Simultaneous generation of longitudinal and shear ultrasonic waves: knowledge summary, PZT piezoelements manufacturing and experiments

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Abstract

Known ultrasonic transducers for simultaneous generation of longitudinal and shear waves are reviewed: quartz and lithium niobate crystals tilted CdS and ZnO films. A special attention is devoted to the rotated cuts of PZT piezoceramics, literature data theoretical background conclusions are analysed. Manufacturing technology of dual mode PZT transducers with different cut angles and thickness was developed. Reliable electrodes suitable for soldering are made chemically in electroless nickel (EN) plating bath. Nickel electrodes are additionally dectroplated with silver. Various types of PZT ceramics were successfully used. From impedance measurements longitudinal and shear resonances were determined for typical thicknesses 45-100 μm. The cut angle 36º for equal efficiency of both waves was experimentally determined. Operation of transducers soldered to the steel rods and measurement bodies of the certain geometry was investigated. Measurements were provided in a temperature range 20–160 ºC. Axial load experiments up to 234 MPa were provided and corresponding linear dependencies were determined. Experiments showed good performance of developed dual mode PZT ultrasonic transducers.

Keywords: dual mode, longitudinal and shear wave simultaneous generation, ultrasonic transducers.

Introduction

Ultrasonic transducers are usually intended for generation and reception of only longitudinal (*L*) or shear (*S*) waves. Very often ultrasonic non-destructive testing (NDT) and evaluation (NDE) requires measurements of both longitudinal (*L*) and shear (*S*) waves in a medium. Thus ultrasonic transducers which generate both *L* and *S* waves simultaneously are requested. For example, reliable determination of axial loads and preloads of screws in structural parts can be provided by measuring delays of both *L* and *S* waves along the screws direction [1].

Historically, various cuts of quartz crystals (AT, SC, BT, IT, AK) operating in a thickness-shear mode were known first. Various cuts were found for highly stable oscillators, SAW devices, temperature sensors, etc. [2].

Thickness-shear mode (TSM) resonators have been successfully used to characterize static rheological properties of plasma and whole blood samples, including blood coagulation tracking throughout the entire process [3].

Nowadays, quartz crystal piezoelements are used less in ultrasonics, as better piezomaterials are accessible.

Lithium niobate crystals

Both *L* and *S* waves can be generated simultaneously and efficiently using 10º rotated Y-cut lithium niobate piezoelements. They are offered commercially by Boston Piezo-Optics Inc. as “Tripple-Mode Transducer Crystals” (longitudinal+shear+dual) [4]. The third harmonic of the longitudinal mode coincides with the fifth harmonic of the shear mode. For example, a crystal with a thickness 0.684 mm will oscillate at its fundamental longitudinal mode of $f_L = 5.0$ MHz, its fundamental shear mode $f_S = 3.0$ MHz and its dual mode frequency is $f_D = 15$ MHz. The 22 crystals are available with $f_L = 1 \div 31.7$ MHz, $f_S = 0.6 \div 19.0$ MHz; thus $f_D = 3.0 \div 95$ MHz.

As seen, in dual mode piezoelements $f_L > f_S$. It is due to the fact, that always, including piezomaterial, ultrasound velocity of *L* wave is larger than velocity of *S* wave, i.e. $c_L > c_S$.

Tilted CdS and ZnO films

A separate group of dual mode ultrasonic transducers compile artificially made CdS and ZnO films [5-10]. In thick CdS films with low disorientation the longitudinal mode *L* is easily excited. In this case *C* axis of the CdS crystal is perpendicular to the sample surface, $\Theta \sim 0º$. *S* mode requires $\Theta = 90º$, this corresponds to surface excitation, which possible only theoretically. The requirement $\Theta > 90º$ may be achieved the tilting the sample with respect to the mean direction of the CdS beam during the vacuum deposition of the piezoelectric layer. In [10] CdS experimental results are reported. Thick 40-50 μm disorientated layers operated in a dual *L*/*S* mode in the frequency range 50-100 MHz. *L* and *S* echo patterns were observed on Al_2O_3 single-crystal substrate.

For high-frequency ultrasonic applications ZnO piezoelectric film transducers are widely used and most studied. It is well known that ZnO film with *C* axis (crystalline *Z* axis) normal to the substrate surface can excite longitudinal waves. Shear waves are excited if *C* axis is 41º tilted. At the 16º tilted angle *L* and *S* modes are almost equal [5]. Experiments described in this article were performed also with a 60º tilted ZnO thin film, *L*/*S* pulse echo trains were observed in a fused quartz substrate at frequencies 350 - 510 MHz.

As ZnO films can operate in the dual *L*/*S* mode, alternative experiments are known with the goal to produce ultrasonic transducers with a pure longitudinal wave for ultrasonic microscopes and other imaging systems at frequencies greater than 100 MHz. The same reason concerns AlN films [9].

Simultaneous generation of longitudinal and shear bulk ultrasonic waves in solids was investigated in [6, 7]. It is emphasized that in the 50 MHz – 1 GHz frequency range $LiNbO_3$ (in the form of platelets bonded onto the substrate, lapped to the desired thickness and then polished) and CdS or ZnO (in the form of evaporated and deposited layers) are the most often used piezoelectric transducer materials. Simultaneous generation of longitudinal and shear bulk waves is possible when using *Y*-cuts rotated at the angle Θ with respect to the *X* crystallographic axis. Transducer configurations comprising a single transducer or two transducers (the same piezoelectric material with different cuts or different piezoelectric materials) are analyzed. In a single layer transducer, when the cut angle Θ varies with respect to the *X*-axis, the wave velocities (and thus the thickness required for operating at a given frequency) vary. An innovative two-layer transducer solution was investigated. A systematic study was performed using nine combinations available with the choice between CdS, ZnO and $LiNbO_3$ for both the first and the second piezoelectric layers. Several solutions have been found for efficient wideband generation of the *L* and *S* modes.

Thin films stack transducer for simultaneous generation of longitudinal and shear waves at the same frequency is proposed and investigated in [11]. Earlier simultaneous generation of both waves at the same frequency has not been achieved, because extensional mode and the thickness shear mode of the piezoelectric layer are different. The stack transducer consists of two-layered *C*-axis tilted ZnO film. The upper and the lower layers have the same thickness, and *C*-axis tilt direction in both layers is symmetric with respect to the surface normal. In this structure, a thickness extensional mode is excited as the fundamental mode, whereas a thickness shear mode is excited as the second overtone mode. At the *C*-axis tilt angle of 23º, the quasi-longitudinal wave velocity of 6136 m/s is exactly twice the quasi-shear wave velocity of 3068 m/s, thus both waves can be generated efficiently at the same frequency. It is declared, that both modes have high electromechanical coupling coefficients: $k'_{33} = 0.20$, $k'_{15} = 0.38$. This thin film stack transducer was made on a silica glass substrate, *L*- and *S*-waves were successfully excited at adjacent frequencies $f_L = 278$ MHz, $f_S = 266$ MHz with a high efficiency.

Other methods

Laser generation and detection of longitudinal and shear waves in a diamond anvil cell was investigated in [12]. Acoustic waves were excited with "pump" laser (neodymium doped yttrium aluminium garnet laser, 100 mV power at 1064 nm, 0.5 ns pulse at 20 kHz repetition frequency). For detection of acoustic waves "a probe" laser was necessary ("Compass" laser with a power 150 mV at 523 nm). Longitudinal and shear waves were detected and their velocities were measured at pressures up to 23 GPa.

A simple solution for generation of *L* and *S* waves in a low MHz frequency range is published in [13]. In apparatus for simultaneous determination of longitudinal and shear wave velocities in rocks under pressure ultrasonic transducer is a sandwich of two crystals, one (inner) generating longitudinal waves and one (upper) generating shear waves.

Mode conversion

Extensive investigations in the field of high-temperature integrated ultrasonic shear and longitudinal wave probes are known [1, 14-18]. In these metallic (aluminium) probes shear waves are generated due to mode conversion from longitudinal to shear waves because of reflection inside the metallic substrate having a specific shape (64.6º angle). In the case of a mild steel probe, this angle is equal 61.5º). An additional 45º angle plane with respect to the *L* wave ultrasonic transducer was machined onto the *S* wave probe. Thus one half of the ultrasonic beam from the transducer is used at the 64.6º plane for mode conversion from *L* to *S* waves, the second half of this beam (*L* waves) only changes direction at the 45º plane. In this probe both *S* and *L* beams propagate parallel, to each other, but not along the same path. With a high temperature piezoelectric film with a PZT composite attached onto the substrate by a paint-on method these probes successfully operated up to 150 ºC. When bismuth titanate powders instead of PZT powders as a piezoelectric material were used, a good signal to noise ratio S/N has been obtained at 350 ºC.

The same idea of mode conversion was used by same authors in making screws as axial load and temperature probes using an integrated ultrasonic transducer [2, 17]. In order to propagate *L* wave along the axial direction of the screw back and forth a 45º reflection (steel/air) was used. *L* to *S* mode conversion is observed at the 61.4º reflection angle. This angle is chosen so that the mode converted S wave will propagate back and forth along the axial direction. The ultrasonic transducer was fabricated directly onto the lateral surface of the head of the screw by the sol-gel sprayed method. 45º and 61.4º reflection surfaces were machined from the head of the screw. In this experiment $f_L = 17$ MHz, $f_S = 13.8$ MHz.

Using the mode conversion method two orthogonal polarized shear $S_{\perp}$ and $S_{=}$ waves were obtained from two *L* wave transducers. This probe, simultaneously producing one longitudinal and two shear waves was used for on-line polymer injection moulding process diagnostics [17].

Longitudinal and shear waves simultaneously can be transmitted and received by small piezoceramic transducers. Barium titanate transducers, smaller in dimensions than the wavelengths of elastic waves in solids (1÷3 mm thickness, 1÷3 mm in diameter) transmit simultaneously *L*, *S* and surface waves of ultrasonic frequencies when subjected to an electrical pulse [19]. Directivity patterns of these transducers were investigated.

Dual mode PZT transducers

PZT piezoceramic is the most used piezoelectric material. These transducers are much requested but up to now only theoretical studies are known with a little experimental confirmation [20-23]. The aim of these studies was to find a proper cut of PZT piezoceramic, which can simultaneously respond to both pressure and shear waves. In these studies, all possible rotated ceramic cuts were examined by analyzing the piezoelectric properties, elastic and dielectric constants through numerical simulation and experiments. The optimal cut for simultaneous generation of *L* and *S* waves of equal strength was found. According to the theory, the simultaneous generation of *L* and *S* modes is possible only when PZT *Z* axis is rotated with respect to the crystal *X* or *Y* axis. Rotation with respect to either *X* axis or *Y* axis does not make any difference. Equations presented in [22] confirm the fact that we can generate both longitudinal and shear waves with a single element made of PZT, once it is rotated appropriately. Calculations were provided for PZT-5H piezoelectric material, because it is widely used for ultrasonic probes. Variation of the coupling factor k^2 versus the crystal *Z* axis rotation angle Θ was determined. According to the figure presented, when the crystal *Z* axis is rotated 35.7º, the PZT element possesses equal efficiency in exiting each of the *L* and *S* waves. In practice, in the medium investigated these waves will not be equally strong, because of impedance mismatch between the PZT and the medium, which will be different for *L* and *S* waves. When $\Theta < 35.7º$, PZT element put more emphasis on the *L* wave, when $\Theta > 35.7º$ *S*-waves dominate.

These double mode PZT rotated piezoelements have advantage over mode conversion transducers, as *L* and *S* waves propagate in one beam, along the same path, what may have a decisive influence in some cases.

Information regarding the properties of various rotations of poled PZT-5A is presented in [21]. Experimental values for 45º and 60º rotated elements were compared with theoretical values.

Analyzing the literature data about dual mode PZT rotated piezoelements, we can conclude that most information concerns theoretical analysis and there is a lack of experimental verification.

Therefore, we have decided to develop manufacturing technology of dual mode PZT piezoelements in usual ultrasonic laboratory conditions and their optimization for real experimental requirements.

Manufacturing of a dual mode PZT piezoelement

According to the theory [20, 22, 23], this piezoelement can be manufactured as rotated *Z* – cut from a large thick PZT block (Fig. 1).

In Fig. 1 *Z* axis is rotated with respect to the crystal *X* axis. The same result will be if the rotation would be with respect to the *Y* axis. Actually, we don't know precisely where in the rectangular PZT block, and especially PZT disc, these axes are. Thus the main requirement is the value of the inclination angle Θ.

Indeed, the inclination angle of the surface of the dual mode piezoelement with respect to the surface of the initial PZT block is the same as the cut angle Θ.

The first experiments were provided with the cut angle Θ=45º, a thin disc diamond saw was used for this procedure. Initially, piezoelement thickness was 0.5 mm. Later the piezoelements were lapped to the smaller thickness, depending on the required frequencies f_L and f_S.

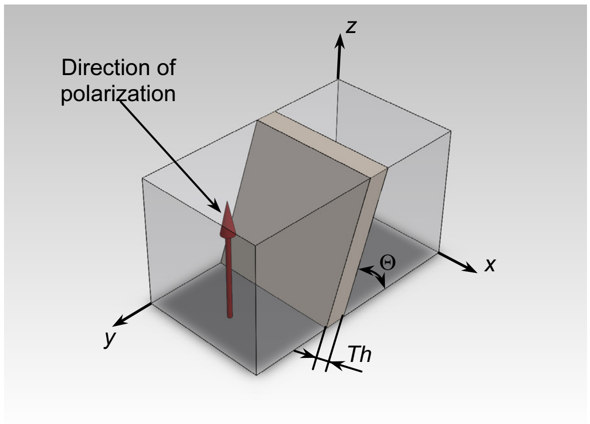

Fig. 1**. Rotated *Z* – cut dual mode *L*/*S* transducer; Θ – cut angle, *Th* – piezoelement thickness**.

During the lapping, piezoelements were bonded onto the precise flat surface with cyanocrylate based fast-acting adhesive. Both sides of the piezoelement are lapped in two steps, consecutively. It is necessary to achieve uniform thickness of the piezoelement in the whole its area. For that purpose a special precise device was manufactured, allowing to fix the necessary thickness in advance. After lapping, the piezoelements are removed from the flat substrate with acetone in an ultrasonic bath. Electrodes are made chemically in electroless nickel (EN) coating bath. At first the sensibilization, activation and reduction procedures were carried out for the coating of the piezoelements. After all these pre-treatments operations the samples are entered into the electroless EN plating bath. The composition of the bath is given in Table 1.

Table 1. **Chemical composition of electroless Ni-P plating**

Chemical	Formula	Concentration
Nickel(II) chloride hexahydrate	$NiCl_2 \times 6H_2O$	40-50 g/l
Ammonium chloride	NH_4Cl	45-55 g/l
Sodium citrate	$Na_3C_6H_5O_7 \times 5.5H_2O$	40-50 g/l
Sodium hypophosphate	$NaH_2PO_2 \times H_2O$	10-20 g/l

The temperature for the reaction process of plating must be in the interval 80÷88 ºC. Its duration was 7 min and 1 µm electrode thickness was achieved. For a better soldering, additionally 2÷3 µm of Ag are covered electrochemically; typical cyanide silver plating solution was applied. After the manufacturing, the piezoelement was tested and *L* and *S* antiresonant frequencies were determined (Fig. 2).

At the 45º cut angle the *S* wave resonance (17 MHz) was stronger than the *L* wave (35 MHz) (Fig. 3). This experimental result confirms the theoretical conclusions.

Contrarily, at the $\Theta = 30º$ cut angle, the *L* wave resonance is stronger (Fig. 4).

The angle $\Theta = 36º$ with equal sensitivities of *L* and *S* waves was found experimentally (Fig. 5). Incredibly, it perfectly coincides with the theoretical value 35.7º [20-23]. The angle $\Theta = 36º$ was determined independently of the theoretical conclusions.

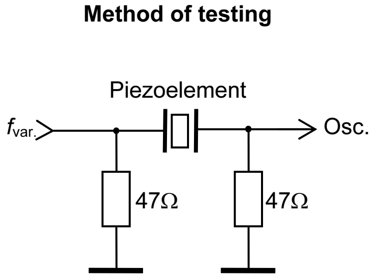

Fig. 2. **Dual mode piezoelement impedance testing method**.

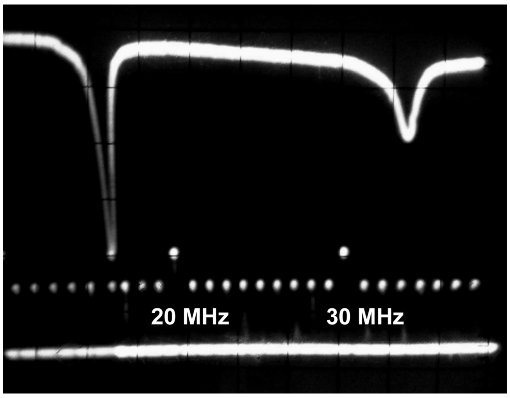

Fig. 3. **At the cut angle Θ = 45° *S* wave resonance (17 MHz) is stronger than the *L* wave (35 MHz). Piezoelement thickness is 64 ÷ 65 µm**.

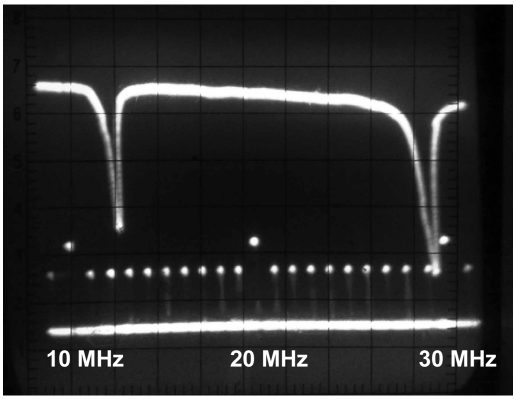

Fig. 4. **At Θ = 30° cut angle the *L* wave resonance is stronger (f_S = 12.5 MHz, f_L = 29 MHz). Piezoelement thickness is about 70 µm**.

In these impedance measurements the piezoelement thickness must be precisely the same in the whole its area. Else, different sites of the piezoelement will be characterized by different frequencies and the resonance peaks will be distorted. The *L* wave resonance is especially sensitive to this distortion, as its frequency is higher (Fig. 6).

Experiments

The piezoelement operating frequencies decrease after it's soldering to a substrate. The rate of this decrease depends on the substrate impedance and bonding method. In our experiments the piezoelements were soldered.

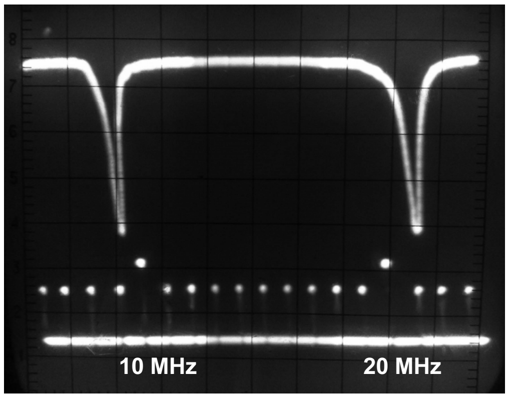

Fig. 5. **At the cut angle Θ = 36° piezoelement sensitivities (peak amplitudes) of *L* and *S* waves are equal. Here piezoelement thickness is 104 µm, thickness variation is within 1 µm, f_L = 21 MHz, f_S = 9 MHz.**

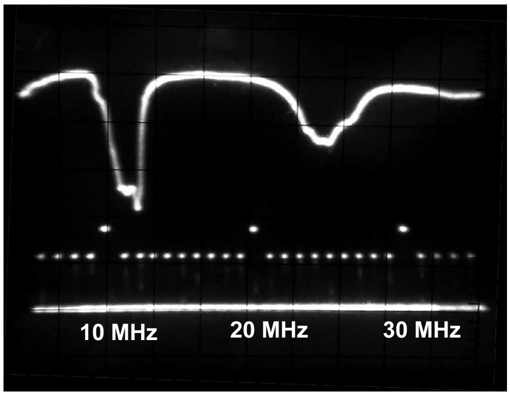

Fig. 6. **Distortion of resonance peaks in the case of non-uniform thickness of the piezoelement: thickness *Th* = 100 µm; Δ*Th* = 10 %.**

(solder 60Sn40Pb, *T*=188 ºC) to the stainless steel (*Z* = 45 MRayl) waveguides and bodies. Thus piezoelements were highly damped and the significant decrease of the frequencies must be expected. For easy soldering stainless steel was electroplated with Ni (solution for stainless steels) and Ag. When the 70 µm thickness piezoelement was soldered to the stainless steel, the *L* wave frequency decreased from 29 MHz to 21 MHz, the *S* wave from 12.5 MHz to 6.5 MHz. For a thinner 45 µm piezoelement this decrease was even larger, more than twice: 47 MHz → 19 MHz (*L*) and 21 MHz → 9 MHz (*S*).

The first practical operation of the piezoelements was investigated when they were soldered to the stainless steel rods with the diameter 10 mm, and the length h = 10 mm or 15 mm. As *L* and *S* wave frequencies are always different, their optimal excitation requires various durations of the excitation pulse.

When the 36º rotated PZT-401 ("Morgan") double mode Ø5 mm 90 µm thickness piezoelement was soldered to the 10 mm rod, the observed *L* and *S* wave pulse responses (back reflections) are shown in Fig. 7.

The L_1 and S_1 are the first back reflections of *L* and *S* waves, the L_2 is the second back reflection of *L* waves. S_1 and L_2 nearly interfere due to the fact, that the *S* wave velocity is almost a half of the *L* wave velocity:

c_S = 3.13 mm/μs, c_L = 5.77 mm/μs. The pulses don't depend on the piezoelement shape - disc or rectangular. When the excitation pulse was optimal for L waves (40 ns), the best signals L_1 and L_2 were observed, the S_1 was reasonably good. When excitation was optimal for S waves (80 ns), the signal S_1 increased, but L_1 and L_2 became distorted. Thus simultaneous measurements can be provided with 40 ns excitation. At lower frequencies (thicker piezoelements) the signals will have larger durations, so, in a shorter body (e.g. 5 mm), the reflections S_1 and L_2 will overlap each other. Contrarily, in a larger 15 mm body these signals are even more separated (800 ns).

Dual mode piezoelements from various PZT piezoceramics were investigated when soldered to similar steel rods. Pz27, Pz29 ("Ferroperm"), CTS-19 (Russian) showed similar operation as "Morgan". The Pz29 piezoelement is very sensitive but has a lower Curie temperature; it can't be soldered with 60Sn40Pb solder, the lower melting temperature is necessary.

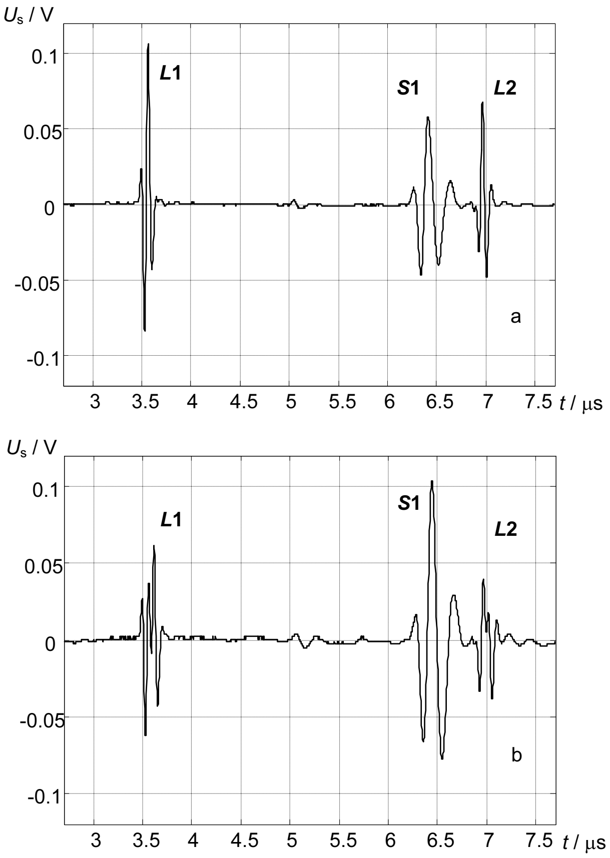

Fig. 7. **L and S wave reflections in a steel rod (Ø10 mm, h = 10 mm): a - excitation pulse duration 40 ns, b - duration 80 ns. Here L_1 and S_1 are the first back reflections of L and S waves, L_2 is the second back reflection of L waves.**

Measuring bodies with dual mode waves may have different geometry. It is routine, that such rods have a step near the end (Fig. 8a) for the temperature measurement possibility [1]. If this end part of a smaller diameter is long, it may serve as well as a load or stress sensor (Fig. 8b).

In such experiments it is requested that the amplitudes of the necessary signals would be of similar amplitudes. It can be achieved coordinating the body geometry, the cut angle Θ and piezoelement dimensions. In a short 17/15 body (Fig. 8a) the piezoelement diameter is 6 mm, it is situated in the centre, its Θ =36º. Wave reflections in this body are shown in Fig. 9.

Both L wave reflections, L_{15} and L_{17}, are ideally identical. S wave reflections amplitudes S_{15} and S_{17} differ; more, the second reflections $L_{15\text{-}2}$ and $L_{17\text{-}2}$ interfere with S_{15} and S_{17}. This can be evaded modifying the body geometry. A long body (Fig. 8b) has its specifics, as in a small diameter part due to a waveguide propagation

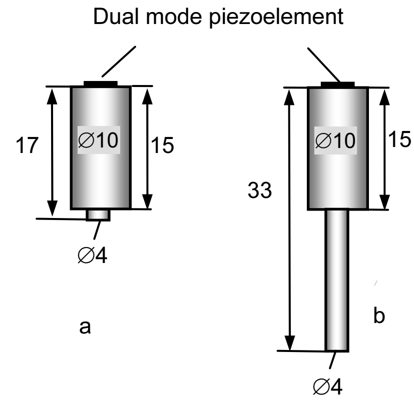

Fig. 8. **Two measurements bodies used for the investigation of double mode wave propagation**

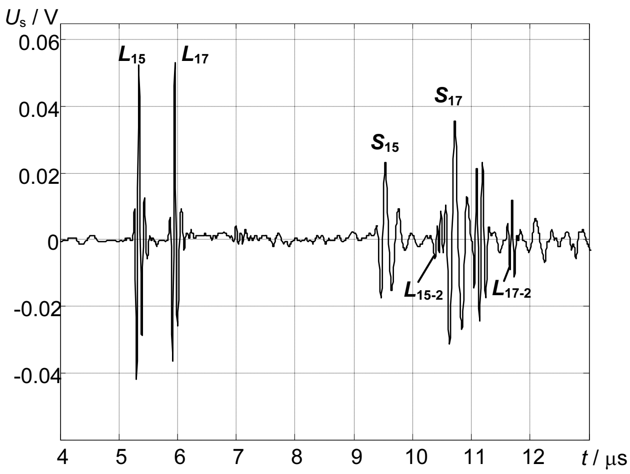

Fig. 9. **Dual mode wave reflections in a short measurement body (17/15), Fig.8a**

spurious signals are observed. They can be eliminated if the cylindrical surface is threaded; thread parameters must correlate with the L and S wavelength in the steel. Thread period 0.22 mm demonstrated good elimination of these spurious signals. Additionally, piezoelement dimensions were modified: better S/N results demonstrated 2×5 mm piezoelement, appropriately centered. With this piezoelement L_{15}, S_{15}, L_{33} and S_{33} reflections are perfectly registered (Fig. 10).

Better results (larger signal amplitudes and S/N ratios) are optimized for "15 mm" (step) and "33 mm" (end) reflections. For example, L_{33} increased from 16 mV (large piezoelement 4×7 mm) to 183 mV (its central disc part Ø2.5 mm). For these conditions, S_{33} increased from 58 mV to 283 mV. The same phenomenon concerns L_{15} and S_{15}

reflections. If a lateral 1.5 mm × 3 mm part of the large 4 mm × 7 mm piezoelement was used, L_{15} signal increased from 38 mV to 156 mV, for S_{15} signal from 24 mV to 115 mV. In this body we escaped from the problem of L wave multiple reflection disturbing influence on the S wave signal; amplitudes can be changed modifying the cut angle Θ, body geometry and especially piezoelement dimensions. So the solution is flexible. After this optimization signal amplitudes reached 400 mV at 10 V excitation pulse, the signal to noise ratio S/N > 100.

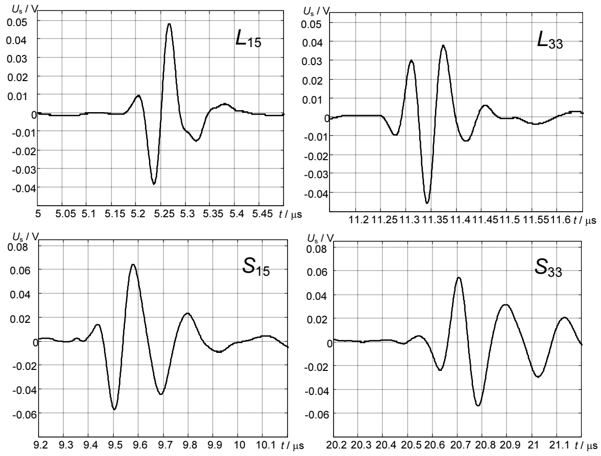

Fig. 10. **Dual wave reflections in a long measurement body (8b)**

Soldering of these PZT piezoelements to the steel body is very reliable if accurately made. Reflections in the 10 mm rod were observed in the temperature range 20 – 160 ºC. The rod was uniformly heated when immersed in silicone oil. The amplitudes of the reflected L and S signals consistently decreased in this temperature range (Fig. 11), but after cooling fully restored.

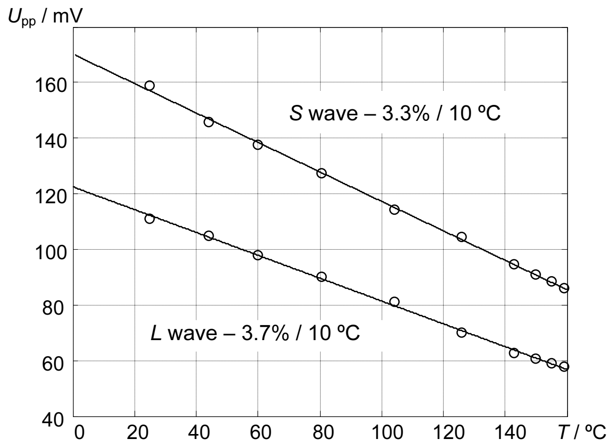

Fig. 11. **The amplitudes of *L* and *S* signals decrease as the temperature grows**

Thus the piezoelement can operate up to 160 ºC reliably. If the solder would be with a higher melting point, higher operation temperatures are expected (up to 250 ºC, as the Curie temperature is T_C=350 ºC for this Pz27). Finally, the delay times of the L and S wave reflections were measured as a function of an axial load. For that purpose the tip of the body was pressed via Teflon layer and the pressure was measured directly in MPa.

For a better accuracy, the time differences were measured:

$$\Delta t_{(S_{33}-L_{33})} = \varphi(P); \quad (1)$$

$$\Delta t_{(L_{33}-L_{15})} = \varphi(P). \quad (2)$$

For both cases good linear dependencies were obtained (Fig. 12 and 13). These are the initial data for calculation of stresses according to the literature formulae [1].

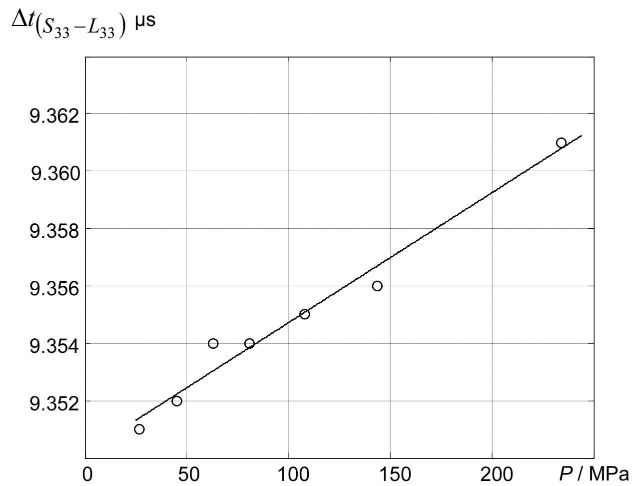

Fig. 12. **Time difference $\Delta t_{(S_{33}-L_{33})}$ as a function of an axial load in a long measurement body (Fig. 8b)**

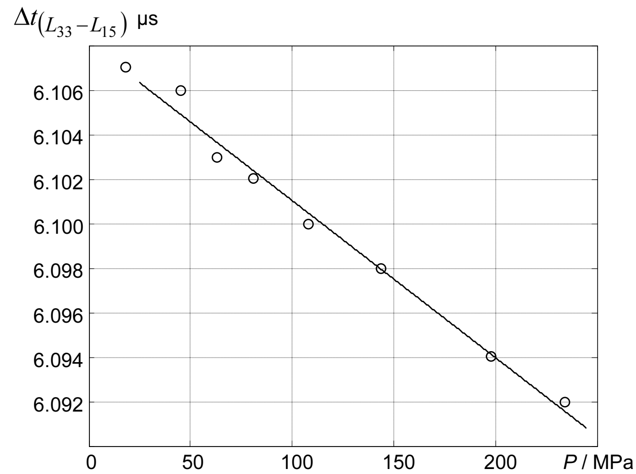

Fig. 13. **Time difference $\Delta t_{(L_{33}-L_{15})}$ as a function of an axial load in the same body (Fig. 8b).**

Conclusions

Dual mode longitudinal and shear wave pjezoelements were manufactured from a thick PZT block using rotated cut method.

At the 36º cut angle equal efficiency of longitudinal and shear waves was obtained. By variation of the cut angle one or another mode can be emphasized. The piezoelement thicknesses were in the range 45-100 µm.

Electrodes were made chemically in electroless nickel (EN) coating bath. Additionally electrodes were covered by 2-3 μm of silver electrochemically. Such piezoelements can be soldered perfectly with 60Sn40Pb solder to steel substrates. The piezoelement operation in a temperature range 20-160^o C was good. Axial load experiments up to 234 MPa were provided and corresponding linear the time-of-flight dependencies were determined for longitudinal and shear waves. Experiments showed eligible performance of dual mode PZT ultrasonic transducers.

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Išilginių ir skersinių ultragarso bangų generavimas: literatūros apžvalga, švino–cirkonio–titanato (PZT) pjezoelementų sukūrimas ir eksperimentai

Reziumė

Apžvelgiami žinomi išilginių ir skersinių bangų generavimo pjezokeitikliai: kvarco ir ličio niobato pjezoelementai, kampu orientuoti CsS ir ZnO pjezosluoksniai. Daugiausia dėmesio skiriama PZT keramikai. Aptariami žinomi teorinių tyrimų rezultatai. Išilginių ir skersinių bangų dviejų modų PZT keitiklių gamybos technologija sukurta taikant skirtingus PZT pjūvio kampus ir pjezoelementų storius. Pjezoelementų elektrodai gaunami cheminio nikeliavimo būdu paskui jie elektrochemiškai padengiami sidabru. Eksperimentiškai nustatyta, kad dviejų modų pjezoelementams vienodai tinka įvairių tipų PZT keramika. Iš impedanso matavimų nustatyti išilginių ir skersinių bangų rezonansiniai dažniai. Tyrinėtų pjezoelementų storiai buvo 45 – 100 μm. Esant 36^o pjūvio kampui, gaunamos vienodo intensyvumo išilginės ir skersinės bangos. Šie pjezoelementai buvo lituojami prie plieno užlaikymo linijos ir specialios formos pavyzdžių. Matavimai buvo atliekami esant iki 160^o C temperatūrai ir iki 234 MPa ašiniam slėgiui. Eksperimentais patvirtintas geras dviejų modų pjezoelementų darbas.

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