OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

18065

PIEZOELECTRIC CERAMICS AND POLYMERS

Dr. Franz Holzer
CLT 89/609, Backstopping Officer: Mr. Dmitriev

CONTENTS

1. Foundations of piezoelectricity

1.1. Parameters for the description of piezoelectric properties

Piezoelectricity is a property of dielectric bodies. A necessary condition for the occurrences of piezoelectricity is the absence of a center of symmetry. Piezoelectric media are therefore intrinsically anisotropic and show a coupling between elastic and dielectric phenomena /1/.

The studies of the relation between pyroelectricity and crystal symmetry led the brothers Pierre and Jacques Curie to the discovery of piezoelectricity of tourmaline in 1880. They found that some crystals are electrically charged when compressed in particular directions of their surfaces, the charge being proportional to the pressure. They found also in what direction pressure should be applied and in which crystals classes the effect was to be expected. A series of crystals were studied such as zinc blende, sodium chlorate, boracite, tourmaline, quartz, calamine, topaz, tartaric acid, cane sugar and Rochelle salt in the paper in which the discovery was announced. The first quanititative measurement of the effect in quartz and tourmaline, and the verification of the reciprocal effect after theoretical predicition by Lippmann in 1881 were also described by the brothers Curie /3/.

The polarization of piezoelectric medium changes if mechanical stress T is applied, which results in an additional term of electric displacement D /8/:

$$D = d\,T \qquad (1)$$

This is called the direct piezoelectric effect. The reciprocal effect shows a mechanical strain S if an electric field E is applied:

$$S = d\,E \qquad (2)$$

These terms occur in addition to the dielectric and elastic equations of the medium. The equations between stress T, strain S, electric field E and electric displacement D of a piezoelectric medium can be described in the following form /1/:

$$
\begin{aligned}
S &= s^{E}\,T + d_{t}\,E,\\
D &= d\,T + \varepsilon^{T}\,E,\\
S &= s^{D}\,T + g_{t}\,D,\\
E &= -g\,T + \beta^{T}\,D,\\
T &= c^{D}\,S - e_{t}\,E,\\
D &= e\,S + \varepsilon^{S}\,E,\\
T &= c^{D}\,S - h_{t}\,D,\\
E &= -h\,S + \beta^{S}\,D,
\end{aligned}
\qquad (3)
$$

Where the subscript t identifies a transposed matrix and the superscripts E, D, T, and S indicate constant conditions of the respective field quantities.

It should be taken into consideration that these relations are tensor equations, and each element consists of a matrix which is typical for every crystal class. Due to the crystal symmetry a number of elements may be equal or zero. The definition of the piezoelectric constants follow from these equations:

$$
\begin{aligned}
d &= \left(\frac{\partial S}{\partial E}\right)_{T} = \left(\frac{\partial D}{\partial T}\right)_{E},\\
g &= \left(\frac{-\partial E}{\partial T}\right)_{D} = \left(\frac{\partial S}{\partial D}\right)_{T},\\
e &= \left(\frac{-\partial T}{E}\right)_{S} = \left(\frac{\partial D}{S}\right)_{E},\\
h &= \left(\frac{-\partial T}{\partial D}\right)_{S} = \left(\frac{-\partial E}{\partial S}\right)_{D}.
\end{aligned}
\qquad (4)
$$

The mechanical and dielectrical constants were denoted as follows:

s....elastic compliance,
c....elastic stiffness,
ε....dielectric constant,
β....dielectric impermeability.

In most cases the set of the first and second equation from (3) is most useful, since electric field and stress are independent variables. An approach of one-dimensional conditions e.g. stress or strain in many applications such as pulse transition and resonant vibrations of a large thin plate in its thickness mode is an useful simplification in most practical cases.

The most important properties of piezoelectric materials are described by their respective piezoelectric coupling factor k.

$$k = U_m / \sqrt{U_l \; U_d} \qquad (5)$$

U_m..... mutual energy density
U_l..... elastic energy density
U_d..... dielectric energy density

The coupling factors are determined for simplified cases e.g. if the number of independent constants is reduced drastically by symmetry, or when most stresses are zero; that includes the influence of boundary conditions also and defines the planar and thickness coupling factor. One of the most important coupling factor is k_t (thickness coupling factor):

$$k_t = h_{33} / \sqrt{c^D_{33} \; \beta^S_{33}} \; . \qquad (6)$$

Piezoelectric materials can be excited to several vibration modes, depending on the direction of the polarization of the material and the applied electric field. Coupling between different vibration modes is also possible. Piezoelectric crystals should be cutted in convenient directions so that polarisation falls in the desired direction. Piezoelectric ceramic and plastic materials can be polarized in a desired direction by applying an external electric field. The mechanical vibration of piezoelectric solids is defined by its structure. In many applications the resonance behaviour of bars, plates, rings, shells and cylinders is used to excite mechanical vibrations, while in some other applications the range outside resonance is used.

Three kinds of piezoelectric effects are of practical interest /8/:

- longitudinal mode (fig. 1a) $D_3 = d_{33} \; T_3$,
- transversal mode (fig. 1b) $D_3 = d_{31} \; T_1$,
- shear mode (fig. 1c) $D_3 = d_{15} \; T_5$.

Generally, the following modes are important for transducer design:

- longitudinal expander (electric field parallel or normal to length)
- thickness expander (electric field parallel to thickness)
- face shear (electric field parallel to larger faces)
- planar mode of a disk
- hoop mode of a ring (axial electric field)
- hoop mode of a ring (radial electric field)
- breathing mode of a spherical shell ,

Especially the thickness expander mode in thin piezoelectric plates is frequently used in ultrasonics, e.g. in transducers for NDT, medical ultrasonics, and many other practical applications. The electrical and mechanical boundary conditions have considerable influence on the behaviour of the modes of vibration.

The laterally clamped condition applies when the lateral dimensions are much larger than in the direction of elastic wave propagation. The electric excitation is parallel to the wave propagation and under these conditions constant strain S and constant dielectric displacement D should be considered. Let us consider a thin transducer plate of thickness t with electrodes normal to the z- or 3- direction. If its lateral dimentions are large compared to thickness, the plate can be considered to be laterally clamped, so that $S_1 = S_2 = S_4 = S_5 = S_6 = 0$; if we deal with an insulating dielectric medium with no electric flux leakage, we can assume $D_1 = D_2 = 0$ and $\partial D_3 / \partial z = 0$.

Under the assumption that the transducer plate vibrates like a piston, which means that the faces move with equal displacement and with no phase difference, a one-dimensional approach can be applied. With D and S as independent variables the vibration can be described as:

$$
\begin{aligned}
T_3 &= c^D_{33} S_3 - h_{33} D_3 \qquad (7)\\
E_3 &= - h_{33} S_3 + \beta^S_{33} D_3 .
\end{aligned}
$$

The resonance vibration is given by the thickness of a half wave length:

$$f = v^D / 2t. \qquad (8)$$

In practice the resonance vibration and its harmonics are superposed by other unwanted modes arising from the finite dimensions of the plate. However, if the ratio of diameter to thickness is larger that 10 and the transducer is loaded, the one-dimesional approach is sufficient for the description of ultrasonic transducers.

But the fundamental equations and their solution are not so frequently used in practical engineering. From these equations a very useful electrical equivalent circuit is derived by MASON /2/. The advantage of such equivalent circuits is that the acoustic problem can be solved by methods of network theory of transmission lines, and if assumptions made in deriving are valid, an exact solution of wave equation is given.

The equivalent circuit for each type of piezoelectric transducer can beobtained by using its equation of motion and the appropriate piezoelectric equation. The boundary condition at the two active or loaded faces of the transducer and the piezoelectric equation, integrated across the transducer, yield three coupled equations describing the transducer system in terms of three dependent and three independent variables, representing a network with one pair of electrical terminals and two pairs of mechanical terminals. With the introduction of an ideal electromechanical transformer, these equations can be related to equivalent circuit where the coefficients to the terms in these equations represent electrical parameters, e.g. impedance, admittance, etc. /1/.

The well known equivalent circuit of MASON in fig. 2 represents the network with two pairs of mechanical terminals with the mechanical terms fo force F_1 and F_2 and velocity v_1 and v_2 as well as one pair of electrical terminals with the electrical terms Voltage U and current i.

The T-network of an acoustical transmission line especially for a thickness mode transducer is determined by its impedances Z_1 and Z_2 /1//2/:

$$Z_2 = \frac{Z_M}{j \sin g}, \qquad Z_1 = Z_M \, j \tan g/2,$$

where $Z_M = \rho v$ mechanical impedance and
$g = l\omega/v_t$ transmission factor.

The transfer characteristics of equivalent circuit can be described by the following equations:

$$\begin{pmatrix} F_1 \\ F_2 \\ U \end{pmatrix} = \frac{Z_M}{j} \begin{pmatrix} 1/\tan g & 1/\sin g & h/Z_M\omega \\ 1/\sin g & 1/\tan g & h/Z_M\omega \\ h/Z_M\omega & h/Z_M\omega & 1/Z_M\omega C_0 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ i \end{pmatrix}$$

The losses in transmission lines can be considered by complex transmission factors. Besides Mason's equivalent circuit the powerful KLM equivalent circuit is frequently used for transducer modelling /18/.

The unloaded piezoelectric resonator is of importance not only as a tool for the measurement of physical properties of the transducer itself, but also as an electric circuit component for use in electromechanical wave filters, e.g. in frequency filters and frequency control circuits. A simple equivalent circuit can be obtained by short-circuiting all mechanical terminal pairs ($F_1 = 0$, $F_2 = 0$). It yields a two terminal circuit. Near its resonance frequency, a circuit with lumped elements as seen in fig. 3 can be derived. The mechanical elements can be expressed in electrical terms by eliminating the transformer using the equivalent relations between electrical and mechanical terms. This equivalent circuit was earlier derived and discussed in detail by CADY /3/. The mechanical and electrical losses introduce a mechanical quality factor Q. The electrical and electromechanical behaviour of the resonance circuit can best be described in terms of a vector admittance diagram as seen in fig. 4. The analysis of electroacoustic constants can be obtained by convenient measurements of characteristic frequencies of the admittance function as suggested from IEEE standards on piezoelectric crystals /4//1/.

The characteristic parameters are listed as follows:

motional (series) resonance frequency f_s: $2\pi f_s = 1/\sqrt{LC}$,
parallel resonance frequency f_p : $2\pi f_p = 1/LC \sqrt{1+C/C}$,
resonance frequency f_r
antiresonance frequency f_a
frequency at maximum admittance f_m
frequency at minimum admittance f_n
mechanical quality factor $Q = (2\pi f_s L)/R = 1/(2\pi f_s CR)$
ratio of capacitances $C/C_0 = (f_p^2 - f_s^2) / f_s^2$.
dynamic electromechanical coupling factor $k^2 = (f_p^2 - f_s^2)/f_p^2$,
normalized bandwidth $BW' = (f_p - f_s)/f_s$.

In this way a convenient determination of characteristic constants of piezoelectric resonators is possible by vector admittance measurements.

1.2. Piezoelectric materials: from history to state-of-the-art

The discovery of piezoelectricity by Pierre and Jacques Curie at the end of the 19th century is connected with the study of crystal structures and their mechanical, dielectrical, optical and thermical properties. The investigation of crystals started in the 18th century with pyroelectric phenomena of tourmaline by Aepinus, and is carried on by Brewster, Lord Kelvin, Canton and Becquerel. Becquerel performed some experiments in which crystals showed electrical effects when compressed, but he actually measured contact electricity. His influence and the knowledge of polar structures of crystals led the Curie brothers to the discovery of piezoelectricity.

Theoretical knowledge, especially the application of thermodynamics to crystals, marked a great advance in the study of crystal physics. The piezoelectric formulation was carried out by Lord Kelvin, P. Duhem, F. Pockels, and most fully and rigoroulsy by W. Voigt. By combining the elements of symmetry of elastic tensors and of electric vectors with the geometrical symmetry elements of crystals he made clear in which of the 32 crystal classes piezoelectric effects might exist, and for each class he showed which of the possible 18 piezoelectric coefficients may have values differing from zero /3/.

In this way many piezoelectric materials were studied at the beginning, but the application of piezoelectric materials started with the development of transducers for underwater echo systems by LANGEVIN in 1914. This new technical development demands high effective transducer materials, and quartz was mostly used.

In the late 1940's this investigation yielded a new area of high effective piezoelectric materials with a range of properties for different applications. Ceramics, especially titanate zirconates became the dominant transducer material for ultrasonic applications in the range up to 20 MHz.
New piezoelectric crystals and film transducers were developed in the 1960's in view of high frequency applications, including materials with electro-optical and semiconductor characteristics /10/.

During the 1970's some other new materials such as piezoelectric plastics and composites become important for transducer applications. In this area a fully new field of hydrophone applications emerged when KAWAI discovered the strong piezoelectric effect in polyvinylidene-diflouride (PVDF) /13/. PVDF foils are now used for high frequency transducers up to 40 MHz and for hydrophones up to 100 MHz. As an example, this most suitable material for hydrophones firstly permitted investigations of nonlinear effects in ultrasonic propagation in the range of medical applications. Also the study of different connectivities of piezoelectric composites and their properties by NEWNHAM led to a new class of piezoelectric materials with a wide variety of applications /12/.

1.2.1. Crystals

There are two groups of piezoelectric crystals: ferroelectric and non ferroelectric ones /1//10/. Ferroelectric crystals are distinguished from other piezoelectrics such as tourmaline and quartz in that the internal moments of the latter cannot be redirected by external electric fields. Ferroelectric crystals have many domains (small polar volume elements with uniform orientation) in the unpoled state.

All ferroelectrics are piezoelectric and pyroelectric. Piezoelectricity extists in a definite temperature range with a transition point, the Curie point - an important feature for application. Piezoelectricity exist in following crystal classes: 2, 3m, 23, mm2, 42m, 4mm and 6mm. Only a few important crystals should be mentioned. The most important crystal is quartz (class 23). It is the most used piezoelectric material for pressure transducers and in high frequency ultrasonic transducers (up to 200 harmonics of the natural frequency are possible), and frequency normals of high precision, whith a typical application in the quartz clock. A phase transition point for quartz at 573°C limits the temperature range. Transducer plates of different orientation (X-, Y-, XY-cut) are cutted for the different applications. High mechanical strength and quality, and high stability of piezoelectric constants in a wide temperature range should be mentioned as essential advantages of the crystal /1//6//10/.

Tourmaline (class 3m) is also used in piezoelectric measuring transducers because of its high temperature range up to 600°C /6/. Single crystals of $Li\,Nb\,O_3$ and $Li\,Ta\,O_3$ also belong to the same crystal class and are high quality transducer materials for very high frequency ultrasonics and for measuring transducers for extremly high temperatures up to 1000°C. The ferroelectric material Rochelle or Seignette salt (class 2) should be mentioned as pick up transducer material from the historical view. Lithium sulfate (class 2) is a very good material for hydrophones with a very high hydrostatic piezoelectric coefficient and a low acoustic impedance. Materials for very high frequency applications are films of CdS, ZnO, CdSe, AlN, and BeO which belongs to the class 6mm. Single crystals of $BaTiO_3$ (orthorhombic and tetragonal) and Pb (Zr, Ti) O_3 (tetragonal) are the piezoelectric materials for ferroelectric ceramics in which they exist in form of many multidomain crystallites /10/.

1.2.2. Ceramics

Piezoelectric ceramics consisting of ferroelectric crystallites are the most used transducer materials in ultrasonics. When these ceramics are poled, domain twinning is drastically reduced, but not eliminated, and strong piezoelectric effects occur. Piezoelectric ceramics have been optimized for specific applications in a large variety by compositional adjustment. By far the most widely used compositions are based on lead titanate-lead zirconate (PZT) solutions. The dielectric and piezoelectric properties are influenced by substition of calcium, strontium, barium, and other electron acceptors, and ceramics with a wide range of applications are developed /1//10/.

Besides PZT-ceramics, barium-titanate, barium-titanate-potassium-titanate-mixtures and lead-metaniobate-transducers are used for ultrasonic broadband transducers with very low mechanical quality factors /10/. The vibration modes of piezoelectric ceramics are strongly coupled. This coupling can be deminuished by dotation of strontium, magnesium and niob which is necessary for medical transducer arrays with samll elements /11/. The mechanical impedance of piezoelectric ceramics is high compared to water and biological tissues. The problem is that a great amount of sound enery is reflected on surfaces between transducer and medium. Ultrasonic transducers for the use in immersion techniques and in medical ultrasonic systems need an acoustical matching between ceramic transducer element and medium. This is done by one and more quarter-wave-length matching layers.

These matching layers transform the low acoustical impedance of the medium to the high impedance of the ceramic material which is connected with a mechanical damping of the transducer. High resolution of pulse echo systems call for short pulses generated by highly damped transducers. Generally a strong direct backing and a matching to load are used to get a desired resolution.

Especially the fabrication of transducers with multiple matching sections is very complicated and demands a high technological level of the producer /19-22/. In this way new piezoelectric materials were investigated such as piezoelectric plastics and composite materials. Nevertheless, piezoelectric ceramics are currentlythe the most important transducer materials, because of their high piezoelectric coefficients and coupling factors, their variability for different technical applications, and their moderate costs. A disadvantage for medical transducer applications is their high mechanical quality and impedance as well as the strong coupling between the different vibration modes.

Ceramic transducers are typically used up to 15 MHz. The Curie point of ceramics is in the order of 150°C. An other advantage is that the transducers easy can be produced in many geometrical forms such as discs, rectangular plates, curved discs and plates, bars and rings.

The improvement of piezoelectric ceramics shows a certain "saturation effect" in the last twenty years. Progress in material science has entered a new area, namely the investigation of heterogeneous systems. The search for the best combination of materials in a multi-phase system opens new possibilities with a number of material parameters to be optimized /12/.

Scientific development of ceramic composites in the view of improved mechanical, electrical, piezoelectric and pyroelectric properties leads to a new ultrasonic transducer material. The variability of piezoelectric, dielectric, mechanical properties, of geometrical dimensions and connectivities of the two phase materials yield a very high number of new possibilities. Systematic development is necessary to achieve a set of desired material parameters. Diphasic systems are used for ultrasonic transducer applications. The parallel structure of piezoelectric rod/polymer composites have found fruitful application in transducers for pulse-echo medical ultrasonics /12//16//17/. Composite piezoelectric provide properties superior to both the ceramics and polymers. The acoustic impedance is much lower compared to ceramic transducers, and depends on ceramic content. Piezoelectric constants are in the range of ceramics, and coupling constants can be larger than those of piezoceramics.

The difference of acoustic impedances between transducer materials and biological tissue is reduced, and matching problems are not so important. The material is easy to form and flexible, which is advantageous for the construction of focussing systems. A high sensitivity is expected because of low dielectric and high g-constants.

The materials are successful in hydroacoustic applications in the range up to 40 kHz. On the other side, the geometrical dimensions of composite structures are in the order of the wavelength in the range of diagnostic ultrasound. Hence, the thickness mode vibration of the transducer is accompaned by a series of coupled modes, which influence the transfer function as well as the acoustic field structure.

The properties of diphasic systems are governed by the ratio of two components and their connectivities. The connectivity is most important for physical properties. The quality can change by many orders of magnitude depending on the manner in which connection is made in multiphase systems. There are ten possibilities for two-phase systems. In addition, mixtures of ceramic powder in polymer, parallel and serial layered structures, and interpenetrating three-dimensional networks like a sponge or coral structure are of interest for technical applications. Especially a parallel structure of piezoelectric ceramic rods in a polymer matrix is advantageous in ultrasonic transducer constructions.

In contrast to the mixture and serial structures with lower piezoelectric constants mentioned above, the parallel and interpenetrating network structures have constants which are comparable with or better then those of ceramics. The dependence on volume fraction of PZT of the rod/polymer system was measured in a comprehensive study by Newnham et.al.. The resulting piezoelectric constants d and g are in the order of those of the ceramic material, depending on the volume content of the two-phase materials, their product as a key feature for the efficiency of ultrasonic transducers may be larger then that of piezoceramics. Also the coupling coefficient for the thickness mode k increases with increasing ceramic content to a saturation value and is of the same order as pure ceramic for 25 % ceramic content. The coupling coefficient for the radial mode of 0.2 is relatively small. Both the mechanical quality and the density are lower /17/.

1.2.3. Polymers

Piezoelectric properties of plastics and organic materials were already investigated in the past. The breakthrough came in 1969, when Kawai discovered the strong piezoelectric effect in polyvinylidenefluoride (PVDF) /13//15/. PVDF exhibits considerably stronger piezoelectric activity (d - coefficient) than other polymers. This behaviour is related to its high dielectric constant. The discovery of piezoelectric and pyroelectric properties of PVDF is connected with an extensive use of this material in a number of applications. PVDF is a semicrystalline polymer consisting of long chain molecules with the repeat unit

$$-[CF_2 - CH_2 -]n$$

where n is typically between 2,000 and 12,000. The material is in a partially ordered structure with crystalline domains and amorphous regions. Four crystalline forms of PVDF are known. The modifications can be influenced by mechanical stretching, by casting from different solutions, by cooling from the melt, and by poling in electric fields. The properties depend strongly on this treatment.

PVDF differs in very significant ways from conventional piezoelectric materials. It is available in thin films of considerable size. Thus large area transducers can be designed in a wide variety of geometries, e.g. curved focusing elements. Other examples of the special features are its low quality and its relatively low acoustic impedance which is near to that of water. The relative high g constant indicates the use of PVDF for receivers. The maximum strain achievable with this material is very large due to its high depolarization field. In all these respects PVDF is superior to conventional piezoelectric materials.

Typical applications are known, such as audio frequency transducers (microphones, telephone transmitter, headphones, loudspeakers, accelerometers, medical sensors), ultrasonic and underwater transducers (ultrasonic transmitters and receivers, bulk wave transducer, hydrophones, light modulators), electromechanical transducers and devices (contactless switches, bimorphs, display devices, variable focus mirrors, mechanical transformers) and as pyroelectric and optical devices (infrared detectors, vidicons, infrared to visible converters, reflectivity detectors) /15/.

2. Applications of piezoelectric devices

2.1. Non-destructive testing (NDT)

Ultrasound of sufficiently high frequency propagates as a beam in homogeneous media, such as solids or liquids. Disregarding absorptive processes, the wavefield propagation in such media is uniform, unless regions, enclosures or boundaries of different mechanical impedance are encountered. In an ideal (lossless) medium, mechanical impedance is just the mass density times the velocity of sound. At such inhomogenities a part of the impinging beam is reflected or backscattered. The reflectivity coefficient R for normal incidence under ideal conditions is defined by

$$R = (m - 1) / (m + 1)$$

whereby m is the ratio of the mechanical impedance values, as previously defined, for the two materials in question. For a steel/air boundary m is of the order 10^5, R thus is practically unity. In other words:

a) we have an almost complete reflection at any gaseous inclosure in metals, and a corresponding lack of the transmitted signal; both phenomena are easily detectable.

b) since absorption of ultrasound in metals, in general, is very low (compared to the propagation in gases), backscattered and transmitted parts of the impinging wave can be detected even in specimen of big dimensions, where x-rays would not yield any detectable signal.

These two reasons are the practical foundations of NDT.

In the following we will consider first the transmission mode of ultrasonic NDT, which is mostly restricted to the inspection and quality control of plates and bars of uniform dimensions (generally before being stocked, sold or processed by the customer). Then the more recent and widespread pulse-echo method is described.

2.1.1 Transmission method of ultrasonic NDT

First applications of this method go back as far as 1929 by SOKOLOFF /29/. The principle of the method is illustrated in Fig. 8.

2.1.2 Pulse-echo method of ultrasonic NDT

This method follows from early experiments in underwater detection of icebergs and submarines in the years after 1912. In principle, the piezoelectric element is driven by periodical series of electric pulses, thus emitting a corresponding series of ultrasonic bursts, whose duration or bandwidth depends a) on the bandwidth of the driving pulse, b) on the properties of the backing material of the piezoelectric element, c) on the piezomaterial itself, d) on the facing material and, finally, e) on the load material.

Axial and lateral resolution depend essentially on signal bandwidth, so that in practice there is a great vartiety of transducer solutions for different applications. Piezomaterials for pulse-echo NDT are usually piezoceramics as PZT and LM.
PZT is lead zirconate titanate, often used in narrow-band transducers, or where high sensititivity is more important than resolution. LM is lead metaniobate, which under the same conditions produces a broader bandwidth.

2.1.3 Thickness gaging and flaw detection transducers

For this application we have different solutions:

a) Dual-element pitch-catch transducers (Fig. 9)

These transducers are espescially suitable if near-surface resolution is required. One ceramic (semicircular) element acts as transmitter, the other is the receiver. The transducer is of the contact type, viz., acoustic coupling must be achieved by a drop of liquid in order to avoid disturbing reflections at the transducer facing / specimen interface (illustration: Nortec Corp., Richland, WA 99352, USA)

b) Single element - contact type (Fig. 10)

In this solution, the piezoceramic element acts as both transmitter and receiver. Consequently, the material under inspection must have a minimum thickness, as received echoes cannot be detected separately before the end of the emitted pulse (trailing edge)

c) Single element - immersion type (Fig. 11)

Immersion of transducers gives good acoustic coupling even at relatively rough surfaces and allows also a better inspection of near-surface regions, as the water column acts as a delay line. For this application the facing material has to be selected in order to match the mechanical impedance of water, usually epoxy instead of ceramic material such as Al_2O_3 in contact-type transducers.

2.1.4. Weld inspection transducers

The most usual method of weld inspection with ultrasound consists in the use of coupling wedges in order to achieve an oblique incidence of the ultrasonic beam. Usual wedge angles are 45 , 60 , 70 , or 90 (shear waves). The principle is illustrated in Fig. 12 (after ref./5/):

2.2. Medicine and Biology

Ultrasonic transducers are used in medicine and biology for ultrasonic power applications, ultrasonic imaging and ultrasonic Doppler techniques /7//8/.

The main problem is the energy transfer into the biological medium. Due to its high acoustical impedance the piezoelectric transducer elements need a matching to biological medium. The spatial resolution and sensivity are also important features of medical ultrasonic transducers /8/19-22/.

2.2.1. Ultrasonic power application

In medicine and biology ultrasonic power system in the frequency range of 20 kHz are used for cleaning of instruments, for surgical instrumentation, and especially in biology for desintegration of matter. The transducer in this system consists of two mass loaded piezoelectric discs, shown in fig. 5. The resonance of the whole transducer system is in the range of 10 to 30 kHz but the active piezoelectric elements have a much higher resonance frequency. The resonance of the whole system depends on the actuall load and the power generator compensates these changes /1//8/.

For ultrasonic therapy in the frequency range of about 800 kHz, transducers of ceramic discs with a matching to tissue by quarter-wavelength layers and air backing are used in most cases. The housing of the transducer should be acoustically isolated to avoid hazards for the medical personnel.

2.2.2. Ultrasonic imaging

In ultrasonic imaging two types of transducers, namely single element and transducer arrays (multielement) are used. Generally a hard backing with tungsten epoxy resin is used, the vibrating element being a ceramic disc with one or more quarter-wavelength matching layers wich provide the damping of the transducer, in order to reach a good axial resolution and broad transfer characteristics. Fig. 6 shows the construction principle of a single element transducer and fig. 7 that of a transducer array. The acoustical impedance of the quarter wave length layer should be about the geometrical mean of the impedance of the transducer material and the biological tissue, respectively, which can be realized by mixtures of epoxy resin and fillers. The transfer characteristics can be estimated by the equivalent circuit of the transducer /19/. The common frequencies of medical ultrasonic transducers are in the range from 2 to 8 MHz, and for high resolutions systems with a short penetration depth in the range from 8 to 20 MHz. The bandwidth of the system reaches from 30% to 90% of the center frequency /8//19-28/.

2.3 Pressure transducers / sensors

Piezoelectric pressure transducers are used in a widespread field of applications. Their sensitivity goes from a few microbars (1 bar = 10^5 pascals) in audio-acoustics, over some millibars (in the atmospheric pressure regime) to kilobars in technical applications, including a temperature range from kryotechniques to high-temperature measurements in internal combustion engines test stands. A typical pressure transducer design is illustrated in Fig. 13.

It is important to note that piezoelectric pressure transducers are not approriate for truly static measuremet applications. In any case the lower frequency has to be taken in consideration for quasi-static measurement problems.

The piezoelectric material which is mostly used for pressure transducers is quartz, both as natural crystal and as fused silica single crystals. Tourmaline, lithiumniobate and lithiumtantalate single crystals and, finally, piezoceramics and piezopolymers as described in section 1. For additional information see ref./6/.

2.4 Ranging and distance control

Pulse-echo devices, as used in medicine and in NDT (see previous chapters of this section) can also be applied succesfully to several problems in the large field of liquid-borne ultrasound. This includes naval sonar (e.g., sea bottom relief detection) , in which reflection occurs at a liquid/solid interface, as well as level meters in containers of water, gasoline and other liquids, whereby reflection at the (upper) liquid/air interface is the essential phenomenon. There is a great variety of transducers used in this field: from magnetostrictive type (not considered in this paper) in the kHz range up to usual PZT immersion transducers as used in NDT in the lower MHz range. In addition to the capability of measuring distances in different liquids, additional electronic equipment leads to setting of minimum distance (or filling height) alarms and non-contact proximity switches.

A few words should be added to air-borne distance metering by ultrasound. Absorption of ultrasonic waves in in air is by far greater than in water and most other liquids. As an example, at the same emitted and detected intensity level, an ultrasonic signal in water at 1 MHz reaches a distance of 40 m, whereas in air the distance reduces to about 2 cm. In addition, the great impedance mismatch between solid transducer elements and air leads to technological problems for the emission of sufficient US power. Therefore US applications for distance metering in air are restricted to close-up applications whereby resolution and acccuracy are not crucial, as in photographic camera automatic focusing and indoor burglar alarms.

3. Basic technologies for the construction and production of piezoelectric sensors, witch particular regard to the constraints in developing countries

Ultrasound is a low-cost and easy to access technology, excluding some sophisticated and patented applications. As a matter of fact, a great bulk of the basic literature comes from India, headed by a brilliant individual as Nobel laureate C.V. Raman. As a marginal and rather funny consequence, we find measured values of the velocity of sound in patchouly perume oil (by Pancholy, Sarande and Parthasarathy, quoted in ref, /5/). In addition, the manufacturing of single-element transducers for medical applications (A and B-mode) as well as for the neighboring field of NDT, to which we should restrict our attention in this section, is more a handicraft art than industrial technology.

The manufacturing skills of well-trained people are the principal perequisite for the production of basic US devices. One must consider in this context, that the import of complete medical US devices from industrialized countries not only includes the heavy load of financing expensive equipmnet for hospitals, but also necessitates the supply of training for the medical staff in using a sophisticated equipment which in many cases provides far more features as might be well expected for basic medical assistance in developing countries.

As an example it should be mentioned that in 1982 the number of medical ultrasound equipment in Egypt was 39. At the same time, the inbelievable number of 22 companies had agencies in Egypt for marketing of medical US equipment. In addition, a great part of the existing equipment was continuously out of order due to insufficient training of medical staff, lack of spare parts and need of maintenace which could be only provided by the manufacturer at prohibitive financial terms /31/

In conclusion, it should therefore be suggested that appropriate courseware is established by institutions such as UNIDO in providing skills for the manufacturing of basic NDT and A-mode medical transducers. In addition, the rather simple electronics of driving circuitry (not considered in the framework of this report) of such devices should be offered in parallel.

Austrian Universities such as Graz University of Technology are capable to provide and host such courses upon request (see the following section)

4. Austrian R&D centres: potential partners for developing countries.

4.1. Graz University of Technology Att.: Dr. F. Holzer
Lessingstrasse 27
A-8010 Graz
Austria
Tel.: +43 316 873 8395

This University has a two centres dealing with ultrasonic equipment, one in the field of biomedical engineering (including calibration facilities of ultrasonic transducers), the other working in the field of NDT.

4.2 AVL LIST GmbH Att.: Dr. I. Killmann
Kleiststraße 48
A-8010 Graz
Tel.: +43 316 987-0

This company has outstanding expertise in the development of pressure transducers for high temperature applications (internal combustion engines) and related calibration equipment

4.3 Kretz-Technik AG Att.: D.I. C. Kretz
Tiefenbach 15
A-4871 Zipf
Tel.: +43 7632 2261

This company is among the pioneers in the construction of ultrasonic equipment for medical applications (founded in 1948), with an export rate of more than 90%

5. List of figures and figure captions:

Figure 1: Piezoelectric modes in piezoelectric solids

Figure 2: MASON's equivalent circuit

Figure 3: CADY's equivalent circuit

Figure 4: Admittance vector diagram of a piezoelectric resonator

Figure 5: Ultrasonic power transducer (composite system)

Figure 6: Ultrasonic singe element transducer:
  1...ceramic transducer element
  2...backing
  3...quarter-wavelength matching layer
  4...electric shielding
  5...acoustic isolation

Figure 7: Ultrasonic transducer array

Figure 8: Longitudinal section of transmission US NDT (after /30/).
The transducers (both the emitting and receiving one) consist of an air-backed piezoelectric plate Q cemented on a metal cylinder M. Sufficiently good acoustic coupling between transducers and specimen is achieved by a (flowing) water-bath. As the transducers are driven in continuous-wave mode, the driving signal is amplitude and frequency modulated, in order to minimize the generation of standing waves. Using a 1 MHz center frequency, the apparatus is claimed to detect flaws whose cross-section is greater than 5 mm^2. In other applications the liquid immersion is replaced by directly contacting the facing material of the transducer (which in many cases is specifically shaped, such as tips and horns) to the specimen, whereby acoustic coupling is achieved by a thin layer of liquid (e.g. oil or gel). For additional information see ref./5/

Figure 9: Dual-element pitch-catch NDT transducer, contact type

Figure 10: Single-element NDT transducer, contact type

Figure 11: Single-element NDT transducer, immersion type

Figure 12: Principle of weld inspection by oblique-incidence ultasonic beam, using a transducer coupled onto a wedge of appropriate wedge angle.

Figure 13: Schematics of a pressure transducer (after ref./6/) A flexible mebrane 1 is soldered to the transducer shell 6 . A pressure p exerts a force on the hollow-cylinder shaped piezoelectric element 4, which is encapsulated under preloaded conditions in the inner shell 2. Electrical polarisation in this example appears in direction a normal to the cylinder axis (transversal effect), the electrical charge is sensed by a spiral spring electrode and fed to a charge (electrometer) amplifier via plug 7.

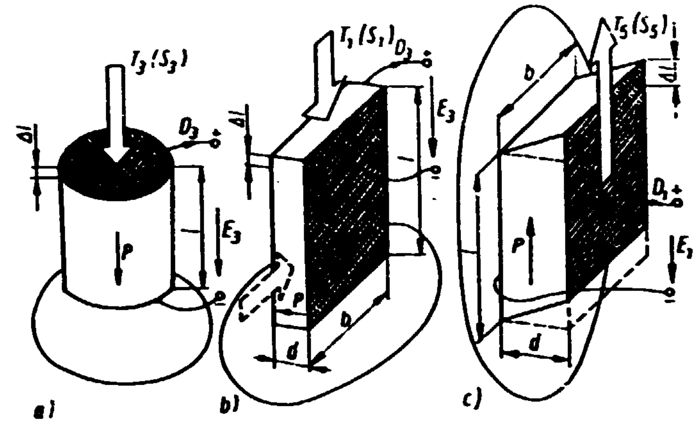

$T_3(S_3)$
Δl
D_3
E_3
P
a)
$T_1(S_1)$
D_3
Δl
E_3
P
d
b
b)
$T_5(S_5)$
b
ΔL
D_1
P
E_1
d
c)

Fig. 1

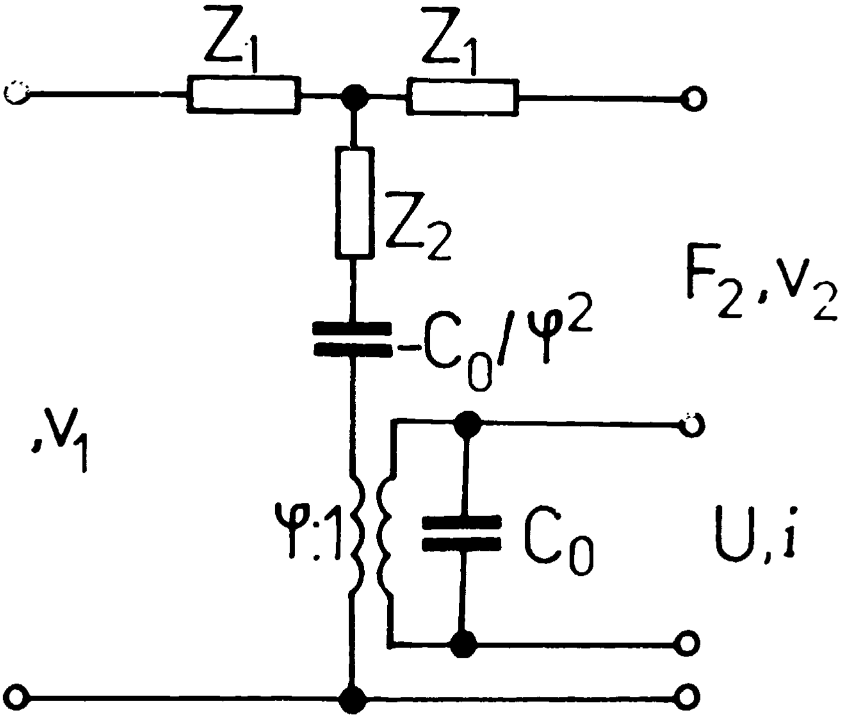

Z_1
Z_1
Z_2
$-C_0/\varphi^2$
F_2, V_2
F_1, V_1
$\varphi:1$
C_0
U, i

Fig. 2.

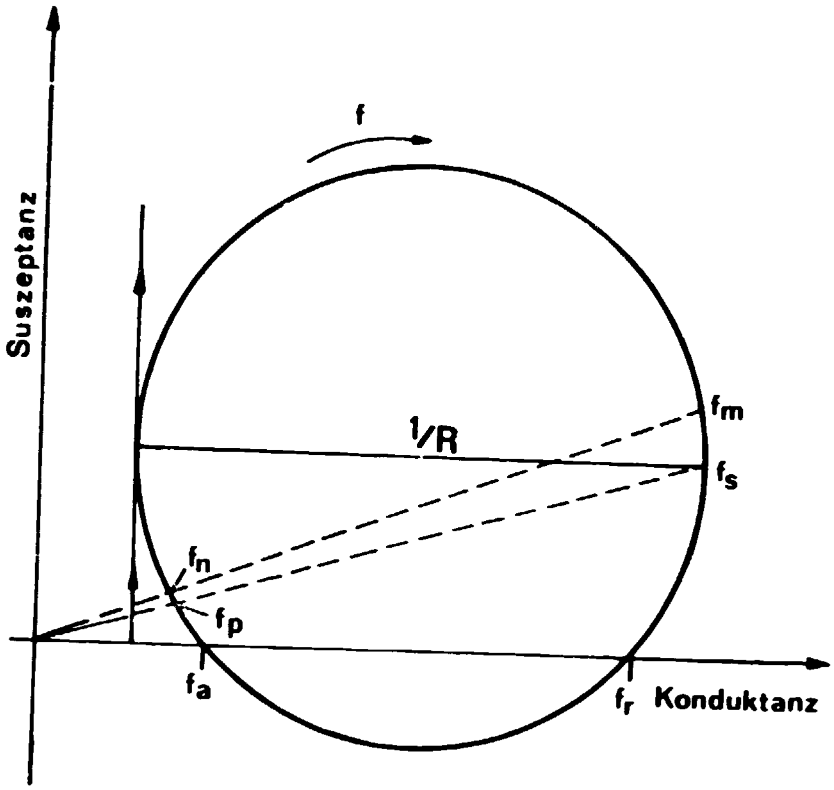


Fig. 4

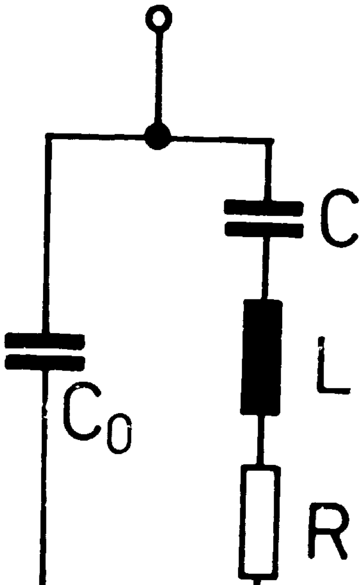


Fig. 3

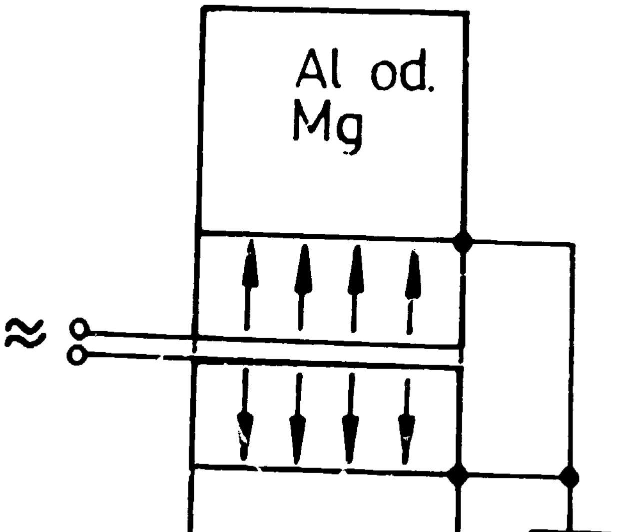


Fig. 5

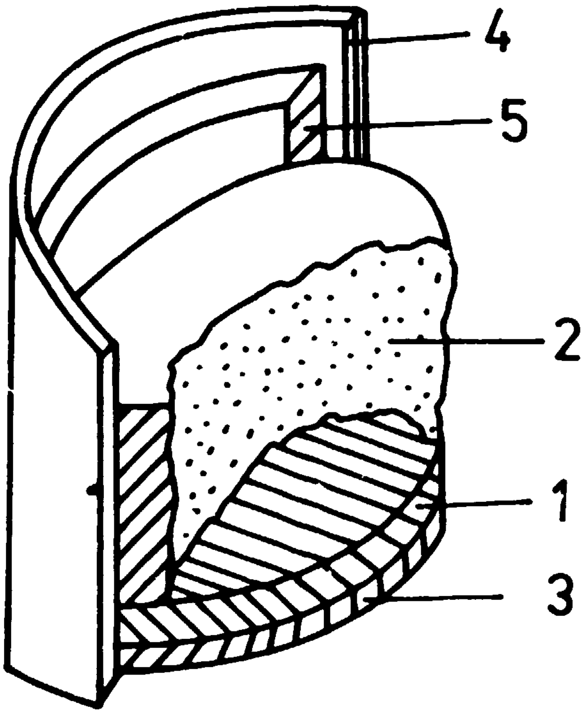


Fig. 6:

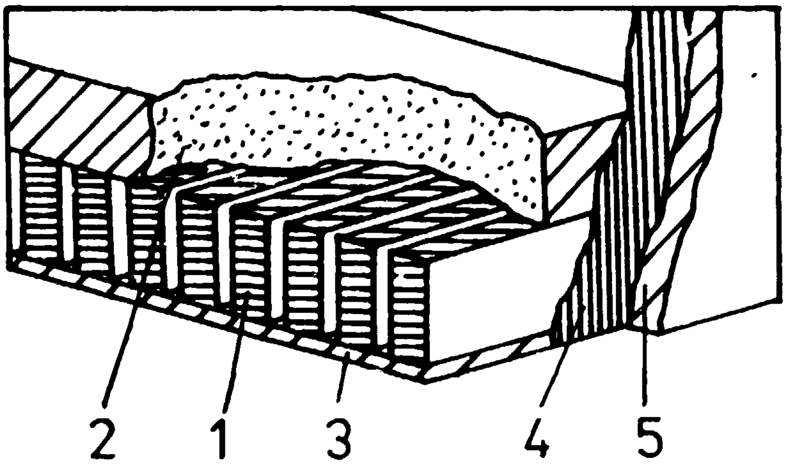


Fig. 7

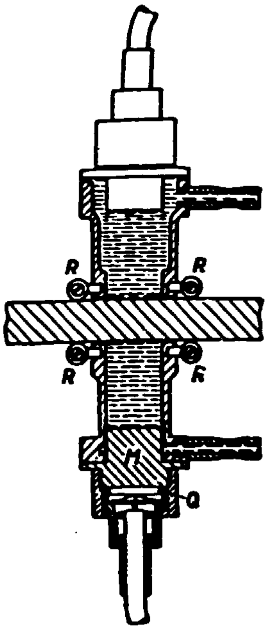
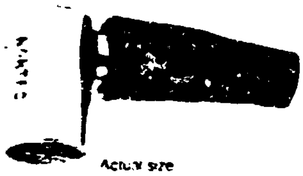


Fig. 8



Actual size

Fig 9

Actual size

Fig. 10

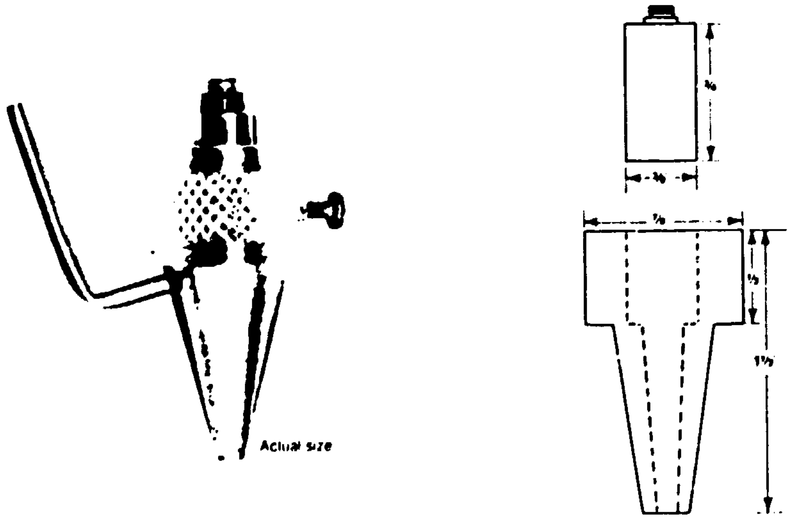


Fig. 11

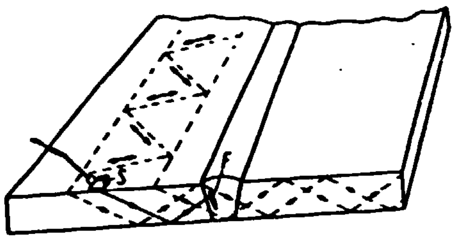


Fig. 12

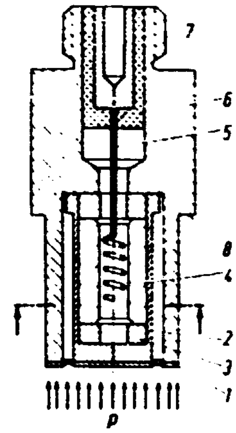


Fig. 13

6. Literature

/1/ Mason, W.P.: Physical Acoustics, Vol I Part A, New York Academic Press 1968 - 515 S.

/2/ Mason, W.P.: Electromechanical transducers and wave filters.- Van Nostrand. Princeton 1948

/3/ Cady, W.G.: Piezoelectricity. -Bd 1. - New edition. - New York: Dover Publications, INC. 1964.- 405 S.

/4/ IEEE Std 1976-1978 Standard on Piezoelectricity

/5/ Bergmann, L.: Der Ultraschall und seine Anwendung in Wissenschaft und Technik. - 6. überarb. und erw. Auflage. - Zürich: S. Hirzel 1954.- 1114 S.

/6/ Tichy, J.; Gautschi, G.: Piezoelektrische Meßtechnik. - Springer. - Berlin. - 1980.- 257 S.

/7/ Lehfeld, W.: Ultraschall kurz und bündig. Physikalische Grundlagen und Anwendungen. - Würzburg Vogel-Verlag 1973

/8/ Millner, R.: Wissensspeicher Ultraschall. - 1. Aufl. - Leipzig. - VEB Fachbuchverlag 1987.- 440 S.

/9/ Krautkrämer, J.; Krautkrämer H.: Werkstoffprüfung mit Ultraschall. - 4. Aufl. Berlin: Springer Verl. 1980. - 669 S.

/10/ Mattiat, O.E.: Ultrasonic Transducer Materials. - New York: Plenum Press 1971. - 185 S.

/11/ Fukumoto, A.; Kawabuchi, M.; Sato, J.I.: Design of ultrasound transducers using a new piezoelectric ceramic material. - In: Ultrasound in Med.Biol. - Oxford 7 (1981) - S.275-284

/12/ Newnham, R.E.; Bown, L.J.; Klicker, K.A.; Cross, L.E.: composite piezoelectric transducers. - In: Materials in Engineering. - New York 2 (1980) - S 93-106.

/13/ Kawai, H.: The piezoelectricity of polyvinylideneflouride. - Japan J.Appl. Phys. - Tokyo 8 (1969) - S.975-976

/14/ Preston, R.C.; Bacon, D.R.; Livett, A.J.; Rajendran, K.: PVDF membrane hydrophone performance properties and their relevance to the measurement of the acoustic output of medical ultrasonic equipment. - In: J. Phys. E: Sci Instrum. - London 16 (1983) - S.786-796

/15/ Sessler, G.M.: Piezoelectricity in polyvinylidenefluoride. - J. Acoust. soc.Am.70 (1981)6 1596-1608

/16/ Gururaja, T.R.; Schulze, W.A.; Cross, L.E.; Newnham, R.E.; Auld, B.A.; Wang, Y.J.: Piezoelectric composite materials for ultrasonic transducer applications. Part I: Resonant modes of vibration of PZT rod-polymer composites. - In: IEEE Trans. Sonics Ultrason. - New York SU-32 (1985) - S.481-497

/17/ Gururaja, T.R.; Schulze, W.A.; Cross, L.E.; Newnham, R.E.: Piezoelectric composite materials for ultrasonic transducer application. Part II: Evaluation of ultrasonic medical applications. - In: IEEE Trans.Sonics Ultrasonics. - New York SU-32 (1985) 4. - S.499-513

/18/ Krimholtz, R.; Leedom, D.A.; Matthaei, G.L.: New equivalent circuits for piezoelectric transducers. - In: Electronic Letters. - London 6 (1970) 13.- S.398-399

/19/ Kossoff, G.: The effects of backing and matching on the performance of piezoelectric ceramic transducers. - In: IEEE Transaction on Sonics Ultrason. - New York SU-13 (1966) - S.20-30

/20/ Desilets, C.S.; Fraser, J.D.; Kino, G.S.: The design of efficient broad-band piezoelectric transducers. - In: IEEE Trans. on Sonics Ultrason. - New York SU-25 (1978) 3. - S.115-125

/21/ Hunt, J.W.; Arditi, M.; Foster, F.S.: Ultrasound transducers for medical imaging. - In: IEEE Trans. on Biomedical Eng. - New York BME-30 (1983) 8. - S.453-481

/22/ Richter, K.P.; Millner, R.; Holzer, F.; Leitgeb, N.; Wach, P.: Design, construction and experimental investigation of ultrasonic pulse transducers with different bandwidths. -In: Ultrasonics. - London 25 (1987) 4. - S.229-236

/23/ Pappalardo, M.: Some experimental data for the design of acoustic arrays. - In: Journ. Sound & Vib. - London 52 (1977) 4. - S.579-586

/24/ Matteucci, M.; Scarano, G.; Furgason, E.S.; Pappalardo, M.: Two-dimensional displacement analysis of piezoelectric transducer array elements. In: IEEE Trans. UFFC. - New York 33 (1986) 6.- S.705-712

/25/ Methods of Measuring the Performance of Ultrasonic Pulse Echo Diagnostic Equipment IEC Technical Committee No. 29D Geneva 1982

/26/ Somer, J.: Electronic sector scanning for ultrasonic diagnosis. - In: Ultrasonics. - London 6 (1968) - S.153-159

/27/ Kikuchi, Y.; Ultrasonic transducers. - Tokyo Corona Publishing Co. 1969

/28/ Kossoff, G.: Design of narrow beamwidth transducers.- In: Journ. Acoust. Soc. Am. - Lancaster 35 (1963) S.905-912/29/Sokoloff, S.; Elektr. Nachr.-Technik, Vol. 6 (1929) p. (454-461)

/30/ Trost, A.; Sheet Metal Industr. (1944), p. 225-227

/31/ Hosni, M. ; Aref, I., Facts and Fantasies bout Ultrasonography in the Developing Countries; Ultrasound '82, Pergamon Press 1983, p. 91-93