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Study of Crosstalk in Linear Ultrasonic Transducer Arrays

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Summary

Ultrasound systems using multielement ultrasonic arrays of piezoceramic transducers play an important role in medical diagnostics for imaging the inside of the human body *in vivo*. In the process of continuous improvements of operation parameters and measurement precision of those arrays, it turns out that crosstalk effects are one of the main reasons of distortions, which negatively affect the quality of the obtained ultrasonic images. Crosstalk is both a very important and complicated undesirable component of ultrasonic array transducer performance. When one element of the array is driven, it generates parasitic displacement fields at the radiating surfaces of the adjacent elementary transducers, which changes the directivity of used aperture. It directly affects low level decay through delayed signals from adjacent elements and it limits angular dispersion by increasing effective element size. This work presents a study of the phenomenon of crosstalk in one-dimensional linear ultrasonic arrays of piezoelectric transducers (designed for medical imaging), depending on the type of the front matching layer. Additionally, the paper covers the analysis of the effect of the array's activated elementary transducer's position on the intensity and symmetry of crosstalk on adjacent transducers.

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1. Introduction

Ultrasonic transducers are widely used for both industrial and medical applications. They are especially important in medical diagnostics, where they are used to image the inside of the human body *in vivo*. The last 20 years saw dramatic developments in the area of design and miniaturization of 1-D, 2-D or even 3-D multielement ultrasonic piezoceramic transducer arrays [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. In the process of continuous improvements of operation parameters and measurement precision it turns out that crosstalk effects are one of the main reasons of distortions, which negatively affect the quality of the obtained ultrasonic images. They take the form of low amplitude signals in piezoelectric transducers (transmitting or receiving), which are electrically or mechanically activated for undesired operation as a result of propagating signals and vibrations between the array's elements [7]. This results from insufficient mechanical and electrical isolation between the elements such an array consists of. Crosstalk depends on many factors, such as: type and geometry of piezoelectric elements, positioning of those elements, the method of connecting electrodes, type of the connected cables, effectiveness of connection screening and array design [11].

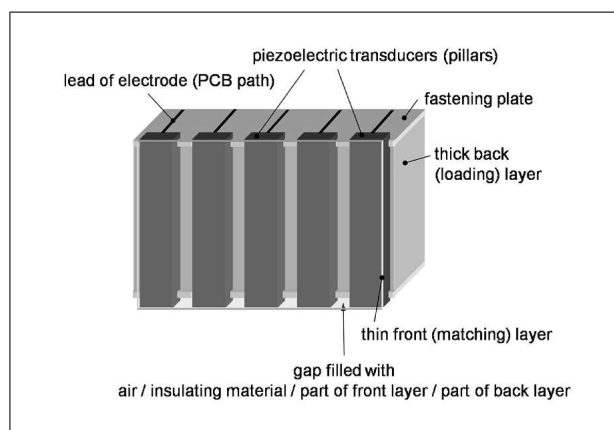


Figure 1. An example of the design of a linear piezoelectric transducer array.

An example of a linear piezoelectric transducer array intended for imaging of internal tissue structure is shown in Figure 1.

Elementary piezoelectric transducers of a linear ultrasonic array operating at the frequency of a few MHz are in the shape of thin pillars with much greater height than width (Figure 1). They are positioned close to one another and supported on both ends in special sockets in PCBs (printed circuit board). The PCBs are distanced in parallel (e.g. with bushings) and make it possible to connect electrodes via tracks suitably etched on their surfaces. Lat-

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eral resolution of ultrasonic imaging of such an array is better, if the elementary transducers are narrower and the distances between them are shorter. Increasing the operating frequency of transducers improves axial resolution (depth), but impairs the range of a medium examination, because of higher attenuation. The effectiveness and sensitivity of transducers depends on their effective radiating surface. In order to maximize it, the transducers are tall. However, their height also restricts vertical directivity characteristics [4]. The arrangement of mounting plates with transducers is filled with special loading mass at the back, which widens the resonance band of transducers (desirable in pulsed operation) and makes it possible to damp the energy that is radiated backwards. The front of the transducers is covered with a thin layer (or several layers) of a material that matches acoustic impedance of piezoceramics to the impedance of the examined medium (tissue). Additionally, this layer has a protective function. Depending on the technology used to manufacture the arrays, the spaces between piezoelectric transducers can be filled with air, back layer material, front layer material or all those media in part.

Electrical crosstalk in an ultrasonic array can be caused by soft capacitive effect between elementary transducers and the material that fills the spaces between them, as well as by electromagnetic induction. Mechanical crosstalk is caused by various modes of vibrations in piezoelectric elements and propagation of those vibrations in the array's construction system. Electrical crosstalk can cause noise, which limits ultrasonic imaging dynamics, and results in appearance of undesirable pulses that distort the image. Mechanical crosstalk usually distorts directivity characteristics of transmission and/or receiving aperture of an array (e.g. occurrence of side lobes) [12]. Mechanical propagation of various vibration modes in the array's construction system can also introduce virtual structures in the ultrasonic images that do not exist in reality. Crosstalk in transmission systems can be a significant problem, because it results in multipath effect during ultrasonic wave propagation. This in turn means that undesirable signals appear in the receiving system closely before the useful pulses, and in effect make it more difficult to make precise measurements of signal runtime between transmitting and receiving transducers of an array [13, 14].

It is, therefore, necessary to eliminate or significantly reduce crosstalk in ultrasonic transducer arrays. A study of the properties of crosstalk and the ways it is generated will make it possible to effectively solve the problem. Literature does not offer much information in this area. There are, however, conference reports covering research on crosstalk in various ultrasonic array types and attempts to reduce the different distortions caused by the phenomenon. Griffith, Lebender and Mueller [15] present methods of minimizing electrical crosstalk by using screened cables – second-generation ribbon-based cables. A work by Dominguez *et al.* [16] presents the evaluation of the crosstalk effects caused by the geometry of the piezoelectric elements in matrix ultrasonic transduc-

ers. As a result it was found that it is possible to reduce the crosstalk effect by using insulating material with low electromechanical coupling coefficient between the ceramics of the array or by using materials that promote good mechanical insulation between the ceramics. Hao-Chung Yang *et al.* [17] suggested an innovative method of using diced 13 piezocomposites with pseudo-random pillars to reduce acoustic crosstalk between high-frequency ultrasonic linear array elements. In the paper by Zhou and Hosack [18] the inter-element acoustic crosstalk problem in capacitive micromachined ultrasound transducer (CMUT) arrays is discussed. A transfer function matrix approach was used to derive modified transmit waveforms on adjacent elements to reduce the apparent acoustic crosstalk. Ballandras *et al.* [19] developed a method of crosstalk prediction that consists in the computation of harmonic admittance (HA) of an elementary cell of the considered transducer array. The mutual admittance (MA) coupling the different elements of the array is obtained via a Fourier transform involving this HA. It is then possible to estimate the crosstalk effects for a given array of transducers. Abboud *et al.* [20] suggested finite element modeling in the design of ultrasonic transducers and imaging arrays, which makes it possible to visualize and analyze various vibration modes in such systems. Bybi *et al.* [21] modeled a transducer array similar to those used in medical imaging and NDT applications by FEM, to better understand the crosstalk effects. It was shown that the filling material and the matching layer are the major factors contributing to this phenomenon. In order to cancel the crosstalk a correction method consisting in applying adapted electrical voltages to each adjacent element of the active one has been used, in order to reduce the displacement field on their active surface. Similar approach for active cancellation of crosstalk effects in ultrasonic arrays is presented in the paper by Zhou *et al.* [22].

The aim of this work is to study the phenomenon of crosstalk in one-dimensional linear ultrasonic arrays of piezoelectric transducers, depending on the type of the front matching layer. Additionally, the paper covers the analysis of the effect of the array's activated elementary transducer's position on the intensity and symmetry of crosstalk on adjacent transducers.

2. Materials and Methods

A few 1-D linear ultrasonic arrays of piezoceramic transducers were designed and realised for the purpose of this research: three 7-element arrays and one 64-element array (Figures 2, 3). All the arrays use the same Noliac NCE51 piezoceramic plates [23] with about 2 MHz resonance frequency, positioned evenly apart (Figure 2). All the arrays were constructed, based on the design shown in Figure 1 and the only difference in the design of the 7-element arrays is the type of front matching layer that was used. The back loading layer in the 7-element arrays is made of silicone with glass microballoons filled with air. The back layer of the 64-element array is made of epoxide

Table I. Dispersions of the measured conductance (in mS) and the resonant frequency values (in MHz) for all elementary transducers of each array (AVG - average value, SD - standard deviation, Δ - maximum range of variation).

	AVG G_r	ΔG_r	SD G_r	AVG f_r	Δf_r	SD f_r
7-element array with a Craft 520	5.125	1.110	0.368	1.968	0.023	0.007
7-element array with MIX	8.873	5.794	1.866	1.969	0.038	0.012
7-element array with URETHAN	6.564	0.544	0.203	1.891	0.013	0.004
64-element array	10.435	12.840	3.262	1.937	0.033	0.008

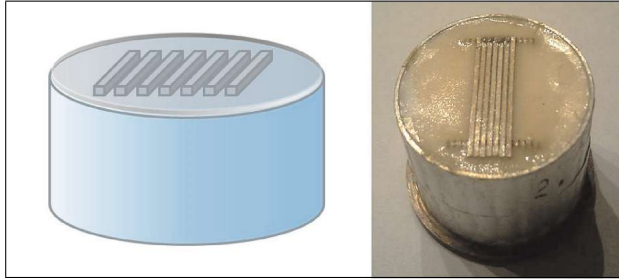


Figure 2. The developed 7-element arrays of piezoceramic transducers.

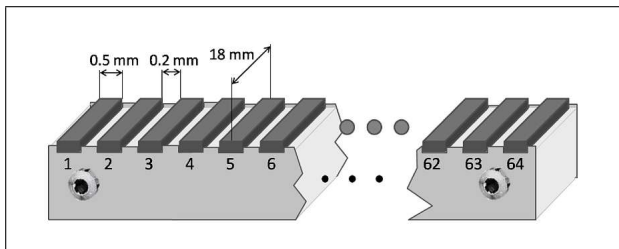


Figure 3. The developed 64-element array of piezoceramic transducers.

resin with added fragmented cork and corundum powder. The surfaces of the transducers in the three 7-element arrays were covered with quarter-wave layers of materials (by spraying over the whole surface of the array) characterised by flexibility ranging from low to high: Craft 520 lacquer, MIX lacquer, isolation coating with added urethan. The 64-element array transducers were not covered with a front layer.

Admittance characteristics $Y = G(f) + jB(f)$ of elementary piezoceramic transducers of elaborated ultrasonic arrays were measured in air and in distilled water using an accurate Wayne Kerr Electronics 65120B impedance analyzer. Results for a sample transducer of each of elaborated arrays were shown in Figure 4. Dispersions of values of the measured conductance $G(f_r) = G_r$ and the resonant frequency f_r in distilled water for all elementary transducers of each array were shown in Table I. Elementary transducers of all elaborated arrays characterised by an average value of the mechanical Q factor in the range of 8–13 and an average value of the electro-acoustic efficiency η in the range of 40–50%. An offset of the susceptance B is caused by the lack of an inductive compensation of the static capacity c_0 of array transducers, which an average value is in the range 90–160 pF.

Block scheme of the measurement setup for measuring crosstalk effects occurring on adjacent transducers of an array, when one of the elementary transducers of this array is activated is shown in Figure 5. Transducers were driven by a single-cycle sinusoidal burst pulse with the frequency of 2 MHz and peak amplitude of 10 V, generated with a 5 ms interval. Signals appearing on other piezoelectric elements of the array were recorded using a digital oscilloscope. The radiating surfaces of the arrays were submerged in a tank with distilled water in order to load the transducers with acoustic impedance similar to the impedance of soft tissue.

3. Experimental Section

Crosstalk measurements were performed for the designed linear ultrasonic arrays (Figure 2, Figure 3) in a measurement setup shown in Figure 5. Measurement results show the differences between crosstalk signals generated on piezoelectric elements of the arrays with increasing distance from the powered transducer.

3.1. 7-element array with a Craft 520 front layer

Figure 6 shows crosstalk signals for a 7-element ultrasonic array with a Craft 520 front layer, recorded for piezoceramic transducers no. 1–6, when transducer 7 was driven.

3.2. 7-element array with a MIX front layer

Figure 7 shows crosstalk signals for a 7-element ultrasonic array with a MIX front layer, recorded for piezoceramic transducers no. 1–6, when transducer 7 was driven.

3.3. 7-element array with an URETHAN front layer

Figure 8 shows crosstalk signals for a 7-element ultrasonic array with an URETHAN front layer, recorded for piezoceramic transducers no. 1–6, when transducer 7 was driven.

3.4. 64-element array without the front layer

Figure 9 and 10 show crosstalk signals for the 64-element ultrasonic array without a front layer, recorded in succession for piezoceramic transducers no. 7–12 and no. 1–6, when transducer 13 was driven.

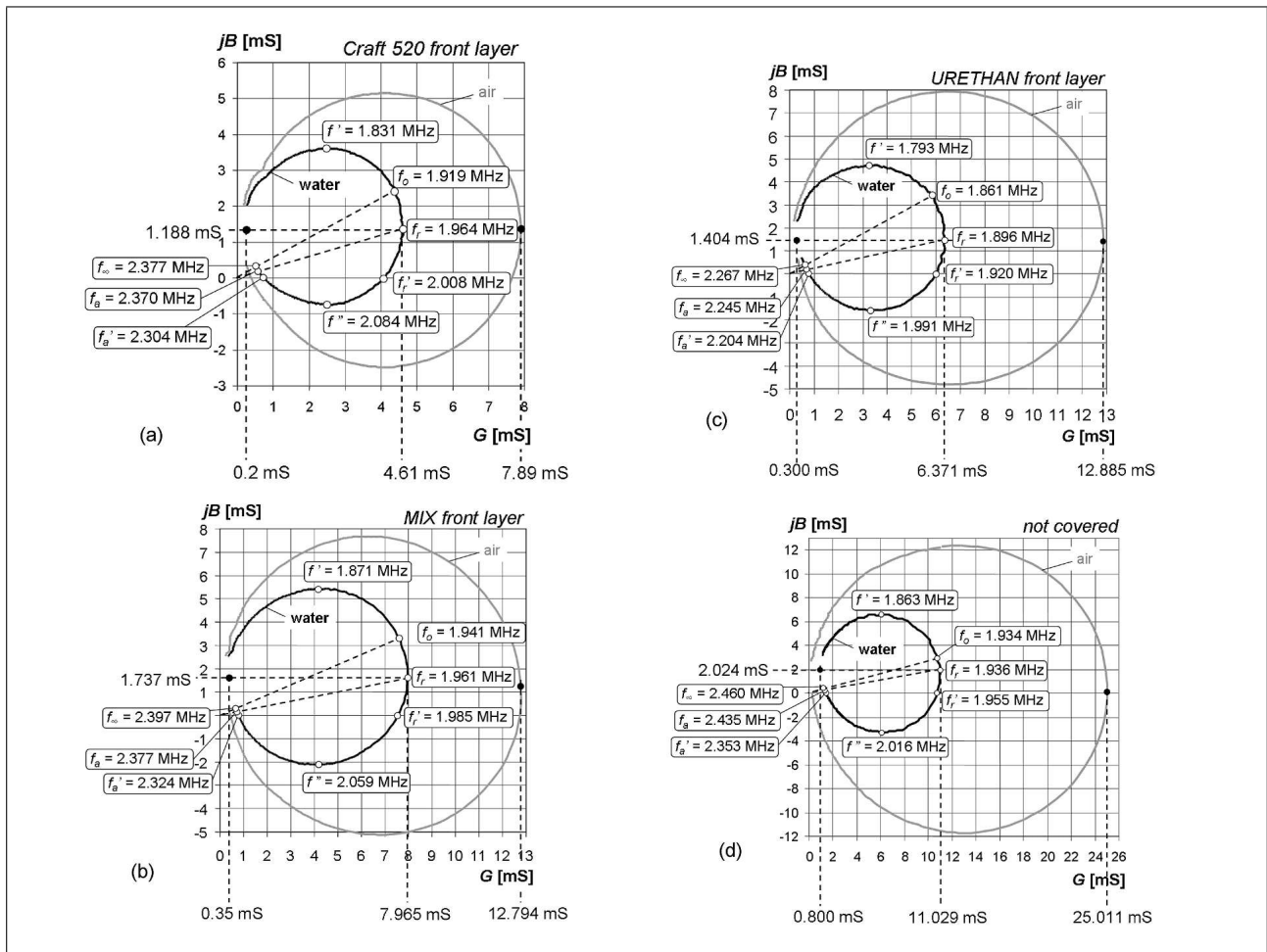


Figure 4. Sample admittance characteristics of a selected elementary piezoceramic transducer of elaborated ultrasonic arrays: 7-element array with a front layer (a-c), 64-element array without a front layer (d).

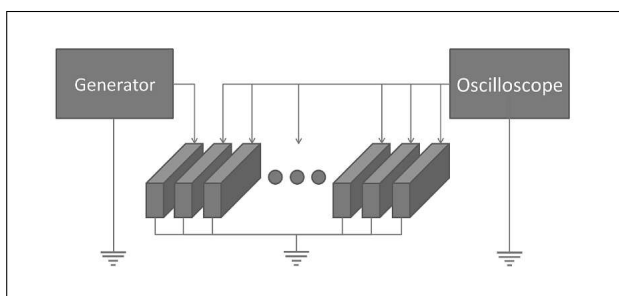


Figure 5. Block scheme of the measurement setup for measuring crosstalk effects in ultrasonic transducer arrays.

4. Results and Discussion

The studies of the linear ultrasonic transducer arrays show occurrence of electrical and mechanical crosstalk effects. Electrical crosstalk results predominantly from transmissivity of the electric activating signal to adjacent array transducers, demonstrated by the pulse recorded at the beginning of the signals (Figures 6–10). Mechanical crosstalk effects occur on adjacent transducers of the array as pulses, the amplitude of which decreases, in relation to the signal activating the transmitting transducer,

with longer distance from the activated transducer. Mechanical crosstalk effects, unlike the electrical ones, occur with a certain delay, which increases with longer distance from the activated transmitting transducer (Figures 6–10). This results from mechanical properties of piezoelectric transducers and structural elements of the array. Ultrasonic waves propagate in them with velocities that are over 5 orders of magnitude lower than the velocity of electromagnetic waves propagation.

Mechanical crosstalk amplitude decreases faster with increasing distance from a transmitting transducer, than electrical crosstalk amplitude. It is also often lower (compare Figure 11 and Figure 12 with Figure 13 and Figure 14).

This section presents the analysis of the changes of amplitude and the delay of crosstalk in relation to the distance from the activated array transducer.

4.1. Electrical crosstalk

Figure 11 shows the relation of electrical crosstalk amplitude on individual piezoelectric transducers to the distance from the activated transmitting transducer no. 7 in 7-element arrays. Figure 12 shows the relation of electri-

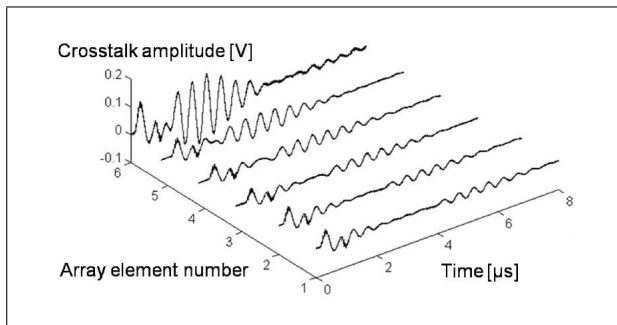


Figure 6. The results of crosstalk effects test for a 7-element ultrasonic array with a Craft 520 front layer, when transducer 7 was driven.

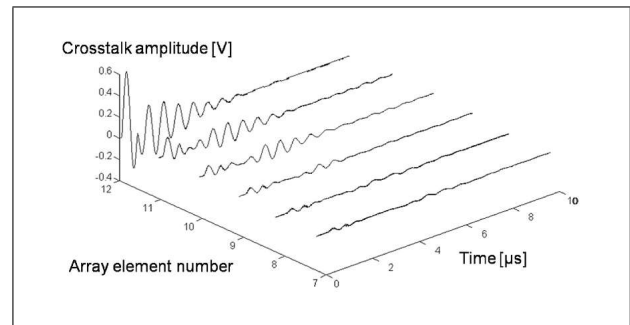


Figure 9. The results of crosstalk effects test for transducer no. 7–12 for the 64-element ultrasonic array without a front layer, when transducer 13 was driven.

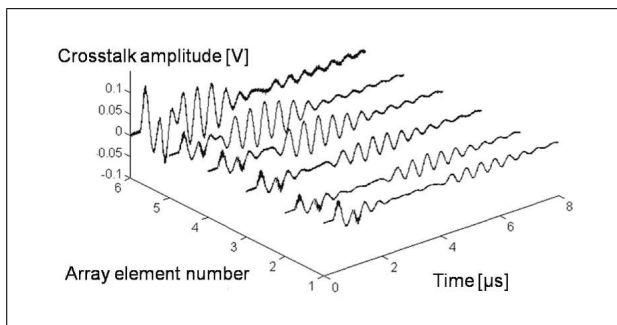


Figure 7. The results of crosstalk effects test for a 7-element ultrasonic array with a MIX front layer, when transducer 7 was driven.

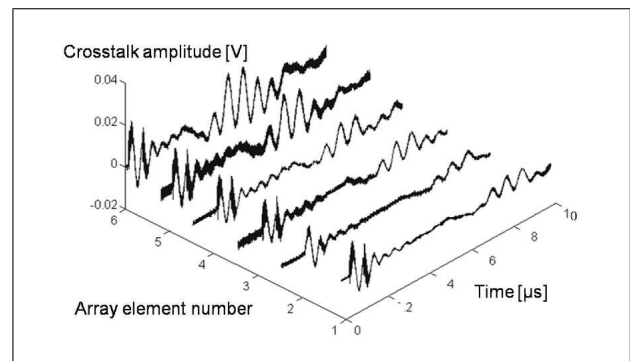


Figure 10. The results of crosstalk effects test for transducer no. 1–6 for the 64-element ultrasonic array without a front layer, when transducer 13 was driven.

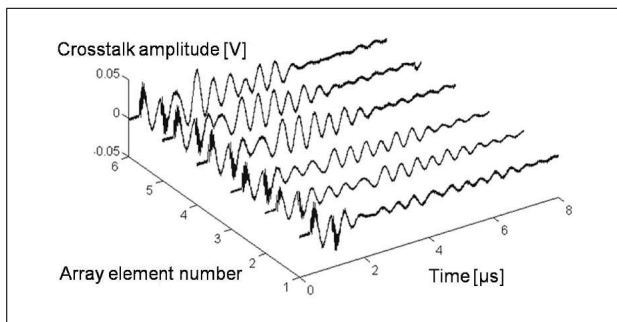


Figure 8. The results of crosstalk effects test for a 7-element ultrasonic array with an URETHAN front layer, when transducer 7 was driven.

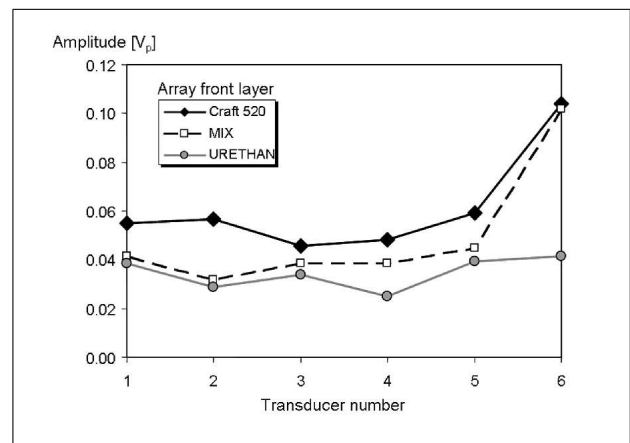


Figure 11. Changes of electrical crosstalk amplitude on individual piezoelectric transducers in the function of distance from the activated transmitting transducer no. 7 in 7-element arrays.

cal crosstalk amplitude on individual piezoelectric transducers to the distance for selected transmitting transducers (no. 13, 16, 19, 22, 25) in the 64-element array.

Electrical crosstalk delay does not change in a way that can be measured by the used measurement system, which is a confirmation of their nature.

The level between the amplitude of the signal activating a transmitting transducer and the electrical crosstalk amplitude on successive transducers in 7-element array with a Craft 520 front layer is about 40 dB for an adjacent transducer and it increases more or less exponentially to about 46 dB for the furthest tested transducer (Figure 11). Crosstalk is slightly lower in 7-element array with a MIX front layer and significantly reduces in 7-element array with an URETHAN front layer (Figure 11).

In case of the 64-element array, electrical crosstalk effects decrease exponentially in the function of distance from a transmitting transducer and are approximately symmetrical in relation to it regardless of its position in the array (Figure 12). The level between the amplitude of the signal activating a transmitting transducer ($10 V_p$) and the crosstalk amplitude on successive transducers is in this case from about 25 dB for an adjacent transducer to a stabilised value of about 55 dB for the series of outmost trans-

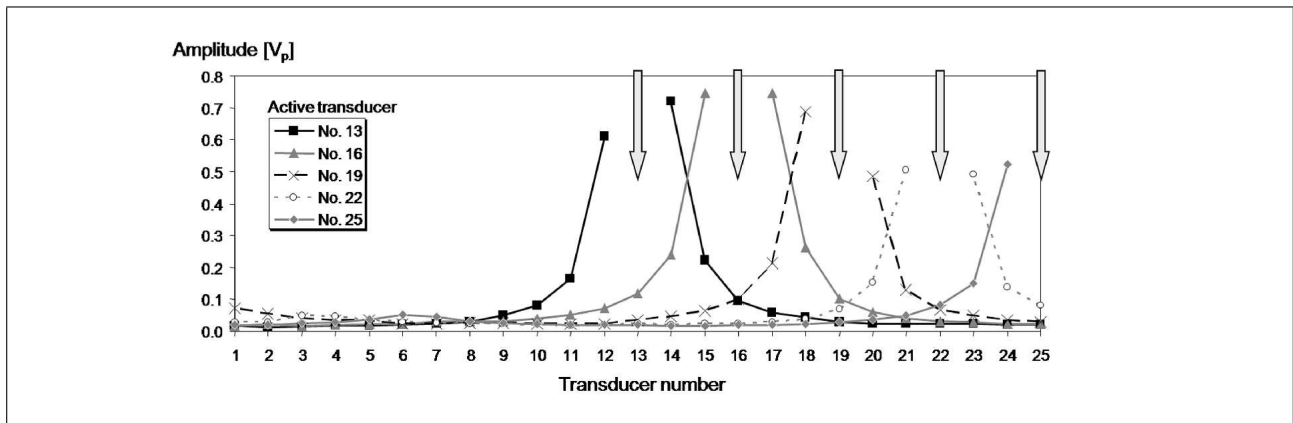


Figure 12. Changes of electrical crosstalk amplitude on individual piezoelectric transducers in the function of distance from selected transmitting transducers of the 64-element array.

ducers (Figure 12). When activating transmitting transducer further from the centre in the direction of the array’s edge, electrical crosstalk amplitude is slightly increased.

It is difficult to find any correlation between the dispersion of parameters of array transducers (Table I, Figure 4) and the electrical crosstalk amplitude irregularity (Figure 11, Figure 12). Irregularity of changes in electrical crosstalk amplitudes for individual arrays is mainly caused by the variation in length, distance and shielding of electrode leads and laying out connections to the sockets. It has been confirmed by the electrical crosstalk study in a multielement ultrasonic transducer circular array designed for tomographic scanning of a female breast tissue [24]. Thus, the crosstalk from distant sections can be sometimes a little higher than from closer ones. The maximal electrical crosstalk amplitude irregularity on transducers no. 1–5 in 7-element arrays can be evaluated as in the range of 13–20% (Figure 11). The maximal electrical crosstalk amplitude irregularity on transducers away from the transmitting one by more than 6 pitches in the 64-element array is in the range of about 50–130%, while the crosstalk amplitude dispersion on transducers adjacent to the transmitting one is about $\pm 21\%$ (Figure 12). The above analysis suggests that the electrical crosstalk is slightly lower for more insulating and flexible materials of the front layer in arrays constructed and activated in a similar way (Figure 6–Figure 8, Figure 11).

4.2. Mechanical crosstalk

Figure 13 shows the relation of mechanical crosstalk amplitude on individual piezoelectric transducers to the distance from the activated transmitting transducer no. 7 in 7-element arrays.

Figure 14 shows the relation of mechanical crosstalk amplitude on individual piezoelectric transducers to the distance for selected transmitting transducers (no. 13, 16, 19, 22, 25) in the 64-element array.

The level between the amplitude of the signal activating a transmitting transducer and the mechanical crosstalk amplitude on successive transducers in 7-element arrays

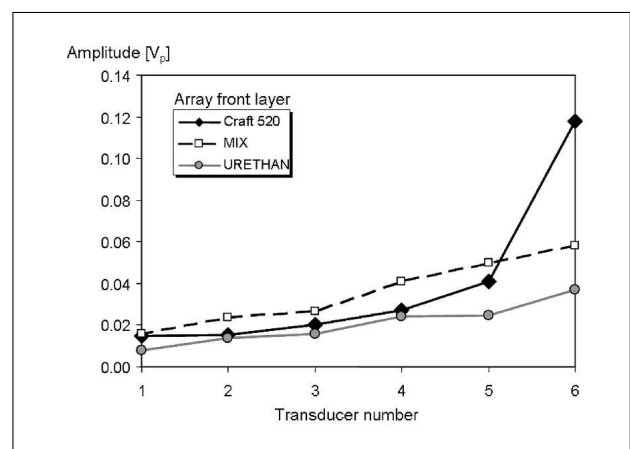


Figure 13. Changes of mechanical crosstalk amplitude on individual piezoelectric transducers in the function of distance from the activated transmitting transducer no. 7 in 7-element arrays.

decreases with shorter distance from a transmitting transducer and is related to the used front layer (Figures 13, 14). Crosstalk on transducers adjacent to the transmitting one is damped the most for array transducers with a MIX and an URETHAN front layer (Figure 13). In case of the 7-element array with a Craft 520 front layer, mechanical crosstalk effects decrease exponentially in the function of distance from a transmitting transducer (Figure 13). The level between the amplitude of the signal activating a transmitting transducer and the mechanical crosstalk amplitude on successive transducers is in this case from about 38 dB for the adjacent transducer (no. 6) to a value of about 48 dB for the next transducer (no. 5) and a value of about 56 dB for the last one (Figure 13). In case of the 7-element array with a MIX and an URETHAN front layer, mechanical crosstalk effect decrease approximately linearly with the level between the amplitude of the signal activating a transmitting transducer and the mechanical crosstalk amplitude on successive transducers from about 45 dB to 56 dB for a MIX front layer, and from about 49 dB to 62 dB for an URETHAN front layer (Figure 13).

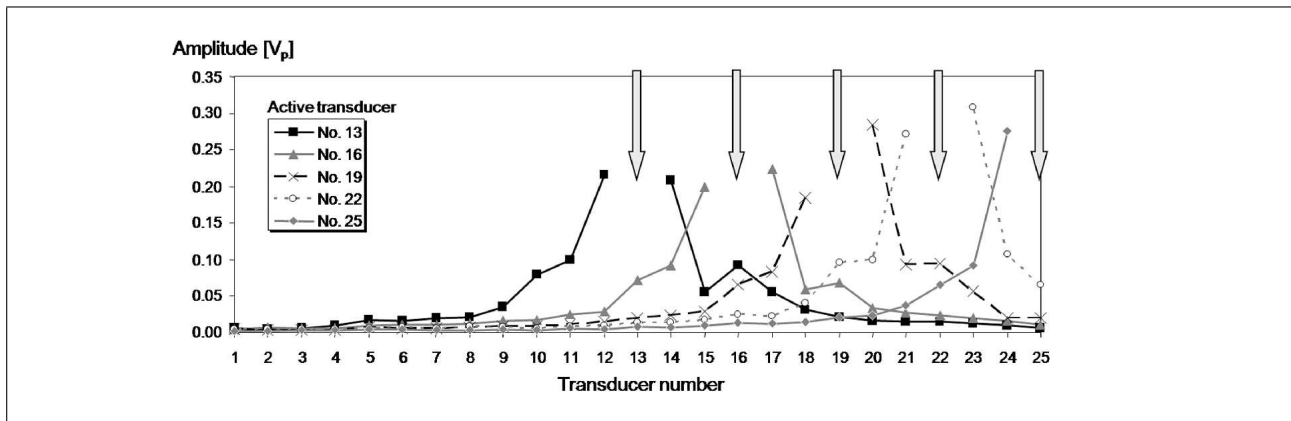


Figure 14. Changes of mechanical crosstalk amplitude on individual piezoelectric transducers in the function of distance from selected transmitting transducers of the 64-element array.

In case of the 64-element array, mechanical crosstalk effects decrease more or less exponentially in the function of distance from a transmitting transducer and are approximately symmetrical in relation to it, regardless of its position in the array (Figure 14). Refractions on the diagrams (e.g. for transducers no. 15–16) are most probably caused by errors resulting from electrical crosstalk overlapping mechanical crosstalk. The level between the amplitude of the signal activating a transmitting transducer and the mechanical crosstalk amplitude on successive transducers is in this case from about 30 dB for an adjacent transducer to a value of about 70 dB for the transducers located 24 positions further (Figure 14). When activating transmitting transducers further from the centre in the direction of the array's edge, mechanical crosstalk amplitude slightly decreases (Figure 14).

Measurements show less mechanical crosstalk for shorter linear ultrasonic transducer arrays (compare Figure 13 and Figure 14). The mechanical crosstalk study in a multi-element ultrasonic transducer circular array [14, 24] shows a mechanical crosstalk amplitude irregularity for adjacent transducers of each active one has been used (Figure 15). A similar effect can be observed for the examined 64-element array, if we look at all nine points adjacent to arrows on Figure 14. It is mainly caused by the dispersion of mechanical parameters of array transducers as well as due to out of phase overlapping mechanical crosstalk pulses by electrical crosstalk ones. The overlapping errors are especially true for transducers adjacent to a transmitting transducer (Figure 6–Figure 10).

Summarizing, it is difficult to determine a clear relation between the mechanical crosstalk effect and the kind or the flexibility of the array transducer front matching layer. However, the 7-element ultrasonic array with an URETHAN front layer shows a very small dispersion of mechanical parameters for elementary transducers (Table I). Therefore, measured mechanical crosstalk amplitudes should also characterize a small dispersion. Thus, it can be concluded the mechanical crosstalk is lower for more flexible materials of the front layer in arrays constructed and activated in a similar way (Figure 6–Figure 8, Figure 13).

Figure 16 shows mechanical crosstalk delay in the function of distance from the activated transducer for all the tested ultrasonic arrays. This delay increases linearly with the distance from a transmitting transducer, based on a similar relation for all the arrays, regardless of the front layer type,

$$\Delta t = 0.53\Delta n + 0.54 [\mu s], \quad (1)$$

where Δn is the absolute value of the difference between the number of the transmitting transducer and the number of the tested one. The small differences are caused by errors in measurement of delay, resulting from electrical and mechanical crosstalk overlapping, especially for low Δn values. The empirical formula (1) is a good approximation of measurements (Figure 16), but it has, however, a constant component, which has no physical confirmation, because there should be no delay for $\Delta n = 0$. A small offset in measurements is caused by an overestimation of measured time values for the mechanical crosstalk pulse beginning, because this beginning is hidden in the decaying end of the electrical crosstalk pulse. Thus, a better approximation without overestimation error is

$$\Delta t = 0.56\Delta n [\mu s]. \quad (2)$$

The obtained results show that the front array layer has minimal effect on the propagation velocity of mechanical crosstalk effects. The average propagation velocity of mechanical crosstalk effects determined from the formula (2) is 1250 m/s. This value is about two times higher than ultrasound velocity in the back layer of 7-element arrays (silicone with microballoons) and about three times lower than ultrasound velocity in NCE51 piezoceramics [23]. Silicone with microballoons is characterised by very high value of ultrasound attenuation coefficient. Ultrasound velocity in distilled water, the surfaces of the tested arrays were submerged in, is 1476–1488 m/s in temperature range of 18–22 °C respectively [13]. Based on this data, it is possible to predict that vibrations of a piezoelectric transmitting transducer in a multi-element ultrasonic array are propagated to adjacent transducers predominantly by the supporting elements (mounting elements), which in

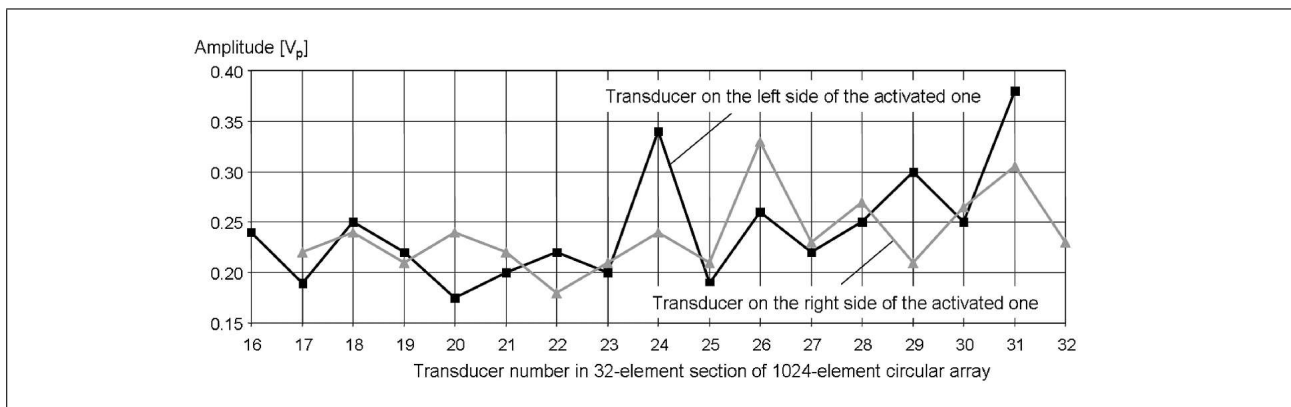


Figure 15. The mechanical crosstalk amplitude irregularity for adjacent transducers of each active one has been used in a 32-element section of the 1024-element circular array.

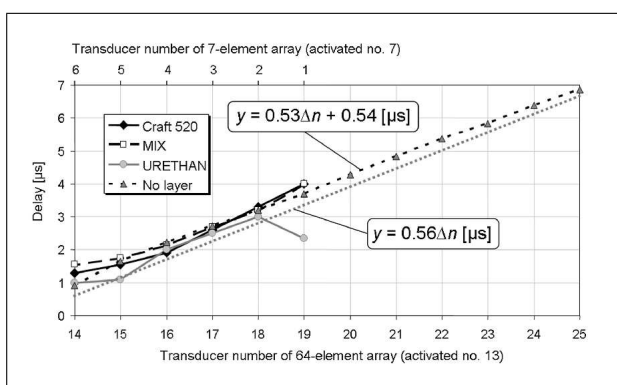


Figure 16. Mechanical crosstalk delay in the function of distance from the activated transducer for all the tested ultrasonic arrays.

this case are the PCBs. Additionally, it can suggest, that it is a transversal vibration mode, most of all, because ultrasound velocity in PCBs is in the range about 3000–3500 m/s [25].

5. Conclusions

Based on the tests of a few designed linear ultrasonic arrays, performed during this study, electrical and mechanical crosstalk effects occurring between elementary piezoelectric transducers were identified and characterised. Measurements show that electrical crosstalk results predominantly from transmissivity of the electric pulse activating a transducer to adjacent array transducers. Even the most distant piezoelectric elements of an array are affected by small electrical crosstalk. Increasing the flexibility of the front layer of the array slightly decreases electrical crosstalk amplitude.

Mechanical crosstalk effects occur on adjacent transducers of the array, with a certain delay, as pulses, the amplitude of which decreases, in relation to the signal activating a transmitting transducer, with longer distance from that transducer. Longer distance causes linear increase of the delay, regardless of the type of the front layer covering the surfaces of the array transducers. This occurs based on

a similar relation for all the arrays. This means that vibrations of an elementary piezoelectric transducer in a multi-element ultrasonic array are propagated to adjacent transducers predominantly by the support points and mounting structures as a transversal vibration mode. This is very important when designing arrays.

Mechanical crosstalk amplitude on successive array transducers decreases with the distance from a transmitting transducer. Increasing the flexibility of the front layer slightly improves attenuation of mechanical crosstalk.

Acknowledgement

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