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Ultrasonic transducers and transducer arrays for applications in air

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Abstract. Many measurement tasks in industrial automation, e.g. non-contact distance measurement, room surveillance, object identification and gas flow measurement can be accomplished by sensors using airborne ultrasound. Their performance is determined by the properties of the ultrasonic transducers. Therefore electrostatic and piezoelectric transducers are compared. In industrial applications piezoceramic transducers presently dominate. They combine a high efficiency factor and ruggedness. The narrow bandwidth of commonly less than 5% leads to a long transient time of the acoustic signals. Thus the achievable resolution of pulse-echo measurement is low.

Composite transducers consisting of piezoceramic and polymer materials show a wider relative bandwidth of about 30% at the expense of efficiency. These transducers are compact and rugged and hence suited for use under rough industrial conditions.

Ultrasonic transducers based on piezopolymer foils offer a variety of acoustic properties at low expenditure. Their bandwidth corresponds to that of composite transducers. Sharp ultrasonic pulses can be radiated and high resolution is thus obtained. Moreover, the 'dead zone' of these transducers is very small. The arbitrary shaping of the radiating surface provides a nearly 'tailor made' radiation pattern.

Composite, as well as piezopolymer, foil transducers are suited to the design of phased arrays. Foil transducers have the additional advantage of very small crosstalk between neighbouring transducer elements. By electronically controlled deflection of the sound beam, lateral details and consequently the spatial structure of objects can also be detected.

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1. Introduction

Sensors are important components in performing automation or surveillance tasks in industrial applications as well as in other areas, e.g. automotive devices or appliances. In flexible systems they supply necessary information about the immediate state of the process. They provide the signals from which the control of the actuators is derived.

Ultrasonic sensors permit non-contact distance measurements based on the pulse-echo method, where the propagation medium of the acoustic signals is air. Typical applications associated with distance measurement are presence detection and identification of objects, measurement of the shape and the orientation of workpieces, collision avoidance and room surveillance, flow measurement and material investigation by measuring the absorption of sound [1–3].

In recent years, the development of microprocessor-based ultrasonic sensors has led to a remarkable increase of the efficiency of acoustic measurement systems using ultrasound. For example, the automatic self-calibration provides high reliability even under unsuitable environmental conditions. Evidently fail safety, reproducibility and accuracy of the measurement results have been improved [4, 5]. By means of more sophisticated evaluation algorithms based on digital signal processing, more complex measurement tasks can be solved [6, 7]. Of great interest are such problems as object identification, or acoustic imaging which competes with optical methods.

The performance of ultrasonic sensors strongly depends on the properties of the electroacoustic transducers used—they can be regarded as the key elements. Therefore, in many laboratories, research work has concentrated on new transducer designs and principles. Priority aims are ruggedness, wide bandwidth, high efficiency and the 'tailor made' radiation pattern.

In section 2, ultrasonic sensors are compared with those using competing principles. Some basic aspects of sound propagation in air are considered in section 3. Section 4 describes the general requirements on ultrasonic transducers operating in air. In section 5 electrostatic and piezoelectric transducer principles are contrasted and the transient behaviour of these transducers is discussed in section 6. In section 7, the design and the properties of transducer arrays based on piezo-polymer foils are presented.

2. Comparison of ultrasonic sensors with other principles

The non-contact measurement principle has some significant advantages in comparison with other methods. Sensors can be mounted at a distance outside the spatial range of movement of an object so that interference with this object is avoided. Dangerous collisions of objects can be prevented by precalculation of their positions or direction and speed of motion. The sensor is not affected by physical contact with the object (friction, wear, pollution). In addition, handling is easy because the sensor may be mounted in a stationary position.

Besides ultrasound, other physical principles are also used for non-contact distance measurement. Capacitive or inductive proximity sensors evaluate the interaction of an object with a high-frequency electric or magnetic field. The advantage of these sensors is their rugged and relatively simple construction, which is an important aspect regarding industrial applications. The main drawback, however, is the very small detection range of capacitive and inductive sensors. Their use is also limited to electrical conducting or magnetic objects respectively. Moreover, the sensitivity depends on the kind of material used and changes non-linearly with measurement distance. Consequently these sensors are preferably used only as proximity switches in a range up to 20 mm.

Optical remote sensors supply measurements for use at much greater distances. Their use, however, strongly depends on the light reflection coefficient of the surface of the object (colour, roughness, orientation). Dust and dirt have considerable influence. Moreover, optical distance detection based on triangulation or laser time-of-flight (TOF) measurement is expensive. If video cameras are used the amount of information is enormous. In this case adequate signal processing requires high expenditure.

The application of airborne ultrasonic sensors provides low-cost distance measurement devices. Because of the low sound velocity in air (343 m s^{-1} at 20 °C) long distance resolution is achieved by relatively simple electronic circuitry. The ultrasonic signal reflected by an object's surface, contains information about its geometric structure in the direction of sound propagation (axial resolution). By the help of echo profile evaluation algorithms, several objects (e.g. workpieces) can be classified [8]. Lateral structure details can be detected by the use of transducer arrays or by moving a single transducer along a given path, e.g. if the sensor is mounted on the arm of a robot.

Ultrasonic sensors for industrial applications are insensitive to dust and dirt. The detection range spans from some millimetres to several metres depending on the frequency of ultrasound.

Ultrasonic flow sensors [9] which measure the volume flow velocity offer almost no interference (e.g. pressure drop) to the flowing medium—they integrate over the flow profile; they are linear and can distinguish between different flow directions; their fast time response (approximately less than 1 ms), high long-term stability and low-power consumption give them significant advantages over competing principles.

3. Sound radiation and propagation in air

Ultrasonic transducers have to meet certain requirements resulting from particular coupling conditions of the vibrating transducer surface with respect to the medium in which the sound propagates. In an electroacoustic transducer only a fraction of the electrical transmission power P is converted into mechanical power P_0. Also, only a fraction of P_0 is radiated as ultrasound into air—the remaining energy is reflected inside the transducer at its boundary surface and is finally dissipated. The electroacoustic efficiency factor describes the ratio of electrical input energy and radiated acoustic energy. In the case of the receiver the conversion of acoustic into electrical energy has to be regarded similarly. Methods for the determination of transducer efficiency have already been suggested by Mágori and Walker [10].

Regarding only harmonic waves the mean value of the sound intensity J in the far field (plane wave) becomes [11, 12]:

$$J = \tfrac{1}{2}\rho \cdot c(\omega\xi_{max})^2 \qquad (3.1)$$

where c is the sound velocity and ξ_{max} is the maximum deflection of the oscillating material particles in the propagation medium, ρ is its specific density. f is the frequency of sound with $\omega = 2\pi f$. The product $\rho \cdot c$ describes the acoustic impedance Z of the propagation medium.

If the value of ξ_{max} is constant, the sound intensity J in any gaseous medium is very low compared with liquids or solids. Therefore, in air a high amplitude ξ_{max} is needed. This requires large mechanical deflections of the radiating surface of an ultrasonic transducer operating in air.

For most practical applications of airborne ultrasonic distance sensors the useful frequency range is limited to below 500 kHz. This is 10 to 100 times less than the frequencies commonly used in liquid or solid materials, e.g. for non-destructive testing methods (NDT). From equation (3.1) it follows that the value of ξ_{max} must be additionally increased in air to compensate for the lower frequency range. These aspects are essential for the construction of transducers operating in air. For example, a conventional piezoceramic transducer designed for applications in water can hardly be used in air because the amplitude of the radiating surface is comparatively small. Limiting factors are the electrical input power and the tensile strength of the ceramic material.

4. Ultrasonic transducers as key elements

The development of efficient transducers for airborne ultrasound requires improvements in the matching of the acoustic impedance to gaseous media. The following features of ultrasonic distance measurement devices are of special interest:

- maximum detection range, resolution, accuracy, reproducibility;
- operation frequency and bandwidth of the transducer;
- radiation pattern (spatial distribution of sound radiation or sensitivity);
- influence of environmental conditions;
- sensitivity to acoustic interference;
- ruggedness, size, cost.

Large maximum detection range is achievable by high transducer efficiency in combination with high transmission power. Resonant-adjusted narrow-band transducers radiate acoustic signals with a long transient time (see figure 1(*a*)). To generate large amplitudes the transducer is excited by a burst signal. Its length commonly corresponds to the transient time of the transducer as illustrated in figure 1(*b*). It has to be considered, however, that high radiation power may cause interfering acoustic signals resulting from multiple echoes within the measurement range.

If high resolution has priority, transducers with a wide bandwidth, which means a low mechanical quality factor Q, are needed. The wide bandwidth is also advantageous for algorithms used in acoustic imaging. An important aspect is the radiation of sharp ultrasonic pulses with short transient times. This is also a precondition for the alternating transmitter/receiver mode of one single transducer with a small 'dead zone' (range immediately in front of the transducer where objects cannot be detected). Beyond that, short pulses are needed for echo profile evaluation, e.g. resolution of overlapping echoes for object identification. Figure 2 illustrates typical pulse response signals obtained from different transducer types. The radiated sound pressure amplitude p at a given distance from the transmitter becomes smaller if its bandwidth increases. For practical applications a compromise between bandwidth and maximum signal amplitude always has to be found.

The selection of the ultrasonic frequency is mainly determined by the measurement problem. With increasing frequency (and thus smaller wavelength) better resolution is achievable. On the other hand, the maximum detection range is reduced because of the increasing attenuation of ultrasound in air.

The amplitude v of the particle velocity $v(x, t)$ of a plane wave propagating in the x direction can be

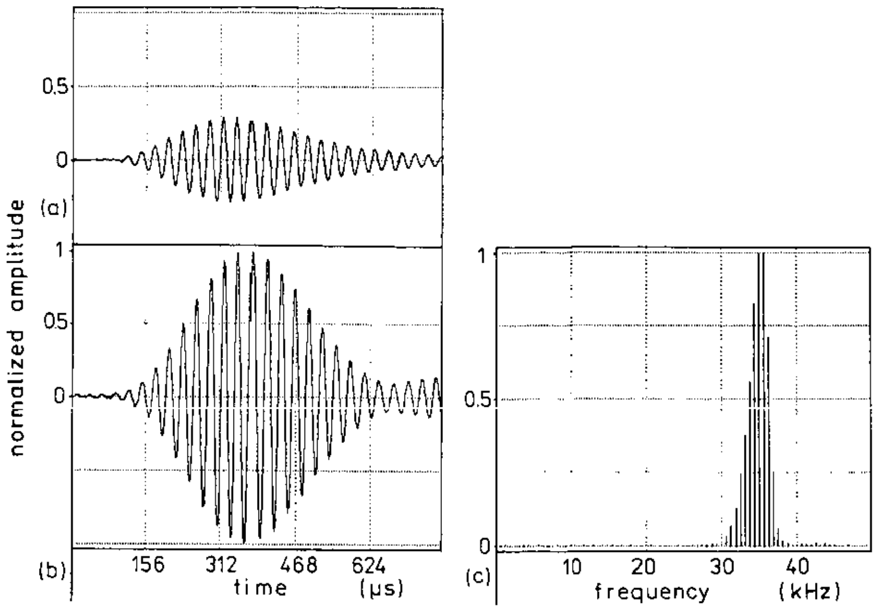

Figure 1. Receiving signal of a conventional piezoceramic sonic transducer (Tridelta AG Hermsdorf). (*a*) Transmitting signal, single pulse; (*b*) transmitting signal, burst signal with four pulses; (*c*) frequency spectrum.

described as follows:

$$v(x) = v(x_0) \cdot \exp(-\alpha x). \qquad (4.1)$$

The absorption coefficient α is approximately proportional to f^2 in the frequency range of interest, f [6, 12]. In air α is approximately $1.6 \times 10^{-10} (f/\mathrm{s}^{-1})^2\ \mathrm{dB\,m^{-1}}$. This value is about 10^3 times greater than the corresponding value in water. Therefore, the operation frequency of industrial ultrasonic devices will hardly exceed 500 kHz. The use of higher frequencies will be limited to special tasks as short range distance measurement (some cm) or acoustic microscopy.

Another limiting factor with respect to industrial applications is given by acoustic interference. In many cases a maximum spectral density of acoustic noise is observed in a frequency range up to 40 kHz [13]. Thus, transducers operating beyond 60 kHz are preferred. Table 1 shows typical operation frequencies and corresponding maximum detection ranges of some commercial ultrasonic distance sensors. Some applications, such as collision avoidance, make use of transducers with a wide main lobe in their radiation pattern. On the other hand, if only objects inside a given spatial range have to be detected, transducers with high directivity (small solid angle in which sound is radiated) are needed.

Table 1. Frequency and maximum detection range of some commercial ultrasonic distance sensors.

f (kHz) up to	Maximum detection range (m)	Manufacturer
20	60	VEGA, Endress & Hauser
30	15	VEGA, Endress & Hauser
100	6	Siemens, Polaroid
200	1	Siemens, Honeywell
400	0.3	Siemens

The directivity of a transducer is determined by its geometric size and shape relative to the sound wavelength, if no additional means (e.g. horns) for acoustic focusing are employed (see figure 3).

In many applications the wavelength is large compared with the surface roughness of relevant reflectors. Then mirror-like reflection dominates which is similar to geometric optics. If sound radiation is focused to a narrow spatial range and the reflecting surface is not oriented perpendicular to the sound beam, only very small signals caused by diffraction will be received—then even large objects may be 'overlooked'.

5. Operation principles

Transducers for airborne sound are classified according to the physical principles which permit the radiation of ultrasound:

electrostatic
electrodynamic
magnetostrictive
piezoelectric
pneumatic transducers.

For distance sensors in industrial applications piezoelectric and electrostatic transducers are of main interest. Dynamic properties of transducers based on other principles are unsatisfactory.

Electrostatic transducers use a thin metal sheet or a single-sided metallized plastic foil as a diaphragm to convert electrical energy into acoustic and vice versa. To this group of transducers belong the usual condenser

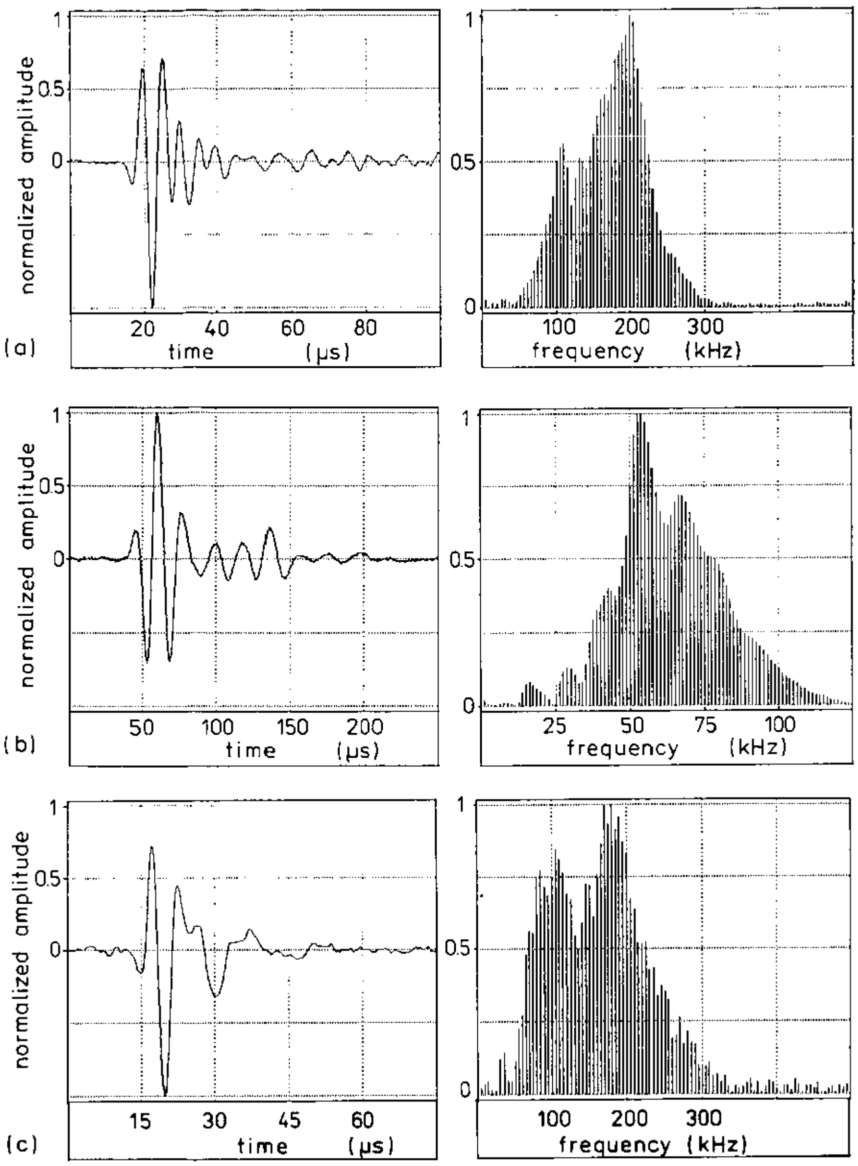

Figure 2. Pulse responses and corresponding frequency spectra of transducers operating in the alternating transmitter/receiver mode (distance to a plane reflector is 60 mm, transmitting voltage is 50 V). (*a*) PVDF transducer, $R = 1.4$ mm; (*b*) PVDF transducer, $R = 6$ mm; (*c*) composite transducer (type L^2QZ [20]).

microphones, Sell- and electret transducers. Piezoelectric transducers are classified according to the piezoelectric material used. Regarding the operation principle a further classification is possible for piezoceramic transducers:

thickness or radial mode transducers, e.g. with quarter-wave matching layer;
bending mode transducers, active–active layer or active–passive layer structure;
transducers using composites of piezoceramics and polymers, e.g. sandwich-layer type.

For piezopolymer transducers:

transducers with curved piezopolymer foil;
bending mode transducers with active–active layer structure;
multilayer transducers.

5.1 Electrostatic transducers

This group of transducers is based on the effect that the spacing between the plates of a condenser may be changed by mechanical or electrostatic forces. The plates are formed by a movable metallized diaphragm and a stationary back electrode as illustrated in figure 4(*a*). Bias voltage U_0 (commonly about 200 V) is applied to this condenser.

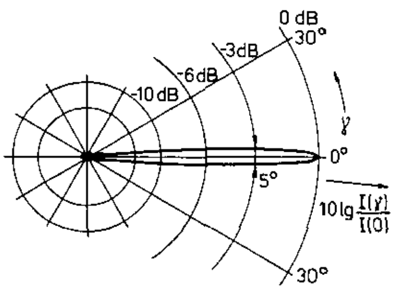

Figure 3. Radiation pattern of a piezoelectric transducer (BERO type [10]).

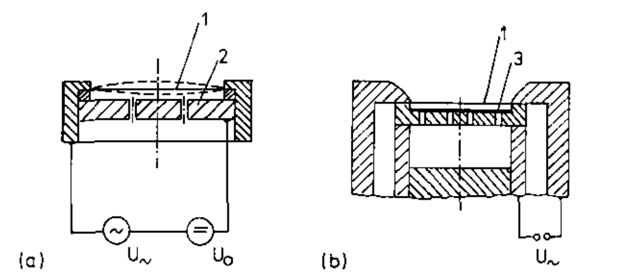

Figure 4. Electrostatic transducer: (*a*) principle; (*b*) electret microphone [14]. 1, Diaphragm; 2, back plate; 3, electret.

By the use of an electret foil which stores permanent dielectric charges on its surface, an external bias becomes unnecessary. Commonly the electret is coated on the back plate (see figure 4(*b*)) [14].

Material parameters, geometric size, mechanical bias stress and bias voltage of the diaphragm mainly determine resonance frequency and sensitivity of electrostatic transducers. The transmission function and the pulse response behaviour can be adjusted additionally by constructive variation of the stationary electrode and the back volume.

The Sell principle provides another type of electrostatic transducer. The special design of the back electrode supplies a group of small partial transducers which operate in parallel. With this method a nearly constant deflection of the whole area of the diaphragm is obtained (piston-like transducer). A distance sensor based on the Sell principle was presented by Polaroid for autofocus cameras (figure 5).

The capacitance of conventional electrostatic transducers is approximately 100 pF. This value corresponds to an electric impedance beyond 10 kΩ (at 100 kHz), which is 10 to 100 times greater than the value of piezoelectric transducers. Therefore the preamplifier has to meet higher requirements with respect to input impedance and signal-to-noise ratio (SNR). A new type of electrostatic transducer based on the Sell principle was presented by Suzuki *et al* [16]. This transducer is manufactured by a silicon micromachining technology and also suited for the design of phased arrays as described in section 7. With the help of this technology very small spacings between the diaphragm and the back electrode become possible. Hence an improved efficiency and a lower electrical impedance, which is comparable to piezoelectric transducers, can be obtained. Manufacturing, however, is expensive.

Advantages of electrostatic transducers are their high transfer coefficients both in the transmitter and receiver mode in combination with a wide bandwidth. The main reason is the low mass of the vibrating diaphragm. Disadvantages are the need for an external bias voltage (excluding electrets), the sensitivity to dust and humidity and low mechanical ruggedness. Moreover, manufacturing becomes even more expensive with complicated transducer shapes, e.g. if curved back electrodes were needed for a special radiation pattern. For these reasons the use of ultrasonic sensors based on the electrostatic principle is limited.

5.2 Piezoceramic transducers

In modern ultrasonic measurement systems for industrial purposes piezoceramic transducers clearly dominate. Typical advantages are their compact, rugged mechanical design, high efficiency and great range of operation temperature. The standard piezoceramic material is lead zirconium titanate (PZT). Important material parameters are listed in table 2.

Piezoceramic transducers make use of the piezoelectric length or thickness extensions of the ceramic. As described above, high transducer sensitivity can be achieved if the acoustic impedance can be decreased and the vibration amplitudes of the transducer surface become large. Different principles are as follows.

(a) The planar strain of a piezoceramic which is electrically excited may be converted into a bending motion by the help of a multilayer structure, e.g. the so called bimorph elements. For this, active–active or active–passive layer structures are applied. The principle is presented in figure 7(*a*), (*b*)

(b) If the thickness or radial extension vibrations of

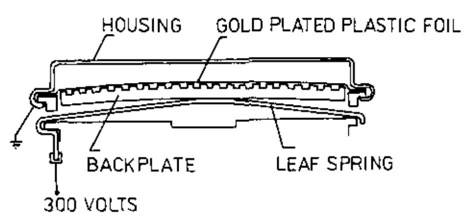

Figure 5. Electrostatic transducer based on the Sell principle [15].

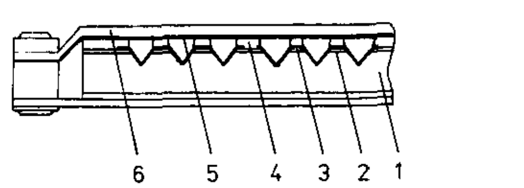

Figure 6. Transducer manufactured by silicon micromachining technology [16]. 1, Si wafer; 2, SiO_2; 3, aluminium (back electrode); 4, CVDSiO_2; 5, aluminium (common electrode); 6, polyester.

Table 2. Relevant material parameters of PVDF and PZT-5.

Parameter	PVDF Uniaxial	PVDF Biaxial	PZT-5
Specific density, ρ ($\times 10^3$ kg m^{-3})	1.78		7.45
Young's modulus, E ($\times 10^9$ N m^{-2})	2.5		62
Mechanical loss factor, $\tan \delta_m$	0.10		0.02
Piezoelectric constants (pC N^{-1}) d_{31}	24	10	−171
d_{32}	2	10	−171
d_{33}	−39		374
Relative permittivity, ε_{33}	10–13		1700
Electromechanical coupling factor, k_{31}	0.12		0.34
Maximum temperature, T_{max} (°C)	80		365

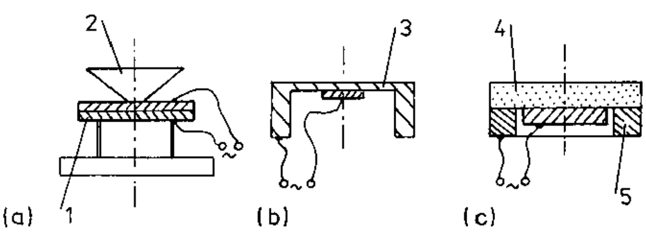

Figure 7. Piezoceramic transducer. (*a*) Bending mode with active–active layer [17]; (*b*) bending mode with active–passive layer; (*c*) radial mode with $\lambda/4$ matching layer [10]. 1, Bimorph, 2, impedance converter; 3, bending plate; 4, matching layer; 5, metallic ring.

piezoceramic discs are used, a matching layer, which serves as an acoustic impedance transformer, improves the efficiency significantly. Its thickness corresponds to a quarter of the sound wavelength inside the matching material. Optimum impedance matching is obtained if

$$Z_M = \sqrt{(Z_C \cdot Z_P)} \tag{5.1}$$

where Z_M, Z_C, and Z_P are the acoustic impedances of the matching layer, ceramic and propagation medium, respectively. For PZT ceramic Z_C is 2.5×10^7 kg m^{-2} s^{-1} and Z_P of air is about 400 kg m^{-2} s^{-1}.

Currently, used matching materials always represent compromises of the acoustic impedance, sound attenuation, mechanical ruggedness and sensitivity to dirt and humidity. The impedance value of present matching layers is about 10^6 kg m^{-2} s^{-1} [10] and thus ten times the optimum value obtained from equation (5.1). A promising alternative is stacks of different quarter-wave matching layers with stepped acoustic impedance or gradient layers with continuously decreasing impedance. The search for suitable matching materials will remain an important aspect in the transducer development.

(c) Another principle of piezoceramic transducers is sandwich configurations usually consisting of piezoceramic discs or rings clamped between metal rods (figure 8). Because of the high tensile strength of metals (approximately ten times higher than piezoceramics) large vibration amplitudes can be achieved. This mechanical amplification, however, is associated with an additional reduction of the narrow bandwidth resulting from the large vibrating mass [18]. Such transducers can be used for the generation of high-power ultrasound.

All types of piezoceramic transducers regarded above are narrow-band mechanical systems to a certain sound wavelength. To achieve the maximum amplitude the transducers are often driven by a burst signal where the centre frequency corresponds to the resonance of the transducer as illustrated in figure 1. The resonance frequency, however, may change with temperature. Therefore in commercial distance measurement systems the transmitting frequency is often supplied either by a temperature-controlled oscillator or by an oscillator which is locked by the centre frequency of the transducer.

In addition to the long transient time of the receiving signal resulting from the small relative bandwidth (about 2%, figure 1(*c*)), the signal form also strongly depends on the radiation direction even within the main lobe. This is another drawback, because many distance sensors evaluate the signal envelope. Therefore high resolution and reproducibility are hardly achievable.

The radiation pattern can be varied by the transducer design, for instance, by increasing the matching layer diameter relative to the diameter of the piezoceramic disc [10]. By doing this the sound beam is focused to a small spatial range as shown in figure 3.

5.3. Composite transducers

Composite materials consisting of piezoceramics and polymers offer new ways for the design of ultrasonic transducers [19]. An example is the sandwich layer

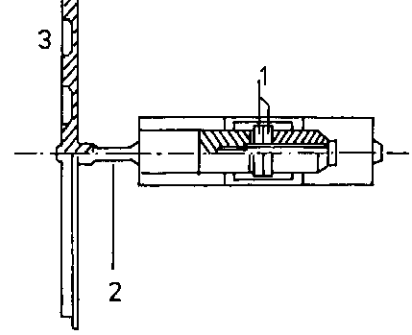

Figure 8. Sandwich transducer for power ultrasonic applications [18]. 1, Piezoelectric ceramics; 2, mechanical amplifier; 3, radiating plate.

transducer introduced by Kleinschmidt and Mágori [20]. It consists of piezoceramic and polymer sheets alternately assembled in a stack as shown in figure 9. The sound is radiated from the relatively broad front side of the composite rather than from the small front side area of the piezoceramic foils. As the ceramic has a higher elastic modulus (about 20 times higher), a thin layer (0.2 mm) can drive a comparatively thick layer of plastic (0.8 mm) and the acoustic coupling of the piezoceramic to air is improved. In this way the composite transducer may be considered as an 'active matching layer'. Moreover the polymer layers provide mechanical damping of the vibration. Therefore the bandwidth is wide, for example nearly 130 kHz, in which the centre frequency is about 160 kHz. The efficiency, however, is also reduced by damping. Preferred applications of these transducers are distance measurements with a resolution between 10 and 100 μm at a medium distance range (maximum 1 m).

The radiation pattern can be easily changed by varying geometric dimensions and the number of the layers in the stack. In particular, appropriate small aperture elements (< half the wavelength, which is about 2 mm) of one- or two-dimensional arrays can be designed. A significant advantage is given by the possible high transmission of approximately 2 Pa at a distance of 1 m and a low driving voltage of 10 V, resulting from the low thickness of the piezoceramic sheets. Moreover the individual sheets can be combined in different ways: in series, in parallel or mixed. By this the electrical impedance of the transducer can be specified according to the requirements of the application, and the signal-to-noise ratio of the receiving signal may be improved.

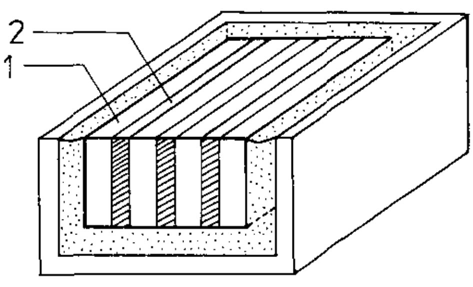

Figure 9. Composite transducer (sandwich layer structure) [20]. 1, Plastic material; 2, PZT lamella.

5.4. Piezopolymer foil transducers

In 1969 the strong piezoelectric effect in the high polymer polyvinylidene fluoride (PVDF) was discovered [21]. Since then ultrasonic transducers using such materials have been the subject of much research. In recent years work has also been concentrated on new copolymers, e.g. of vinylidene fluoride (VDF) and trifluoroethylene (TRFE) [22].

One important aim is the increase of the temperature range in which piezopolymer transducers can operate.

The electromechanical coupling factor of PVDF is less than that of PZT ceramic (see table 2). On the other hand, piezopolymer transducers show excellent dynamic properties (similar to electrostatic transducers) caused by their low vibrating mass and high mechanical damping inside the polymer foil—short pulses can therefore be radiated. The foil thickness is usually 10 to 25 μm. Referring to typical transducer sizes, their related capacitance lies in a range of some 100 pF to some nF. Hence electrical impedance is typically lower than 1 kΩ at a frequency of 100 kHz. Therefore the design and coupling of the preamplifier is uncomplicated. Another advantage of a small foil thickness is that a high electric field strength and hence large mechanical displacement amplitudes of the radiating surface are obtained by a relatively low driving voltage (10–50 V), similar to the sandwich layer transducer discussed above. Therefore lower piezoelectric coefficients compared to piezoceramics are partially compensated.

Polarized and metallized (on both sides) PVDF foils show high mechanical flexibility and low brittleness. Transducers of different shape and size can be easily manufactured. One basic design of piezopolymer transducers is shown in figure 10. The foil is formed as a cylindrical or spherical shell clamped at its edges. Cylindrical transducers make use of uniaxially oriented anisotropic foils, where $d_{32} \gg d_{31}$, see table 2. The direction of orientation (axis 1) is perpendicular to edge clamping.

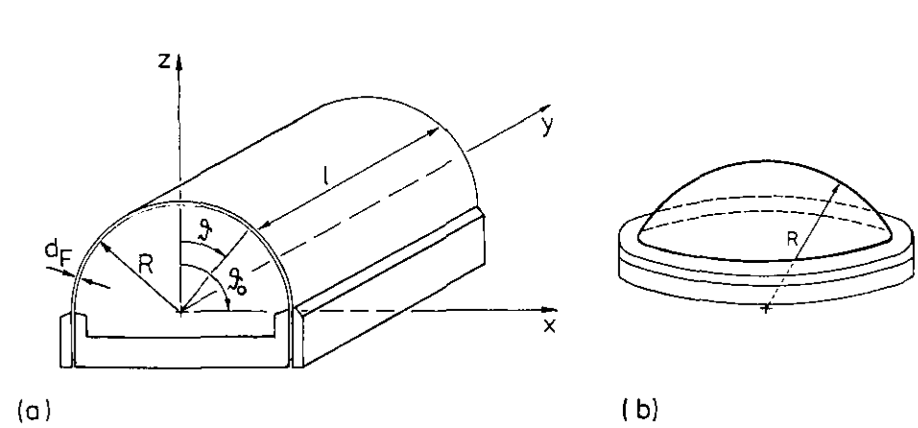

Figure 10. Principle design of airborne sonic transducers using PVDF foils [23]. (*a*) Cylindrically- , (*b*) spherically-curved foil.

For spherical transducers biaxially oriented foils are used.

In the case of electrical excitation (transmitter), in-plane strain vibrations are generated. Because of lateral clamping these vibrations are converted into radial motion of the foil. The curved shape is needed to get a definite direction of the mechanical displacement of the foil when an alternating driving voltage is applied to the transducer. The conversion of in-plane vibrations into radial deflections can be regarded as an increase of the radiating surface by 10^2 to 10^3. This effect is comparable to impedance matching of piezoceramic transducers.

The acoustic excitation of the transducer (operating as a receiver) causes bending vibrations of the clamped foil which lead to in-plane stresses inside the foil and hence to an electrical output voltage. In figure 11, examples are shown for the mechanical deflections of a cylindrically shaped PVDF foil calculated by an analytical shell model. The sound pressure level is 0.1 Pa [24]. The curvature of the foil may be formed freely suspended or supported by foam or rigid elements. Figure 12 shows some relevant transducer designs. Foam support provides additional damping of the vibrating foil and attenuates the sound reflections inside the transducer. The basic principle permits easy manufacturing of transducers for a frequency range up to 200 kHz. At higher frequencies geometric dimensions and therefore the ratio of the active surface to the cross section area of the foil becomes small (see figure 13).

Detailed investigations of PVDF microphones for the audible range were first carried out by Lerch [25].

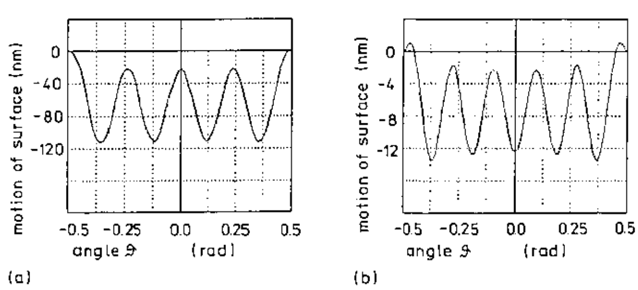

Figure 11. Calculated radial deflections of a cylindrically curved PVDF foil excited by a plane sound wave (sound pressure level
is 0.1 Pa, meaning 74 dB). Parameters: $R = 4$ mm, $\theta_0 =$ 0.5 rad,
$d_F = 20$ μm. (*a*) $f = 60$ kHz; (*b*) $f = 110$ kHz.

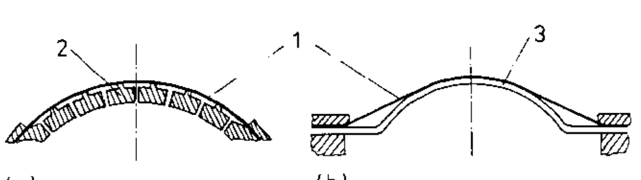

Figure 12. Transducer with rigidly supported PVDF foil. (*a*) Annular or linear support [25]; (*b*) support by plastic diaphragm [26].
1, Piezopolymer foil; 2, supporting plate; 3, plastic diaphragm.

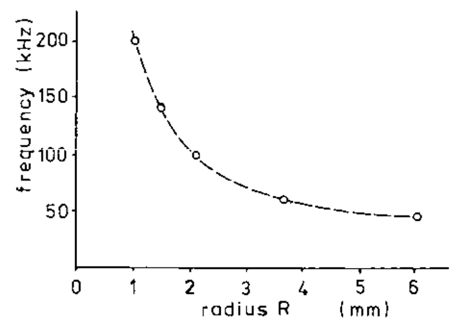

Figure 13. Resonance frequency of a cylindrical PVDF transducer in the receiving mode as a function of radius of curvature R ($\theta_0 = 0.8$ rad).

Properties of piezopolymer transducers operating in the ultrasonic range both as transmitter and receiver were presented by Kroemer [24]. Figure 14 shows the frequency responses of transducers with a foam-supported cylindrical PVDF foil. Because electrical and acoustic excitation of the curved foil cannot be assumed completely equivalent, the values of the corresponding resonance frequencies in the transmitter and receiver mode may differ.

Apart from curved transducers devices using flat PVDF bimorph-type bending mode transducers have also been designed. Similarly to piezoceramic bending transducers, active–active or active–passive multilayer structures are applied [27].

Various transducer shapes can be manufactured because of the high flexibility of piezopolymers. In figure 15 a transducer with multiple curved foil is shown. While the frequency response is determined by the radius R and opening angle θ_0 of the curvature the vertical (yz plane) and horizontal (xz plane) radiation patterns can be adjusted independently by varying the axial length l

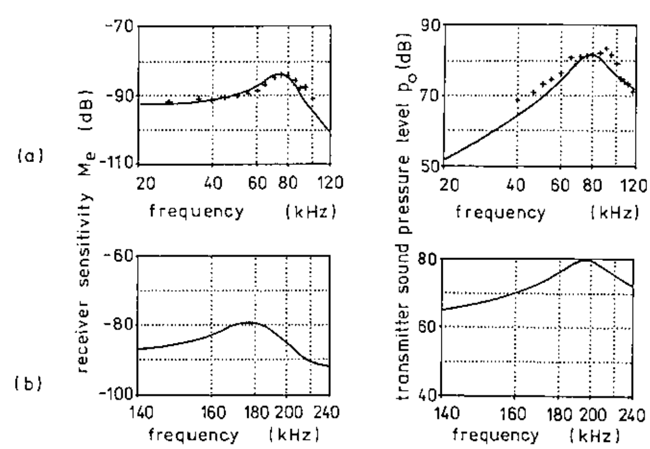

Figure 14. Frequency response functions of cylindrical PVDF transducers in the transmitter and receiver mode. M_e, transfer ratio of the receiver (0 dB = 1 V/0.1 Pa); p_0 sound pressure (distance $r = 0.5$ m) (0 dB = 2×10^{-5} Pa).
(*a*) $R = 2.5$ mm, $\theta_0 = 1.5$ rad, $d_F = 22$ μm, $\tan\delta_m = 0.25$;
(*b*) $R = 1.2$ mm, $\theta_0 = 1.0$ rad, $d_F = 22$ μm, $\tan\delta_m = 0.15$.
+ + + +, measurement;
——, calculation.

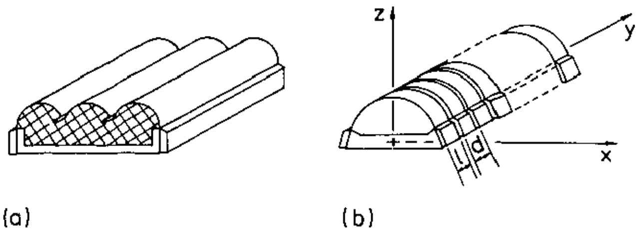

Figure 15. Special designs of PVDF transducers. (*a*) Multiple curved foil; (*b*) linear array.

and the number of curvatures (see figure 16). The directivity gain factor R_E is a function of the radiation angle γ. It may be defined as:

$$R_E(\gamma) = p(\gamma)/p(\gamma = 0). \tag{5.2}$$

In the case of harmonic excitation (*cw* mode) R_E is obtained in the *yz* plane by:

$$R_E = \left| \frac{\sin[\pi l/\lambda \cdot (\sin \gamma)]}{\pi l/\lambda \cdot (\sin \gamma)} \right|. \tag{5.3}$$

For pulse excitation R_E is usually calculated by numerical methods. From equation (5.3) it follows that the main lobe in the radiation pattern becomes narrow if the ratio l/λ increases. Regarding the *xz* plane the width of the corresponding main lobe is reduced if the number of curved elements increases.

6. Transient behaviour of airborne sonic transducers

The pulse response is an important property with respect to high resolution. Another aspect is the use of one single transducer both as transmitter and receiver. Figures 1, 2 and 17 illustrate typical pulse response signals and the corresponding spectra obtained from different transducer types. In the case of piezoceramic transducers as shown in figure 7(*a*) a separate transmitter and receiver were used. In addition the transmitter was excited by a burst signal (see figure 1).

Wide bandwidth transducers have the important

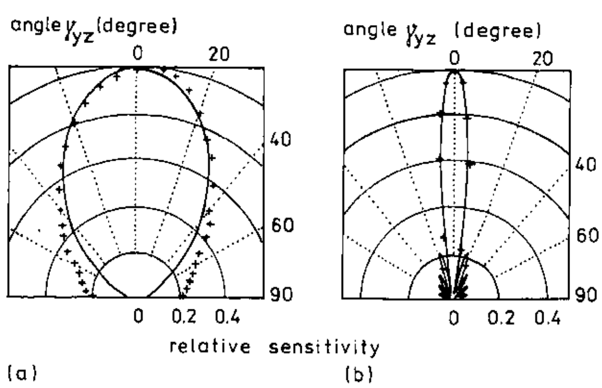

Figure 16. Vertical radiation pattern of cylindrical PVDF transducers. (*a*) $l = 3.5$ mm, $f = 100$ kHz; (*b*) $l = 30$ mm, $f = 60$ kHz.

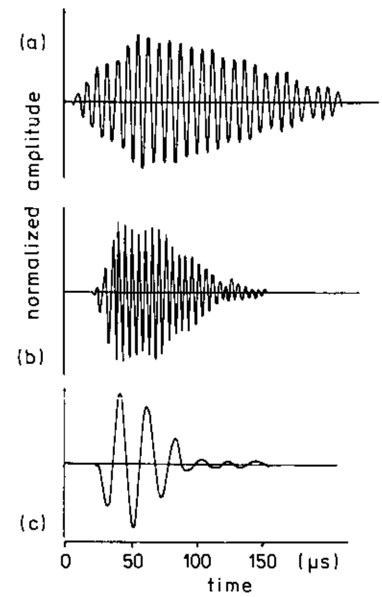

Figure 17. Pulse response of different airborne sonic transducers. (*a*) Type M40, piezoceramic [28]; (*b*) BERO type with $\lambda/4$ matching layer [10]; (*c*) electrostatic Sell transducer [15].

advantage of a short decay time of the vibration amplitude, thus permitting a small 'dead zone' where objects cannot be detected. If a piezopolymer transducer is used the minimum measurement distance to an object is about five times the sound wavelength in air (10 mm at 200 kHz). For composite transducers the value corresponds to about ten wavelengths which is still small. In comparison, piezoceramic resonance vibrations may have a 'dead zone' of some 10 cm to a few metres, corresponding to the time in which the amplitudes of the exciting signal decay to values which are considerably smaller than the echoes to be expected. The most interesting features of relevant airborne ultrasonic transducers are compared in table 3.

7. Transducer arrays

Multi-element transducers with individual single-element excitation offer the capability of electronic control of the radiation pattern. In this way the transducer can be adapted to several measurement tasks.

A commonly used method is amplitude-weighted excitation of single elements. In the case of plane array transducers the directivity factor is described by the Fourier transform of the weighting function of exciting amplitudes. For example, the side lobes in the radiation pattern can be suppressed by using a Gaussian weighting function. Detailed investigations were carried out, for example, by Kuhrt [29]. By time-delayed excitation of every single element (phased array technique) the main lobe of the radiation pattern can be positioned electronically. By this method the spatial range in front of the transducer can be scanned and the positions or lateral details of relevant objects detected. The complete

Table 3. Comparison of transducers for applications in air (typical values of 200 kHz types).

Parameter	Transducer type			
	Electrostatic	Piezoceramic (with matching layer)	Composite (sandwich layer type)	Piezopolymer
Sensitivity				
receiver (mV Pa^{-1})	2	1	0.1	0.4
transmitter (Pa V^{-1}) ($r = 1$ m)	0.2	1	0.3	0.1
Frequency range				
f_{max} (kHz)	200	500	500	200
relative bandwidth	0.3	0.02	0.3	0.3
Capacitance (nF)	0.1	2	30	2
Maximum temperature (°C)	80	>100	>100	80
Ruggedness	low	high	high	low
Variability of the properties	medium	low	medium	high

acoustic image is obtained by the help of special reconstruction algorithms [30] similar to those used in sonography or NDT.

The achievable spatial resolution and the accuracy are mainly determined by the properties of the array transducer. Basically the transducer has to meet the following needs:

low crosstalk between neighbouring elements;
wide opening angle of the main lobe of a single element;
small distances between the single elements;
short transient time of the radiated single signals;
high directivity of the complete array.

Array transducers for industrial purposes always have to be a compromise. Their geometric size and the number of single elements are limited because of increasing expenditure. In addition to this the single elements cannot be manufactured arbitrarily small. In many cases a limited scanning sector is sufficient. Therefore, in general, the array transducer does not have to meet all the requirements listed above at the same time.

For the design of high-resolution arrays, only transducers with a wide bandwidth are suitable. Piezoceramic composite transducers as shown in figure 6 permit very compact arrays with small spacings between neighbouring single elements. This is advantageous with respect to a wide scan sector. The drawback is the large crosstalk between the single elements which leads to a considerable inter-dependence of the corresponding signals.

Foil transducers offer the advantage of a very low crosstalk. On the other hand, the construction is less compact in comparison with piezoceramic sandwich layer transducers. Micro-machining technology leads to a new design of arrays based on an electrostatic principle [30], as discussed above.

The drawbacks associated with electrostatic transducers can be avoided if piezopolymer foils are applied. Figure 15(b) shows an example of the design of a linear multi-element transducer based on cylindrically shaped PVDF foil. The number and width of the single elements can be varied quite simply. In addition to this, further such lines may be attached sequentially or in parallel.

In figure 18 the radiation pattern of an eight-element linear array is shown. The width l of a single element is less than the sound wavelength. Hence, its main lobe in the yz plane is wide. By parallel switching of all the elements the radiation pattern illustrated in figure 16(b) is obtained. If time-delayed excitation is applied, the main lobe is deflected. The deflection angle for a given delay time depends on the quotient λ/d. If long burst signals are applied, interfering side lobes in the inverse direction may appear. Figure 19 shows the corresponding radiation pattern if either a single exciting pulse or eight pulses are used. The delay time between two neighbouring elements corresponds to the pulse length in the transmitting signal (for harmonic excitation this would correspond to a phase shift of π). When d is greater than $\lambda/2$ a definite main lobe is obtained only if the number of radiated pulses is much less than the number of transducer elements—otherwise the envelope of the signal has to be analysed additionally. Therefore, the capability of radiating short pulses is a very import-

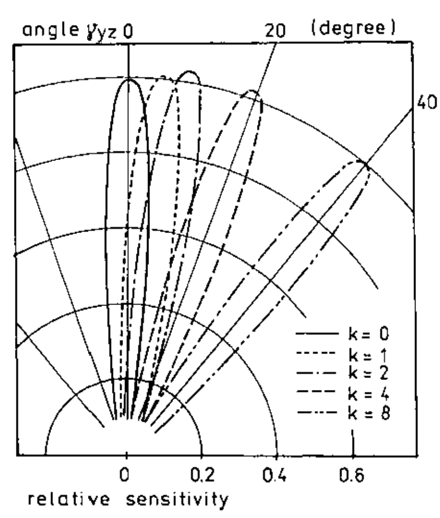

Figure 18. Radiation pattern of a linear PVDF array transducer following from time-delayed excitation of every single element: $\Delta t = (k/8) \times T_{Pulse}$. $l = 5$ mm, $d = 6$ mm, number of elements = 8. Transmitting signal: single pulse ($T_{Pulse} = 11.3$ μs).

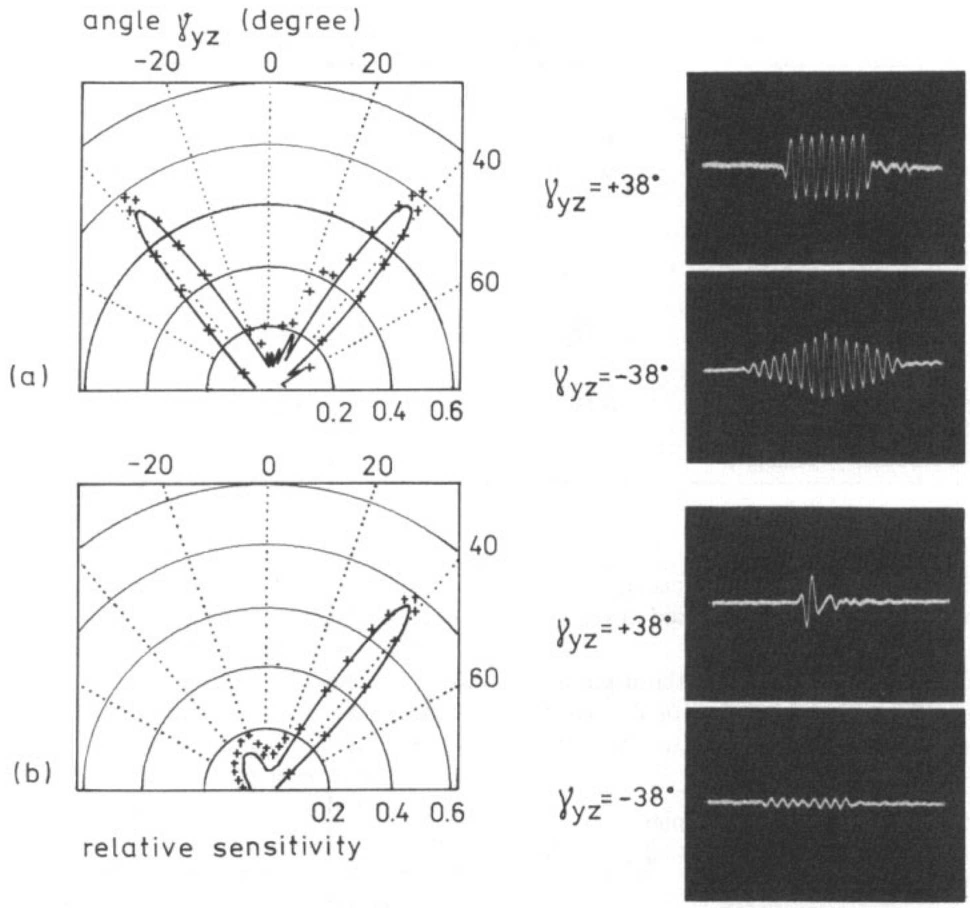

Figure 19. 'Peak value' radiation pattern and corresponding acoustic signals of a linear eight-element array transducer. (*a*) Excitation by a burst signal with eight pulses, $\Delta t = T_{\mathrm{Pulse}}$; (*b*) excitation by a single pulse, $\Delta t = T_{\mathrm{Pulse}}$. + + + +, measurement; ——, calculation.

ant aspect for array design, the scan range is increased and interfering side lobes are suppressed. This emphasizes the advantages of wide band ultrasonic transducers.

8. Conclusions

The varied applications of sensors using airborne ultrasound require adjustment of the acoustic transducer properties to the particular measurement problem. Thus, ultrasonic transducers have to be regarded as the key elements. For many present applications in the industrial area, such as non-contact distance measurement with medium resolution or room surveillance, conventional piezoceramic transducers are sufficient. Their main advantages are their high efficiency factor and compact and rugged transducer design.

For more complex problems such as echo profile evaluaton or distance measurement with high resolution, which will be of increasing interest, transducers with a wide bandwidth are needed. Composite transducers represent a promising development. One example is the sandwich layer design. These transducers provide the required wide bandwidth and are also suitable for the construction of phased arrays. Their compact design is an important advantage with respect to use under rough industrial conditions.

For other applications, where ruggedness is not of major concern, transducers based on piezopolymer foils are an interesting alternative. They offer a great variety of acoustic properties at comparatively low cost. In contrast to electrostatic transducers, no bias voltage and no stationary back electrode are needed. Piezopolymer foil transducers are particularly suited to the design of broad-band phased arrays with low crosstalk between neighbouring transducer elements. This is a precondition for the detection of the lateral structure or spatial distribution of objects. Moreover broad-band transducers also permit precise short range measurement with a very small 'dead zone'.

References

[1] Biehl K E and Müller-Gronau W 1988 Ultraschallsysteme für die industrielle Objekterfassung und -klassifizierung *Technis. Messen* **55** 367–76

[2] Delepaut C, Vandendrope L and Eugène C 1986 Ultrasonic three-dimensional detection of obstacles

for mobile robots *Proc. 16th Int. Symp. Industrial Robots (ISIR 86 Brüssels)* pp 483–90

[3] Michalski B and Berger W 1984 Füllstandsmessung mittels Laufzeit von Ultraschall *Technis. Messen* **51** 306–12

[4] Canali C, De Cicco G, Morten B, Prudenziati M and Taroni A 1982 A temperature compensated ultrasonic sensor operating in air for distance and proximity measurements *IEEE Trans. Ind. Electron.* **29** 336–41

[5] Chande P K and Sharma P C 1984 A fully compensated digital ultrasonic sensor for distance measurement *IEEE Trans. Instrum. Meas.* **33** 128–9

[6] Löschberger J 1987 Ultraschall-Sensorsystem zur Bestimmung axialer und lateraler Strukturen mit Hilfe bewegter Wandler zum Einsatz in der industriellen Automation *Dissertation* Universität der Bundeswehr München, Insitut für Meß- und Automatisierungstechnik

[7] Bernst T, Löschberger J and Mágori V 1986 Moderne Verfahren der Signalverarbeitung bei Ultraschall-Robotik-Sensoren *NTG-Fachberichte* **93** 253–63

[8] Mágori V 1989 Ultraschall-Sensoren mit hoher örtlicher Auflösung *Proc. MIOP'89 4th Exhib. Conf. Ultra High Frequency Technology (Sindelfingen) Feb 28–March 2 1989* p 10

[9] Mágori V 1989 Signal processing for smart ultrasonic sensors *Proc. 3rd Ann. European Computer Conf. (Hamburg) May 8–12 1989* pp 3-21–3-26

[10] Mágori V and Walker H 1987 Ultrasonic presence sensors with wide range and high local resolution *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **34** 202–11

[11] Skudrzyk E 1954 *Die Grundlagen der Akustik* (Berlin: Springer)

[12] Suitlov V A 1984 *Physik des Ultraschalls* (Berlin: Akademie)

[13] Bass H E 1985 Ultrasonic background noise in industrial environments *J. Acoust. Soc. Am.* **78** 2013–6

[14] Zahn R 1983 Kreis- und kreisförmige Rückplatten-Elektretmikrofone: Theoretische und experimentelle Untersuchungen *Dissertation* TH Darmstadt D-17

[15] Biber C, Ellin S, Shenk E and Stempeck J 1980 The Polaroid ultrasonic ranging system *67th Conv. Aud. Eng. Soc. Oct. 1980*

[16] Suzuki K, Higuchi K and Tanigawa H 1989 A silicon electrostatic ultrasonic transducer *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **36** 620–7

[17] Bühling D 1985 Keramische Sensoren *Radio Fernsehen Elektron.* **34** 484–6

[18] Gallego-Juárez J A 1989 Piezoelectric ceramics and ultrasonic transducers *J. Phys. E: Sci. Instrum.* **22** 804–16

[19] Newnham R E, Safari A, Giniewcz J and Fox B H 1984 Composite piezoelectric sensors *Ferroelectrics* **60** 15–21

[20] Kleinschmidt P and Mágori V 1985 Ultrasonic robotic-sensors for exact short range distance measurement and object identification *Proc. IEEE Ultrason. Symp.* 457–62

[21] Kawai H 1969 The piezoelectricity of poly(vinylidene fluoride) *Japan. J. Appl. Phys.* **8** 975–6

[22] Ohigashi H, Koga K, Suzuki M and Nakanishi T 1984 Piezoelectric and ferroelectric properties of P(VDF-TrFE) copolymers and their application to ultrasonic transducers *Ferroelectrics* **60** 263–76

[23] Manthey W and Kroemer N 1989 Ultraschallsensoren auf der Basis piezoelektrischer Polymere *Technis. Messen* **56** 377–84

[24] Kroemer N 1990 Untersuchungen an Luftultraschallwandlern mit gewölbter piezoelektrischer Polymerfolie *Dissertation* TU Karl-Marx-Stadt, Fakultät für Elektroingenieurwesen

[25] Lerch R and Sessler G M 1980 Microphones with rigidly supported membranes *J. Acoust. Soc. Am.* **67** 1379–81

[26] Cragg W D and Tester N W 1977 Telephon-Wandler mit piezoelektrischer Polymer-Folie. *Elektris. Nachrichtenwesen* **52** 359–62

[27] Murphy P V and Maurer G C 1985 Piezoelectric polymer film transducers for communications *Proc. 5th Int. Symp. Electrets (ISE 5) (Heidelberg) 1985* pp 783–8

[28] Knoll A 1988 Fortgeschrittene Verfahren zur ultra-schallbasierten Objektortung in der Robotik.

[29] Kuhrt R 1971 Laufzeitbedingte Impulsverzerrungen bei hydroakustischen Wandlern *Dissertation* University of Rostock

[30] Koyama K, Yamamoto T, Tamura Y and Wada Y 1987 Acoustic holography using omnidirectional copolymer array transducer *Proc. 8th Symp. Ultrasonic Electronics (Tokyo) 1987* pp 218–20

[31] Tanigawa H, Higuchi K and Suzuki K 1987 Airborne ultrasonic array transducer utilizing silicon micromachining *Proc. 1st Workshop on Manipulators, Sensors and Steps Towards Mobility (Karlsruhe) 1987* pp 247–51