High Frequency Piezo-Composite Transducer Array
Designed For Ultrasound Scanning Applications.

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ABSTRACT: A 20 MHz high density linear array transducer is presented in this paper. This array has been developed using an optimized ceramic-polymer composite material. The electro-mechanical behaviour of this composite, especially designed for high frequency applications, is characterised and the results are compared to theoretical predictions.

To support this project, a new method of transducer simulation has been implemented. This simulation software takes into account the elementary boundary phenomena and allows prediction of inter-element coupling modes in the array. The model also yields realistic computed impulse responses of transducers.

A miniature test device and water tank has been constructed to perform elementary acoustic beam pattern measurements. It is equipped with highly accurate motion controls and a specific needle-shaped target has been developed. The smallest displacement available in the three main axes of this system is 10 microns.

The manufacturing of the array transducer has involved high precision dicing and micro interconnection techniques. The flexibility of the material provides us with the possibility of curving and focusing the array transducer.

Performance of this experimental array are discussed and compared to the theoretical predictions.

The results demonstrate that such array transducers will allow high quality near field imaging. This work presents the efforts to extend the well known advantages of composite piezoelectric transducers to previously unattainable frequencies.

INTRODUCTION

Over the last years, constant development and technological progress of ultrasound scanners have led to significant improvements in image quality. New applications, including intravascular, superficial and ophthalmic ultrasound imaging have in parallel focussed the primary requirements in terms of higher spatial resolution associated with good penetration and doppler sensitivity.

To meet these objectives, operating frequency has been increased to the range of 10 to 20MHz, and in some cases, above 50MHz with single element or annular array [1].

This work represents the continuation of the development of high frequency transducer arrays [2]. Preliminary studies have covered the design and fabrication of high frequency ceramic array.

This paper is specifically related to the development of arrays made from piezoelectric composite material, designed to operate at nominal frequency up to 15 - 20 MHz.

The objective aims to push the performance of composite material in this upper range of frequency and to combine the competitive characteristics of this technology in term of sensitivity and resolution.

GEOMETRIC AND ACOUSTIC DESIGN OF THE ARRAY

Arrays have been designed to comply with high frequency imaging applications. Main characteristics are described hereafter.

Specifications of the transducer:
Nominal frequency: 20MHz
Shape of array: linear
Nb of elements: 128
Elevation focus: 12mm
Pitch: 110µm
Elevation height: 2.5mm
Bandwidth: 50%
Cross coupling: ≤ -30 dB

The 12mm geometrical focus is based on clinical experiences to optimize penetration and lateral resolution. Focal parameters (-6dB) have following values: focal point:10.6mm, focal length:9.84mm, and focal width (at 10.6mm): 0.28mm.
Electrical conditions are defined as follow:
100 Vcc negative excitation pulse
2 meters of 50pF/m coaxial cable
tuning coils (serial or parallel inductor)

**TRANSDUCER MODELLING**

Uni-dimensional models for piezoelectric transducer do not include element interactions and take only into account the thickness mode. Usually, designer considers the ceramic vibration as the pure mode, and the crosstalk negligible, thus, classical models (1D model) such as Mason or KLM are sufficient to predict transducer behaviour.

**Model**

Transducer array elements have to be modeled by a bi-dimensional method; however, in the past, it has been demonstrated that when the ratio W/T (width/thickness) is smaller or equal to 0.6 [3], the uni-dimensional model still works, except for neighboring element contribution. Fig 1a 1b.

Based on the works carried out by Pappalardo and Lamberti [4] each array element is considered to be loaded on each lateral side by a semi-infinite medium. In this condition, the lateral contribution is considered as comparable to the contribution of a Lamb wave zeroeth order mode [5], these modes radiate energy into the medium, and their velocity is nearly equal to 2000 m/s.

In order to calculate transducer waveforms, the 2D model takes into account the induced longitudinal vibration of the adjacent elements. Fig.2a,2b,2c,2d

**Acoustic radiating pattern modelling**

Developed in collaboration with the GIP ultrasound laboratory, the ARAPS (acoustic radiating pattern simulation) software programme was started in 1985. It is based on the diffraction impulse theory, and calculates the spatial contribution of any element of the array; the crosstalk is represented by enlarging the element aperture.
The software features include apodisation functions, polar and cartesian scanning, 128 channels aperture, 1ns delay pitch etc.

![Array Amplitude Plot](image1)

*Figure 3: The figure 3 shows the calculated array amplitude plot in the elevation plane.*

**ARRAY FABRICATION**

Manufacturing of the array requires specific arrangements in term of composite processing and matching layers fabrication. The composite is composed of PZT ceramic and hard epoxy.

The transducer backing material has a 3.5 MRayls acoustic impedance, and its attenuation is higher than 5 dB/mm/MHz.

Currently, a 35 µm thick single front layer is deposited on the transducer, this layer exhibits an attenuation coefficient less than 0.3 dB/mm/MHz; multi-layer version is being perfected and results will be available subsequently.

The transducer overall thickness is less than 1mm.

**PIEZO-COMPOSITE DESIGN**

Our main concern was to achieve a 1-3 composite material which exhibits a low cross-talk between longitudinal and lateral modes.

First, different sets of composite characteristics have been modelled to optimize the lateral mode in term of amplitude and frequency. The methodology is to model a said composite with different kerfs and to evaluate the polymer influence on lateral mode. The selected composite configuration for this study is summarized hereby: 55% of ceramic volume fraction and 55µm of pitch, the final thickness is 95µm in order to offer 20MHz anti-resonance frequency.

![Composite Electrical Impedance](image2)

*Figure 4: The curve-plot above shows electrical impedance of composite at optimized thickness, the first resonance (15.6MHz) corresponds to longitudinal mode and the second (28MHz) lateral mode.*

**EXPERIMENTAL ARRAY EVALUATION**

**Acoustic measurement bench**

To carry out accurate measurements of the prototype, the water tank is equipped with 0.01mm step of displacement to allow acoustic radiating pattern and directivity angles control. The positioning device is composed of 4 axis (3 translations, 1 rotation), the array is located on the bottom of the water tank, and the needle hydrophone is moving above.

**Directivity measurement**

Directivity angle measurement has been performed by rotating the element around the elevation axis and looking at the hydrophone located on the focal point. Results were compared to theoretical calculations including adjacent element crosstalk.

**Pulse echo measurement setting**

- **Pulser/Receiver:** Panametrics 5052PR
- **damping:** 50Ω
- **energy:** 1
- **gain:** 20dB
- **attenuator:** 20dB
- **filter:** none

**Medium:** degassed water at 20°C

**Target:** flat (stainless steel) for waveform, needle hydrophone for radiating pattern.

**Electrical measurement setting**

Electrical characteristics were measured with a HEWLETT-PACKARD 4195A network/spectrum analyzer.
MEASUREMENT/SIMULATION COMPARISON

Measurement of the array impedance

<table>
<thead>
<tr>
<th>Element Capacitance</th>
<th>32 pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z Modulus (20MHz)</td>
<td>535 Ω</td>
</tr>
<tr>
<td>Phase (20MHz)</td>
<td>-56 deg</td>
</tr>
</tbody>
</table>

Figures 5a and 5b: show the real and imaginary impedance of an array element loaded by the water. The above table summarizes the basic characteristics.

Modelling datas:
- Velocity: 3850 m/s
- Impedance: 17 MRayls
- Transverse velocity: 2100 m/s
- Keff: 0.5
- Composite Thickness: 0.095 mm
- F.Layer velocity: 2543 m/s
- F.Layer impedance: 3.5 MRayls

Simulated Waveform and Spectrum

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency</td>
<td>18.6 MHz</td>
<td>17.9 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>51.3 %</td>
<td>48.5 %</td>
</tr>
<tr>
<td>Axial Resol -6dB</td>
<td>96 ns</td>
<td>111 ns</td>
</tr>
<tr>
<td>Axial Resol -20dB</td>
<td>232 ns</td>
<td>179 ns</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>n.a*</td>
<td>-46.4 dB</td>
</tr>
</tbody>
</table>

* not applicable.

Cable length and the quality of electrical environment are important in order to obtain optimized transducer sensitivity and bandwidth. The final center frequency measured on the prototype could be slightly changed depending on electrical environment.

Crosstalk
The curveplot, Fig 9, depicts the electromechanical crosstalk between two adjacent elements, cares must be taken to avoid potential disturb due to wires length. The crosstalk measured on the array (-36dB) lets expect good perspective for side-lobe levels.
Angular response in azimuth

The table hereafter shows the comparison between theoretical and experimental angular responses of an array element.

<table>
<thead>
<tr>
<th></th>
<th>theoretical</th>
<th>theoretical including crosstalk</th>
<th>experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directivity (-6dB)</td>
<td>45.2 deg</td>
<td>44 deg</td>
<td>42 deg</td>
</tr>
</tbody>
</table>

CONCLUSION

A new generation of high frequency linear array using 1-3 composite is described. A set of simulation tools has been carried out for modelling composite behaviour, electro-acoustic performance (Simul2D) and acoustic radiating beam pattern (ARAPS). This study demonstrates the possibility of manufacturing composite with higher frequency than currently done. This type of composite will allow novel applications in ultrasound imaging; the prototype hereby performed opens the way to new possibilities of diagnosis even intravascular arrays using circular or cylindrical shape. Performances of this array could be considered as comfortable, regarding to current applications.

Bibliographies