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ULTRASONIC TRANSDUCERS RADIATING INTO THE AIR IN THE FREQUENCY RANGE 50–250 KHZ

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In the paper ultrasonic piezoelectric transducers radiating into the air in the frequency range 50–250 kHz are described. Methods of improving their properties (efficiency, frequency characteristics, directivity characteristics) are discussed. Several types of designed, made and investigated transducers are presented. The transducers have the form of properly shaped piezoelectric plates or an array of plates embedded in plastic. The properties of these transducers enable their application in robotics, e.g., in echolocation or in object identification systems.

1. Introduction

Ultrasonic transducers are applied in robotics in echolocation systems — detection and localization of obstacles on the path of a mobile robot [1, 2], in object identification systems — object localization, identification and classification [4, 7], e.g., in automated production lines and for robot grip position measurements [8, 11]. In such systems transducers radiate ultrasonic energy into the air. The ultrasonic signal range and the electric power necessary for transducer excitation depend on the efficiency of ultrasonic energy transmission into the air. Ultrasonic systems applied in robotics should not require large supply powers, especially in the case of sensors on a mobile robot.

Ultrasonic transducers applied in robotics should also have suitable radiation directivity characteristics and a frequency bandwidth. Directivity pattern widths of transducers applied in echolocation and object identification have a crucial influence on the resolution of systems. Strong acoustic beam side lobes generate parasite signals from surrounding objects. The frequency bandwidth should be wide because these transducers work in the pulse mode. Wide bandwidth of transducers is especially important in object identification systems because the information about the object is contained in the shape of the pulse reflected from this object [4].

Strong mismatching of acoustic impedances impedes considerably the radiation of ultrasonic piezoelectric transducers into the air. The characteristic acoustic impedance of the air is 5 times smaller than acoustic impedances of piezoelectric ceramics and crystals. Owing to this strong mismatching, the acoustic transmission coefficient on the transducer — air boundary is very small (10^{-4}–10^{-5}) and the transducer works in the narrow frequency bandwidth.

Modern technology requires sensor and robots to work with high accuracy and quality respectively. Such devices use suitable instrumentation to obtain objective data and to provide inputs to automatic control systems. These requirements help to speed up the development of microelectronics and ultrasonic technology. This is backed by extensive research on the subject of ultrasonic transducers for the use of on–robots and on–automatic control systems. The purpose of the present paper is to study the radiation property of types of piezoelectric transducers having the form of a piezoelectric plate or an array of plates embedded in plastic, the plates being made of a piezoelectric ceramic. Since such transducers are of rather low cost, it is reasonable to ask: given some knowledge of required accuracy and quality of ultrasonic transducers for the use of on–robots and on–automatic control systems, is it possible to make ceramic plate transducers applicable to these devices? The remainder of this paper is concerned with finding particular answers to this question.

Different methods of impedances mismatching reduction are discussed in Sect. 2. Examples of piezoelectric ultrasonic transducers radiating into the air are presented in Sect. 3. Their properties are summarized in Table 1.

Table 1. Properties of different types of ultrasonic piezoelectric transducers radiating into the air

Nr	f [kHz]	Pressure of acoustic wave generated by the transducer – distance 30 cm [Pa]	Sensitivity for the transducer working as a receiver [μV/Pa]	Beam spread 3 dB [°]	6 dB [°]	Side lobes [dB]	Remarks
5	191	68	50	6	8	−8	mosaic, star-shaped
8	190.5	310	230	3	4	−8	ring, patented
9	190	350	260	3	4	−8 −14	ring, patented
13	153.5	216	160	6	8	—	radial vibrations
15	96.5	270	200	14	16	—	thickness vibrations, $\lambda/4$ plate, patented
17	105.5	270	240	12	14	−20	thickness vibrations, $\lambda/2$ plate
18	190.5	756	560	3	4	−9	3 rings, patented
19	113.5	365	270	8	10	−6 −14	3 plates, thickness vibrations
22	105	297	220	8	10	−12	3 plates, thickness vibrations

2. Improvement of properties of piezoelectric ultrasonic transducers radiating into the air

As we have mentioned in the Introduction strong mismatching of acoustic impedances is the main problem which exists as regards radiation of piezoelectric transducers into the air. Transducers are usually made of piezoelectric ceramic — type PZT. Impedance mismatching is smaller for piezoelectric foils PVDF, their impedance is one order of magnitude smaller than the acoustic impedance of piezoelectric ceramic. Unfortunately, piezoelectric foils have an electromechanical coupling coefficient much smaller and dielectric losses higher than piezoelectric ceramic. Furthermore their low dielectric constant makes difficult their electric matching to transmitting and receiving electronic circuits. Mechanical quality factor of piezoelectric ceramic ($Q_m \geq 50$) impedes its application for work in the wide frequency bandwidth.

The application of one or more quarter-wavelength impedance transformers is the standard method of matching an ultrasonic transducer to a load. This method is successfully applied when a transducer radiates into a solid or liquid. The application of quarter-wavelength transformers to piezoelectric transducers radiating into the air (or other gases) is difficult owing to the lack of materials with properly low acoustic impedances [10]. A matching layer made of silicone rubber filled with hollow glass spheres was the best solution described in the literature. The glass spheres had an average diameter of 80 μm and wall thickness of 2 μm. This composite applied as a quarter-wavelength transformer enabled to reduce considerably losses in comparison with the same transducer without the matching layer [17].

The other method of reducing impedance mismatching and of increasing ultrasonic energy transmission into the air is to apply composite transducers: piezoelectric ceramic-plastic material [16]. Such a composite is a two-phase material in which the ceramic produces the piezoelectric effect while the plastic reduces density and increases elastic compliance. The acoustic impedance of composites is several times smaller than the acoustic impedance of piezoelectric ceramic. Transducers made of composites have Q_m = 5 – 15 and a wide frequency bandwidth.

The shape of a transducer radiation directivity characteristic (beam width proper to the application, side lobes reduction) is very important from the practical point of view. The radiation directivity pattern depends on the vibration distribution on the transducer surface [13]. One obtains the directivity pattern without side lobes when the vibration distribution is described by the Gauss function. When vibration distribution approximates the Bessel function J_0, the radiated beam has a very small divergence. One can form the directivity pattern by selecting a proper type and mode of vibrations [13], the dimension and shape of the transducer, and by applying nonuniform polarization of piezoelectric ceramic [5] or electrode apodization [9]. It is also possible to use an array of several transmitting transducers [12] or a properly driven segmented transducer [3].

The realization of efficient quarter-wavelength transformers as well as composite transducers requires special materials and complicated technologies. In Sect. 3 we shall describe several ultrasonic transducers designed and made by us. They have the form of properly shaped piezoelectric plates or of a proper array of piezoelectric plates embedded in plastic. It is not possible to obtain complete impedance matching this way but acoustic energy radiation efficiency is sufficient for the applications of robotics. Such transducers have simple technology; their mechanical quality factor Q_m is reduced and one can form properly their directivity patterns. The theoretical analysis of vibrations of piezoelectric plates such as plates applied in these transducers has been presented earlier elsewhere [6, 13, 14].

3. Examples of piezoelectric ultrasonic transducers radiating into the air

3.1. Transducers with thickness vibrations of piezoelectric plates

Piezoelectric plates excited to thickness vibrations have a complicated deformation structure depending on the ratio of the plate diameter D to the plate thickness d. Different modes of vibration exist [13]. The radiation directivity characteristics of these plates differ considerably from the simple case of piston vibrations. There are vibration distributions, especially for the small ratio D/d, which have better directivity patterns than the piston transducers. These vibration distributions are characterized by a small amplitude of vibrations on the transducer edges, by the lack of distinct vibrations nodes on the transducer surface and by insignificant phase difference on the vibrating surface [13]. The electromechanical coupling coefficient is large for thickness vibrations; this makes it possible to use smaller supply voltage.

Three types of transducers with thickness vibrations of piezoelectric plates embedded in polyurethane resin have been made. The resin improves matching of acoustic

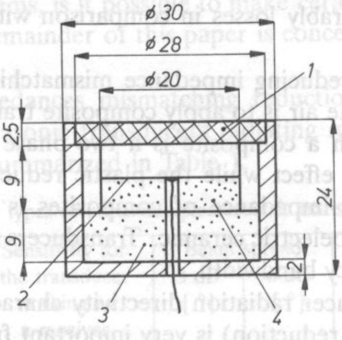

FIG. 1. Transducer with piezoelectric plate vibrating in the thickness direction. *1* — polyurethane resin, *2* — piezoelectric ceramic plate, *3* — epoxy resin with tungsten powder, *4* — passive ceramic with high ρc.

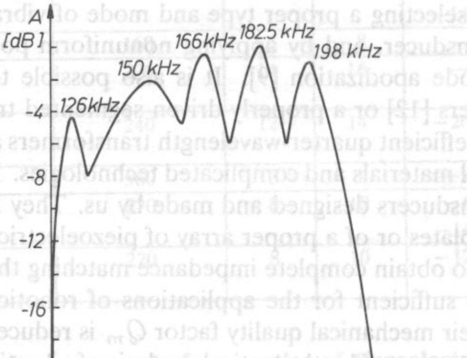

FIG. 2. Frequency characteristic of the transducer shown in Fig. 1. Arbitrary units.

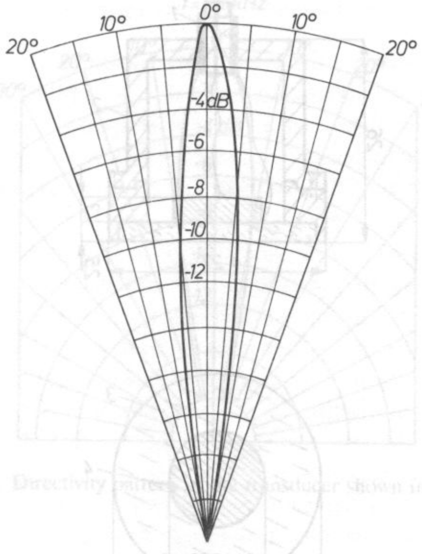

FIG. 3. Directivity pattern of the transducer shown in Fig. 1.

impedances and decreases the mechanical quality factor. In the first type of transducers a piezoelectric ceramic (type PZT) plate with thickness $\lambda/2$ was applied. In the second type — a piezoelectric plate with thickness $\lambda/4$ was placed on the base with high acoustic impedance — Fig. 1. The reduction of the plate thickness makes it possible to decrease an exciting voltage. The frequency characteristic of such a transducer is presented in Fig. 2 the directivity pattern recorded under quasi-continuous conditions — in Fig. 3. The lack of side lobes in the directivity pattern is worth noticing. Further reduction of an exciting voltage was possible using a pile of thin plates of piezoelectric ceramic connected electrically in parallel. By applying such a transducer as a transmitter and transducer with a pile of plates connected electrically in series as a receiver, one can considerably increase the radiation range.

3.2. Transducer with radial vibrations of piezoelectric plate

A piezoelectric plate excited to radial vibrations may radiate a wave in a direction perpendicular to its surface. This is possible because deformation in the radial direction causes also a change of the plate thickness. Coupling between radial and axial deformations depends on the Poisson constant of the piezoelectric material. The greatest amplitude of vibration in the direction perpendicular to the surface occurs at the centre of the plate, vibrations vanish in the direction of the plate edges. For the mode $(0, 1)$ of radial vibrations of circular plates, one obtains the amplitude distribution of vibrations near the Gauss function. The near field is reduced and the side lobes of the directivity pattern are strongly damped [14]. It is also possible to excite higher modes of vibrations but then electromechanical coupling is lower.

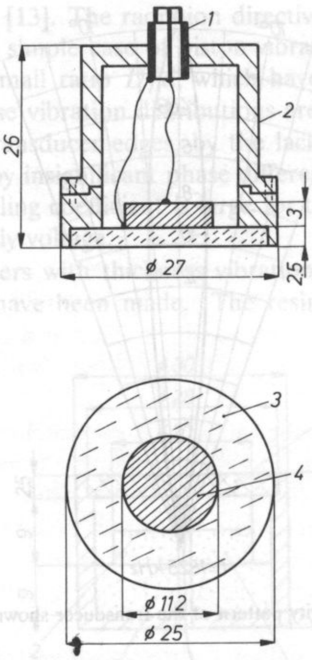

FIG. 4. Transducer with radially vibrating piezoelectric plate. *1* — BNC junction, *2* — casing, *3* — polyurethane resin, *4* — piezoelectric ceramic.

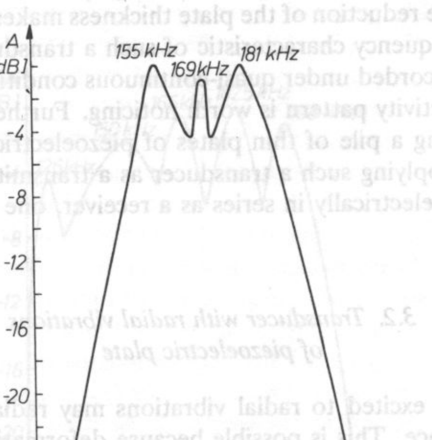

FIG. 5. Frequency characteristic of the transducer shown in Fig. 4. Arbitrary units.

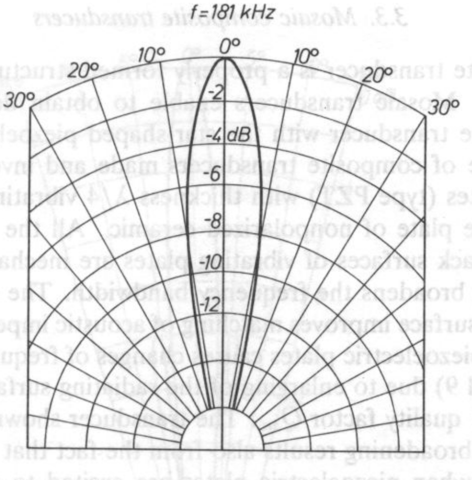

FIG. 6. Directivity pattern of the transducer shown in Fig. 4.

Figure 4 shows the design of the transducer with a radially vibrating plate of piezoelectric ceramic, Fig. 5 — its frequency characteristic, Fig. 6 — its directivity pattern. One can see that the radiation directivity pattern without side lobes has been obtained. Polyurethane resin improved matching of acoustic impedances and reduced the mechanical quality factor.

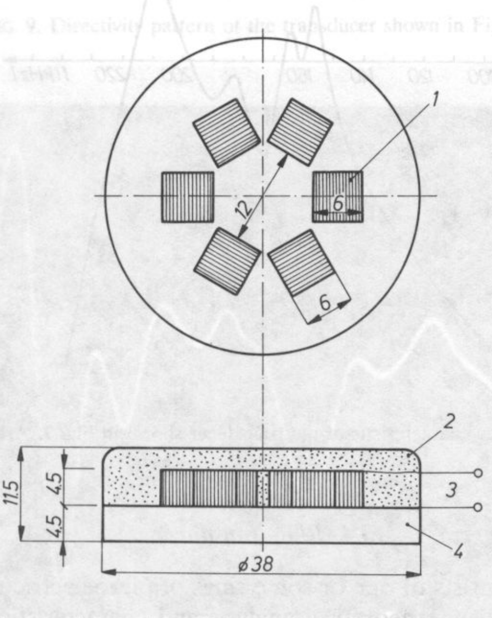

FIG. 7. Composite mosaic transducer with star-shaped arrangement of piezoelectric plates, *1* — piezoelectric ceramic, *2* — polyurethane resin, *3* — electrodes, *4* — passive ceramic.

3.3. Mosaic composite transducers

A mosaic composite transducer is a properly formed structure of piezoelectric plates embedded in plastic. Mosaic transducers enable to obtain desired radiation directivity characteristics. The transducer with the star-shaped piezoelectric plate arrangement (Fig. 7) is an example of composite transducers made and investigated by the authors. The piezoceramic plates (type PZT) with thickness $\lambda/4$ vibrating in the thickness direction are placed on the plate of nonpolarized ceramic. All the plates are submerged in polyurethane resin. Back surfaces of vibrating plates are mechanically loaded by passive ceramic. This loading broadens the frequency bandwidth. The quarter-wavelength resin layer on the radiating surface improves matching of acoustic impedances. The plastic mass vibrating jointly with piezoelectric plates causes changes of frequency and directivity characteristics (Figs. 8 and 9) due to enlarging of the radiating surface and decreasing of the transducer mechanical quality factor Q_m. The transducer shown in Fig. 7 has $Q_m = 12$. Frequency bandwidth broadening results also from the fact that this transducer can work at a lower frequency when piezoelectric plates are excited to contour vibrations. This transducer is especially useful for pulse work owing to its broad frequency bandwidth. The pulse response of the star-shaped transducer has been investigated in the shock tube — Fig. 10. Damped oscillations for time greater than 20 μs were caused by spurious oscillations of the tube itself. The other realized composite mosaic transducers were described in [15].

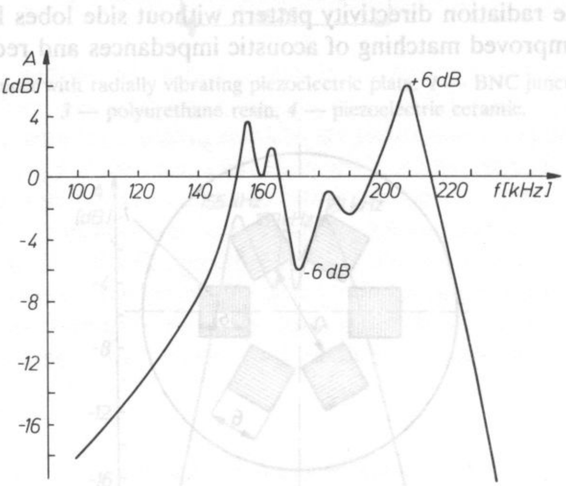

FIG. 8. Frequency characteristic of the transducer shown in Fig. 7. Arbitrary units.

3.4. Ring transducer

A ring transducer consists of one or some rings of piezoelectric ceramic embedded in polyurethane resin. Designs, theoretical analysis and characteristics of ring transducers are described in [6].

The resonance vibrations of ring and plastic mass appear in a ring transducer filled by a plastic material. By selecting properly ring dimensions, one can obtain coupling between

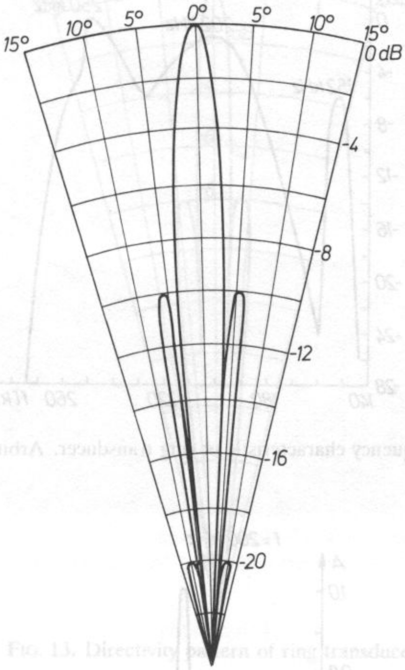

FIG. 9. Directivity pattern of the transducer shown in Fig. 7.

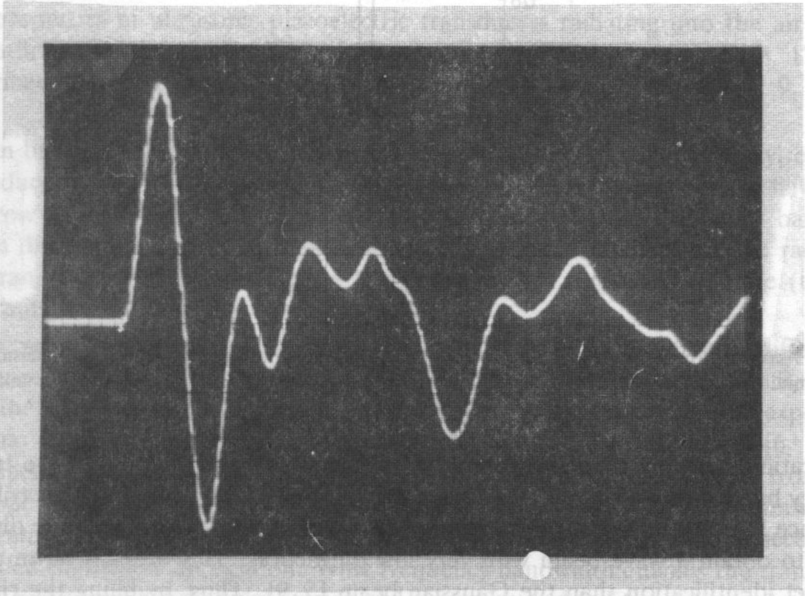

FIG. 10. Pulse response of the transducer shown in Fig. 7 measured in shock tube, 5 μms/div.

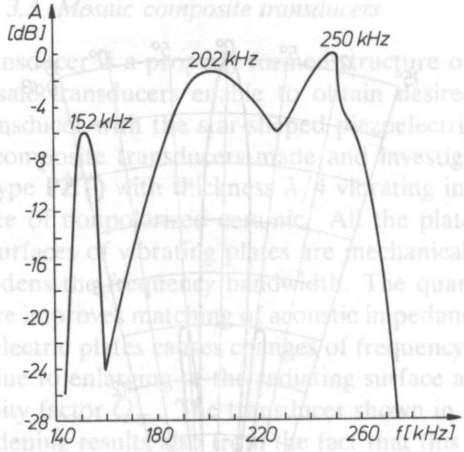

FIG. 11. Frequency characteristic of ring transducer. Arbitrary units.

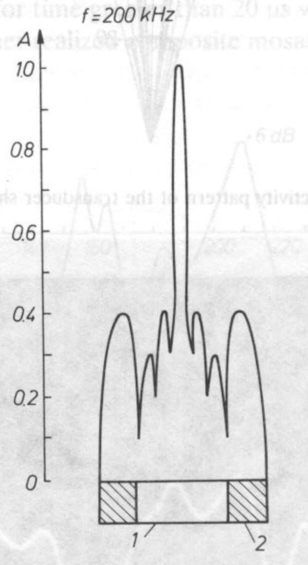

FIG. 12. Acoustic pressure in the air, distance 10 mm from the surface of ring transducer, measured using miniature microphone, *1* — polyurethane resin, *2* — piezoelectric ceramic. Arbitrary units.

ring vibrations and plastic mass vibrations. This produces broadening of the transducer frequency bandwidth — Fig. 11. Plastic mass vibrations have an amplitude distribution on the surface like the zero order Bessel function — Fig. 12. Such an amplitude distribution permits to obtain a wave beam with very low diffraction. This beam is more useful for the object identification than the Gaussian beam [5, 9]. Thus, by filling the ring with a plastic, one obtains better matching to the air, a wider frequency bandwidth and a wave beam with very small divergence — Fig. 13.

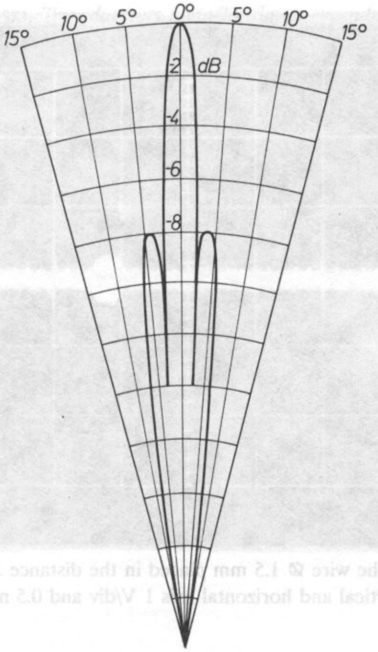

FIG. 13. Directivity pattern of ring transducer.

4. Conclusion

The properties of ultrasonic piezoelectric transducers radiating into the air realized by the authors are compiled in Table 1. Designs of the transducers nos. 15, 17, 19, 22 are described in Sect. 3.1, nr 13 — in Sect. 3.2, nr 5 — in Sect. 3.3, nos. 8, 9, 18 — in Sect. 3.4.

As can be seen in Table 1, the ring transducers have the highest efficiency, especially the transducer with three piezoelectric rings (nr 18). The ring transducers have also a very narrow main lobe of radiation directivity pattern and wide frequency bandwidth. Radiation directivity patterns without side lobes have been obtained for the radially vibrating transducer (nr 13) and for the transducer with a piezoelectric plate (thickness $\lambda/4$) vibrating in the thickness direction (nr 15).

These transducers have been successfully applied for the localization of different objects. Figure 14 shows pulses reflected from a wire with the diameter 1.5 mm, distance between the wire and the ring transducer 30 cm, $f = 200$ kHz. Conducted experiments proved that the realized transducers are proper for applications in robotics [6, 15]. Radiation efficiency, especially for ring transducers, ensures a suitable range (from above 1 m for one transducer working as transmitter – receiver at 200 kHz to several meters for two transducers at 100 kHz). It is possible to shape directivity patterns according to the provided transducer application. Wide frequency bandwidth enables the transmission of narrow pulses (with sinusoidal carrier and short rise and fall time) without significant distortions.

Two types of transducers are patented.

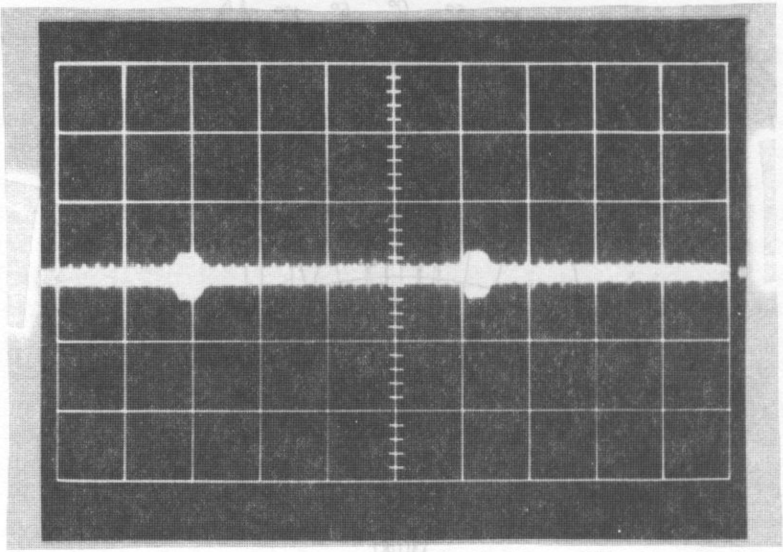

FIG. 14. Pulses reflected from the wire Ø 1.5 mm placed in the distance 30 cm from the ring transducer, f = 200 kHz. Vertical and horizontal axis 1 V/div and 0.5 ms/div, respectively.

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