PIEZOTRANSDUCERS WITH ACOUSTIC LENSES FORMING NARROW WEAKLY DIVERGING ULTRASONIC BEAMS

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The properties of acoustic fields produced by piezoelectric transducers with "logarithmic" lenses are analyzed. It is demonstrated theoretically and experimentally that such a lens has the ability to collimate the acoustic beam, i.e. transducer with "logarithmic" lens forms a narrow weakly diverging ultrasonic beam. This transducer has a "stretched" focal zone and provides a high lateral resolution within a long axial range. The length of the focal zone and beam diameter can be controlled by varying the lens shape, probe aperture diameter, and center frequency. The "logarithmic" lenses can be employed with very different types of transducers: immersion and contact, spherically and cylindrically focused, high and low frequency, large and small, non-damped and highly damped, and so on.

1. Introduction

One of the principal requirements in ultrasonic systems for non-destructive evaluation and medical diagnostics is a high lateral (frontal) resolution throughout a large depth of field. This requirement can be met if the piezoelectric transducer (transmitter-receiver) used in the system forms a narrow weakly diverging ultrasonic beam within a large axial range (collimated beam). Many papers, books and patents have addressed this problem due to significant practical benefits that are offered by ultrasonic systems capable of producing collimated beams.

Several types of piezotransducers have been designed to address the need for high lateral resolution. The most commonly used approach is to employ a focusing transducer forming a narrow ultrasonic beam in its focal spot. However, the major disadvantage of this design is that the beam widens before and after the focal spot. The focusing in such a transducer is provided either by the shape of the piezoelement or by spherically focusing acoustic lens. The application of different shape lenses allows the creation of a transducer with a stretched focal zone [1-3]. Some improvement in lateral resolution can be achieved by using the multi-pointed star-shaped electrodes [4, 5], acoustic zone plates, zone lenses, stepped lenses or annular transducers [4, 6].

In recent years the transducers creating so-called "Bessel beams" or "limited diffraction beams" have been extensively studied [7-10]. Such non-uniformly excited (apodized) piezoelements give a line focus with depth independent beam-width out to a certain depth.

A somewhat different and more general approach to develop the non-uniformly excited piezotransducers, which can form a specified directivity pattern (e.g. with a narrow main lobe and low level side lobes), has also been developed [11-14].

At present time, multi-element transducers (phased arrays) provide the best results in acoustic field focusing throughout a large depth of field. In such arrays, each piezoelement (in transmission mode) is excited by a uniform electric field of specific amplitude and phase independently of all other elements. As a result, different elements radiate different acoustic signals. With the proper choice of exciting electric signals, the interference of the transmitted ultrasonic waves will generate a narrow main lobe and low-level side lobes in the directivity function. However, such transducers need fairly complex electronic circuitry and operational software, have low energy efficiency and low lateral elevation resolution (for linear phased arrays), are large in size and fairly expensive.

Naturally, each type of transducers mentioned above has its advantages and disadvantages. This paper presents an analysis of special acoustic lenses with “logarithmic” profile. These lenses offer the simplest and least expensive route to obtain a stretched focal zone with fairly high lateral resolution and energy efficiency, thus providing a good sensitivity and lateral resolution over a large depth of field. At the same time, the transducers with such lenses are pretty simple and can be manufactured in a variety of sizes and frequencies to match the application. It is mostly for these reasons that different lenses forming relatively narrow and weakly diverging ultrasonic beams have been studied and developed in recent years [1-3, 6, 9, 14-17].

2. Theory

Let the piston transducer of radius R positioned at $z=0$ in axial direction has in transmission mode the axially symmetric pressure distribution $P(\rho)$ on its front surface. Then, pressure field $P(r,z,t)$ created by this transmitter at any point (r,z) can be written for a monochromatic continuous signal as [19]

$$P(r,z,t)=-\frac{j\,k\exp(j\,\omega t)}{4\pi}\int_0^R\int_0^{2\pi}P(\rho)\frac{\exp(-j\,k\,r)}{r_0}\left(1+\frac{z}{r_0}\right)\rho\,d\rho\,d\varphi\,, \qquad (1)$$

where ρ and φ are the polar coordinates of the radiation point, $k=2\pi/\lambda$ is the wave-number, λ is the wave-length, $r_0=\sqrt{z^2+\rho^2+r^2-2r\rho\cos\varphi}$ is the distance between transmission and observation points, and ω is the angular frequency.

For transducers with non-flat front surface the integration should be performed by this curvilinear surface. Note, that since time-dependent factor $\exp(j\omega t)$ does not influence the subsequent analysis for monochromatic continuous signals, it can be omitted.

It is well known, that in general case double integral (1) cannot be reduced to a single integral in the near (Fresnel) zone [19]. However, for standard axially symmetric piston with constant pressure distribution $P(\rho)=consant$ on its front surface for the paraxial area and in the Kirchhoff approximation ($kr>1$ and $kR>1$) it can be done [20]. Method developed in [20] presents acoustic field in the near zone of piston axially symmetric transmitter as a single integral with fixed limits. Pressure $P(r,z)$ is a modulus of complex function

$$P(r,z)=\left| \exp(-j\,k\,z)+\int_0^{\pi} \exp(-j\,k\,s)\,\frac{z}{s}\,\frac{R\,r\cos\psi - R^2}{R^2+r^2-2\,R\,r\cos\psi}\,d\psi \right| , \qquad (2)$$

where $s^2 = z^2 + R^2 + r^2 - 2\,r\,R\cos\psi$.

Using this method, the near zone acoustic field of an annular transmitter can be obtained by subtracting the results for two disks of different radii. This method was applied to compute the acoustic field of transducer with lens, i.e. field created by probe with non-uniform pressure distribution on the front surface. To do it, the transducer was represented as a set of rings [14]. Then the reversed technique was developed, which allowed solving the synthesis problem, i.e. calculating the lens shape depending on the required acoustic field. However, this calculation technique is a very complicated one: it contains many steps including integration by curvilinear surface of the lens.

Another, more simple theoretical approach was also used for lens shape calculation. This simple method was based on the geometrical acoustics and assumed that lens areas with different radial coordinates focused acoustic beam in different axial areas.

These two calculation techniques, which allow performing the lens synthesis, i.e. computing shapes of various acoustic lenses depending on the required acoustic field, were used to calculate lenses with different logarithmic profiles, which form narrow weakly diverging acoustic beams (see [14] for details). Note that both methods of computation gave similar results. Performing these calculations, the optimum lens profile was computed, at which a special criterion of beam narrowness reaches the maximum [14]. In other words, the optimum shape of lens maximizing this criterion, leads to the formation of a narrow weakly diverging ultrasonic beam within a specified axial range.

The shape of a typical logarithmic acoustic lens is shown in Fig. 1. Such a lens forms a narrow weakly diverging acoustic beam throughout the required axial range. Central part of the lens focuses the UT waves close to the transducer (blue rays in Fig. 1), while the peripheral part of the lens focus the UT waves far from the transducer (red rays in Fig. 1).

In other words, a logarithmic lens is a focusing acoustic lens with a varied focal length: small for the central part of the lens and large for the peripheral part of the lens. As a result, the acoustic field created by such a transducer has a stretched focal zone, where the UT beam is narrow and collimated. By changing the lens shape, the beam diameter and length of focal zone can be controlled. Although a logarithmic lens is not the best technique to form a narrow collimated beam (non-uniformly excited apodized piezoelements with a system of annular electrodes and oscillating pressure distribution on the surface provide better results, see [14] for details), it is the simplest and most energetically efficient way to do it.

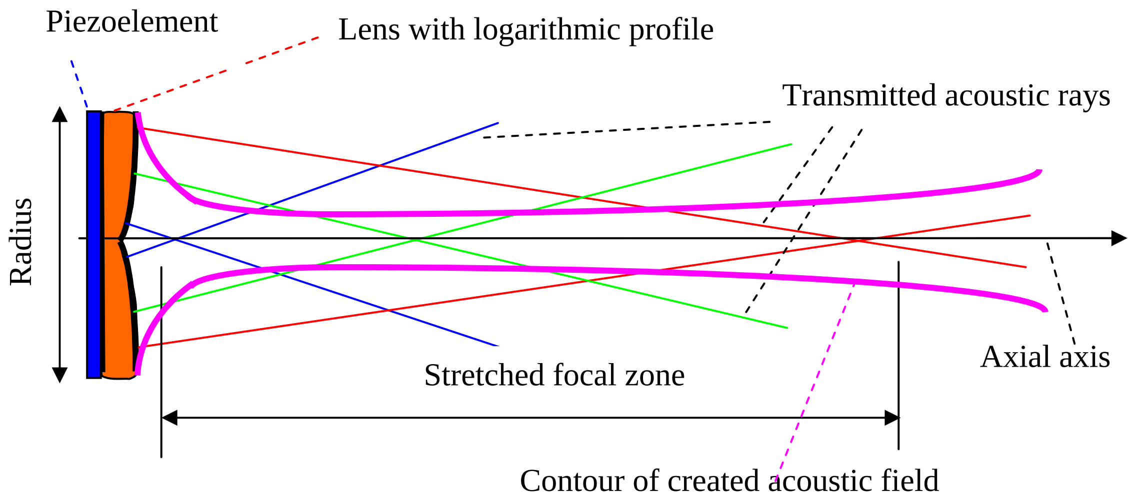

Figure 1. Typical acoustic lens with logarithmic profile.

Transducer with an axially symmetric logarithmic acoustic lens forms a narrow axially symmetric weakly diverging UT beam. Transducer with a cylindrical logarithmic lens creates a “knife-like” ultrasonic beam: narrow and weakly diverging in one direction but wide and uniform in the perpendicular direction.

If logarithmic surface of the lens is attached to the piezoelement and the front (radiating) surface is flat, then such a probe can be used as an immersion or contact transducer. At the same time, this transducer has a stretched focal zone, providing focusing within a large axial range. The logarithmic lens can be machined e.g. on the inner surface of a removable delay line. The cavity between the lens and probe’s flat surface should be filled with oil or some other suitable material to facilitate coupling.

3. Design

Acoustic logarithmic lenses (both spherical and cylindrical) with different dimensions, focusing UT beam within the specified axial ranges were calculated for transducers with various center frequencies.

Piezoelectric probes with these lenses were manufactured at UTX, Inc. (Holmes, NY). Piezoelectric materials, such as PZT-5H piezo-ceramic, 1-3 piezo-composite and lead metaniobate K-83, were used as the active elements. Round and rectangular elements were used for spherically and cylindrically focused transducers, respectively. All probes were highly damped to produce a broad bandwidth. The lenses were cast from epoxy and had the required logarithmic profile. Transducer with diameters of 6.35, 9.5 and 15.9 mm and center frequencies of 10, 15 and 20 MHz were manufactured (see Fig. 2).

Figure 2. Transducers with acoustic logarithmic lenses.

Transducer with cylindrically focused logarithmic lens creates a “knife-like” ultrasonic beam: narrow and weakly diverging in one direction but wide and uniform in the other direction.

Besides the immersion probes, a few contact transducers with removable acrylic delay lines were manufactured. Logarithmic acoustic lenses were machined on the inner surface of the delay lines and cavities between the lenses and active elements were filled in with oil. All transducers had metal cases with standard connectors.

4. Experimental results

The acoustic fields of different transducers with logarithmic lenses were measured in an immersion tank in pulse-echo (PE) mode according to standard techniques [18]. A 1.5mm stainless steel ball was used as a test target (reflector) and a UTEX UT-340 pulser-receiver was used for transducer excitation. The immersion tank had a computerized scanning bridge that allowed motion of the ball-reflector in three dimensions with 0.25mm accuracy.

Note that in accordance with [3] the ball-target diameter should be greater than at least ten wavelengths of transducer center frequency in water. It makes the reflector non-directional, allows examination of small spatial variations in the acoustic field, while at the same time producing a sufficient energy response.

The results showing acoustic fields of different transducers with logarithmic lenses [17] are presented in Figs. 3-10. Color pictures show the axial-radial cross-section of the probes acoustic field, where color determines the intensity of the acoustic field (PE response amplitude). The top graph represents the amplitude distribution along the transducers axial axis. The left graph gives the amplitude distribution in the radial direction (beam profile).

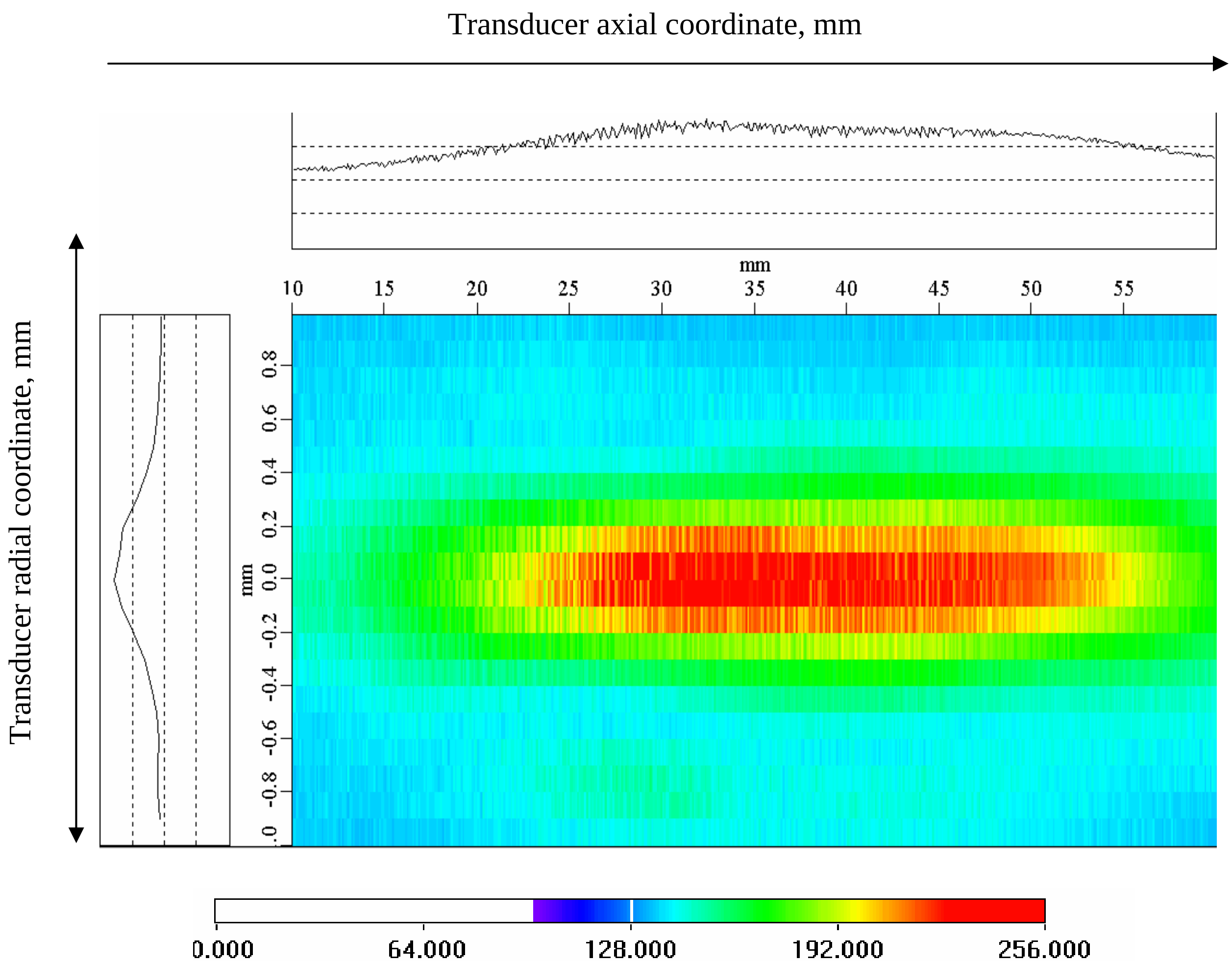

Figure 3. Axial-radial cross-section of acoustic field of an immersion transducer with logarithmic lens. Measured in immersion tank in PE mode with 1.5mm ball-reflector. Probe made from lead metaniobate Keramos K-83, aperture diameter D=9.5mm, center frequency f=20MHz, stretched focal zone FZ=~23-54mm at –6dB level (see top graph), beam diameter d=~0.4mm at –6dB level (see left graph). Radial and axial coordinate axes are shown on the left and on the top respectively. (Note that calculations and design of this probe were based on the objective to create 20MHz transducer able to provide acoustic beam with FZ=15-50mm and d=0.5mm).

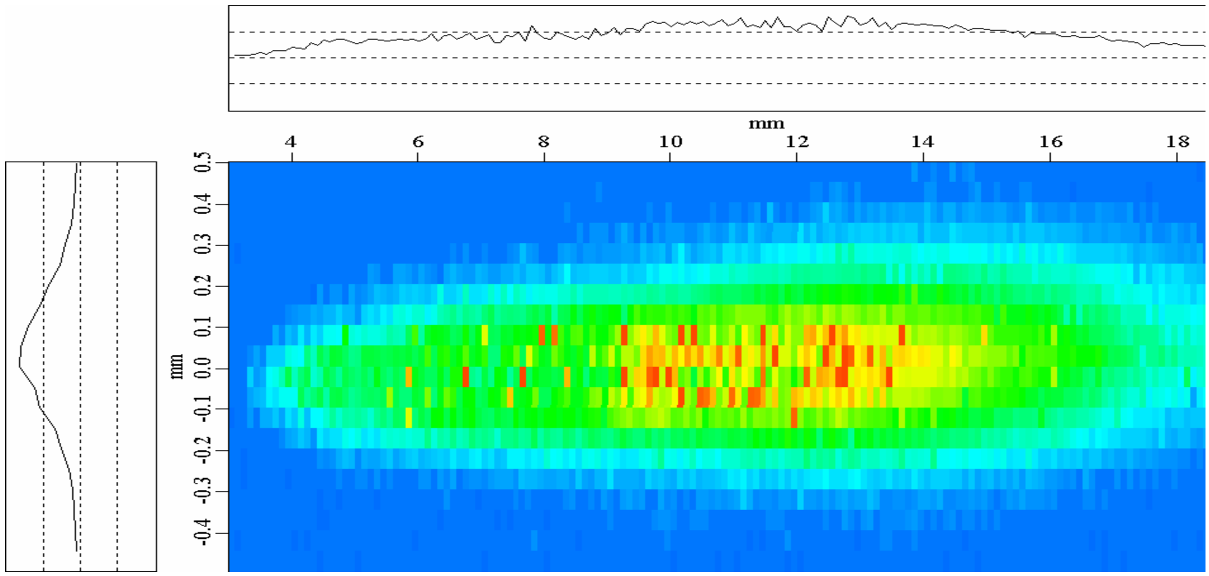

Figure 4. Axial-radial cross-section of acoustic field of immersion transducer with logarithmic lens. Measured in immersion tank in PE mode with 1.5mm ball-reflector. Probe from K-83, D=6.35mm, f=20MHz, FZ=~7-15mm at –6dB level (see top graph), d=~0.2mm at –6dB level (see left graph). Color scale and coordinate axes are shown in Fig. 3. (Calculations and design of this probe were based on the objective to create 20MHz transducer able to provide acoustic beam with FZ=5-20mm and d=0.2mm).

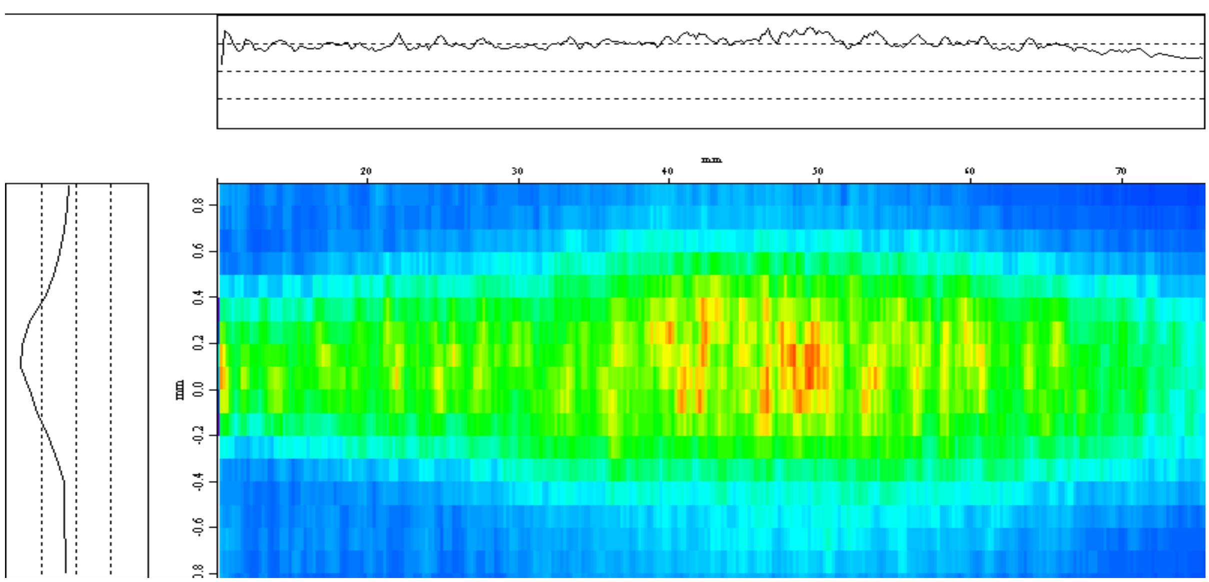

Figure 5. Axial-radial cross-section of acoustic field of immersion transducer with logarithmic lens. Measured in immersion tank in PE mode with 1.5mm ball-reflector. Probe from K-83, D=9.5mm, f=15MHz, FZ=~15-64mm at –6dB level (see top graph), d=~0.6mm at –6dB level (see left graph). Color scale and coordinate axes are shown in Fig. 3. (Calculations and design of this probe were based on the objective to create 15MHz transducer able to provide acoustic beam with FZ=10-80mm and d=0.5mm).

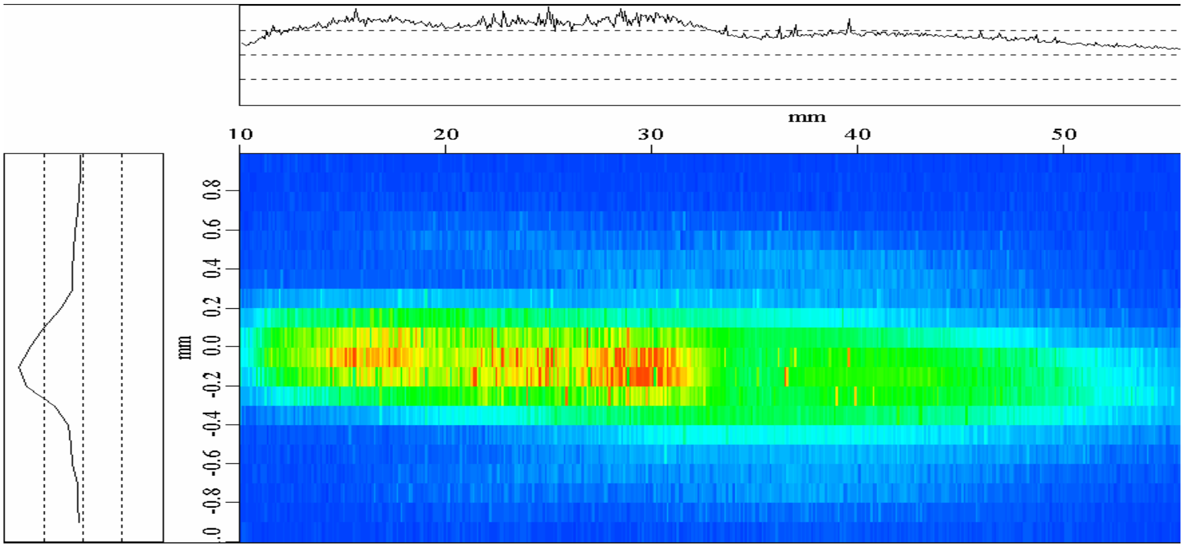

Figure 6. Axial-radial cross-section of acoustic field of immersion transducer with logarithmic lens. Measured in immersion tank in PE mode with 1.5mm ball-reflector. Probe from K-83, D=9.5mm, f=15MHz, FZ=~15-42mm at –6dB level (see top graph), d=~0.4mm at –6dB level (see left graph). Color scale and coordinate axes are shown in Fig. 3. (Calculations and design of this probe were based on the objective to create 15MHz transducer able to provide acoustic beam with FZ=10-50mm and d=0.3mm).

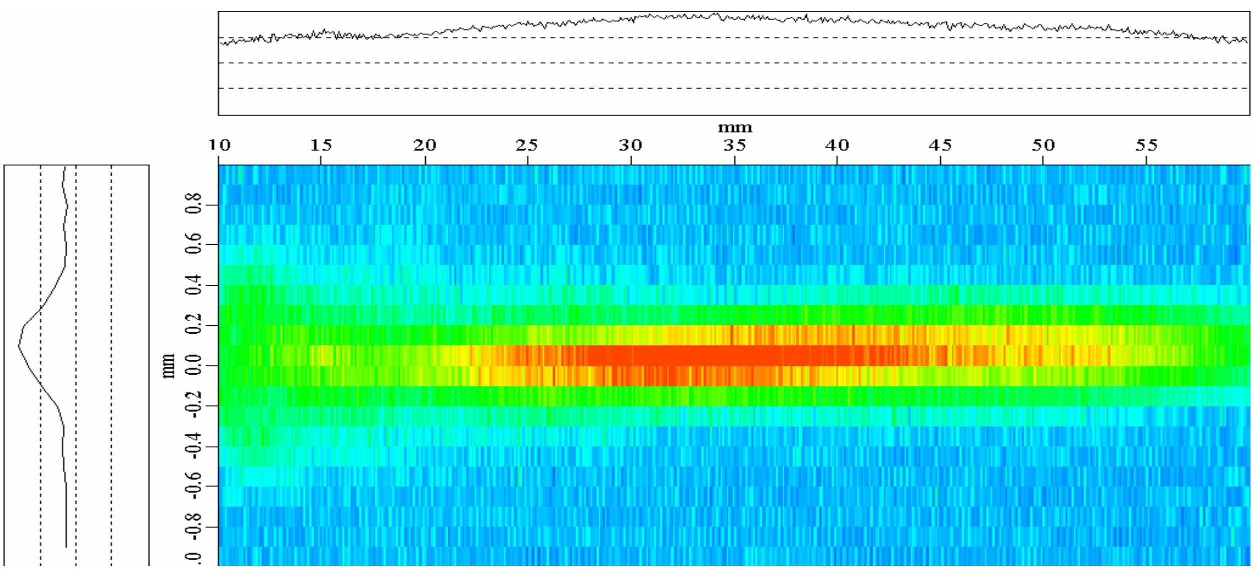

Figure 7. Axial-radial cross-section of acoustic field of immersion transducer with logarithmic lens. Measured in immersion tank in PE mode with 1.5mm ball-reflector. Probe from K-83, D=15.9mm, f=20MHz, FZ=~17-56mm at –6dB level (see top graph), d=~0.4mm at –6dB level (see left graph). Color scale and coordinate axes are shown in Fig. 3. (Calculations and design of this probe were based on the objective to create 20MHz transducer able to provide acoustic beam with FZ=10-50mm and d=0.3mm).

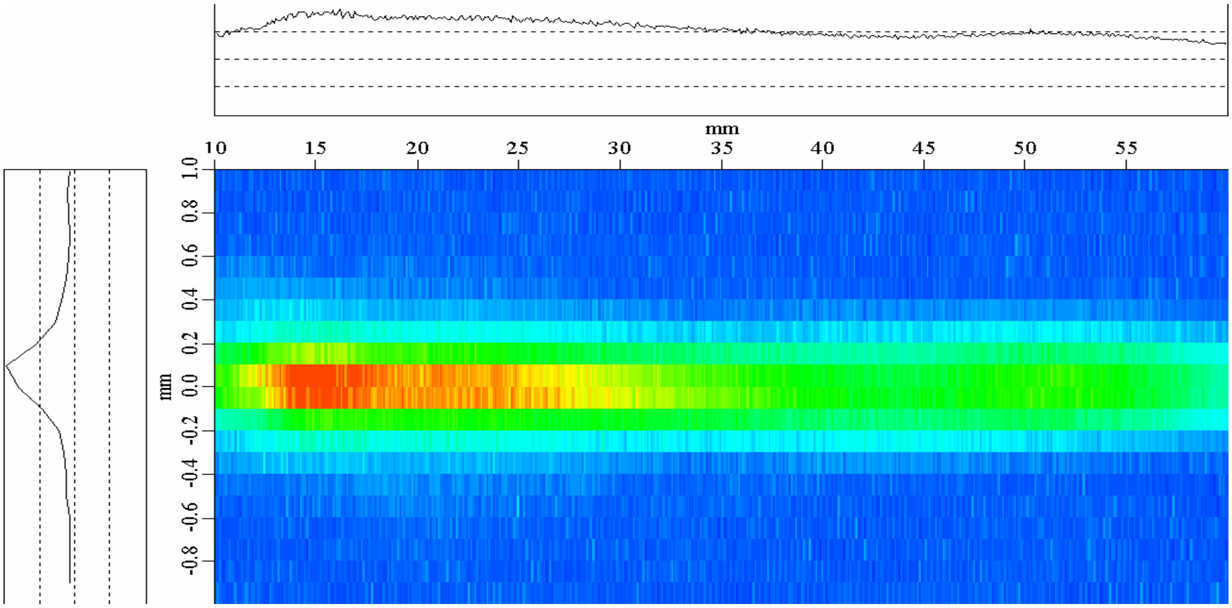

Figure 8. Axial-radial cross-section of acoustic field of immersion transducer with logarithmic lens. Measured in immersion tank in PE mode with 1.5mm ball-reflector. Probe from K-83, D=15.9mm, f=20MHz, FZ=~12-53mm at –6dB level (see top graph), d=~0.4mm at –6dB level (see left graph). Color scale and coordinate axes are shown in Fig. 3. (Calculations and design of this probe were based on the objective to create 20MHz transducer able to provide acoustic beam with FZ=15-60mm and d=0.4mm).

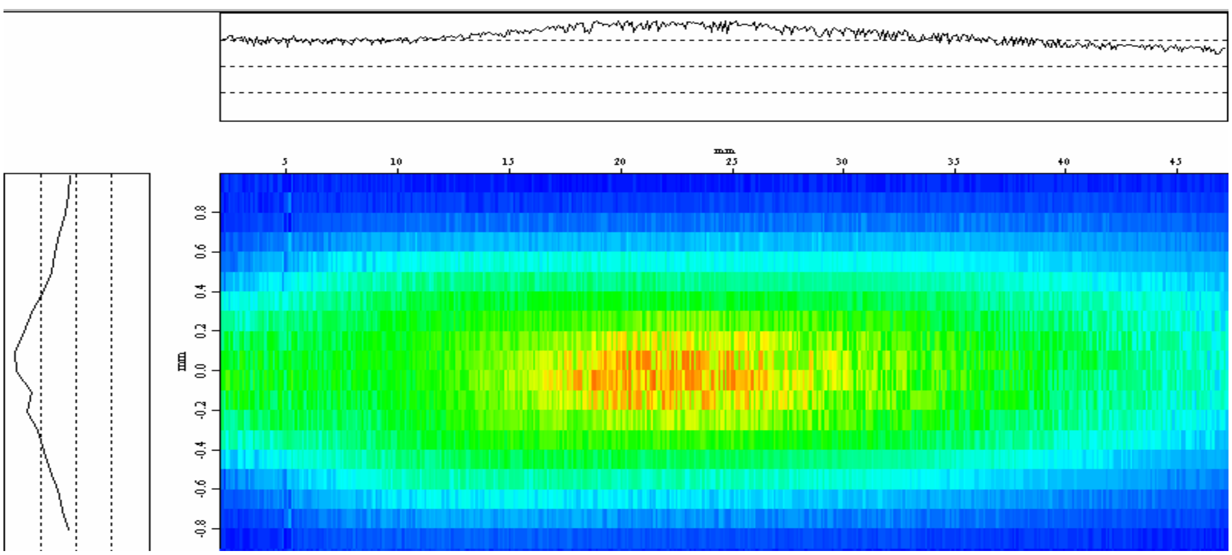

Figure 9. Axial-radial cross-section of the acoustic field of a contact transducer with logarithmic lens. Measured in an immersion tank in PE mode with a 1.5mm ball-reflector. Probe from PZT-5H, D=6.35mm, f=15MHz, FZ=~2-38mm at –6dB level (see top graph), d=~0.8mm at –6dB level (see left graph). Color scale and coordinate axes are shown in Fig. 3. (Calculations and design of this probe were based on the objective to create 15MHz transducer able to provide acoustic beam with FZ=0-50mm and d=0.7mm).

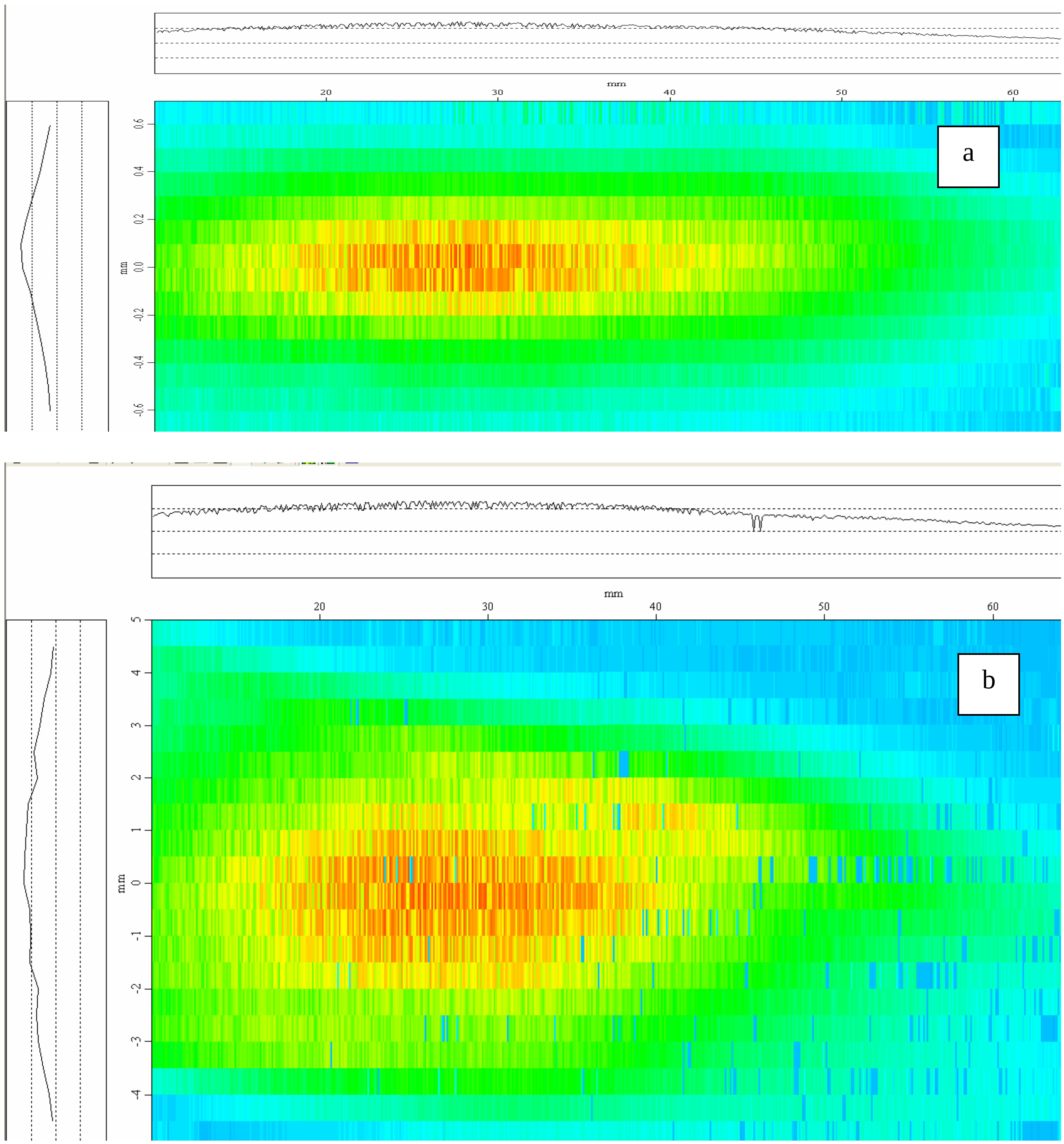

Figure 10. Axial-radial azimuthal (a) and elevation (b) cross-sections of acoustic field of immersion transducer with cylindrical logarithmic lens. Measured in immersion tank in PE mode with 1.5mm ball-reflector. Probe from K-83, rectangular 9.5x9.5mm^2, f=10MHz, FZ=~15-45mm at –6dB level (see top graphs in "a" and "b"), and d_1=~0.7mm at –6dB level (see left graph in "a") in azimuthal direction and d_2= ~8mm at –6dB level in elevation direction (see left graph in "b"). Color scale and coordinate axes are shown in Fig. 3. (Calculations and design of this probe were based on the objective to create 10MHz cylindrically focused transducer able to provide acoustic beam with FZ=10-50mm and "knife-like" beam: narrow (d_1=0.6mm) in azimuthal direction and wide d_2=9mm in elevation direction).

Figs. 3-10 clearly demonstrate that transducers with logarithmic lenses create narrow collimated acoustic beams. As one can see from captions to Figs. 3-9, the real focal zones of these probes, measured in water, are pretty close to theoretical stretched focal zones, transducers were calculated for. It confirms the initial assumptions, general approach, method and accuracy of calculations.

The length of the focal zone and UT beam diameter depend on the lens shape, probe aperture diameter, and center frequency. For example, Fig. 3 shows that a logarithmic acoustic lens of 9.5mm diameter attached to a 20MHz piezoelectric disk can create a UT beam 0.4mm diameter at –6dB level stretched from 20mm to 55mm. Recall, that if transducers aperture diameter and center frequency are fixed, the beam diameter and length of the focal zone can be controlled by changing shape of the lens.

Logarithmic lenses can be employed in various types of transducers: immersion and contact, spherically and cylindrically focused, high and low frequency, large and small, non-damped and highly damped, and so on.

5. Conclusions

1. Acoustic lenses with logarithmic profiles forming narrow weakly diverging ultrasonic beam were computed. The lens synthesis problem was developed and solved, enabling the determination of the lens surface profile forming the desired acoustic field. This method was applied to a lens creating a narrow weakly diverging axially symmetric ultrasonic beam in the near zone.
2. Collimating transducers with such lenses were designed and manufactured. These probes were made from different piezoelectric materials; they had round and rectangular shapes, various sizes and center frequencies. The logarithmic lenses were axially and cylindrically shaped. Besides the immersion probes, a few contact transducers with removable acrylic delay lines and logarithmic lenses on its top were manufactured.
3. The acoustic fields of different collimating probes with various logarithmic lenses were measured in an immersion tank in PE mode. The measurement data match the computations and thus confirm the theoretical approach and calculation method.
4. The obtained results clearly demonstrate that transducers with logarithmic lenses create narrow collimated acoustic beams, thus providing high lateral resolution of the UT inspection system. The length of focal zone and UT beam diameter depends on the shape of the lens, probe aperture diameter, and center frequency. If transducer aperture diameter and center frequency are fixed, than beam diameter and length of the focal zone can be controlled by changing the shape of the lens.
5. Logarithmic lenses can be employed in very different types of transducers: immersion and contact, spherically and cylindrically focused, high and low frequency, large and small, non-damped and highly damped, and so on.

6. References

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