic sources can be found in Scruby’s standard work *Laser Ultrasonics* \([2]\). Equations (1) and (2) are taken from this textbook to calculate the angular distribution of longitudinal \(u_r\) and transversal wave displacements \(u_\theta\). It is important to mention that these directivity patterns are only valid within the Fraunhofer region of a source. Further, they depend only on the materials elastic properties which are represented by the longitudinal and transversal wave speeds \(c_L\) and \(c_T\).

\[
    u_r \propto \frac{\sin 2\theta (k^2 - \sin^2 \theta)^{1/2}}{(k^2 - 2\sin^2 \theta)^2 + 4\sin^2 \theta |\cos \theta| (k^2 - \sin^2 \theta)^{1/2}}
\]

\[
    u_\theta \propto \frac{k \sin 4\theta}{k(1 - 2\sin^2 \theta)^2 + 4\sin^2 \theta |\cos \theta| (1 - k^2 \sin^2 \theta)^{1/2}}
\]

Herein, the parameter \(k\) is the ratio of longitudinal to transversal wave speed and can also be expressed simply by Poisson ratio \(\nu\) of the material

\[
    k^2 = \frac{2(1 - \nu)}{1 - 2\nu}
\]

The analytic solutions according to Equations (1) and (2) result in directivity patterns as shown in figure 2 for aluminium \((c_{L,Al} = 6400 \text{ m/s}, c_{T,Al} = 3150 \text{ m/s})\) and for steel \((c_{L,St} = 5100 \text{ m/s}, c_{T,St} = 3250 \text{ m/s})\). Typical for thermoelastic waves in the far field is the missing radiation at the direction perpendicular to the surface \(\theta = 0^\circ\) which is caused by the opposing stresses within the dipole. The transversal wave has a second root at the critical angle \(\theta_c = \sin^{-1}(1/k)\). Unfortunately analytic formulations are only valid for point-like or symmetric source geometries. In most cases, real sources exhibit arbitrary shapes which can’t be handled by these approaches (figure 1). Alternatively, one can utilize FEM software to study the source properties which may easily cause high computational efforts as shown in \([7]\). To reduce the complexity of simulation work, analytical and experimental data can be combined to perform a hybrid point source synthesis HPSS. By this, information from optics and mechanics are merged. The importance of such linking is also supported by figure 3. In contrast to figure 1 these images show the materials.

![Figure 2](image-url)  
**Figure 2.** Computed thermoelastic source’s directivity of transversal (left) and compression waves (right) at a free surface of aluminum (solid line) and steel (dashed line).
Figure 3. Images of normal surface displacement during thermoelastic excitation as seen by the laser doppler interferometer just after the laser pulse (left) and 200 ns later (right)

mechanical reaction after an optically introduced disturbance. Based on the asymmetric beam profile of the excitation laser a non-uniformly distribution of surface normal displacements are observed which justifies the importance of including the lasers beam profiles in the acoustic design and interpretation of ultrasonic signals.

2.2. Algorithm
As published in [5], the HPSS algorithm combines three main types of input. The first one is the spatial intensity distribution across the source area, acquired from the laser beam profile at the excitation spot. To avoid spatial aliasing, a CCD camera system was utilized having a resolution at least ten times smaller than the smallest acoustic wavelengths considered. The second input is the time resolved surface displacement, as measured by a laser doppler interferometer. By this, no assumptions concerning the temporal properties of the ultrasonic signal are necessary. Finally, a set of material parameters consisting of the wave speeds $c_L$, $c_T$ and if necessary the wave’s attenuation are included. These values are taken from textbooks or measured by subsequent experiments. The algorithm starts to analyse the beam profile and locates a calculation area perpendicular to the surface aligned at the center of the source. Subsequently, each pixel within the beam profile is considered as a single point source. By this, the asymmetric source is divided into point-symmetric sub-sources having the angular intensity distributions according to equations (1) and (2). Furthermore, the transient characteristic is assumed to coincide with the surface displacement, scaled by the pixel’s intensity. This is supported by the Poisson ratio, which is linearly linking orthogonal forces, strains or stresses. Finally, a linear superposition of all sub-sources (known as PSS) is used to map the time-resolved 3D wave propagation into the desired 2D area of analysis.

3. Results
All results presented below were taken from experiments performed at the Laser Ultrasonics Laboratory at the Fraunhofer IZFP, Dresden branch. Besides of the examples shown the given conclusions are supported by additional studies concerning variations in frequency and laser spot shape. First we found coincidence in using equation 4 for estimating the bandwidth of the acoustic waves as found in several publications (e.g. [2]). Using the pulse length $t_p$ of the excitation laser, frequencies up to 100 MHz at significant amplitudes are observed.

$$f(\text{-6dB}) \approx \frac{0.1874}{t_p}$$  (4)
Figure 4. Calculation and spatial decomposition of pressure wave fields excited by a thermoelastic asymmetric source. x- (left) and y-displacement (second left) as orientations parallel to surface, z-displacement (second right) perpendicular to surface and absolute value of all three orientation (right). Each picture is scaled to its maximum value starting at blue for weak up to red for high displacements.

Due to this still high bandwidth as compared to conventional contact based ultrasonic transducer used in NDT, short transient signals can be excited which helps to distinguish closely located scatterers. Analysing the spatial decomposed sound fields reveals additional information about the source properties, which are mostly estimated in a general manner but not in detail as given by such simulation work. In figure 4, four different images are shown which all result from the same asymmetrical thermoelastic source. In these images, the value of each pixel corresponds to the maximum amplitude of the time signal after a Hilbert function based envelope. Besides the absolute value of displacement (most right image) a decomposition into the three spatial orientations was done. All images are scaled to its maximum value. For comparing among themselves the maximum values are $x_{\text{max}} = 0.46$, $y_{\text{max}} = 0.55$ and $z_{\text{max}} = 0.76$ related to $\text{avg}_{\text{max}} = 1$. Herein the x direction is orientated parallel to the specimen’s surface, the y direction perpendicular to x and again parallel to the surface and finally z perpendicular to the surface. In the most left image, depicting the x component, differences in the distribution of displacement is clearly visible. Two superelevations, one in the left main lobe and a second more widespread in the right side lobe is noticeable. Although the excitation area was kind of a superposition of two tilted elliptic shapes, the distribution of y component (second left) differs dramatically having a single hot-spot close to the surface just below the source. The image corresponding to the z component (second right) is surprisingly almost symmetric. However, the focal region is significantly deeper located than the horizontal orientated one. Finally, the average of all three components is mainly dominated by the strongest z component but has a hot-spot region in a mid-depth and a slightly left shifted distribution of displacements.

A determination of the simulated sound fields accuracy was done by measurements according to a method published in [8]. Using an aluminum alloy sample of 5 mm thickness having wavesthes of $c_L = 5100 \text{ m/s}$ and $c_T = 2840 \text{ m/s}$ and a stepwise shifting of the excitation location by keeping the detection location the dashed curve was obtained as shown in figure 5. The solid line corresponding to the simulated values was taken from a simulation as discussed earlier but done for a single line at a distance of 5 mm below the surface by using the wave speeds as measured. Comparing simulated and measured values basic analogies like two sidewise shifted maxima or the presence of significant amplitudes at zero degree are observed as well as discrepancies in the angular position of maxima and its symmetry.
4. Discussion and conclusion

Thermoelastic laser-acoustic methods hold both, challenges in simulation or optimization and perspectives in non-contact measurements for NDT&E. As shown here as well as by other researchers simplifications are still necessary to calculate the real sound field in solids. Using hybrid point source synthesis (HPSS) enables to incorporate real spatial source intensity distribution and measured transient displacement signal as a precise replacement for simple assumptions. Common to all methods are their specific restrictions as estimation towards the real physics, which always should be kept in mind during interpreting the results. HPSS incorporates reliable measurements and offers to analyse the different displacement component distributions as an important information for serious interpretation of ultrasonic signals. At the moment, discrepancies between simulated and measured results are still present. Approaches for improvements are seen in incorporating thermal linking between single sources and by replacing the analytic source description by CEFIT simulation of the thermoelastic source [4]. Although at this early stage, the HPSS method was successfully used to improve an laser-ultrasonic setup. Before starting the measurement itself, several intensity distribution of the excitation laser were created and checked versus their sound field in principle. As a result, favourable beam shapes were found and tested at an transmission setup. The corresponding B-scan images of an aluminium sample (thickness 5 mm) having seven drilled holes as artificial defects of 0.7 mm diameter at rising depths are shown in figure 6. Both images were converted to grayscale images, improved in brightness and contrast for better illustration at the same time and cut into single images afterwards. The improvement in SNR and ability to indicate the location of defects is clearly visible. Especially for advanced NDT&E systems, designed for locating scatterers of specific orientation or responding differently to pressure and shear forces, it is inevitable to have

**Figure 5.** Simulated (solid line) and measured (dashed line) amplitudes over different angles of direction according to a source as shown in fig.1 right image.

**Figure 6.** B-Scan transmission images by using raw laser beam (left) and shaped beam after HPSS analysis (right). Horizontal axis location, 70 mm at 250 µm pitch, vertical axis time, 0 to 3 µs starting at bottom line
knowledge about the sensors characteristics. Further by knowing the focal region, unwanted side lobes or the distribution of different wave types one gets able to correctly interpret ultrasonic signals. In a first successful application, HPSS was used to tailor the laser-acoustic source shape of an experimental setup wherein an automated laser-acoustic scan was done for locating defects inside a metallic sample. For both, reflection and transmission B-scan images, the signal to noise ratio could be improved just by changing the energy distribution across the excitation area.

References
[1] G. F. Miller and H. Pursey, *The field and radiation impedance of mechanical radiators on the free surface of a semi-infinite isotropic solid*, Proc. R. Soc. A, Vol. 223, No. 1155, pp. 521-541, The Royal Society, 1954.
[2] C. B. Scruby and L. E. Drain, *Laser ultrasonics techniques and applications*, Taylor & Francis, 1990.
[3] J.F. Ready *Effects of high-power laser radiation*, Academic Press, New York, NY, 1971
[4] F. Schubert, B. Koehler and A. Peiffer, *Time domain modelling of axisymmetric wave propagation in isotropic elastic media with CEFIT/Cylindrical elastodynamic finite integration technique*, Journal of Computational Acoustics, Vol. 9, No. 03, pp. 1127–1146, World Scientific, 2001.
[5] T. Windisch and F. Schubert, *Ultrasonic wave field determination of laser-acoustic sources with arbitrary shapes*, Ultrasound Symposium (IUS), 2012 IEEE International, pp. 2184–2186, 2012, IEEE
[6] T. Sanderson, C. Ume and J. Jarzynski, *Longitudinal wave generation in laser ultrasonics*, Ultrasónicas, Vol. 35, No. 8, pp. 553 - 561, 1998.
[7] D. Cerniglia, A. Pantano and C. Mineo, *Influence of laser beam profile on the generation of ultrasonic waves*, Applied Physics A: Materials Science & Processing, Vol. 105, No. 4, pp. 959-967, Springer, 2011.
[8] J. M. S. Sakamoto, B. R. Tittmann, A. Baba and G. M. Pacheco, *Directivity measurements in aluminum using a laser ultrasonics system*, Journal of Physics: Conference Series, Vol. 278, 2011, IOP Publishing