Design, Fabrication and Testing Highly Sensitive Single Element Doppler Transducers

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Abstract —Three common piezoelectric materials have been studied for use in pulsed wave Doppler ultrasound, where high sensitivity is required, while bandwidth is less important. A large transducer aperture, 80 mm^2, results in a low electrical impedance, making the transducers challenging to drive with conventional electronics and cables. Air-backed transducers with electrical tuning circuitry and cable assembly were made using the piezoelectric materials Pz24, Pz27, and Pz29. Pz24 is a hard PZT, with dielectric constant of 240, the other materials are soft PZT with dielectric constants around 1000. It was found that the transducer made with Pz24 gave 2 dB better two-way sensitivity compared to those made with the other PZT-variants. The improved performance is explained by the higher electrical impedance from using Pz24.

Keywords— Doppler, High Sensitivity, Transducer, Ultrasound

I. Introduction

Doppler measurements is a common diagnostic ultrasound technique used to detect blood flow or muscle movement. Echoes scattered by the red blood cells carry information about the velocity of the blood. These echoes are weak, so the transducer should have a high sensitivity, while a large bandwidth and short pulse length are less important. The aim of this study was to design, build, test, and compare a variety of single element ultrasound transducers optimized for high sensitivity.

Three different piezoelectric materials were tested, Pz29, Pz27 and Pz24 (Meggitt A/S, Kvistgaard, Denmark). Soft piezoelectrics, e.g. Pz29 and Pz27, having large dielectric constant ϵ_r are commonly preferred in medical ultrasound applications. However, for single-element Doppler transducers having a large aperture area, the resulting high capacitance and low impedance may be difficult to drive electrically, especially through a long, thin cable. Hence, for this particular application, a hard piezoelectric with lower ϵ_r , e.g. Pz24, might be preferred.

II. Method

A. Design

All transducers were designed for 8 MHz center frequency. The transducers were aimed at high sensitivity with less requirements to the bandwidth, so a solution with one acoustic matching layer in front and air backing was chosen. The matching layer thickness was, based on transmission line theory [1], set to be a quarter of the wavelength in the matching layer material. Two different geometries were investigated, one rectangular and one circular. The active element of the rectangular transducers was 16 mm by 5 mm, while that of the circular transducers was 10 mm diameter, giving close to equal active aperture areas.

Piezoelectric materials with high coupling coefficients were selected to achieve high sensitivity. Conventional soft PZT materials, Pz27 and Pz29 were chosen due to their frequent use in medical ultrasound transducers. However, for this frequency the surface area 80 mm^2 is large. This gives a low electrical impedance, which makes the active elements hard to drive. To investigate the effect of this, a "hard" PZT material, Pz24, with low dielectric constant, was also tested. A list of the central material properties is given in Table 1. An electrical tuning network was implemented to match the electrical impedance to 50 Ω. The one-dimensional Mason model [2] was used to predict the performance of the transducers prior to fabrication, and when evaluating the fabricated transducers. SolidWorks 2016 (Dassault Systems SolidWorks Corp. Waltham, MA) was used to design models for encapsulation of the transducers.

Table 1 –Properties of the piezoelectric materials [3]

Property	Unit	Pz24	Pz27	Pz29
Electromechanical coupling coeff. k_t	(-)	0.508	0.469	0.524
Piezoelectric constant d_{33}	pC/N	149	425	574
Clamped dielectric constant $\epsilon^S_{33r}/\epsilon_0$	(-)	239	914	1220
Dielectric Loss $tan\ \delta$	(-)	0.002	0.017	0.016
Density	kg/m^3	7700	7700	7460
Longitudinal wave velocity	m/s	4851	4331	4498
Characteristic acoustic impedance	MRayl	37.35	33.35	33.56

B. Transducer Fabrication

The piezoelectric plates and discs came polarized in the thickness direction and had silver painted electrodes. A matching layer of Eccosorb MF112 (Laird N.V. Geel, BE) was lapped down to the desired thickness. The matching layer was made larger than the piezoelectric, to act as support when mounting the transducer in the housing. This allows the piezoelectric element to be air-backed and have unclamped edges, see Figure 2 for illustration. After lapping, the matching layer was covered with a tape-mask, sputtered with a seed layer of chrome to promote adhesion, before sputtering on a conductive layer of gold.

The PZT was bonded to the sputtered matching layer using epoxy (Scotch-Weld Epoxy Adhesive DP460, 3M, Maplewood, MN). Conductive silver epoxy was used to connect wires to the electrode on the back of the PZT and to the gold sputtered on the matching layer. Silver epoxy was chosen to allow easy assembly and avoid localized heating from a soldering iron, which could cause de-poling.

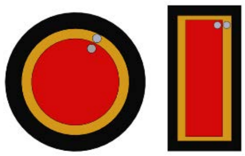

Figure 1 – The two transducer geometries used, circular aperture with diameter 10 mm diameter and rectangular with dimensions 5 mm by 16 mm. Red indicates the piezoelectric, gold indicates the sputtered surface of the matching layer, and black indicates the unsputtered surface of the matching layer. The grey dots show where wires were attached using silver epoxy.

A stereolithographic 3D-printer was used to print the models designed in SolidWorks, shown in Figure 2. The transducer stack was assembled in the bottom compartment the main house, and the tuning electronics in the upper. A flat disc was put on to seal the upper compartment after assembly.

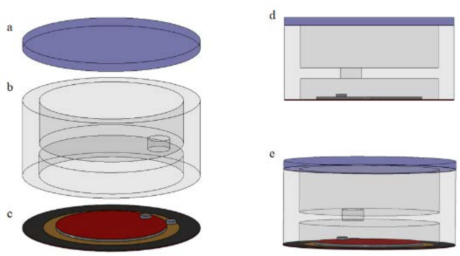

Figure 2 – Design of the circular transducer-stack and housing components. (a) The cover to seal the transducer housing. (b) Main housing. (c) Piezoelectric with a single matching layer. (d) Side-view of the three parts assembled. (e) Assembly tilted at an angle for a 3D-impression

The transducers were electrically matched to 50 Ω, by adding a parallel inductor, 0.15µH for Pz27 and Pz29 and 0.47µH for Pz24, and a transformer with turns ratio 2:1. The housed transducers were electrically shielded to reduce pick-up of environmental noise. This was achieved by sputtering a layer of chrome and then gold, covering the whole transducer assembly. The finished transducer was connected to a tri-axial cable, where the two inner conductors were interconnected with the piezoelectric, and the outer conductor was connected to the shielding of the transducer housing.

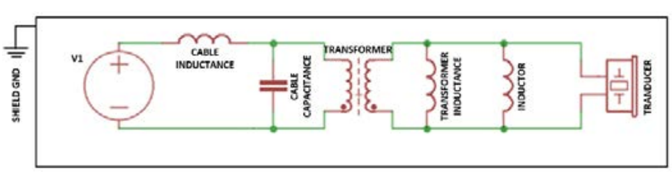

Figure 3 – Circuit diagram of the shielded transducer with tuning components and cable. The LC circuit represents the cable. The whole diagram is enclosed in a Faraday cage, consisting of the outer shield of the triaxial cable and the chrome-gold enclosing the transducer housing..

C. Characterization

Fabricated transducers were characterized by electrical impedance measurements, acoustic beam profile measurements and acoustic pulse-echo measurements. Electrical impedance was measured in air and in water using a network analyzer (Rohde & Schwarz ZVL, Munich, Germany).

Beam profiles were measured in an Onda AIMS III measurement tank (Onda Corp. Sunnyvale, CA), controlled by Onda AIMS Soniq 5.2 software. The transducers were driven by a Manus Scanner (Aurotech, Tydal, Norway). The resulting sound beams were scanned laterally at a fixed distance, using an Onda HGL-0200 hydrophone with an AG-2010 Preamplifier, calibrated in the frequency range 1 to 20 MHz. The output was digitized at 250 MSa/s in a Picoscope PS5244A analog to digital converter (Pico Technology. St Neots, UK), and digitized pulses transferred to a computer to be stored and analyzed in Matlab.

Two-way sensitivity of the transducers was investigated in a pulse-echo system, using an 18 mm diameter stainless steel sphere as reflector. The reflector was positioned for maximal reflection at a fixed lateral position, 157 mm away from the transducer.

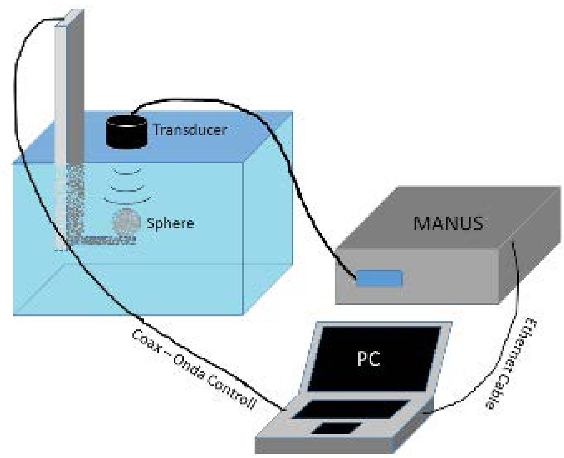

Figure 4 - Pulse-echo system for measuring the sensitivity of the transducers. The reflector was a stainless steel sphere positioned for maximal reflection, 157 mm from the transducer. A Manus scanner was used to drive the transducers, and acquire the received echoes. Received pulses were transferred to a computer, to be stored and analyzed in Matlab.

III. Results

Five transducers were fabricated and characterized. Three were made with rectangular aperture, two using Pz27 and one with Pz29, and two with circular aperture, one with Pz29 and one with Pz24. A picture of two of the finished transducers can be seen in Figure 5.

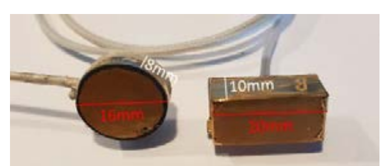

Figure 5 – Two finished transducers.

A. *Electrical Impedance*

Measured electrical impedance of the three piezoelectric materials is shown in Fig. 6. The Pz24 sample is circular, while the Pz27 and Pz29 samples are rectangular. The surface area of the three elements are close to equal, and therefore comparable. Note the higher impedance in the Pz24 sample.

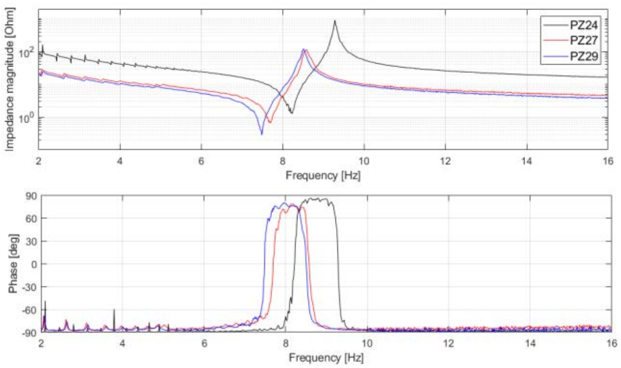

Figure 6 – Electrical impedance of the piezoelectric plates, without matching layers, measured in air.

Electrical impedances of the finished transducers measured in water is shown in Fig. 7. These transducers have a single acoustic matching layer, are electrical tuned to 50 Ω, and have similar cable lengths.

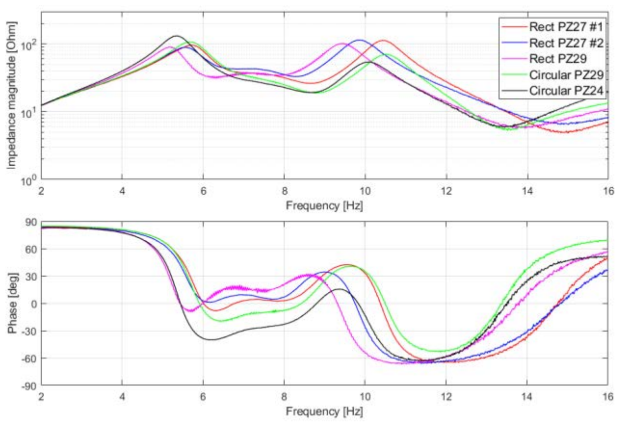

Figure 7 – Electrical impedance measured in water for the compete transducer assemblies, including tuning and cable.

B. *Beam Profile Measurements*

Fig. 8 shows the beam profile of the circular aperture transducer from Pz29, and one of the rectangular aperture transducers with Pz27. All are measured at 3 mm distance from the transducer surface, with 100 μm lateral resolution.

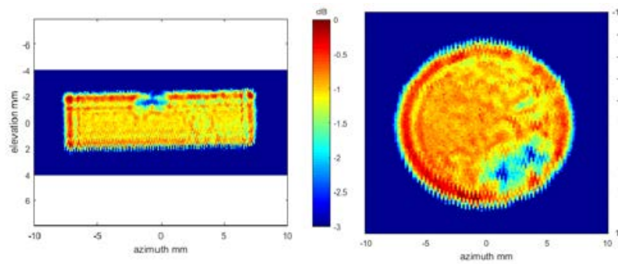

Figure 8 – Beam profile of transducers at 3 mm distance from the transducer. The left panel shows one rectangular aperture transducer made from Pz27, the right panel shows the circular aperture transducer made from Pz29

C. *Pulse Echo Using Sphere Reflector*

The pulse echo measurement setup was used to compare the sensitivity between the transducers. The envelope of the received signals was acquired after around 210 μs, corresponding to 157 mm distance between the transducer and reflector. Envelopes of the received echoes are shown in Fig. 9, and corresponding power spectra in Fig. 10. The envelope verifies that the distance between transducer and reflector was the same, and gives an indication of the signal to noise ratio.

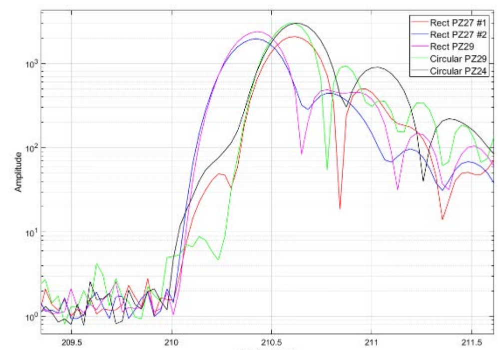

Figure 9 – Envelope of the received signal from a stainless steel sphere reflector at 157 mm distance from the transducer.

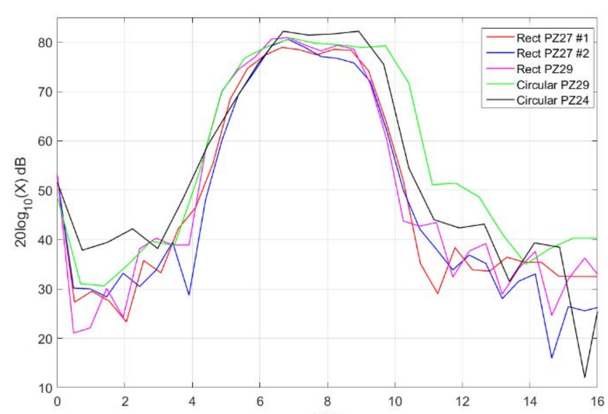

Figure 10 – Power spectra of the received signals in Fig. 9.

IV. Discussion

A. Electrical Impedance

The large surface area of the aperture results in a low impedance, which may make the transducers difficult to drive. This was the reason for including the 'hard' Pz24 material, with its low dielectric constant. This is seen in the electrical impedance results in Fig. 6. However, after tuning with transformers, the finished transducers show similar electrical impedances. The slightly lower phase of two circular transducers in the resonance region may be explained by imprecise thickness of the matching layer, or by the tuning components. After tuning, the impedance magnitude at 8 MHz was between 20 and 40 Ω and the phase within ±25 degrees, for all transducers, when measured in water. For all transducers, tuning circuitry was able to move the impedance into a region suitable for conventional driving electronics. However, this tuning has to be placed at the transducer end of the cable, thereby increasing its size and weight, which may not always be acceptable. The impedance measurement on the Pz24 transducer demonstrate how this material can be chosen to achieve a higher impedance, avoiding a tuning transformer.

B. Beam Profile

The beam profiles in Figure 8 show small regions with reduced radiated energy. This corresponds to the positions where wires were connected to the back-electrode of the PZT using silver epoxy. This absorbed some energy, causing a 3 dB reduction in transmitted energy. This result demonstrates that the influence of the wire connection is not negligible, a careful application of silver epoxy is important to minimize the influence on the transducer vibrations, while ensuring a secure connection.

C. Pulse Echo

From Figure 9, it can be seen that the peak of the transducers named "Rect PZ27 #2" and "Rect PZ29" have a slight offset compared to the others. This is explained by a small inaccuracy in the positioning of the measurement setup, and does not influence the results.

When comparing the spectra in Figure 10, it can be seen that the two transducers with rectangular aperture made with Pz27 are not identical. The transducer "Rect PZ27 #2" has an uneven top with its peak at 6.8 MHz, while the transducer "Rect PZ27 #1" has a more flat top. The difference at 8 MHz is 1 dB, and may be explained by process variations, e.g. inaccuracies in thicknesses of the matching and bonding layers. The third rectangular transducer "Rect PZ29" displays the same uneven top as the transducer "Rect PZ27 #2", and has 0.6 dB higher sensitivity than "Rect PZ27 #1". This can be explained by the higher coupling coefficient, k_t, of the Pz29 material, as seen in Table 1.

Of the transducers with a circular aperture, the transducer made with Pz24 yielded a 2 dB-improved sensitivity over the transducer made with Pz29. The lower permittivity of Pz24 gives a higher electrical impedance, which for this large element area makes it easier to drive.

The transducers made with a circular aperture have an overall higher sensitivity than the rectangular transducers, due to the different beam pattern from the two geometries. Overall, the transducers performed well, with signal strength 75 to 85 dB above the recorded noise level. The -3dB bandwidth for the transducers was found to between 30% and 40%, which is suitable for the pulsed wave Doppler application they were targeted at.

V. Conclusion

We have designed, built and tested transducers made from three different piezoelectric materials. The transducers were targeted at pulsed Doppler applications, where high sensitivity is a major requirement, while the bandwidth requirement is more relaxed. The resulting large aperture area causes a low impedance, which is challenging for the driving electronics.

Two conventional soft PZT materials with high coupling coefficients, Pz27 and Pz29, were compared to a hard PZT, Pz24, with low dielectric constant. The results show that the transducers performed similarly, but using the hard Pz24 made it possible to increase the sensitivity by 3 to 5 dB compared to the other materials.

Acknowledgment

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References

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