HIGH FREQUENCY TRANSDUCER DEVELOPMENT FOR ULTRASONIC TESTS ON CERAMIC COMPONENTS

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INTRODUCTION

The detection of critical flaws in ceramics requires the use of high frequency ultrasonics. Whilst shorter wavelengths are necessary to detect low micrometer range flaws, so the higher the frequency, the higher the attenuation and so ultimate power and sensitivity is required from examining transducers. This paper outlines the development of such devices. Satisfactory transducers in the frequency range 30-100 MHz are not available commercially and the characteristics of a number of piezoelectric materials for the purpose of their development are being established. Properties such as composition, electrodes, backing and lenses are being investigated.

In the present paper, one material (Sodium Potassium Niobate, SPN), and its use in transducers is discussed. SPN was selected for its attractive coupling coefficient, high sound velocity (thick elements) and low dielectric constant.

CHOICE OF MATERIALS FOR HIGH FREQUENCY TRANSDUCERS

Piezoelectric materials can be classed into three groups (Fig. 1) i.e. single crystals, polymers and piezoelectric ceramics. With single crystals and polymers the electromechanical coupling coefficient \(k_{33}\) is very low. The highest in these two groups is lithium niobate which, when cut along the 36° Y axis, can be used to generate compressional waves, but other wave modes are also excited. Single crystals do not allow composition changes so that the bandwidth \((Q_m)\) and the dielectric constant cannot be altered. For this reason they were considered unsuitable for high-frequency ultrasonic transducers.

In contrast, piezoelectric ceramics allow an endless number of compositions and manufacturing procedure variations, facilitating the development of required characteristics \([1,2]\). Coupling coefficients \((k_{33})\) are usually between 30 and 70% and dielectric constants vary from 200 to 4000. The special requirements of high frequency transducers can be fulfilled by elements in this group.
Fig. 1. Choice of materials for high frequency transducers.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>k_{33}</th>
<th>Dielectric Constant</th>
<th>Acoustic Impedance Tg/m²s</th>
<th>Sound Velocity km/s</th>
<th>t for 100 MHz (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINGLE CRYSTALS</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Quartz</td>
<td>10</td>
<td>4.5</td>
<td>14</td>
<td>5.7</td>
<td>29</td>
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<tr>
<td>Lithium sulfate</td>
<td>38</td>
<td>10.3</td>
<td>11</td>
<td>5.5</td>
<td>27</td>
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<tr>
<td>Lithium niobate</td>
<td>45</td>
<td>3.0</td>
<td>34</td>
<td>7.3</td>
<td>37</td>
</tr>
<tr>
<td>POLYMERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyvinyl di fluoride (PVDF)</td>
<td>10</td>
<td>10</td>
<td>4</td>
<td>2.3</td>
<td>12</td>
</tr>
<tr>
<td>PIEZOELECTRIC CERAMICS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-zirconate-titanate (PZT)</td>
<td>60-70</td>
<td>400-4000</td>
<td>30</td>
<td>3.3</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Lead Metaniobate</td>
<td>40</td>
<td>300</td>
<td>20</td>
<td>3.3</td>
<td>16</td>
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<tr>
<td>Lead titanate</td>
<td>50-60</td>
<td>200</td>
<td>35</td>
<td>4.0</td>
<td>20</td>
</tr>
<tr>
<td>Sodium-potassium niobate (SPN)</td>
<td>42</td>
<td>400</td>
<td>31</td>
<td>7.0</td>
<td>35</td>
</tr>
</tbody>
</table>

Fig. 2. Grain structure of SPN hot-pressed element.

MATERIAL QUALITY

The transducer elements, which are a half wavelength in thickness, become exceedingly thin and fragile for frequencies above 30 MHz. The stronger and denser the material, the thinner it can be ground. Densities >99% of theoretical with grain sizes in the 2-3 µm range can be obtained by hot-pressing fine powder compositions (Fig. 2). The more common sintering
process produces 96% density and 2 to 15 μm grain sizes. Hence, hot pressing provides greater control and a stronger end product. Hot pressed fine-grained elements have been lapped <60 μm and incorporated into transducers. (35 μm corresponds with 100 MHz for SPN).

SELECTED MATERIALS FOR TRANSDUCER ELEMENTS

The program of investigation involved PZT-4, PZT-5, PZT-7 and SPN in both the sintered and hot-pressed condition. SPN was favored for its high compressional wave velocity and low dielectric constant. Its coupling coefficient was sufficiently high. The high sound velocity allows a thicker element for the same frequency and this is an advantage where the thickness is the critical parameter. SPN, with 6.9 km/s was considerably better than the best of the PZT's (4.9 kg/s). In terms of a 100 MHz element, this means 35 μm of SPN, vs 25 μm for the best PZT.

The capacitance of an element with electrodes increases rapidly with decreasing thickness according to the following relation;

\[ C = \frac{\varepsilon_r \cdot \varepsilon_0 \cdot A}{t} \]

where
\[ C \] = capacitance (farad)
\[ \varepsilon_r \] = dielectric constant (dimensionless)
\[ \varepsilon_0 \] = free space dielectric constant \( (8.85 \times 10^{-12}) \) F/m.
\[ A \] = area \( (m^2) \)
\[ t \] = distance between electrodes \( (m) \)

To maintain as small a capacitance as possible, \( \varepsilon_r \) and the area (diameter) should be small and \( t \) large. But \( t \) must be small for 100 MHZ and a certain element area is needed to provide enough power for the ultrasonic test. This leaves \( \varepsilon_r \) as the only controllable variable. Here too SPN was the best with \( \varepsilon_r = 380 \), with PZT-7 a close second at \( \varepsilon_r = 450 \). Other PZT's had much higher dielectric constants.

The acoustic impedance of SPN is 31 Gg/m².s. This value is lower than that of PZT-7 (39 Gg/m².s) allowing a slightly better contact with water (1.5 Gg.m².s), and a closer match to backing materials.

The other overriding quality of SPN was the reproducibility with which elements could be manufactured from it.

THE POLING OF THE PIEZOELECTRIC ELEMENTS

Man-made piezoelectric elements must be poled to develop their piezoelectric properties. If all dipoles of an element were aligned, the output would be 100%. Dipoles can be classed in two categories; 180°-dipoles and non-180° dipoles (referred to as mechanical dipoles) (Fig. 3a). During poling, the 180° dipoles completely switch (Fig. 3b) with no internal material stresses. The mechanical dipoles can be forceably aligned in the poling direction but with considerable internal stress development due to structural changes [3] (Fig. 3c). These structural changes cause an increase in the sound velocity in the poling direction and this change can be precisely measured (Fig. 4). By forcing more and more mechanical dipoles to align, the sound velocity could be increased by 9% and the planar coupling factor could be pushed >70% for some materials. The resulting internal stresses will eventually exceed the material strength and micro-cracking will occur throughout the element. Material poled to a high degree is also unstable for use as a transducer. Repeated electrical excitation allows a number of the mechanical dipoles to return to a lower stress condition with the resultant loss of signal strength and decrease in frequency.
POLING OF PIEZO-ELECTRIC CERAMICS

Fig. 3a, b and c.

Fig. 4. Increase in sound velocity due to poling.
Clearly poling must be kept below the internal cracking range [4] but stability with time can be improved via an aging process (200°C for 2 hours) which anneals the internal stresses whilst maintaining most of the mechanical dipole orientation. The coupling coefficient and the sound velocity are also reduced somewhat but the element is stable with time.

TRANSUDCERS USING SPN ELEMENTS

The elements were fitted with silver electrodes and mounted in a holder. Contact wires were attached and the holder filled with backing material. The assembly was placed in a housing which attached to a precision scanner.

TRANSUDCER LENSES

At high frequencies, epoxy lenses absorb an appreciable amount of sound. Experiments with aluminum lenses showed promising results and could also be used as the front electrode of the transducer. Furthermore, they were changeable, giving a transducer of variable focal length. Figure 5 shows 3 transducers, the 30 MHz one having the interchangeable lens capability.

TRANSUDCER EXCITATION

Very thin elements cannot withstand high voltage shock pulses (150 V), yet the thinner the element, the weaker the output so the more excitation is needed. Consequently wave train excitation was used wherein several low voltage oscillations (e.g. 30 V) set the element in motion. The output was maximized by tuning the applied pulse frequency to the element resonant frequency.

Fig. 5. Three transducers (Al lens exchangeable).
It was discovered that the low-damped SPN transducers could also be excited at lower frequencies (sub-harmonic excitation) and an example of this is shown in Figures 6(a), (b), and (c). Some of the lower frequencies produced stronger signals than the resonant frequency as sound absorption in the lens and water at high frequencies decreased the round trip efficiency.

**SOUND BEAM PROFILING OF THE SPN TRANSDUCERS**

Beam profiling was carried out by scanning the transducers over tiny targets. Targets much larger than the focal diameter of the transducer were used to detect the beam stepdown from an edge. These results allowed determination of the beam diameter. A limit of 90% of the signal on target and 10% off the target was chosen. On targets much smaller than the focal diameter, (0.2 mm $\phi$) a profile of the local sound field strength was obtained. Early attempts at making transducers yielded a non-uniform field strength near the focus. Later transducers exhibited much more uniformity, (Fig. 7) and compared favorably with commercial transducers of lower frequency.

The axonometric of Fig. 7 was made digitally so all the parameters are precise and can be used for measurement purposes. The resulting composite profile is shown in Fig. 8. If the top of the cone is cut 3 dB below the peak, the computer prints the $-3$ dB profile. This and the $-10$ dB and $-20$ dB profiles were retrieved and are included. The figure indicates a) the quality of the transducer, b) the diameter of the focus and c) the length of the useful portion of the focus (Fig. 8).

![Fig. 6 (a). 50 MHz transducer, excited at 50 MHz.](image)
Fig. 6 (b). 50 MHz transducer excited at 25 MHz.

Fig. 6 (c). 50 MHz transducer excited at 10 MHz.
The efficiency of the SPN transducers

The most important parameter of any ultrasonic transducer is the signal-to-noise ratio. No matter how weak or strong the signal, if the S/N ratio is small, the transducer cannot be used. S/N ratios for the SPN transducers constructed in this work were in excess of 90 dB, a number typical of piezoelectric ceramics.
CONCLUSIONS

SPN elements for ultrasonic transducers were made in dense and pure form. They were strong and uniform and were lapped down to 30 μm thickness (>100 MHz). They had a capacitance low enough to allow high frequency excitation and an output useful for high frequency transducer construction for ultrasonic testing.

REFERENCES