Design and construction of ultrasonic Doppler transducers for blood flow measurement using Finite Element Analysis

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Abstract

This paper describes the design and construction of two ultrasonic Doppler transducers using Finite Element Analysis for blood flow measurement. These transducers were constructed using as sensing element, commercial 8 MHz PIC255 piezoceramic discs, EPO-TEK 301 and Rexolite 4422 as backing and matching layer materials respectively. The objective of this work was to design and construct two single element transducers for pulsed wave Doppler blood flow measurement, one with an angle of 30° to 45° and another with no angle (0°), both resonating at approximately 5 MHz. These transducers should work with the associated electronics using a quadrate demodulation for the blood flow Doppler ultrasonic signal detection.

Keywords: Finite Element Analysis, Doppler transducer, Blood flow measurement, ANSYS.

Introduction

An ultrasonic transducer converts electrical energy into acoustic energy during transmission when its active element is excited by a voltage or current signal. Conversely, during reception, the acoustic energy of the returned ultrasound is converted into an electrical signal. The active elements of transducers used in diagnostic medicine depend on piezoelectric effect for their operation. The most commonly used materials for these active elements are piezoelectric ceramics for example made of lead Zirconate Titanate (PZT) [1].

Different design and construction models with these piezoelectric elements are described in this paper regarding the application of a pulsed Doppler blood flow detector device for a bidirectional Doppler ultrasonic system for the evaluation of coronary bypasses.

Design

The goal is to design and construct a single element transducer for pulsed wave Doppler blood flow measurement with included known angle of 30° to 45° and the frequency of 8 MHz. This transducer should work with the electronic device using a quadrate demodulation for the blood flow Doppler ultrasonic signal detection.

The detection device brings as output the Doppler signals I (In phase) and Q (in Quadrate) in audible range. A personal computer sound card line in is fed with these signals for its processing. The sampling volume is limited to carry out the superficial monitoring on arteries of 2 – 4 mm of diameter for coronary bypasses.

Special attention should be taken to the easy construction with available materials. Therefore materials are introduced and described regarding the use in the transducer.
Ultrasonic matching materials

The coupling of energy between an ultrasonic transducer and some transmission medium (e.g. blood in vessels or water) is maximized when the medium and transducer have the same specific acoustic impedance. Any mismatch in impedance results, in the case of ultrasound generation, in a proportion of the generated energy being reflected back into the transducer and being lost through absorption and leakage from the back face of the transducer. A similar energy loss in the medium occurs where the transducer acts as a receiver of ultrasound.

An ultrasonic matching layer is a passive layer, which is fixed to the front face of an ultrasonic transducer in order to improve the coupling of energy to and from the transmission medium. Under narrow-band conditions, coupling is maximized when the thickness of the matching layer is equal to one quarter of the wavelength (or an odd multiple of a quarter wavelength) of the energy being transmitted (see figure 2).

![Fig 1. ultrasonic transducer with backing and front matching material](image)

Wide bandwidth and sensitive ultrasonic transducers are needed in numerous medical and non-destructive applications.

As the characteristic impedance of the PZT ($Z = 33 \text{ MRayl}$) is greater than that of water or blood ($Z = 1.5 \text{ MRayl}$), the $0^\circ$ transducer must be matched.

In order to match the piezoelectric transducer to a vein or artery, matching layers must be used. Theoretically, solutions proposed in the literature consist in using one or more quarter-wave layers on the front face of the transducer.

Without having the technology for the $\lambda/4$ matching, the research for materials is focused on impedance matching between the piezoceramic made of PZT and the human vessel. In addition some other materials for the construction are introduced; the need of easy handling and forming makes epoxies an attractive material to work with.

Ultrasonic backing materials

The backing is most commonly a highly attenuate and very dense material and is used to control the vibration of the transducer crystal by absorbing the energy that radiates from the back face of the piezoelectric element. When the acoustic impedance of the backing material matches that of the piezoelectric crystal, the result is a highly damped transducer with excellent resolution. By varying the backing material in order to vary the difference in impedance between the backing and the piezoelectric crystal, a transducer will suffer somewhat and resolution may be much higher in signal amplitude or sensitivity.

Materials

A. Piezoceramics

Piezoelectric ceramics belong to the group of ferroelectric materials. Ferroelectric materials are crystals which are polar without an electric field being applied. This state is the thermo-dynamically stable reversibility of the axis of polarization under the influence of an electric field, described graphically by a hysteresis loop. The reversibility of the polarization, and the coupling between mechanical and electrical effects are of crucial significance for the wide technological utilization of piezoceramics.

The main piezoceramics in use today are made of PbTiO$_2$ they are synthesized from the oxides of lead, titanium and PbTiO$_2$ zirconium. Special doping of these lead-zirconate-titanate ceramics (PZT), for example used in PIC 155 and PIC 255 [2], make it possible to adjust individual piezoelectric and dielectric parameters as required.
PIC 255

PIC 255 is a modified PZT material with extremely high Curie temperature, high permittivity, high coupling factor and high charge constant. The material has been optimized for actuator applications under dynamic conditions and high ambient temperatures. The high coupling factor, low mechanical quality factor and low temperature coefficient make this material particularly suitable for low-power ultrasonic transducers.

PIC 155

PIC 155 is a modification of the PIC 255 material distinguished by high piezoelectric stress coefficients and lower frequency constants. It is used in applications where a high g-constant is required, such as in microphones.

Table 1 piezoelectric elements used; from PI ceramics

<table>
<thead>
<tr>
<th>position</th>
<th>part number</th>
<th>device</th>
<th>material</th>
<th>dimensions</th>
<th>frequency</th>
<th>decades</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>POY-V-2506</td>
<td>10</td>
<td>PIC</td>
<td>plate 10mm x 10mm x 1mm</td>
<td>2.8 MHz</td>
<td>silver (screen)</td>
</tr>
<tr>
<td>2</td>
<td>POY-V-0110</td>
<td>20</td>
<td>PIC</td>
<td>plate 20mm x 10mm x 1mm</td>
<td>8.6 MHz</td>
<td>silver (screen)</td>
</tr>
<tr>
<td>3</td>
<td>PRK-V-0112</td>
<td>10</td>
<td>PIC</td>
<td>disc 0.5 mm x 10mm x 1mm</td>
<td>8.0 MHz</td>
<td>silver (screen)</td>
</tr>
<tr>
<td>4</td>
<td>PRK-V-0206</td>
<td>10</td>
<td>PIC</td>
<td>disc 0.5 mm x 20mm x 1mm</td>
<td>2.3 MHz</td>
<td>CoNi (screen)</td>
</tr>
</tbody>
</table>

B. Front matching materials

- **Rexolite 4422**

Rexolite has outstanding dielectric properties with a dielectric constant of 2.53 (up to 500GHz) together with extreme low dissipation factor and excellent acoustic impedance close to water. Velocity 93x10^2 cm/second. It’s valuable for microwave lenses, microwave circuitry, antennae, coaxial cable connectors, sound transducers, TV satellite dishes and sonar lenses. Other uses include non-destructive material testing devices, surveillance equipment, radar windows, radomes and missile guidance system housings. One interesting application is for radar lenses which are used for mapping the earth’s surface from fast high-flying aircraft.[3], [4], [5], [6], [7], [8], [9], [10]

- **Insulcast 501 American Safety Tech. Roseland, NJ**
  - Density 3.86 g/cm^3
  - Velocity 1900 m/s
  - Impedance 7.3 MRayls
  - Loss 13.8 dB/mm

- **EPO-TEK 301 Epoxy Tech., Billerica, MA**
  - Density 1.15 g/cm^3
  - Velocity 2650 m/s
  - Impedance 3.05 MRayls
  - Loss 9.5 dB/mm

- **Parylene Specialty Coating systems, Indianapolis**
  - Density 1.18 g/cm^3
  - Velocity 2200 m/s
  - Impedance 2.8 MRayls
  - **Araldite 502**
  - Density 1.16 g/cm^3
  - Velocity 2620 m/s
  - Impedance 3.04 MRayls

C. Backing materials

- **E-SOLDER 3022 Conductive epoxy Von Roll Isola Inc., New Haven CT**
  - Density 3.20 g/cm^3
  - Velocity 1850 m/s
  - Impedance 5.92 MRayls
  - Loss 110 dB/mm

- **Conductive Epoxy CW2400**
  - The acoustic properties of the conductive Epoxy CW2400 are not known.

Simulations

To check the materials used in the construction, ANSYS simulations were done and measurements of the ceramics, the backing material and the front matching material were carried out using the frequency analyzer, One example of the simulation is shown in figure 3.
Using the ANSYS tool, the vibration mode of the PIC255 piezoceramic disc was simulated, figure 2 shows the displacement of the disc when this is excited (intermediate displacements, minimum and maximum stress).

**Construction**

Two different models of construction are presented. These two transducers based on different design ideas were constructed and tested. Both show a certain function together with the hard- and software device for the blood flow measurement in the phantom as well as in tests directly at the vein of the arm through the skin. To get the full characterization about the transducer amongst others the Impedance and phase over frequency has to be analyzed.
Transducer

In figure 4, the two different models including the design ideas are shown. Both consist of two tubes, one inner plastic tube as carrier material for the ceramic and one outer metallic tube as protection case. The 0° transducer uses an undefined non-conductive epoxy as backing material. The connection between the (+) electrode and the coaxial wire is bonded with a droplet of conductive epoxy. The front electrode is also bonded with conductive epoxy to a wire, which is guided through a channel on one site from the plastic tube to the inside coaxial wire. The backing material of the 35° transducer is completely made of conductive epoxy. This allows easy handling of the connection to the piezoceramics and to the plastic tube as well as the connection to the coaxial wire.

Results

After construction both transducers were tested using an impedance analyzer, a frequency sweep from 1 to 10 MHz was done to verify their oscillating frequency. Results (see figure 5) showed that the simulated performance of both transducers was achieved. The observed oscillating frequency was 5.83 MHz, the frequency shift was probably due to the soft-layer and the backing material used in the construction (see figure 6) of both transducers.

Fig 4. models of the two ultrasonic transducers constructed

Fig 5. Frequency and phase response using the impedance analyser from a) 0° transducer and b) 30° transducer.

Fig 6. Ultrasonic transducers

To improve the acoustic properties and consequently the sensibility of the transducer a front matching is needed. For example Rexolite can fill out the space between the ceramic and the vessel; so that the acoustic waves are guided in this front matching material and just two reflection sites exist. Figures 7 and 8 show...
Conclusions

The design and construction of two different transducers were presented. These two transducers based on finite element analysis were constructed and tested. Both showed a good performance when working with the associated electronics for blood flow measurement in the phantom as well as in tests directly with real veins. To get a full characterization of the transducers, the impedance and phase over a frequency range was analyzed.

As already mentioned in the results section, after construction both transducers were tested using an impedance analyzer, a frequency sweep from 1 to 10 MHz was done to verify their oscillating frequency. Results showed that the simulated performance of both transducers was achieved. The observed oscillating frequency was 5.83 MHz, the frequency shift was probably due to the soft-layer and the backing material used in the construction of both transducers.

Results show that the overall performance of the transducers fulfills the requirements of their design using Finite Element Analysis and it is possible to use them in blood flow measurement applications.

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References