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DETERMINING THE ACOUSTIC FIELD DISTRIBUTION OF ULTRASONIC MULTI-ELEMENT PROBES

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The paper presents a universal method of determining the distribution of acoustic field of multi-element probes designed for applications in ultrasound transmission tomography (UTT). This method allows us to calculate the acoustic field for different sectors of the probe with assigned geometry of elementary transducers' location. The idea is to sum acoustic fields generated by all elementary transducers with the use of geometrical transformations of coordinates of location of the discussed points of the acoustic field against each of the transducers. In order to verify the calculation results measurements of acoustic field distribution were also carried out for selected sectors of these probes. On the basis of an analysis of calculation results the size of electronically switched transmitting sector was optimized (in the sense of the number of concurrently radiating elementary transducers) for a linear and a ring ultrasonic multi-element probes from the point of view of their use for visualizing the inside of a biological structure by means of UTT.

Key words: acoustic field, ultrasonic multi-element probes, piezoelectric transducers, ultrasound transmission tomography.

1. Introduction

In Ultrasound Transmission Tomography (UTT) it is possible to choose different kinds of scanning geometries of the investigated object in order to visualize its internal structure (Fig. 1). Yet in each of these geometries it is necessary to use a transmitter-receiver setup [1]. The use of multi-element linear ultrasonic probes with the possibility of fast switching over particular transducers (parallel-ray projection geometry [1]) allows us to eliminate the movement of the pair of single-element transmitting and receiving probes along the object. To eliminate the movement of the pair of probes both along and around the object, it is most advantageous to elaborate one multi-element transmitting-receiving ring probe (fan-beam geometry [1]), maintaining equal angles between particular elementary transducers. In addition, multi-element probes allow us to shape the directional characteristic of the ultrasonic wave source depending on the number of excited transmitting transducers and to increase the level of the acoustic pressure produced.

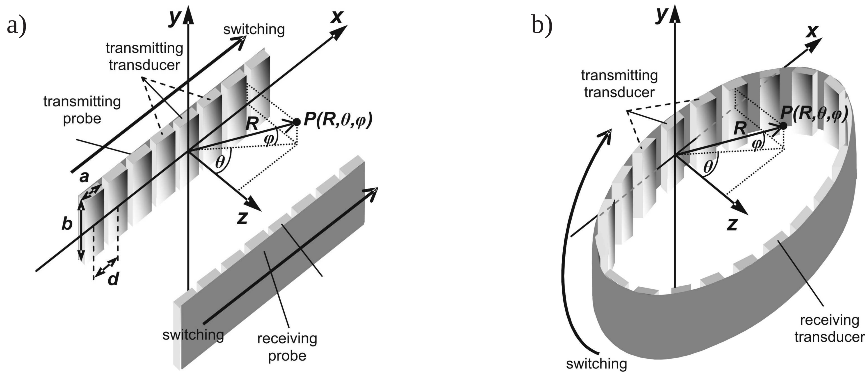

Fig. 1. Scanning geometry of object in UTT by means of ultrasonic multi-element probes: a) pair of linear probes, b) ring probe.

This paper investigates and analyzes the distributions of the acoustic field of the elaborated multi-element (linear and ring) probes from the point of view of their applications for visualizing the inside of biological structures by UTT.

2. Construction of the probes

For UTT two 128-element linear probes working at the frequency of 1.8 MHz [2] were elaborated. Each probe can work both as the transmitter and as the receiver. The probes are made of rectangular piezoelectric elements measuring $0.5\ \mathrm{mm} \times 18\ \mathrm{mm}$ and 1 mm thick, placed at 0.2 mm intervals on a plexiglass plate 20 mm thick. What was also elaborated was a 1024-element ring probe working at the frequency of 1.7 MHz [2]. The ring probe is made of rectangular piezoelectric elements measuring $0.5\ \mathrm{mm} \times 18\ \mathrm{mm}$ and 1 mm thick placed at 0.2 mm inside a plexiglass ring with a diameter of 228 mm and height of 90 mm. All elementary transducers of the probes can work as transmitters or as receivers and can be combined into groups both while transmitting and while receiving.

3. Calculations

The multi-element tomographic probes are designed for operating in the water serving as a medium coupling ultrasonic transducers with the investigated biological structure. The amplitude of the acoustic velocity was assessed basing on the assumption that the value of the shift amplitude of a vibrating water particle was ca $1\ \mu$m. At the frequency of ca 1.8 MHz the time it takes to reach such a deflection is $0.25/1.8\ \mathrm{MHz} = 0.1389\ \mu$s, which enables assessing the amplitude of acoustic velocity $V_0 \approx 7$ m/s. The remaining parameters necessary for calculating the acoustic field distribution in the water were assumed according to Table 1.

Table 1. Values of parameters assumed for calculations.

V_0 [m/s]	c [m/s]	ρ [kg/m^3]	f [MHz]	λ [mm]	k [rad/mm]	a [mm]	b [mm]	d [mm]	N	$\tilde{p}_0$ [µPa]
7	1490	1000	1.8 1.7	0.82778 0.87647	7.59043 7.16873	0.5	18	0.7	128 1024	1

The effective value (RMS) of the acoustic pressure level radiated by the linear probe at point $P(R,\theta,\varphi)$ in the far field and in the setup of coordinates as in Fig. 1a was determined by means of a formula included in the paper [3].

For a sector of the multi-element ring probe (with the elementary transducers placed inside the ring) a method of determining the level of acoustic pressure at point $P(R,\theta,\varphi)$ in the far field was proposed in the setup of coordinates as in Fig. 1b as a sum of geometrical transformations of fields calculated for all single elementary transducers of the sector:

$$L_{\tilde{p}} = 20\log\left\{\left|\sum_{i=0}^{n-1} -\frac{j\rho c k V_0}{2\pi R_i} ab\, e^{j(\omega t - kR_i)}\left[\frac{\sin\left(\dfrac{u_i a}{2}\right)}{\dfrac{u_i a}{2}}\right]\left[\frac{\sin\left(\dfrac{wb}{2}\right)}{\dfrac{wb}{2}}\right]\right| \cdot \frac{1}{\sqrt{2}\tilde{p}_0}\right\}, \tag{1}$$

where n – the number of transducers in the sector, $u_i = 2\pi \cdot \sin(\theta_i)/\lambda$, R_i, θ_i – polar coordinates of point $P(R,\theta,\varphi)$ corrected in relation to the location of the $(i+1)$-th transducer in the sector, ρ – the medium density, c – the sound velocity in the medium, λ – the wavelength, k – the wave number, V_0 – the amplitude of acoustic velocity, $\tilde{p}_0$ – the reference pressure for an ultrasonic wave propagated in the water, a – the width of the elementary transducer, b – the height of the elementary transducer, whereas:

$$u = \frac{2\pi\sin\theta}{\lambda}, \qquad w = \frac{2\pi\sin\varphi}{\lambda}. \tag{2}$$

In the case of the ring probe, the geometrical transformation of the location of every point in the field $P(R,\theta,\varphi)$ in Eq. (1) is conducted symmetrically towards each $(i+1)$-th transducer in the sector by turning around the symmetry axis a probe with coordinates $O(r = R_p,\, \theta = 0)$ parallel to the y axis (where R_p denotes the probe's inner diameter) by the appropriate multiple of the half of the angle $\beta = i \cdot 2\pi/N$ (where N is the number of all the transducers of the probe). The complex values of the pressure corrected this way are next summed for all n points, giving us the resultant pressure in each considered point of the field $P(R,\theta,\varphi)$ generated by the analyzed sector of the probe. The corrected coordinates of point $P(R,\theta,\varphi)$ for subsequent turns in the Cartesian setup can be determined by means of the following equations:

$$\begin{aligned} x_i &= x\cos(\beta_i) - (z - R_p)\sin(\beta_i)\,, \\ z_i &= R_p + (z - R_p)\cos(\beta_i) + x\sin(\beta_i), \end{aligned} \tag{3}$$

where, because of the necessity to maintain the symmetry towards the assumed set of coordinates, $\beta_i = ((n-1)/2 - i) \cdot \beta$ for the range $i = 0, \ldots, n-1$ ($i+1$ denoting the number of the transducer). It must be emphasized that this method enables calculating the acoustic field for different sectors of any multi-element probe with an assigned geometry of placing the elementary transducers (e.g. for the linear probe the geometrical transformation is moving a single transducer). The attenuation of the acoustic wave in the water was included in the calculations by means of the equation $\alpha = 0.00022$ dB/mm/MHz$\cdot f^2$ [3].

4. Measurements

The measurements of the field distribution of the multi-element probes were conducted in the degassed water with a hydrophone HP 0.5 mm manufactured by Precision Acoustics, in the measurement setup as in Fig. 2. The results were recalculated to the level of the acoustic pressure effective value (RMS) in the water ($\tilde{p}_0 = 1$ μPa) taking into account the hydrophone sensitivity (250 nV/Pa) and the amplification in the receiving path (ca 52 dB). The measurements were conducted with a resolution of 0.5 mm, moving the hydrophone in the plane parallel to the surface of the central transducer in the investigated group (1, 3, 5, 7), at the distance of 5 cm and in the range of 8 cm (Fig. 2). The transducers were excited with *burst* pulses (10 cycles, 20 Vp-p).

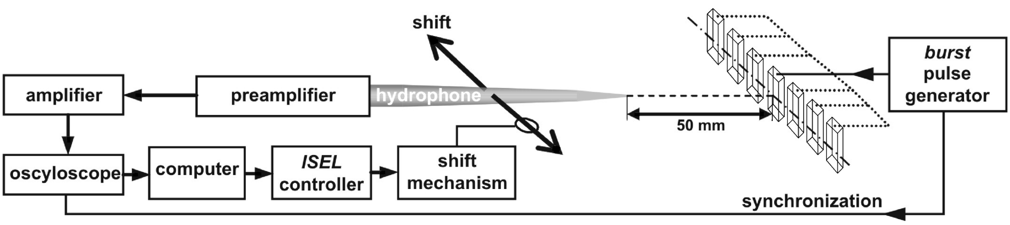

Fig. 2. Scheme of measurement setup.

5. Results

Figures 3 and 4 show a comparison of the calculation results (black line) with the measurements (white line) of the acoustic field distribution for the linear probe and the ring probe. Calculation values were corrected by a stable level -20 dB for the linear probe and -22 dB for the ring probe. Such a correction means decreasing about 10 times the earlier assumed value of the shift amplitude of a vibrating water particle (Sec. 3), that is 0.1μm.

A small asymmetry of the measurement curves is caused most probably by the asymmetry of the probe placement towards the hydrophone. Discrepancies between calculations and measurements can result from the asymmetry of fixing particular elementary transducers on the plexiglass plate.

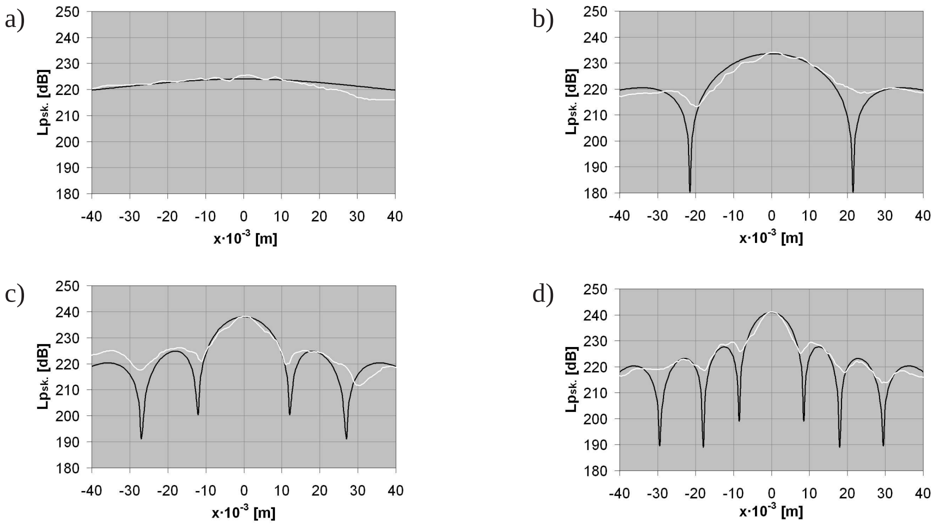

Fig. 3. Comparison of results of calculations and measurements of acoustic field for linear probe: a) 1 transducer, b) 3 transducers, c) 5 transducers, d) 7 transducers.

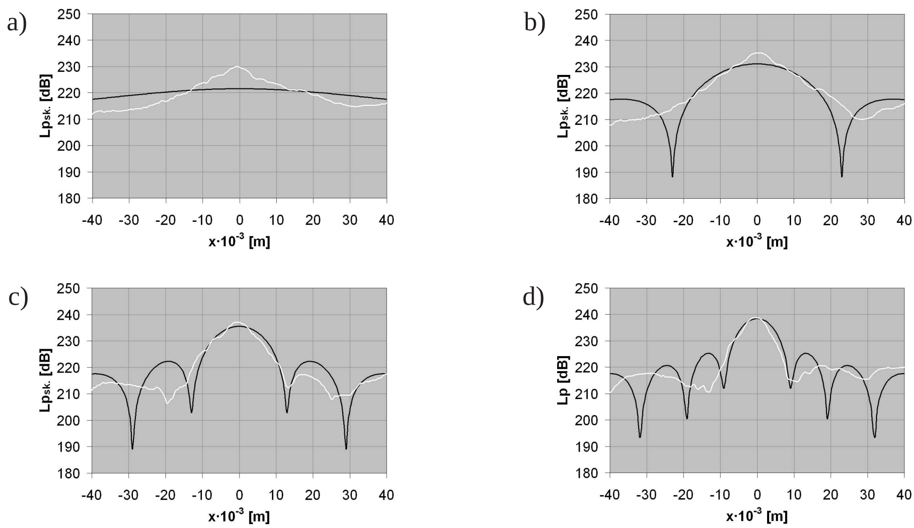

Fig. 4. Comparison of calculations and measurements of acoustic field for ring probe: a) 1 transducer, b) 3 transducers, c) 5 transducers, d) 7 transducers.

6. Conclusions

The results of calculations and measurements confirmed the possibility of shaping the directivity characteristic of multi-element probes and of increasing the pressure level of the radiated ultrasonic wave by exciting different numbers of elementary transmitting transducers. In the case of the linear probe, compared to the ring probe, the increase of the acoustic pressure level as the result of exciting the subsequent transmitting transducers is larger, whereas the width of the main lobe and the lateral lobes is narrower. For the ring probe the level of the main lobe in relation to the lateral lobes is higher than for the linear probe, and the level of the lateral lobes is more equalized. What seems optimal and satisfactory is the use of 1–8 elementary transmitting transducers working simultaneously.

Assuming the linear way of the ultrasonic beam rays, the directivity of ultrasonic probes used in UTT should be as high as possible. Yet because of the occurrence of the refraction and bending effect of the ultrasonic beam rays while running through a heterogeneous structure, with to narrow an angle of the beam's divergence in relation to the angle of its deflection from the transmitter-receiver axis, the ultrasonic pulse may not reach the receiving probe [4]. The wide angle of the beam divergence may be in turn a source of imaging errors, because what will reach the receiving probe will be rays largely deflected from the transmitter-receiver axis, after running through structures from a side [5]. An additional source of errors of the amplitude measurements and the measurements of the runtime of the ultrasonic pulse is the asymmetry of the probe's directivity characteristics results from the non-coaxial positioning of the pair of transmitting and receiving probes [4]. Because of the finite angle of the beam's divergence, the non-coaxial positioning of the probes causes the changes of the shape of the received signal to be different while scanning the object from the left and from the right. Errors of this kind most often introduce an asymmetry of changes of values of signal amplitude and runtime for measurements of the object from the left and from the right. Shaping the directivity characteristics of multi-element tomographic probes by exciting a fixed number of elementary transmitting transducers renders possible the proper adjusting of the transmitting setup parameters to the structure investigated.

The herein presented universal method of determining the acoustic field distribution of multi-element probes will be used in the future for determining the acoustic field distribution with an assumed asymmetry of elementary transducers' positioning.

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